Vaasan yliopisto
UNIVERSITY OF VAASA

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Distributed Control Strategy for Energy Storage Systems in AC Microgrids

Towards a Standard Solution

ACTA WASAENSIA 356

ELECTRICAL ENGINEERING 5

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Julkaisija
Vaasan yliopisto

Julkaisupäivämäärä
Syyskuu 2016

Tekijä(t)
Omid Palizban

Julkaisun tyyppi
Artikkeliväitöskirja

Julkaisusarjan nimi, osan numero
Acta Wasaensia, 356

Yhteystiedot
Vaasan yliopisto
Teknillinen tiedekunta
Energiatekniikka
PL 700
FI-65101 VAASA

ISBN
978-952-476-694-4 (painettu)
978-952-476-695-1 (verkkojulkaisu)

ISSN
0355-2667 (Acta Wasaensia 356, painettu)
2323-9123 (Acta Wasaensia 356, verkkojulkaisu)
1799-6961 (Acta Wasaensia. Sähkötekniikka 5, painettu)
2343-0532 (Acta Wasaensia. Sähkötekniikka 5, verkkojulkaisu)

Sivumäärä
174

Kieli
englanti

Julkaisun nimike
Energiavarastojärjestelmien hajautettu säätöstrategia vaihtojännitteisissä mikrosähköverkoissa: Tavoitteena standardiratkaisut

Tiivistelmä

Energiavarastot ovat merkittävä osa mikrosähköverkkoa. Tässä väitöskirjassa esitellään akkupohjaisten energiavarastojen hajautettu säätötapa, joka perustuu kunkin yksittäisen akkuvaraston energia- eli varaustasoon. Menetelmän toimivuus on verifioitu simulointien avulla. Akkuvaraston varaustason poikkeama määritellään sekundäärisellä säätötasolla. Sieltä se välitetään primääriselle säätötasolle, jossa tehty ohjaus palauttaa varaustason haluttuun ohjearvoon. Primäärisellä säätötasolla käytetään muokattua P/f-Q/V droop-säätöä, joka ottaa huomioon akkujen varaustason.

Säätö asettaa droop-kertoimet perustuen kunkin akkuvaraston varaustasoon siten, että kerroin on kääntäen verrannollinen varaustasoon akun purkamisen aikana ja suoraan verrannollinen akun latauksen aikana. Tällä säätöstrategialla varastoyksikkö, jolla on korkein (alin) energiataso, syöttää enemmän (vähemmän) tehoa kuormaan varastojen toimiessa tuotantoyksikköinä ja vastaanottaa energiaa pienemmällä (suuremmalla) teholla sähkön tuotannon ylittäessä kysynnän.

Viime vuosina on pyritty löytämään standardiratkaisuja mikrosähköverkkoihin ja tähän liittyen väitöskirjassa ehdotetaan IEC/ISO 62264 standardin soveltamista mikrosähköverkkoihin ja energiavarastoihin. IEC/ISO 62264 standardissa määritellään viisi tasoa, joilla on samat tavoitteet aivan kuten hierarkkisessa mikrosähköverkkojen ja energiavarastojen säädössä. Kehitettyä säätömenetelmää on tässä väitöskirjassa arvioitu myös sovelletun standardin kannalta perustuen IEC/ISO 62264 standardin eri tasojen määritelmiin ja vastaaviin hajautetunsäädön tasoihin.

Asiasanat
Hajautettu säätö, energiavarastojärjestelmät, hierarkkinen säätö, mikrosähköverkko, IEC 62264 standardi

Publisher Vaasan yliopisto	**Date of publication** September 2016	
Author(s) Omid Palizban	**Type of publication** Doctoral thesis by publication	
	Name and number of series Acta Wasaensia, 356	
Contact information University of Vaasa Faculty of Technology Energy Technology P.O. Box 700 FI-65101 Vaasa Finland	**ISBN** 978-952-476-694-4 (print) 978-952-476-695-1 (online)	
	ISSN 0355-2667 (Acta Wasaensia 356, print) 2323-9123 (Acta Wasaensia 356, online) 1799-6961 (Acta Wasaensia. Electrical Engineering 5, print) 2343-0532 (Acta Wasaensia. Electrical Engineering 5, online)	
	Number of pages 174	**Language** English

Title of publication

Distributed Control Strategy for Energy Storage Systems in AC Microgrids: Towards a Standard Solution

Abstract

The energy storage system is a major part of a microgrid. A decentralized control system for battery energy storage that operates on the basis of the energy level of each storage unit is presented in this doctoral dissertation together with some simulation based verifications. The deviation of the SoC in the secondary control level is determined here through proposed secondary control and sent to the primary control to restore it. The primary level uses the *P/f–Q/V* droop control method, and a modified droop control in the primary level based on the SoC of the storage units is also employed here.

To set the droop coefficients based on the energy level of each storage unit, the droop coefficient is inversely proportional to the energy level during the discharging period and directly proportional during the charging period. When this strategy is implemented, the storage unit with the *highest* (*lowest*) energy level provides *more* (*less*) power to support the load when the storage unit operates as a power supplier, and absorbs *less* (*more*) power when the power generated exceeds the demand.

Over the last several years, efforts to standardize MGs have been made, and it is in light of these advances that the current doctoral dissertation also proposes the application of IEC/ISO 62264 standards to MGs and ESSs. The IEC/ISO 62264 standard has five levels, with the same objectives at each level as the hierarchical control of MGs and ESSs. Considering the definitions of each level of the IEC/ISO 62264 standard and the matching roles of the levels in decentralized control, the proposed method is also evaluated based on the adopted standard.

Keywords

Distributed control , Energy storage system, Hierarchical control, Microgrid, IEC 62264 standard

ACKNOWLEDGEMENT

This work has been carried out at the Smart Electric System (SES) research group of the Department of Electrical Engineering and Energy Technology, University of Vaasa (UVA) from 2012 to 2016. Part of the research behind this thesis has been conducted within the Smart Grids and Energy Market (SGEM) research program of CLEEN Ltd. and funded by Finnish Funding Agency for Technology and Innovation (Tekes). Furthermore, part of the doctoral dissertation has been supported by UVA graduate school through two years of scholarship grants.

First of all, I would like to express my gratitude to the Almighty for His infinite kindness. Next, I am indebted to the supervisor of this work, **Professor Kimmo Kauhaniemi**, and I wish to express my deepest gratitude to him for his guidance, encouragement, and valuable contributions during this work and his long-time support of my research path. I am also thankful to **Professor Josep M. Guerrero** of the Department of Energy Technology, Aalborg University, Denmark, for his excellent advice and experience in encouraging my publications and thesis. Moreover, I would also like to express thanks to **Mr. Timo Kankaanpää**, who first introduced me to the leader of SES research group.

I thank the preliminary examiners, **Professor Olli Pyrhönen** from Lappeenranta University of Technology (LUT) and **Associate Professor Alberto Borghetti** from the University of Bologna for their valuable feedback and comments, as well as their genuine interest in the topic and their willingness to engage in the pre-examination process.

In addition, I would like to thank my research colleagues at SES research laboratory who have created a great atmosphere for carrying out research work.

September 2016

Omid. Palizban

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Abbreviations

ANM	Active network management
BESS	Battery energy storage system
BESU	Battery energy storage unit
BMS	Battery management system
CAES	Compressed air energy storage
DCS	Decentralized control strategy
DER	Distributed energy resource
DESS	Distributed energy storage system
DG	Distributed generation
DLC	Double layer capacitor
DR	Distributed resource
ESS	Energy storage system
ESU	Energy storage unit
FES	Flywheel energy storage
MG	Microgrid
MGCC	Microgrid central controller
MS	Micro source
MV	Medium voltage
PCC	Point of common coupling
PCS	Power converter system
PHS	Pumped hydro storage
PV	Photovoltaic
RES	Renewable energy source
SMES	Superconducting magnetic energy storage
SoC	State of charge
LV	Low voltage

List of symbol

E	Source voltage of the equivalent circuit
f	Frequency
f^{ref}	Reference of frequency
f_{mg}	Frequency in MG
f_{mg}^{ref}	Reference of frequency for MG
f_{BESU}^{ref}	Reference value of frequency in BESU
$\bar{f}_{BESU_k}$	The average frequency of $BESU_k$
$G_{p(v/f/Q)}$	Proportional gain for (voltage/frequency/reactive power) in different control levels
$G_{i(v/f/Q)}$	Integration gain for (voltage/frequency/reactive power) in different control levels
G_{PP}	Proportional gain for active power at the tertiary level compensator
G_{PS}	Proportional gain for SoC control
G_{iS}	Integration gain for SoC control
N	Number of BESUs
P	Active power
P^{ref}	Reference of active power
P_{grid}	Active power (grid side)
Q	Reactive power
Q^{ref}	Reference of reactive power
Q_{grid}	Reactive power (grid side)
Q_{BESU_k}	The reactive power of unit k
$\bar{Q}_{BESU_k}$	The average reactive power of $BESU_k$
R	Resistor

SoC_{BESU_k}	The SoC of BESU$_k$
$So\overline{C}_{BESU}$	The average value of the SoC
SoC_{Total}	The sum of the SoC values
$T_{P(s)}$	Droop Coefficient of active power
$T_{Q(s)}$	Droop Coefficient of reactive power
$T_{P(N_{kd})}$	Droop coefficient value for discharging period
$T_{P(N_{kch})}$	Droop coefficient for the charging period
V	Voltage
V^{ref}	Reference of voltage
V_{mg}	Voltage in MG
V_{mg}^{ref}	Reference of voltage for MG
V_{BESU}^{ref}	Reference value of voltage in BESU
$\bar{V}_{BESU_k}$	The average voltage of BESU$_k$
X	Inductance
θ	Phase-angle difference between the two voltages
δf_s	Synchronization term
δ_{SoC_k}	The control signal in the secondary control level
Δf	Deviation of frequency
Δf_{BESU_k}	Restoration value of the frequency
ΔQ_{BESU_k}	Restoration value of the reactive power
ΔV	Deviation of Voltage
ΔV_{BESU_k}	Restoration value of voltage

List of publications:

The dissertation is based on the following appended papers:

1. Omid Palizban, Kimmo Kauhaniemi "*Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode*" Elsevier, Renewable and sustainable energy review, Volume 44, page797-813, 2015
2. Omid Palizban, Kimmo Kauhaniemi "*Energy Storage Systems in Modern Grids – Matrix of Technologies and Applications*" Elsevier, Journal of Energy storage, Volume 6, Page 248-259, 2016.
3. Omid Palizban, Kimmo Kauhaniemi, Josep M. Guerrero "*Microgrid in Active Network Management-Part I; Hierarchical Control, Energy Storage, Virtual Power Plant and Market Participation*" Elsevier, Renewable and sustainable energy review, Volume 36, page 428-439, 2014.
4. Omid Palizban, Kimmo Kauhaniemi, Josep M. Guerrero" *Microgrid in Active Network Management-Part II; System Operation, Power Quality and Protection*" Elsevier, Renewable and sustainable energy review, Volume 36, page440-451, 2014.
5. Omid Palizban, Kimmo Kauhaniemi "*Distributed Cooperative Control of Battery Energy Storage System in AC Microgrid Applications*" Elsevier, Journal of Energy storage, Volume 3, page 43-51, 2015.
6. Omid Palizban, Kimmo Kauhaniemi, Josep M. Guerrero "*Decentralized Secondary Control of Energy Storage Systems in Autonomous Microgrids*", Submitted to IET Generation, Transmission & Distribution Journal 2016.
7. Omid Palizban, Kimmo Kauhaniemi, Josep M. Guerrero "*Evaluation of the Hierarchical Control of Distributed Energy Storage Systems in Islanded Microgrids Based on Std IEC/ISO 62264*" IEEE-PES General Meeting, Boston, USA , 17th -21st July 2016.

1 INTRODUCTION

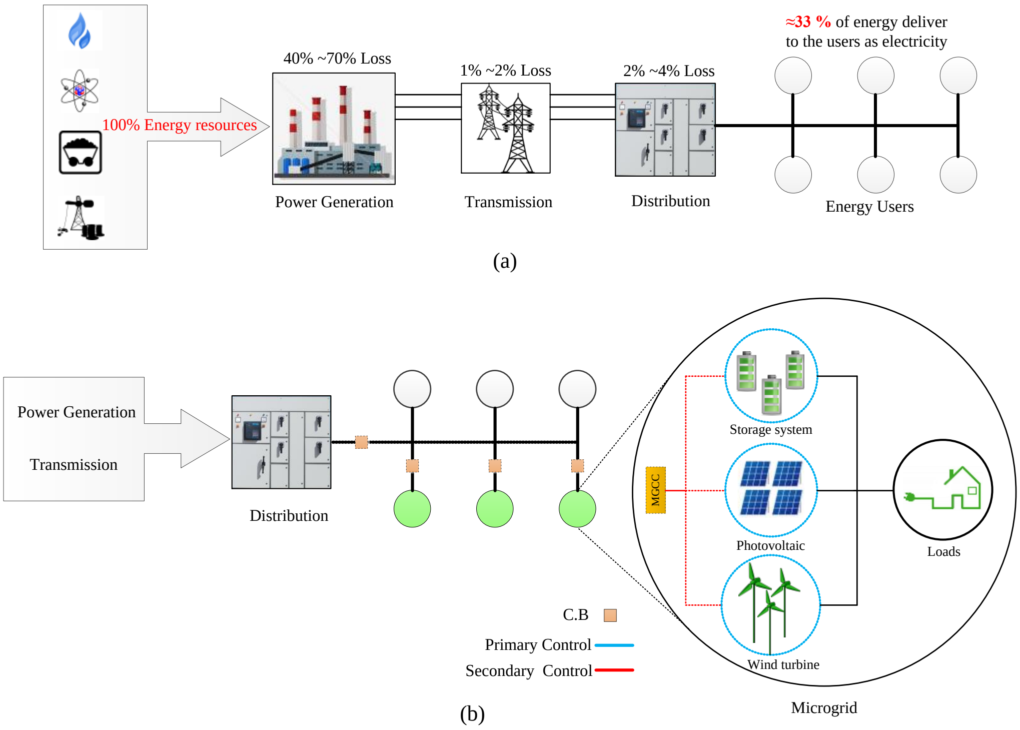
1.1 Microgrids

In recent years, the structure of the electrical power system has changed, and power generation has shifted towards Distributed Generation (DG). Although the increase in the demand for energy and environmental concerns about traditional power generation have been mentioned as reasons for this shift, another crucial motive is the large amount of energy lost in traditional methods: when power is generated from fossil fuels, 40%–70% of the energy present in the resource is lost as heat. Another 2% and 4% is then lost in transmission lines and distribution, respectively. Overall, as shown in Figure 1.1(a), just 33% of the energy input to generation makes it to the user as electricity. Unlike conventional systems, DGs are installed beside the load and use low-capacity power generation resources, which may also include renewable energy sources (Fig. 1.1 (b)). Solar energy (photovoltaic cells) (Markvart, 2000; Parida, 2011; Singh, 2013) and wind turbines (Gipe, 2004; Kling, 2002; Martinez, 2004) are the most popular of the Renewable Energy Sources (RESs) that can be integrated into the main network in the form of DGs or Microgrids (MGs). Indeed, MGs consist of a number of such DG systems (Ackermann, 2001; Barnes, 2007; Gu, 2014; Lasseter, 2002; Logenthiran, 2008; Pogaku, 2007) organized together in a way that increases the system capacity and improves the power quality (Li, 2009; Palizban, 2015).

There are three different types of benefits associated with MGs: technical, economic, and environmental. From the technical point of view, DGs can support the power of remote communities and give higher energy efficiency while lacking the vulnerability of large networks and helping to reduce blackouts (Abu-Sharkh, 2006; Li, 2009). Economically, DGs reduce emissions, line losses, and interruption costs for the customer while minimizing the cost of fuel, ancillary services, and so on (Basu, 2011). The environmental benefits of MGs are discussed in (Morris, 2012), and include lower emissions of pollutants and greenhouse gases, a generation system that requires a smaller physical footprint, an increase in the number of clean energy sources incorporated in the grid; and decreased reliance on external fuel sources.

MGs may be found in low voltage (LV) and medium voltage (MV) distribution networks, and can operate in grid-connection mode or island mode (Guerrero, 2013; Guerrero, 2011; Katiraei, 2005). The switching between these operation modes is controlled through a circuit breaker at the Point of Common coupling

(PCC) (Kroposki, 2010; Sao, 2008). Moreover, MGs can be categorized as AC microgrids (Hatziargyriou, 2007; Katiraei, 2008) or DC microgrids (Kwasinski, 2011; Shafiee, 2014).



(a)

(b)

Figure 1.1 (a) Energy losses in traditional grid (b) Concept of new power generation methods

The general configuration of a hybrid (AC–DC) MG is shown in Figure 1.2. Indeed, the power output by most of the DGs is DC, while the DG sources outputting AC have high levels of variation in frequency and voltage, and thus cannot be directly connected to the AC bus. A power electronic interface is thus needed to implement the MGs. The main control objectives in an AC MG are voltage stability, frequency synchronization, loads sharing considering inverter ratings, and managing power to create ancillary services for the main grid. On the other hand, there are some advantages to DC MGs over AC MGs: they are highly efficiency because of the reduction in conversion loss; frequency and phase control is not required, and there is no need for synchronization. Indeed, the main control objectives in DC MGs are adjusting the DC voltage to the acceptable value, sharing power based on the rate of conversion, and regulating the current flow to or from an external DC source (Shafiee, 2014). However, the AC MGs are still dominant, especially in island applications, because of their similar intrinsic characteristics to traditional distribution systems. Since the present research has focused on load sharing and power management in an island MG, it is only AC MGs that have been considered in this doctoral dissertation.

Without the doubt, in modern grids, power management and stability assurance are critical because of the variables involved on the generation and demand sides. Using energy storage to absorb and inject energy as needed can be the best solution to managing this issue (Gellings, 2009; Guerrero, 2008; Chuanwen, 2008). In fact, energy storage systems (ESSs) are crucial in both AC and DC MGs.

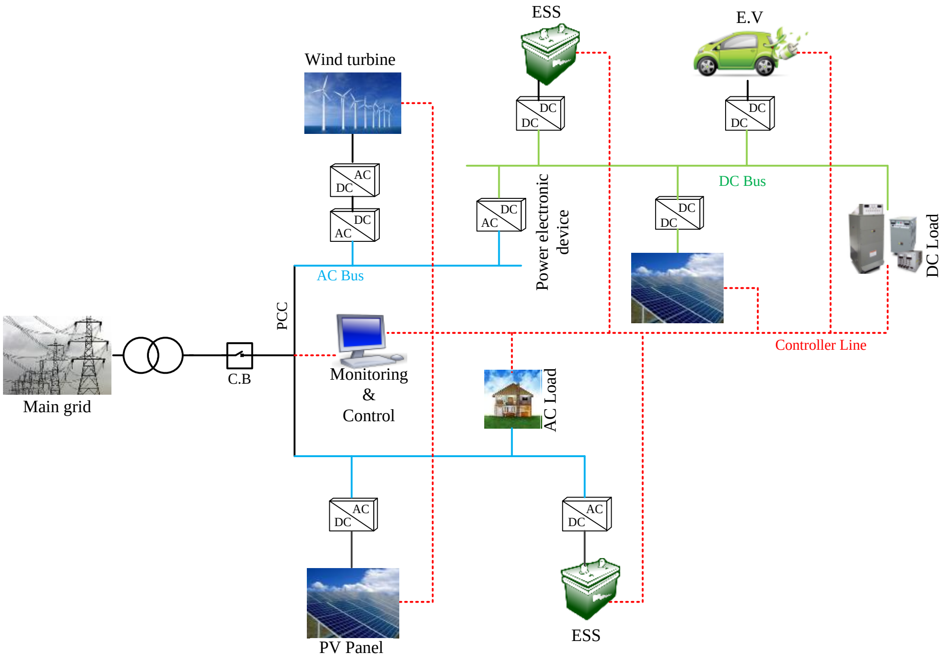


Figure 1.2 General view of a Hybrid MG

1.2 Energy Storage Systems

Managing power balance and stability is a challenging task in MGs, as they depend on a number of variables. There are different techniques for dealing with this challenge, including de-loading sources (especially in RESs), load shedding during a shortage to provide energy to the user, and combining ESSs with DGs to manage power during surpluses and shortages of energy (Xu, 2015).

Storage units can be located beside each DG and connected through individual power electronic interfaces (the distributed model) (Tan, 2013) or they can be connected to MG through a central ESS, operating on similar principles to the master unit (the centralized model) (Li, 2007). Electrical energy can be stored by converting it to another form of energy, such as chemical, mechanical, thermal, or electrochemical. There are different methods available for each of these forms.

For instance, flywheels and hydro pumps can be used in the conversion of electrical energy to mechanical form, while batteries store electrical energy in various chemical forms, depending on the type of battery.

Energy storage is most useful when the system is operating in island mode, where the main control objective of ESSs is to control the voltage and maintain the frequency of the system during island operation. Moreover, storage units should be able to respond sufficiently rapidly to transient power changes in grid-connected mode and to keep themselves fully charged. There are also many other applications that can utilize ESSs in MGs, such as ancillary services, customer energy management and the integration of RESs.

The control of such a system is critical, and implementing a hierarchical control system is necessary if optimum performance is to be achieved. For MGs and ESSs, hierarchical control can be described as consisting of four levels with different definitions and responsibilities. Generally, hierarchical control level needs to exert control over the power generated by the DG units, the power management and interface between the ESSs and DGs so as to provide a highly reliable system.

1.3 Standardization

There are different types of DGs, power electronic interfaces, and interconnections that can function as components of a microgrid. Recently, experts have been working on standards for designing the most suitable overall MG. For instance, IEEE 1547 is an adoptable standard that discusses the interface between distribution resources and the main grid, and establishes criteria and requirements for the interconnection (Ustun, 2011). The IEEE 61000 standard provides requirements, rules, and general conditions for achieving electromagnetic compatibility (Planas, 2013). For standardization of the two most popular renewable energy sources, the minimum design requirement for wind turbines and all related subsystems is described in the IEC61400 standard, while the critical requirements for interconnecting photovoltaic systems to the main grid are covered in the IEEE 929 standard (IEEE, 2000). Since communication is a significant part of power systems, and especially of MGs, identifying a communication protocol standard is required. In this regard, IEC61850 was presented in 2003 to describe communications in power substation automation systems and further extended to cover distributed energy sources in 2009. (Mackiewicz, 2006). Indeed, a lack of suitable standards to cover the variation in power generation and interconnections—as well as in the electrical interfaces between different sources, energy storage systems, and the main grid can be a gap for employment of the new technology.

1.4 Motivation for the work

Monitoring and supervising the MG may be centralized or decentralized. In centralized systems (Dimeas, 2005; Tsikalakis, 2011), the power management and power balancing between the DGs and ESSs is the responsibility of the Microgrid Central Controller (MGCC). One challenge to reliability is the high risk of instability: when a malfunction arises in the MGCC, the control level accomplished by the MGCC can lose control of the system. Several different distributed control strategies have been proposed to deal with this in recent years (Shafiee, 2014). Although distributed control helps to eliminate the MGCC from the MG, there are some challenges when implementing the control strategy. Since most studies of this control method have focused on island mode, the inability to control the system during the transient and persistent faults that cause blackout situations in MGs (as well as black-start coordination) without an MGCC and some of the other management functions of the MG presents a challenge to implementing a fully decentralized control system.

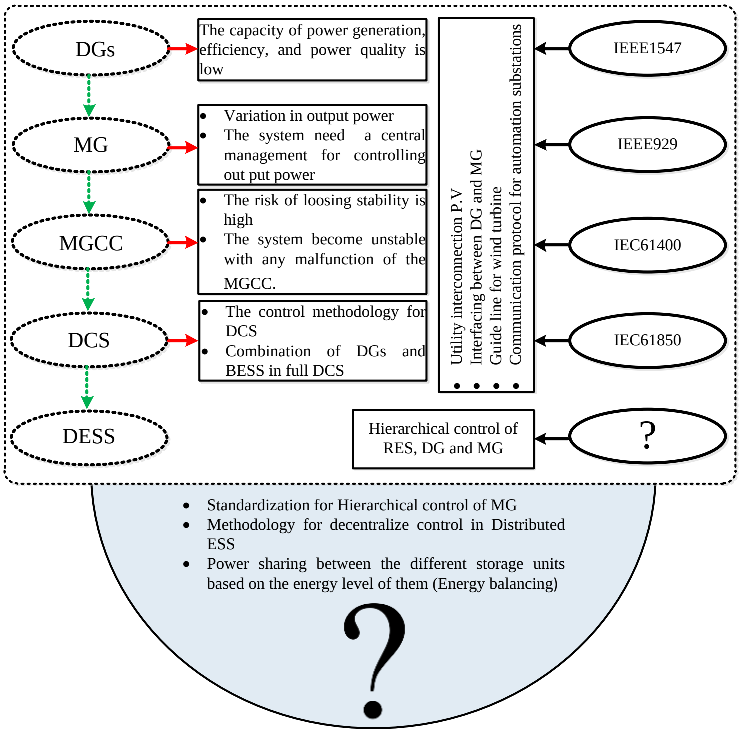


Figure 1.3 Challenges and open research questions

One way of dealing with these challenges and of achieving a greater level of control in practice is to use a Distributed Energy Storage System (DESS) installed beside each DG. To implement the power management in the combined system, the states of all parts of the MG—that is, the amount of power provided by RES, the energy level in the ESS, and power demand—must be considered (Wu, 2015). Since the ESS is a very important part of the power balance target, the way in which power is shared between the storage units is a key issue for the coordinated system operation.

Most of the approaches that have been used to balance energy storage in distributed Battery Energy Storage Units (BESUs) (Dragicevic, 2014; Kakigano, 2013; Li, 2014; C. D. Li, 2014; Lu, 2012; Zhang, 2012) operate with centralized control methods and also employ a communications system. As mentioned, operating the system under these control methods involves a high level of risk. Thus, some distributed secondary control methodologies for balancing energy in ESSs have recently been proposed in parallel to the research on this doctoral dissertation (Lu, 2014; Morstyn, 2014).

On the other hand, implementing the hierarchical control by applying a suitable standard is another challenge in the modern grid. As mentioned in Section 1.3, there are some standards that applicable when designing and implementing an MG, such as IEEE 1547, IEEE 61000, IEC61400, IEEE 929, and IEC61850. In fact, much research has been carried out in the field of MGs on both the technical and standardization aspects. However, how power can be shared between ESSs—taking into account the energy level of each unit and the standardization for hierarchical control in MGs and ESSs—is still open to research. The motivation and open research questions in MGs are summarized in Figure 1.3.

1.5 Objectives of the work and research methods

The first theme of this dissertation is the hierarchical control of DGs, MGs, and ESSs. As shown in Figure 1.2, main part of the distributed energy resources of future grids is expected to be connected to the system through power electronic devices. In this doctoral dissertation, the design and operating requirements for the hierarchical control of power electronic devices are addressed. To investigate the hierarchical control of MGs, the dissertation investigates the control of power generation from the zero level up to the third control level. Moreover, different technologies and applications of ESSs in modern grids are analyzed to find the most suitable storage technologies for implementation in MGs.

The second theme of this dissertation is the standardization of the hierarchical control of MGs and ESSs. One of the objectives is to adapt an international standard to this part of the system and to analyze it against the functionality and target of the hierarchical control. The main research issue in this phase is to determine a standard that is organized on the basis of different steps while having the same objective as the hierarchical control on each level of the MG and ESS. Hence, the first research challenge concerns the structure and aims of the control levels and also involves analyzing the available standards that could be adapted to hierarchical control levels.

The third theme of this dissertation is a Decentralized Control Strategy (DCS) for distributed Battery Energy Storage Systems (BESSs). A further objective is to implement a distributed control method for BESS by incorporating a voltage, frequency, and reactive power sharing method into a BESS that is used together with DGs, so as to achieve a fully decentralized control of MG. The main research issue in implementing the method is the energy level of each storage unit, which may be different in each energy storage unit. To implement the distributed control strategy, the following issues should be considered:

- Obtaining an accurate reference value for the energy levels in the distributed system,
- Sharing power between the different storage units based on the energy level of each unit,
- Managing the power sharing method for the both charging and discharging period.

In this dissertation, a literature study is conducted to investigate the standardization research gap and developing a standard solution for hierarchical control. The main research methods applied to the distributed control strategy for BESS are calculation and simulations performed in the PSCAD/EMTDC environment.

1.6 Scientific Contribution

The scientific contributions of this doctoral dissertation are as follows:

- It studies the hierarchical control strategies in MGs, analyzing in particular the primary and secondary control levels.

- It studies the different technologies and applications in ESSs so as to create a matrix that can be used to find more suitable storage technologies for implementing an MG based on the application requirements.
- It analyzes the possibility of adapting an international standard to the hierarchical control of MGs in order to further develop MG standardization.
- It investigates the different decentralized control strategies for implementing a distributed secondary control method for BESS and for combining it with DGs which are also controlled in a decentralized manner.
- It analyzes a voltage, frequency, and reactive power sharing method used in DGs to adapt an ESS so as to approach a distributed control strategy. The doctoral dissertation incorporates this approach into an ESS to achieve a decentral control of MG.
- It develops a cooperative method for controlling a distributed BESS. The thesis proposes a method for sharing power between different storage units basing on their available energy levels.
- It develops a SoC-based droop control method for AC MGs. The thesis employs a modified droop-control approach to power sharing between the ESS units. This would be based on their energy levels and would thus lead to energy equalization between the units.
- It evaluates the proposed distributed secondary control as well as the modified droop control method using the adapted international standardization.

1.7 Outline of the thesis

This doctoral dissertation contains the appended original publications and a number of descriptive and summarizing sections. The introduction to the thesis describes the concept of MGs and ESSs, and discusses the motivation, objectives, and contributions. The rest of the summary material is found in five chapters:

Chapter 2 contains a literature study of hierarchical control of MGs, covering the control of power generation from the zero level up to the tertiary control level. Moreover, some research questions are presented, the answers to which can help improve the performance of the hierarchical control, especially in secondary decentralized control and energy storage systems. The second part of the chapter presents an investigation into a number of different technologies and applications of ESS in modern grids. It also presents a matrix of the available technologies and applications, which is the result of a comprehensive analysis of the various technologies and applications.

Chapter 3 presents an adapted standard for hierarchical control in MGs and ESSs. The adapting of the IEC/ISO 62264 standards to MGs with advanced control techniques and ESSs is described here. In order to have complete review of the standardization, existing standards applicable to MGs are also investigated in this chapter.

Chapter 4 considers a distributed secondary control for battery energy storage systems. Firstly, the proposed method is evaluated when the battery operates as a power supply (in discharging mode). This is then combined with DGs, also controlled through the decentralized method, and the charging mode of the system is investigated. In this chapter, power sharing is investigated in a distributed energy storage system operating on the basis of a decentralized structure in the secondary level, which leads to energy equalization in the storage units.

Chapter 5 of the thesis ties together Chapters 3 and 4 by evaluating the proposed method and considering hierarchical control through the adapted IEC/ISO 62264 standard. By analyzing the definition of the different levels in the IEC/ISO 62264 standard and those of the decentralized control of DGs and BESSs, the compatibility of these two are future discussed in this chapter.

Chapter 6 concludes the thesis. A summary of the contributions of the research, along with a description of some open research questions for future work, is presented.

1.8 Summary of publications

The doctoral dissertation consists of seven publications, six of which are refereed journal articles and one of which is a refereed conference publication. All the papers were published during the doctoral research, with the first article appearing in 2014 and the last in 2016. The author of the dissertation is the primary and corresponding author of all the publications.

Publication I investigated the hierarchical control of MG and covers the control of power generation using two popular RESs—wind turbines and photovoltaics—step by step from the zero level up to the tertiary control level. This paper examined a number of different methodologies that can be implemented in primary control and also studied the concept of secondary control in both centralized and decentralized methods. In this publication, the author of the dissertation determined the limitations of the full decentralized control approach.

Publication II first investigates the range of different storage system technologies and applications. A matrix of relations between the technologies and applications is then presented. Many different parameters, such as capacity, storage power, response time, discharge time, lifetime, efficiency, and others, are compared to produce the matrix. Electrochemical storage turns out to be the most commonly used technique; it is useful in many applications, and especially in ancillary services.

Publications III and IV examine the application of the IEC/ISO 62264 standards to MGs containing advanced control techniques, energy storage systems, and market participation in both island and grid-connected modes (in publication III). The principles of MG design are also described considering the operational concepts and requirements that arise from participation in active network management. In order to complete the standardization, those operational concepts of MGs that have some impact on participation in such a network are described in publication IV: these include power quality, the principles behind island detection methods, black-start operation, fault management, and protection systems; these are investigated taking into account the IEC/ISO 62264 standard. These two publications have been written at the University of Vaasa by the author of the present doctoral dissertation, though comments and advice from Professor Josep M. Guerrero, the leader of the microgrid research program at Aalborg University, were made use of during the preparation.

Publication V describes a distributed secondary control for battery energy storage systems, when the battery operates as a power supply. The method proposed in this paper involves taking into account the energy level of the different units and sharing the power between them based on the SoC of each. Moreover, a modification to the droop control method is also employed: in the new droop control method, the output signal of the secondary control is added to the droop coefficients for the discharging periods.

Publication VI investigates the method implemented in publication V combined with DGs and controlled through the decentralized method, using the system's charging mode. Power sharing is here investigated in a distributed energy storage system operated on the basis of a decentralized structure in the secondary level, which leads to energy equalization in the storage units. Also presented and evaluated here is the proposed modified droop control for sharing power in the charging period between the different storage units, based on the energy level of each unit rather than the power. In this paper, the comments of Professor Josep M. Guerrero are also considered.

Publication VII ties together publications III, V, and VI. In this paper, the proposed method and hierarchical control are evaluated through the adapted standard (IEC/ISO 62264). Taking into account the different levels in the IEC/ISO 62264 standard and hierarchical control in DGs and BESSs, these two issues are made to conform to each other in publication VII. The paper is a joint paper with Aalborg University and made use of some comments received from Professor Josep M. Guerrero.

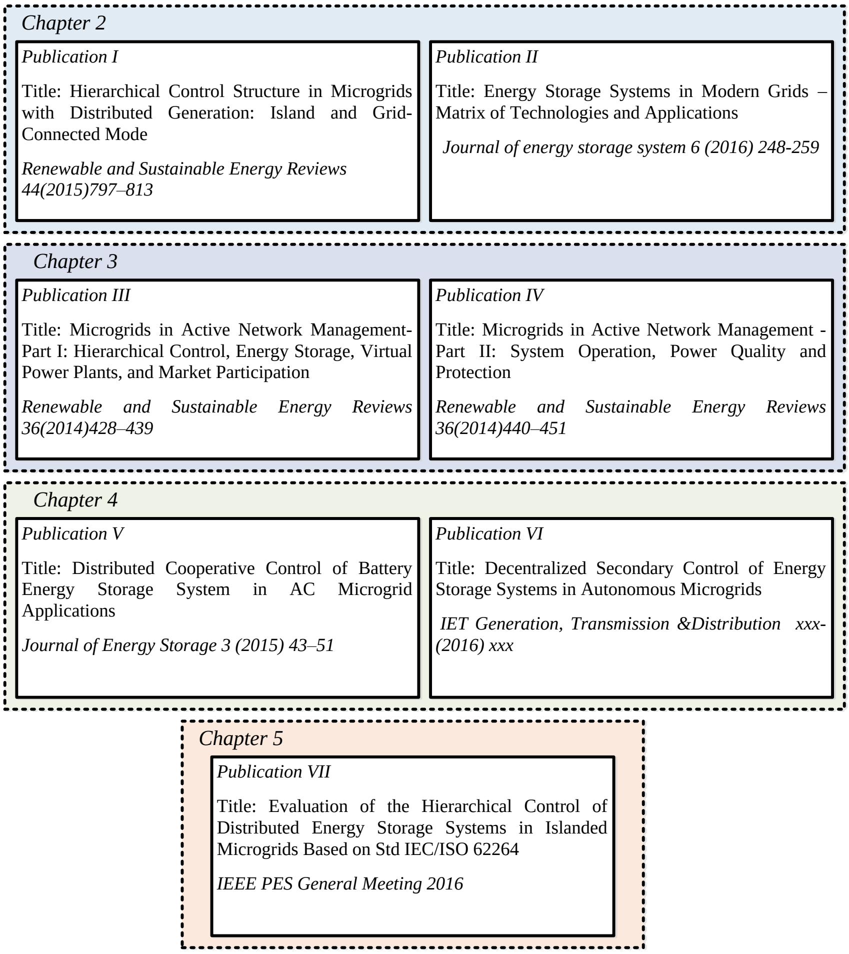
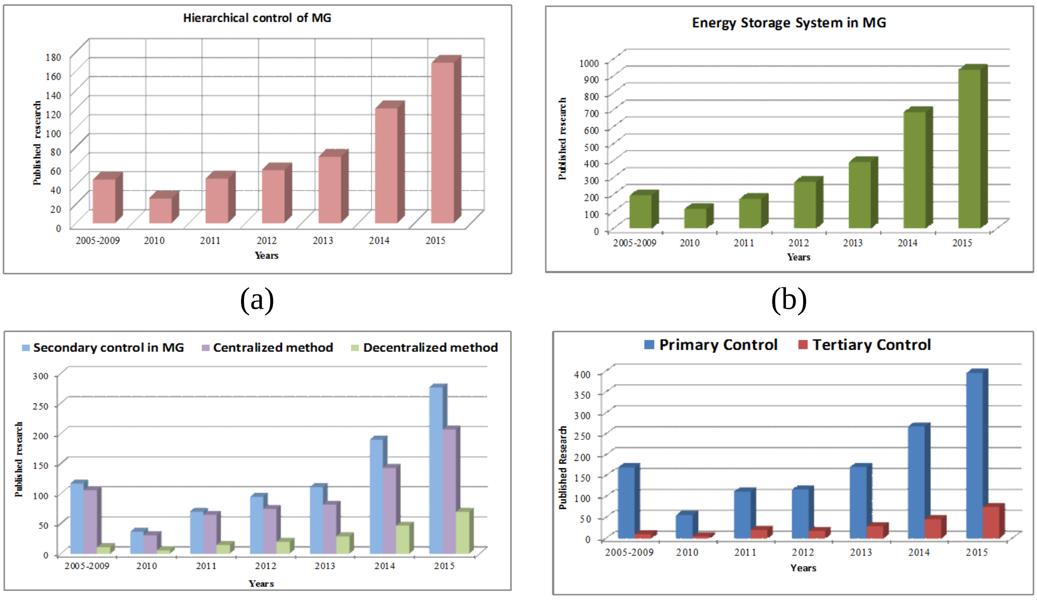


Figure 1.4 Publications in each chapter

The above seven publications, as well as their objectives, are summarized in Figure 1.4. The author of this doctoral dissertation has also authored a number of other publications closely related to the topic and they will also be cited in this dissertation when appropriate.

2 THEORETICAL FOUNDATION

Hierarchical control and energy storage in modern grids are popular research topics: a brief statistical study using the *Web of Science* and the *IEEE xplore* search engine showed an increase in research into these subjects over the last ten years (Fig. 2.1). The principle of hierarchical control is presented in this chapter, and also a matrix of the available technologies and applications of energy storage systems is demonstrated.



(a) (b)

(c) (d)

Figure 2.1 Statistics about (a) hierarchical control of MG, (b) ESS, (c) Secondary control, (d) Primary and tertiary control

2.1 Hierarchical control

The hierarchical control structure of an MG is divided into four different levels. The output voltage and current from the grid-side power converter of the RESs act as the input data for the inner control loop (level zero). Accurate references are required for effective management; these are passed through sensing and adjusting in the primary control. The strategy of the control level is to have an independent local control to increase the reliability of the power system. On the next level, the secondary control deals with the MG and power management (using the ESS) in island mode, and also regulates output power on the basis of network data in grid-connection mode. The processes function by monitoring the system and collecting the necessary information from the DGs and ESSs. In the final step, the tertiary control level establishes an interface between the MGs and the main grid in order to exchange the information from the secondary control with the network for the purpose of maintenance and optimization (Guerrero, 2011). The hierarchical control is described in Publication I and each control level is summarized here:

2.1.1 Inner control loop (*Zero level*)

The main goal of *level zero* is to manage the output power of the Micro-Sources (MSs). This is generally accomplished through the inner current and voltage control loop. The first step in MG control is the control of the source operating point using power electronic devices (Bidram, 2012).A block diagram of the control level is shown in Figure 2.2. Since wind power and PV are popular RESs, *Publication I* investigates their power generation and control strategies. After stabilize the power generated by the RESs, the reference value for the inner control loop is determined through the primary control level and it depends on the state of the MG connection.

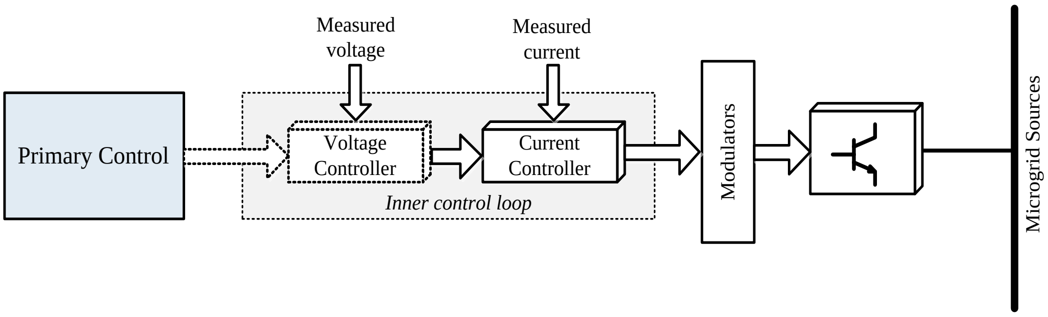


Figure 2.2 Control block diagram for zero level

2.1.2 Primary control

The primary control level (*level one*) is used to adjust the frequency and amplitude of the voltage references, taking into account the calculated deviation in frequency (Δf) and voltage (ΔV) originating from the upper control level. These references are fed to the inner current and voltage control loops. Indeed, this control level is the first step in the regulation, and so it should have the fastest response to any variation in sources or demand—on the order of milliseconds. The principle of this control level in MGs is shown in Figure 2.3. Power converters for DG units fall into two general categories: the grid-forming type and the grid-following type. A comprehensive review of primary control in grid-forming strategies is presented by *T.L. Vandoorm et al.* (Vandoorn, 2013), while grid-following techniques are discussed by *F. Blaabjerg et al.* (Blaabjerg, 2006). With respect to this classification, a complete overview of the different techniques of primary control is also available in *Publication I*.

In order to eliminate the problems that arise from the parallel multiple power electronic converters in the AC system, droop control can be employed in this control level. The concept of conventional droop control in a synchronous generator has been adapted to parallel inverters by (Chandorkar, 1993) (Tuladhar, 2000) and has been used in a small grid by (Lasseter, 2002). Since this doctoral dissertation proposes a modified droop control in Chapter 4, the conventional droop control is discussed here.

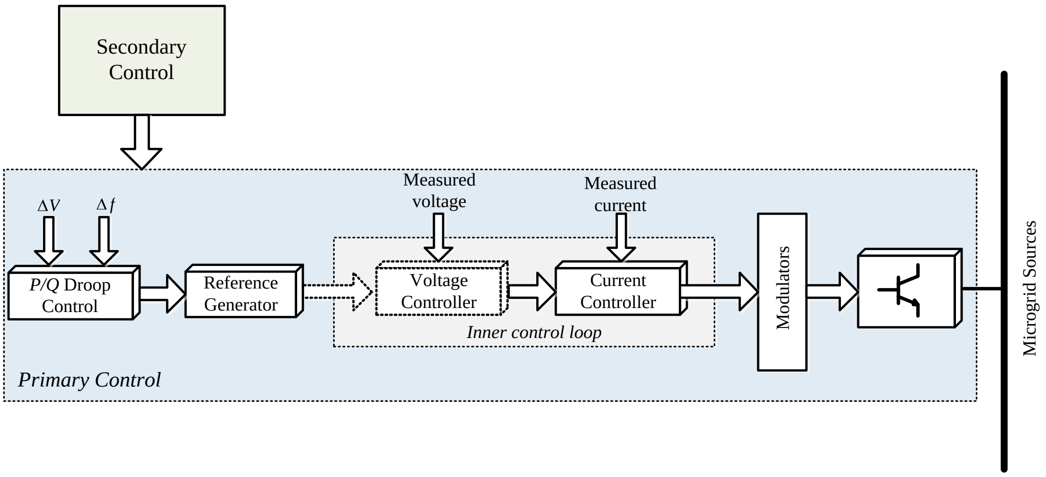


Figure 2.3 Control block diagram for primary level

Droop control

The ESS provides the power required for achieving the power balance in the islanded MG and thus the power is equal to the difference between the total power generated by the DGs and the total power demand. Conventionally, the absorbed and injected power of the ESS is positive when operated in discharging mode and negative in charging mode. Because of the lack of inertia in MGs, the droop control method used depends on whether the line impedance is resistive or inductive (Guerrero, 2013). Based on single phase equivalent circuit of the three phase power converter connection to the grid shown in *Publication I*, active and reactive powers are defined as:

$$P = \frac{E}{R^2 + X^2}\left[R(E - V\cos\theta) + XV\sin\theta\right] \qquad 2.1$$

$$Q = \frac{E}{R^2 + X^2}\left[-RV\sin\theta + X(E - V\cos\theta)\right] \qquad 2.2$$

Where,

P	Active power [W]
Q	Reactive power [VAR]
R	Resistor [Ω]
V	Grid voltage [V]
E	Source voltage of the equivalent circuit [V]
X	Inductance [Ω]
θ	Phase-angle difference between the two voltages

When the line impedance is almost inductive, the resistive part of the above equation can be removed without any loss of accuracy. For this reason θ is also very small and it can be supposed that Sinθ=θ and Cosθ=1; equations (2.1) and (2.2) can thus be rewritten as:

$$P \approx \frac{EV\theta}{X} \qquad 2.3$$

$$Q = \frac{E^2 - V}{X} \qquad 2.4$$

In inductive lines, (*P/f, Q/V*) droop control as discussed in (Chiang, 2001; Guerrero, 2007; Piagi, 2006; Planas, 2013; Sao, 2008) is employed; the principle is illustrated in Fig. 2.4 (Guerrero, 2009; Laaksonen, 2008). Generally, the frequency and voltage of droop control for large and medium systems can be determined thus:

$$f = f^{ref} - T_{P(s)}.(P - P^{ref}) \qquad 2.5$$

$$V = V^{ref} - T_{Q(s)}.(Q - Q^{ref}) \qquad 2.6$$

Where,

f	Measured frequency [HZ]
f^{ref}	Reference of frequency [HZ]
P	Measured active power [W]
P^{ref}	Reference of active power [W]

Q	Measured reactive power [VAR]
Q^{ref}	Reference of reactive power [VAR]
V	Measured voltage [V]
V^{ref}	Reference of voltage [V]
$T_{P(s)}$	Droop Coefficient of active power
$T_{Q(s)}$	Droop Coefficient of reactive power

On the other hand, due to the coupling of active and reactive power in DG units when inductance is not present, this method can create a particular problem for systems with resistive line impedance (Li, 2009). Since (*P/f, Q/V*) droop control method is considered in this doctoral dissertation, (*Q/f, P/V*) is not discussed here; however, more information on it is available in *Publication I*.

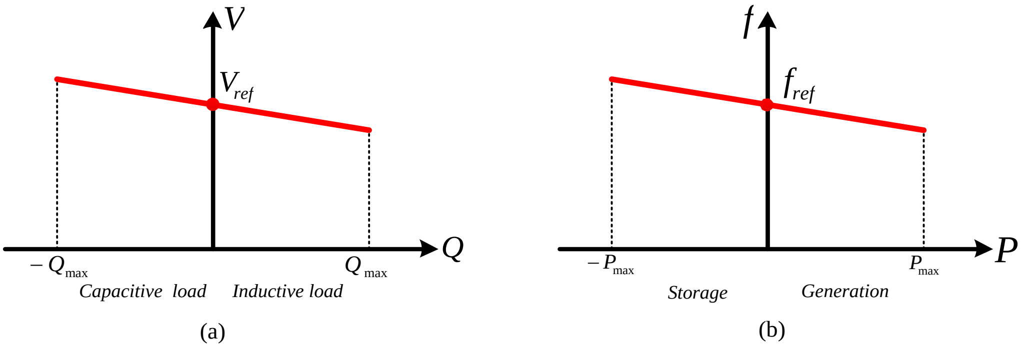


Figure 2.4 Droop control (a) *Q/V* (b) *P/f*

2.1.3 Secondary control

Due to transients in power generated by RESs and variation on the demand side, there are many unplanned situations that can occur during MG operation. To restore frequency and voltage, a secondary control is implemented to return the MG to normal operating conditions after each variation. In the second control level, all the required information is collected from the DGs, Energy Storage Units (ESUs), and loads, and the new reference values are sent to the primary control level. The block diagram of the control level is shown in Figure 2.5. The main purpose of the secondary control is to modify the characteristics of the droop control to restore the frequency and voltage to their normal values (Shafiee, 2014).

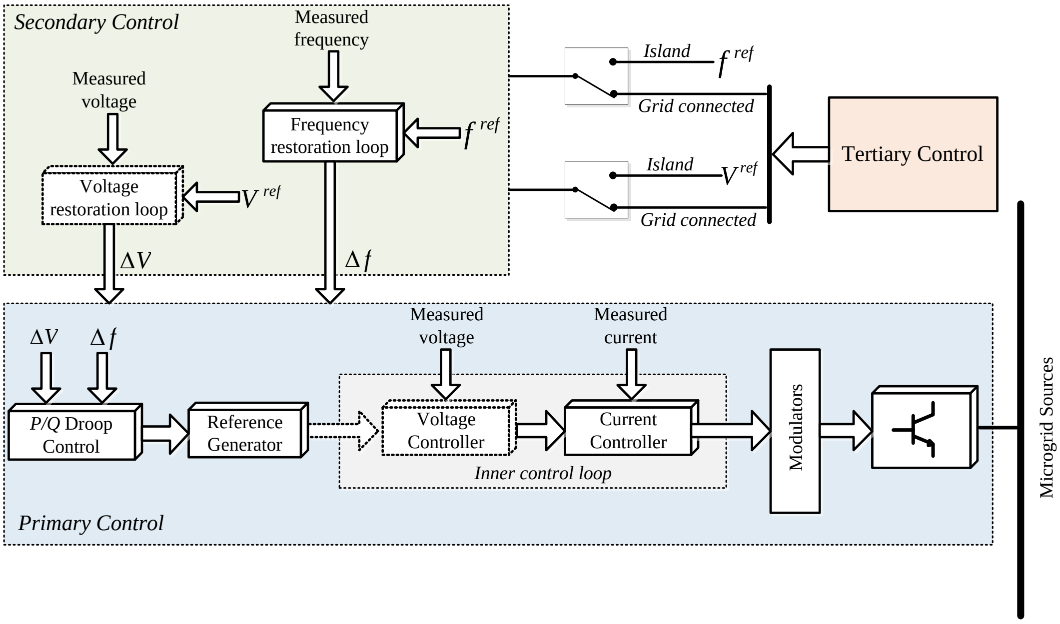


Figure 2.5 Control block diagram for secondary level

As mentioned in *Publication I*, the outputs of the MGCC are sent to the primary and inner control loop in order to regulate the reference values of voltage and frequency (Justo, 2013). The frequency and voltage amplitude of DER is measured and compared with the reference value received from the main network (if the MG is in grid-connection mode). The measurement error will then be sent to primary control to restore the voltage and frequency; the restoration compensator can be defined through:

$$\Delta f = G_{pf}(f_{mg}^{ref} - f_{mg}) + G_{if}\int (f_{mg}^{ref} - f_{mg})dt + \delta f_s \qquad 2.7$$

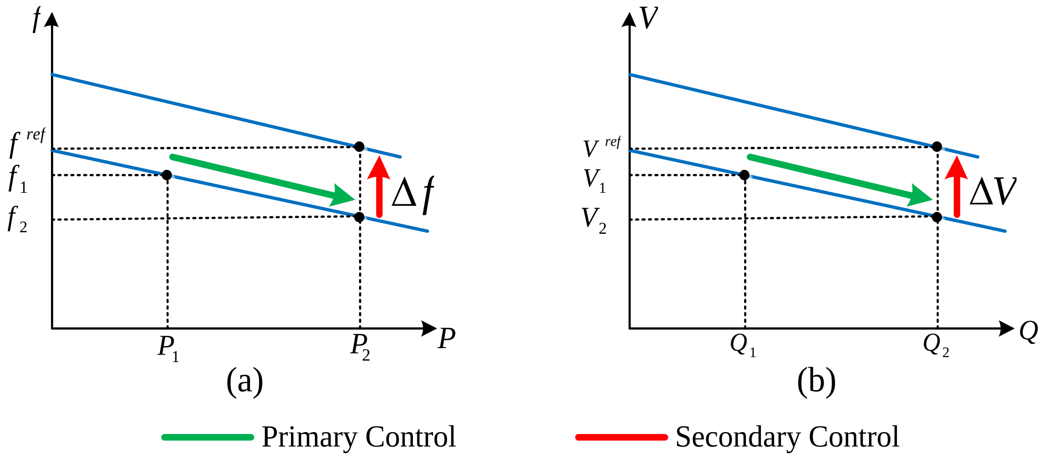
$$\Delta V = G_{pv}(V_{mg}^{ref} - V_{mg}) + G_{iv}\int (V_{mg}^{ref} - V_{mg})dt \qquad 2.8$$

Where,

f_{mg}	Frequency in MG [Hz]
f_{mg}^{ref}	Reference of frequency for MG [Hz]
G_{if}	Integration gain for frequency at the secondary level compensator
G_{iv}	Integration gain for voltage at the secondary level compensator
G_{pf}	Proportional gain for frequency at the secondary level compensator
G_{pv}	Proportional gain for voltage at the secondary level compensator
V_{mg}^{ref}	Reference of voltage for MG [V]
V_{mg}	Voltage in MG [V]

Δf	Deviation of frequency [Hz]
ΔV	Deviation of Voltage [V]
δf_s	Synchronization term (equal to zero in island mode)

Figure 2.6 shows how the control level carries out this restoration. For instance, with *P/f* droop control, Figure 2.6 (a) illustrates that the output signal from the secondary control influences the reference value of the frequency by shifting the droop line up and down, so that the frequency reaches its the nominal value. (Shafiee, 2014)



(a) (b)

Figure 2.6 Restoration in droop control (a) *frequency* (b) *Voltage*

The secondary control also has some additional responsibilities for the storage system. The ESS can fail if it is the only element involved in stabilizing the MG, so load-sharing of the burden on the ESS and the DG units' output power is necessary (Kim, 2012). The power output set-point of each MS should be calculated and communicated through the secondary control function. First, the responsibility of the secondary control in the storage system is to monitor system fluctuations. Then, having compensated for the power variation through the primary control in the storage, and having increased the power generation, the secondary control brings the power output of the ESS back to zero (Kim, 2010).

Unlike the primary control level—in which a decentralized control loop is implemented and a controller is located beside each DG and ESS—secondary control can be implemented as either centralized or decentralized (Hatziargyriou, 2014), both of which control methods are described in the next subsection. The focus of this doctoral dissertation is on the decentralized secondary control.

The secondary control may have a centralized or decentralized structure, as illustrated in Figure 2.7 (a) and (b), respectively. Whether the system is considered centralized or decentralized depends on the location of the MGCC (Banerji, 2013; Mehrizi-Sanir, 2009; Vasquez, 2010). In centralized structures, the output value of each DG is measured using remote sensing and sent to the central control; in decentralized control, the sensing and measurement of the value is performed at the terminal of each DG unit and send to other neighbors. (Vandoorn, 2013). One disadvantage of using an MGCC in the secondary control is that it may malfunction, which can affect the reliability of the MG. To account for this, a distributed secondary control can serve as an alternative to improve the reliability of the MG. In the decentralized method, the primary and secondary controls are merged and are connected to a local controller. Although the MGCCs in the MGs are replaced by decentralized control methods, it is still necessary to use a central control for some coordination functions (Shafiee, 2013; Shafiee, 2012). The classification of control system structure is the same in the case of controlling the storage units and follows the same principle as the DG control.

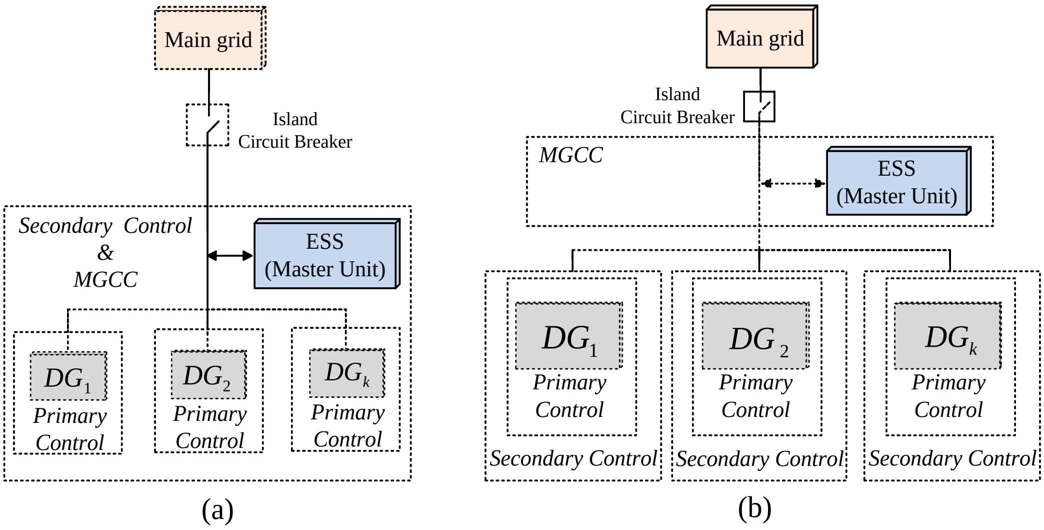


Figure 2.7 Secondary control level (a) Centralized (b) Decentralized

2.1.4 Tertiary Control

The purpose of tertiary control is to manage power flow by regulating voltage amplitude and frequency when the MG is in grid-connected mode. This control level is the final and slowest part of the hierarchical control. Its layout is shown in Figure 2.8. Unlike primary control and secondary control, a centralized strategy is usually used in the third control level. This control level is disabled when the MG operates in island mode.

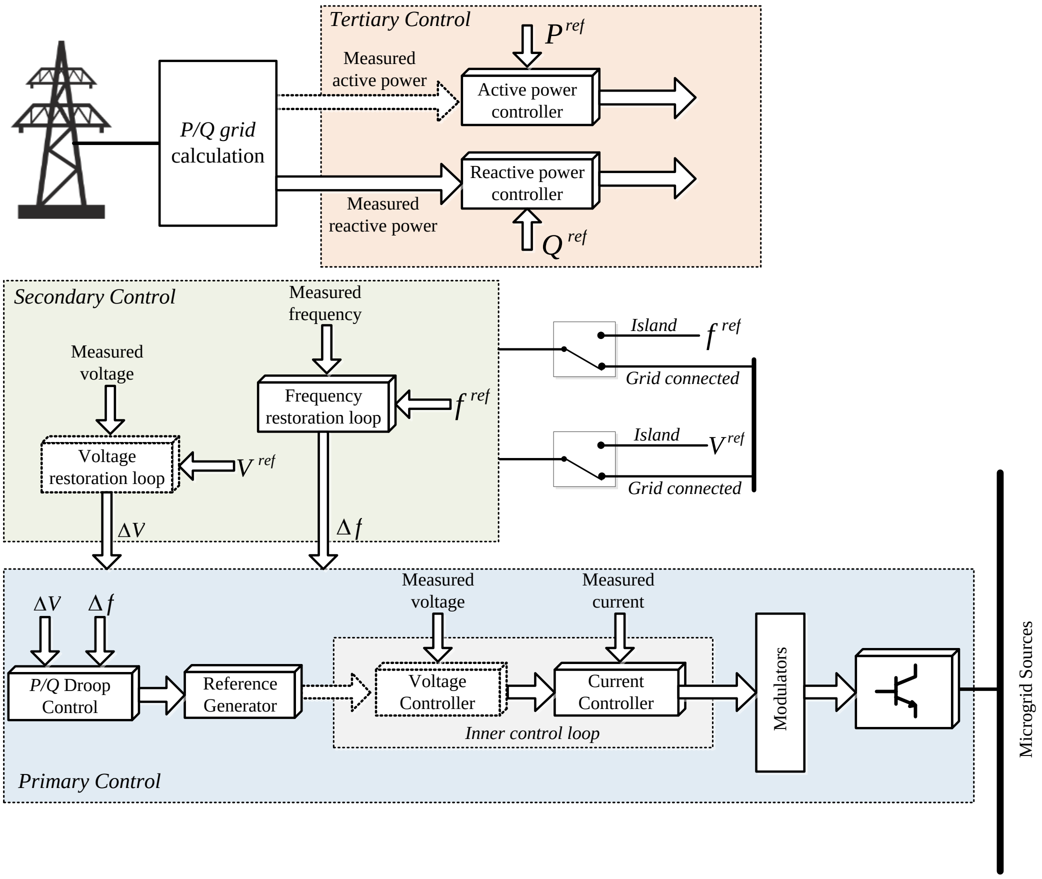


Figure 2.8 Control block diagram for tertiary control

By measuring the *P/Q* ratio through the PCC, the grid's active and reactive power can be compared to the desired reference. The frequency and voltage reference defined in follow:

$$f^{ref} = G_{PP}(P^{ref} - P_{grid}) + G_{ip}\int(P^{ref} - P_{grid})dt \qquad 2.9$$

$$V^{ref} = G_{PQ}(Q^{ref} - Q_{grid}) + G_{iQ}\int(Q^{ref} - Q_{grid})dt \qquad 2.10$$

Where,

f^{ref}	Reference of frequency [Hz]
G_{ip}	Integration gain for active power at the tertiary level compensator
G_{iQ}	Integration gain for reactive power at the tertiary level compensator
G_{PQ}	Proportional gain for reactive power at the tertiary level compensator
G_{PP}	Proportional gain for active power at the tertiary level compensator

P^{ref}	Reference of active power [W]
P_{grid}	Active power (grid side) [W]
Q^{ref}	Reference of reactive power [VAR]
Q_{grid}	Reactive power (grid side) [VAR]
V^{ref}	Reference of Voltage [V]

2.2 Energy storage systems

Energy storage technologies are used in modern grids for a variety of applications. In order to simplify the choice of the technologies available for an application, *Publication II* presents a matrix of the available technologies and applications. These ESS technologies and applications are then described thoroughly and compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, and life time. In the rest of the chapter, the matrix is discussed and important information about ESSs is presented.

2.2.1 Energy storage technologies

Electrical energy may be stored in various ways by converting it into another form, such as electrochemical, mechanical, or thermal energy. A complete classification of ESS technologies is presented in *Publication II*. Recently, researchers have produced comprehensive reviews in this area, such as those by (Tan, 2013), (Carnegie, 2013), (Bradbury, 2010), and (Cavanagh K, 2015).

Electrochemical storage technologies (batteries) are the most popular type of storage and are investigated by (Yang, 2011) and (Divya, 2009). Generally, the storage methods consist of various technologies such as lead–acid (Palo, 2009), sodium–sulfur (NaS) (Díaz-González, 2012; Hadjipaschalis, 2009), and lithium-ion (Nair, 2010). Moreover, flow batteries—in the form of redox and hybrid flow batteries—is another type of storage method (Blanc, 2008; Huang, 2008; Joerissen, 2004).

Mechanical storage techniques for electrical energy include flywheel energy storage (FES) (Hotakainen, 2011; Hyytinen, 2013; Veszpremi, 2007), pumped hydro storage (PHS) (Alto, 2012), and compressed air energy storage (CAES)

(Hotakainen, 2011; Oberhofer, 2012). In the electrical storage type, double layer capacitors (DLC) ("Electrical Energy Storage", 2011) and superconducting magnetic energy storage (SMES) (Salameh, 2014) are usually employed. Finally, the thermal storage method is based on converting energy to ice or hot water. There are many different approaches to using such thermal energy storage, as investigated in (Farid, 2004; Sharma, 2009; Zalba, 2003).

Table 2.1 Characteristics of energy storage Technologies in modern grids

Technologies				Capacity (MWh)	Power (MW)	Response time	Discharge time	Life time (years)	Efficiency (%)
Electrochemical	Lead-acid			0.25~50	≤ 100	millisecond	≤ 4 h	≤ 20	≤ 85
	Lithium-ion			0.25~50	≤ 100		≤ 1h	≤15	≤ 90
	NaS			≤ 300	≤ 50		≤ 6 h	≤15	≤ 80
	Vanadium redox			≤ 250	≤ 50	≤ 10 min	≤ 8 h	≤ 10	≤ 80
	FES			≤ 10	≤ 20	≤ 10 ms	≤ 1 h	≤ 20	≤ 85
Mechanical	PHS	small		≤ 5000	≤ 500	sec ~ min	6 ~ 24 h	≤ 70	≤ 85
		large		≤ 14000	≤1400	sec ~ min			
	CAES	underground	small	≤ 1100	≤ 135	≤ 15 min	≤ 8 h	≤ 40	≤ 85
			large	≤ 2700	≤ 135	≤ 15 min	≤ 20 h		
		Above ground		≤ 250	≤ 50	≤ 15 min	≤ 5 h		
Electrical	DLC			0.1~0.5	≤ 1	≤ 10 ms	≤ 1 min	≤ 40	≤ 95
	SMES			1~3	≤ 10	≤ 10 ms	≤ 1 min	≤ 40	≤ 95
Thermal				≤ 350	≤ 50	≤ 10 min	N/A	≤ 30	≤ 90

In *Publication II*, these techniques are analyzed comprehensively and energy calculation principles are presented for each technique. Moreover, the significant characteristics of the storage units are presented in *Publication II* and they are also available here in Table 2.1. It should be noted here that the characteristics of storage technologies in this table take into account their role in the modern grid. To design an ESS for a system, four vital items are needed: storage capacity, power, response time, and discharge time. By examining Table 2.1, it can be seen that the greatest storage capacity is exhibited by the mechanical techniques—and especially by PHS and underground CAES. The electrical methods have the lowest capacities. The situation is same in terms of power. However, these methods have immediate response times to any variation. In particularly, the response time of batteries is instantaneous. However, in DGs and MGs, this also depends on the control method and on the relative performance of the power electronic devices. Hence, the response times of batteries (apart from the redox battery) are on the order of milliseconds.

2.2.2 Energy storage applications

There are different applications that can be provided by ESS. These are described by (Akhil, 2013) and (Eyer, 2010) and are also classified into four different groups in *Publication II*.

The investigation in *Publication II* indicates that bulk energy method is a key application for integrating a great deal of variation into modern grids. There are two major types: *Energy arbitrage* and *peak shaving* (Chua, 2013; Levron, 2012). The principle of these two methods is rather similar in that energy is stored during times of low demand and price and injected into the system when the load is peaking. The difference between the two applications is that peak shaving does not follow the economic target as much as energy arbitrage. The other type of ESS application is ancillary services, which provide support to the system in various operational tasks. The different ancillary service applications include *load following*, *spinning reserve*, v*oltage support*, *black start*, and *frequency regulation*.

Since the load can undergo frequent variations, energy storage is more suitable for load-following applications. In fact, in this application, the responsibility of energy storage is to create a balance between the generation and the load (Kirby, 1999). Spinning reserve is a part of the capacity of the source that is not used in normal operation. However, the source can cover a power shortage in the system by injecting power for specific period (ABB, 2014; Brown, 2008). To achieve stability in the power system, reactive power needs to be managed, so that with an ESS for voltage support, the resource can be regulated accurately. However, reactive power cannot reasonably be transferred over long distances, so a voltage support application is used locally to manage the problem (Akhil, 2013; Eyer, 2010). In black out (black start) application, for energizing distribution lines, or as startup power for large power plants, the energy storage system generates active power, which can manage power and control the voltage (Akhil, 2013). Frequency regulation is very important for covering the small variations that occur in power systems.

Table 2.2 Characteristics of energy storage applications in modern grids

Application			Storage power (MW)	Response time	Discharge time	Cycle	Desired life time (years)
Bulk Energy	Energy arbitrage		≤ 500	Minutes	≤ 10 h	300-400/yr	≤ 20
	Peak shaving		≤ 500		≤ 6 h	50-250/yr	≤ 20
Ancillary Service	Load following		≤100	Minutes	≤ 4 h	N/A	≤ 20
	Spinning reserve		≤100	≤ 4 h	≤ 5 h	N/A	≤ 20
	Voltage support		≤ 10	≤ 100 ms	≤ 1 h	5000/yr	≤ 20
	Black start		≤ 50	≤ 2 h	≤ 16 h	10-20/yr	≤ 25
	Frequency regulation	Primary	≤ 40	Instant	30 min ≥ t ≥ 15 min	8000/yr	≤ 15
		Secondary	≤ 40	Minutes	1 h ≥ t ≥ 30 min		
		Tertiary	≤100	Minutes	≥ 1h		
Customer Energy Management	Power quality		≤ 10	≤ 200 ms	≤ 2 h	50/yr	≤ 10
	Power reliability		≤ 10	Minutes	≤ 4 h	≤ 400/yr	≤ 15
Renewable energy Integration	Time shift		≤ 500	≤ 30 min	≤ 5 h	≤ 4000/yr	≤ 15
	Capacity firming		≤ 500	≤ 30 min	≤ 4 h	300-500/yr	≤ 20

The energy storage system as a frequency regulator serves power systems by correcting the frequency deviations to within the permissible limits. There are three types of frequency regulation application: primary, secondary, and tertiary (Vuorinen, 2008). The responsibility of the primary reserve control is to create a balance between generation and demand, and to restore the frequency within 5–30 s for the generator control (Galiana, 2005; Ribeiro, 2001; Vuorinen, 2008). The secondary reserve has two objectives: to serve as a backup for primary regulation and to ensure that the frequency is set to the reference value, while avoiding imbalances in the interconnection. This control level reacts to the primary control reserves for 5–15 minutes (Galiana, 2005; Rebours, 2007; Vuorinen, 2008). In the last level, the tertiary reserve has the same objective as the secondary reserve and also aims to balance load, generation, and sales, thus helping to keep the system synchronized. This reserve level is operated manually and needs to reach its target in 15 to 60 minutes, depending on the country (Vuorinen, 2008).

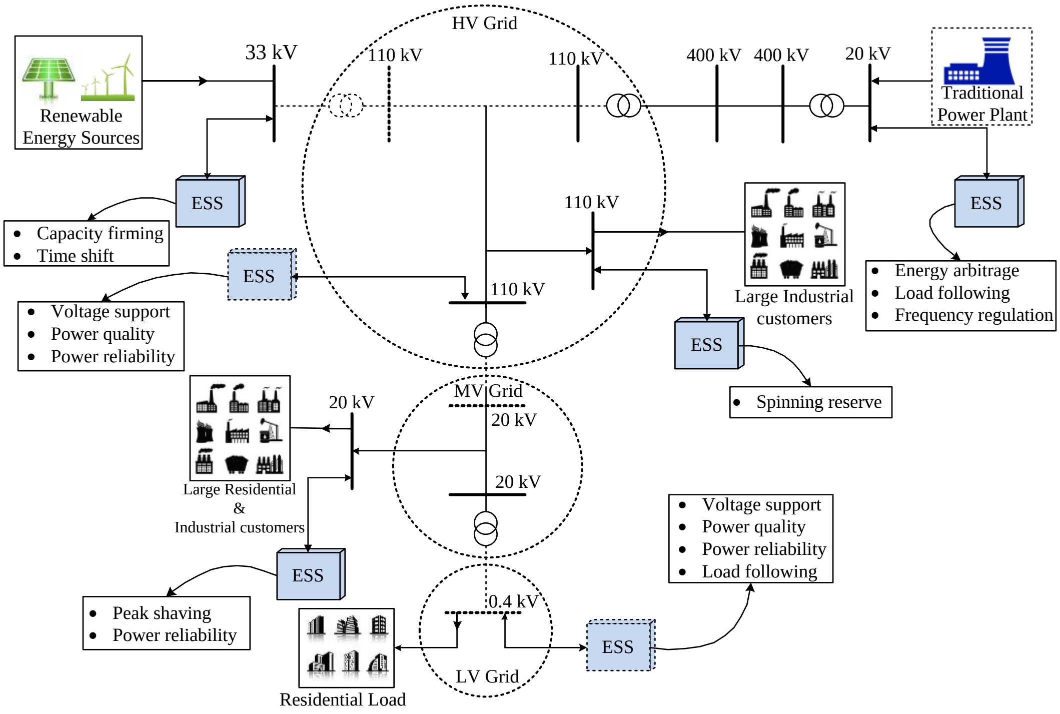


Figure 2.9 Location of each ESS application in power system

Two important objectives for supporting customers—the quality and reliability of power delivery—are provided by ESS in energy management applications. The principle of the power quality is rather similar to that of power reliability. The ESS in this application should support the system with the high reliability and highest quality power (Carrasco, 2006). The last type of ESS application is the renewable energy integration. These applications are divided in two different categories: *time shifting* and *capacity firming*. The principle of both methods is to store the energy when demand is lower than generation and to inject the power into the system during shortages. There are several applications that can be used in different parts of a power system. In this regard, the locations of each energy storage application in the power system are shown in Fig 2.9. As mentioned earlier, in designing the storage system it is needed to consider some important system parameters. Moreover, the discharge and response times, power, and desired life cycles for each application are presented in *Publication II* and they are also available here in Table 2.2.

2.2.3 Matrix of technologies and applications

As can be seen from the analysis in sections 2.2.1 and 2.2.2, power storage comes in many different technologies and can be used in many different applications. A matrix of the relationships between the energy storage technologies and their application is given in *Publication II* and reproduced here in Table 2.3, which has been developed on the basis of (Carnegie, 2013) and (Gyuk, 2013). When developing the matrix, the storage technologies and applications have been compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, life time, and efficiency. As illustrated in the matrix, electrochemical storage methods can cover a system for ancillary services, customer energy management, and renewable energy integration applications. From the mechanical technologies, the flywheel method is usually used for low-energy applications, emergency devices, and load levelers. In applications that need a quick response, electrical energy storage techniques can be implemented.

Table 2.3 A matrix of technologies and applications

			Electrochemical				Mechanical					Electrical		
							CAES		PHS					
			Lead-acid	Lithium-ion	NaS	Vanadium redox	Underground	Above ground	Small	Large	FES	SMES	DLS	Thermal
Bulk Energy	Energy arbitrage		🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟥	🟥	🟥	🟩
	Peak shaving		🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩	🟥	🟥	🟥	🟩
Ancillary Service	Load following		🟩	🟨	🟩	🟩	🟨	🟨	🟨	🟥	🟩	🟥	🟥	🟩
	Spinning reserve		🟨	🟥	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟥	🟥	🟨
	Voltage support		🟩	🟩	🟩	🟨	🟥	🟨	🟥	🟥	🟩	🟥	🟥	🟥
	Black start		🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟨
	Frequency regulation	Primary	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟥	🟨	🟥	🟥	🟥
		Secondary	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥
		Tertiary	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥
Customer Energy Management		Power quality	🟩	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟥
		Power reliability	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟩	🟨	🟥	🟥
Renewable energy Integration		Time shift	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩
		Capacity firming	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥

🟩 Suitable application 🟨 Possible application 🟥 Unsuitable application

Table 2.4 Summarized of hierarchical control

Descriptions		Target of levels in DGs	Target of levels in ESSs
• The hierarchical control structure of MGs and ESS classified into four different levels. • Power converters for DG unit are classified into two general categories: grid-forming and grid-following. • Droop control is more reliable and of lower cost than communication methods for implementing primary control in MGs • The secondary control level can be divided into centralized and decentralized controls. • The definition of centralization or decentralization is based on the position of the MGCC	Level zero	Managing the output power of micro sources is the main goal of *level zero*, and is generally accomplished through the inner current and voltage-control loop.	The target of the level is same as the objective of zero level in control of DGs. Managing the output power of ESS is the main goal and is generally also accomplished through the inner current and voltage-control loop.
	Level one	In *primary control* adjust the frequency and amplitude of the voltage references that feed the inner current and voltage-control loops.	Controlling the active power in the MG is the responsibility of the storage system, which must monitor it continuously by detecting frequency variations.
	Level two	The responsibility of *Secondary control* is to supervise and monitor the system, to adjust for deviations in both voltage and frequency.	The responsibility of the secondary control in storage system is monitoring the system fluctuations. Then, after compensating the power variation, the secondary control brings the power output of the ESS back to zero.
	Level three	The purpose of the *tertiary control* is to manage power flow by regulating amplitude voltage and frequency when the MG is in grid-connected mode.	As the third level is labeled as a connection element in the main grid, and the storage system is based on island mode, storage control does not contain tertiary controls

2.3 Summary of the chapter

In this chapter, a theoretical foundation for hierarchical control in MG and ESS is presented. Moreover, a matrix of the available energy storage technologies and applications is proposed. As can be seen from the statistics provided in this chapter, hierarchical control and energy storage in modern grids are very interesting topics, and research in this area has grown rapidly in the last ten years. The hierarchical control structure of MGs, which consists of four control levels, is discussed in this chapter along with the objectives of each control level and their principles. Storage technologies and applications are also introduced and the proposed matrix of technologies and applications is comprehensively analyzed. The chapter is based on Publications *I* and *II*, which are also summarized in Tables 2.4 and 2.5.

Table 2.5 Summarized of ESS in modern grid

Descriptions	Technologies	Applications
•Energy storage technologies are used in modern grids for a variety of applications and with different techniques. • A matrix of the available technologies and applications has been presented in this chapter. • The technologies and applications of ESSs are described thoroughly and are compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, and life time. • For implementing an optimum storage project, different steps need to be considered: ➢ Investigating the type and size of the storage system and selecting the one that is best for the system Defining the best control strategy for the application considering the selected storage system	• Energy storage can be achieved in the storage element by converting electrical energy into another form. • Technologies of ESS classified in five main types: ✓ Electrochemical ✓ Electrical ✓ Thermal ✓ Mechanical ✓ Chemical • Electrical energy storage techniques have only a limited number of potential applications, focusing on power system transient issues, such as improving power quality. • Electrochemical storage is the most commonly used technique and covers many applications, such as voltage support, black start, and frequency regulation.	•Different applications can be provided with ESS to MG, which are classified into four different groups: ✓ Bulk energy ✓ Ancillary service ✓ Customer energy management ✓ Renewable energy integration • There are several applications which can be used in different parts of a power system. This chapter demonstrates the locations of each energy storage application in power system. • The battery's energy storage can support the system in ancillary service and customer energy management applications. The technique is also possible for renewable energy integration, such as time shifting and capacity firming.

3 STANDARDIZATION

The other main challenge in modern grids is the standardization of hierarchical control. Recently, researchers have investigated different parts of the system to establish an association between MGs and international standards. A brief statistical study using the *Web of Science* and the *IEEE xplore* search engine showed an increase in research into these subjects over the last ten years (Fig. 3.1). Indeed, the research described in the literature includes all elements of the system, both those in the security and communications part and those in the electrical part. A conceptual model of the modern grid for the purposes of standardization is shown in Fig. 3.2. Apart from the general issues of applying standards to modern grids, the figure illustrates specific application areas where suitable standardization is necessary, such as (IEC Roadmap, 2010):

- Transmission
- Advanced distribution management
- Distribution automation
- Substation automation
- Distribution energy resources
- Demand response and load management
- Electrical storage
- Renewable energy generation

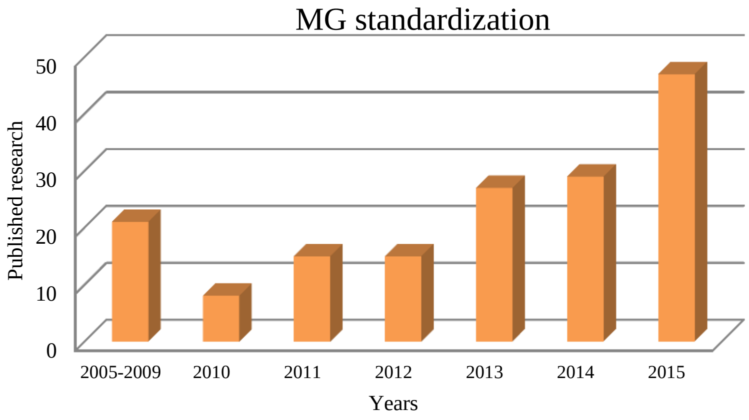


Figure 3.1 Statistic of MG standardization

Since this doctoral dissertation concentrates on the distribution system, an investigation of standardization in this topic is presented in the following chapter. In this chapter, to address the existing research questions on standardization (mentioned in Chapter 1), the IEC/ISO 62264 international standard is adapted to MGs and ESSs, which are considered from a hierarchical control viewpoint. In this standard, the interface between the manufacturing control functions and the other enterprise functions is considered.

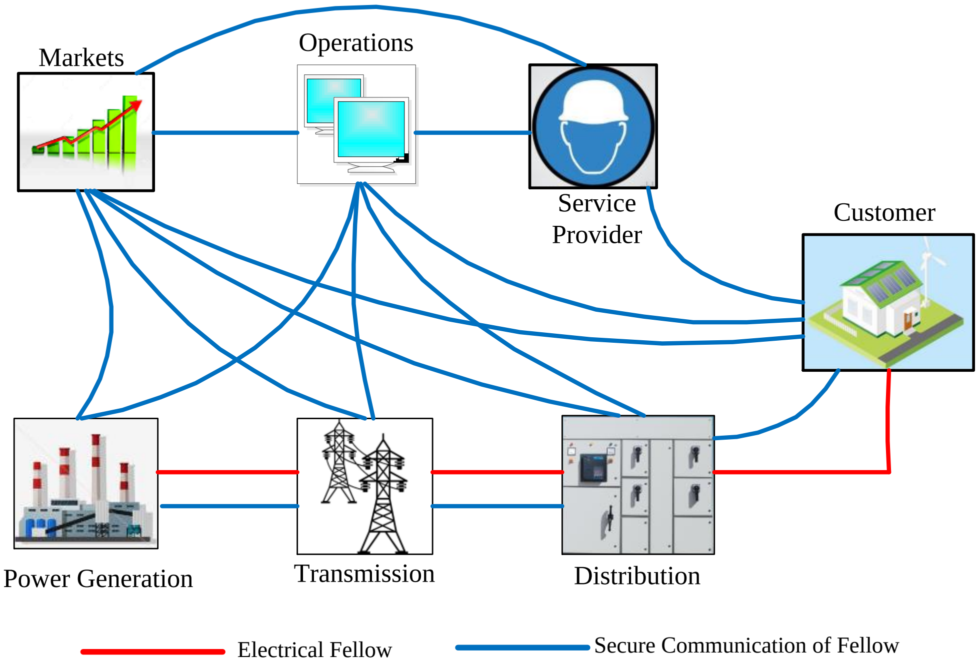


Figure 3.2 Overview of the electrical and communication flows in modern grid (IEC Roadmap, 2010)

3.1 Distribution system standardization

The IEEE and IEC are two impressive collections of standards that cover the standardization of different parts of the distribution system. Indeed, some parts of these standards can be considered to be the core of standard to be implemented in the modern grid.

3.1.1 IEC standards

The Distributed Resources (DR) in modern grids may include photovoltaic, wind turbine, distributed energy storage systems and so on. The standardization for photovoltaic systems is provided by *IEC 60904* for photovoltaic devices; *IEC 61194* for the characteristic parameters of stand-alone PV systems; *IEC 61724* for guidelines for measurement, data exchange, and analysis of performance of photovoltaic systems; *IEC 61730* for PV qualification of module safety; *IEC/TS 61836* for the terms, definitions, and symbols for PV systems; *IEC 62446* for requirements for system documentation, commissioning tests, and inspection of grid-connected PV systems; and *IEC/TS 62257* for recommendations for small renewable energy and hybrid systems. For standardization of the other most popular renewable energy sources, the minimum design requirement for wind turbines and all related subsystems is described in the *IEC61400* standard, parts one to three (*IEC 61400 1-3*) of which involve the design requirements for general, small, and offshore wind turbines.

Since communication is a significant part of power systems, and especially of MGs, identifying a communication protocol standard is required. In this regard, *IEC61850* is presented to describe communications in power substation automation systems. The standard is divided into a number of different parts, the first five of which present basic issues such as principles, general requirements, systems and project management, and communication requirements. In the sixth part, the configuration of substation automation systems is considered; the basic communication structure is described in part seven. There are some extensions in this part related to distributed energy resources that are present in IEC 61850-7-420, and which might be used in designing the communication system for DGs (Cleveland, 2008). Finally, mapping to manufacturing message specifications, measuring, and conformance testing are discussed in parts 8, 9, and 10, respectively. Moreover, part 25 of *IEC 61400* discusses the standardization of communication for the monitoring and control of wind power plants. The five series in this part (*IEC61400-25-1 … IEC61400-25-5*) respectively describe principles and models, information models, information exchange models, mapping to communication profile, and conformance testing. (IEC Roadmap, 2010)

3.1.2 IEEE standards

In the US, the energy policy established *IEEE 1547* as the national standard which concerns interfacing between DRs and the main grid; it also establishes the criteria and requirements for the interconnection. The requirements are related to operation, performance, safety considerations, and maintenance of the interconnection. However, this standard is not concerned with DR self-protection or with planning, designing, or operating the main grid. IEEE 1547 exists in a number of different series. In the first series of the standard, *IEEE1547.1*, the requirements specified in IEEE 1547 must be considered for interconnection equipment that connects the DGs to the main grid. To this end, UL 1741 also can serve as an alternative standard (Ustun, 2011). The second series of the standard, *IEEE1547.2*, discusses the technical background and application details for supporting the interconnection. The next series, *IEEE1547.3*, considers the issues of monitoring and communicating between DGs for the purpose of exchanging information and controlling the interconnection between the resources and the main grid (Basso, 2004). *IEEE1547.4* is one of the fundamental standards focused on MG standardization. The series deals with the integration of an island system with the main grid and covers planning and operating aspects, such as the impact of voltage, frequency, power quality, protection reserve margins, and load shedding. Given advancing technologies and the appearance of some large capacity systems, the first series of the standard cannot cover systems with electrical power sources greater than 10 MVA, so the target of *IEEE1547.5* is to provide guidelines for such systems. In the *IEEE1547.6*, the integration of secondary distribution networks with the main grid is described. The most important step in the standardization is in *IEEE1547.7*, which considers DGs and MGs. The series investigates the impact of the DG in the system, taking into account the required methodologies and testing steps. Finally, in the last series (*IEEE1547.8*), practices for establishing methods are recommended (Planas, 2013).

In US also the critical requirements for interconnecting photovoltaic systems to the main grid are covered in Standard *IEEE 929*. This standardization effort applies to utilities interconnecting photovoltaic power systems operating in parallel with the main grid through inverters to adaptation DC to AC. The standard contains guidelines related to equipment and requirement functions for compatible operation of the photovoltaic system. The guidelines also describe personal safety, equipment protection, and power quality (IEEE, 2000).

3.2 Hierarchical control based on IEC62264 standard

The electrical connection point of the DER defines the characteristics of the interaction between other sources or electrical power systems, such as MGs, isolated loads, and utility power systems. The connection point between different parts of the system is hierarchical and, as discussed in Chapter 2, control of the system is also based on a hierarchical method. Indeed, the variations in power generation and interconnection, as well as the electrical interface between different sources, energy storage, and the main grid, may be barriers to the achievement of a common standard for connecting DERs to the grid (Planas, 2013). In order to deal with these issues, this doctoral dissertation suggests that the IEC/ISO 62264 international standard be applied to MGs, which are considered in *Publication III* from the hierarchical control, energy storage, and energy market perspectives. In order to present a complete standard solution, those operational concepts of MGs that have some impact on participation in active network management including power quality, the principles behind island detection methods, black-start operation, fault management, and protection systems, are described in *Publication IV.*

In this standard, the interface between manufacturing–control functions and other enterprise functions is considered (IEC, 2003). As mentioned in *Publication III*, the objective of IEC/ISO 62264 is to offer consistent terminology for supplier and manufacturer communications, and to thus serve as a foundation for clarifying applications and information.

Among the benefits of the standard are that it can reduce the time necessary to achieve high production levels, reduce the cost of automation of the manufacturing process, and optimize supply chains. Moreover, the standards do not suggest that there is only one way of realizing the integration of control systems and neither do they limit the developer of the control system on the basis of the subsequent control methods. The IEC/ISO 62264 is based on the target of each control level and is not concerned with details such as the type of control. (IEC, 2003)

In *Publications III* and *VII*, the target of each level in the standard is defined. The IEC/ISO 62264 standard has five levels: *Level zero* indicates the process of manufacturing or production (in this application the power generation) and deals with the fundamental information and management. *Level one* specifies sensing, sensors, and actuators to monitor and regulate generation. On this level, direct control for providing stable output from units and the measurement of deviations in response to each immediate variation in the system are discussed. Moreover, the collection of data and the transmission of information to the upper control level are further objectives of this level. *Level two* involves control activity for monitoring and supervising the process in order to keep it stable. In this level, the information received from level one is analyzed to determine the limits of the system. Moreover, the position of the system is determined and used to optimize the operation of the system. *Level three* creates a connection between two different part of the control system, taking into account the demand and detecting energy limitations. *Level four* concerns the market structure and the business model of the system. In this level of the standard, the exchange of production between the generator and the consumer, capital and how to exploit it, and consumer service are considered. Indeed, all the level strategies are investigated in terms of three different categories (IEC, 2003):

- Control implementation: the responsibility and location of each level, as well their evaluation in response sequencing;
- Coordination and collecting: how information is gathered and how interfacing with other levels is performed;
- Reliability and stability: the effect of each control level on the system's stability.

Based on this standard, control of the system is in hierarchical form and all commands are executed by imposing them from a higher level.

3.3 Microgrid control standardization based on IEC 62264

Advance hierarchical control methodologies for MG and ESS under the IEC/ISO 62264 standard are presented in *Publication III* and the adaptation of standard is illustrated in Figure 3.3. Based on the discussion of hierarchical control in Chapter 2, the control of the MG is divided into four different levels in order to achieve the optimum operational reference value. The foundational control level is the inner control loop (*Zero level of IEC/ISO 62264*), which is implemented through voltage and current control loops for power management inside the sources. Determining an accurate reference value for the voltage and frequency to provide optimum control of the power converter is the responsibility of the primary control level (*first level of IEC/ISO 62264).* The second control level of the MG hierarchical control can then be covered by the *second level of IEC/ISO 62264.* As mentioned in Chapter 2, this control level involves two different approaches: grid-connected and island mode. In grid-connected mode, active and reactive power of the system is controlled; in island mode, the system operates on the basis of voltage and frequency control. Monitoring and supervising the variation in power, voltage, and frequency—as well as determining the reference value for primary control based on variation—is the responsibility of the control level. Power management and the reinstatement of secondary control is the objective of the tertiary control level (*third level of IEC/ISO 62264*). Finally, optimizing the set-point operation of the system from both technical and economic points of view is also the objective of the fourth level of control in the MG (*fourth level of IEC/ISO 62264*).

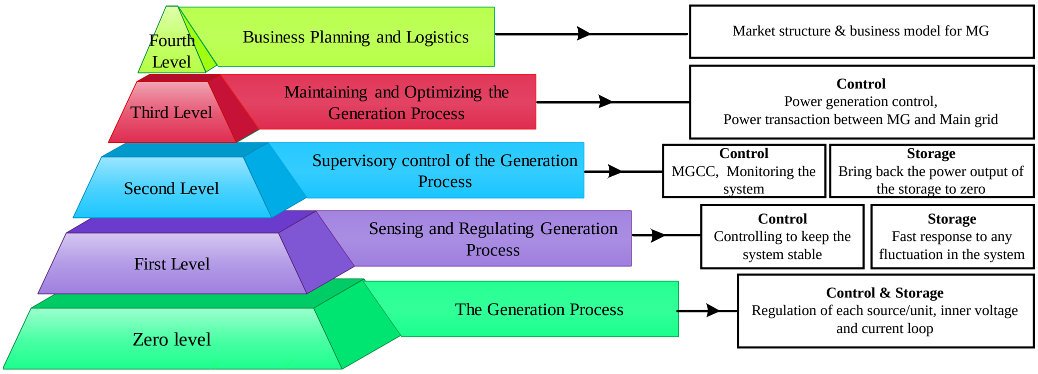


Figure 3.3 Adopting the hierarchical control to std. *IEC/ISO 62264*

As described in Chapter 2, since storage units typically play a significant role when the system operates in island mode, storage control does not contain a tertiary control, and consists only of zero, primary and secondary control levels. The principle of the zero level control in ESS (*Zero level of IEC/ISO 62264*) is the same as that of the same control level in the DG control. In the primary control (*first level of the IEC/ISO 62264*), the frequency of the system is monitored so that, if the frequency of the system exceeds the maximum value, the need arises for the surplus energy to be absorbed by the storage system. On the other hand, with an increase in demand, the frequency decreases toward the minimum frequency, and the storage system must begin to inject power into the system to maintain stable operation by covering the shortage in power generation.

However, the storage capacity of the energy storage system is not infinite, so a secondary control level must be implemented. In the secondary control (*second level of the IEC/ISO 62264*), the rate of stored energy and power is monitored to avoid any overcharging or over discharging of the energy storage system. Hence, after covering the shortage of power, the energy storage must be recharged for the next such shortage. In Figure 3.4, the hierarchical control of energy storage based on the IEC 62264 standard is shown (Kim, 2010).

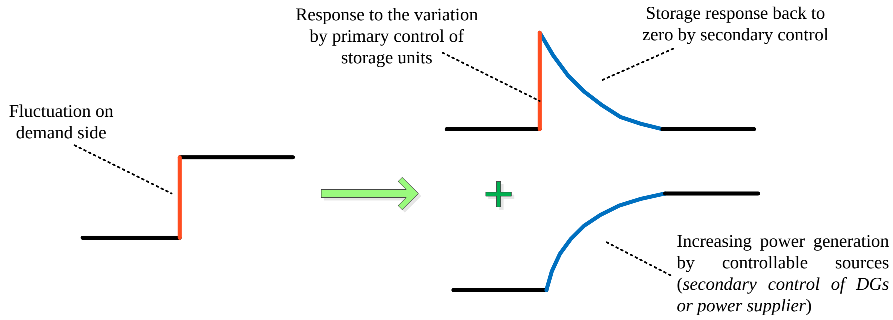


Figure 3.4 Hierarchical control of ESS

The final level of the IEC/ISO 62264 standard concerns the business model and market structure. There are, in general, three main transactional models: the pool, the bilateral contract, and combinations of these two methods (Chowdhury, 2009). Since the business model and market structure are not the main topics of this doctoral dissertation, they are discussed only briefly here and some relevant references are given. Additional information is also available in *Publication III*.

Finally, considering the information on the hierarchical control of MGs and ESSs in Chapter 2 and the standard proposed in the present chapter, advanced MG control techniques using the IEC/ISO 62264 standard are summarized in the flowchart (Fig. 3.5).

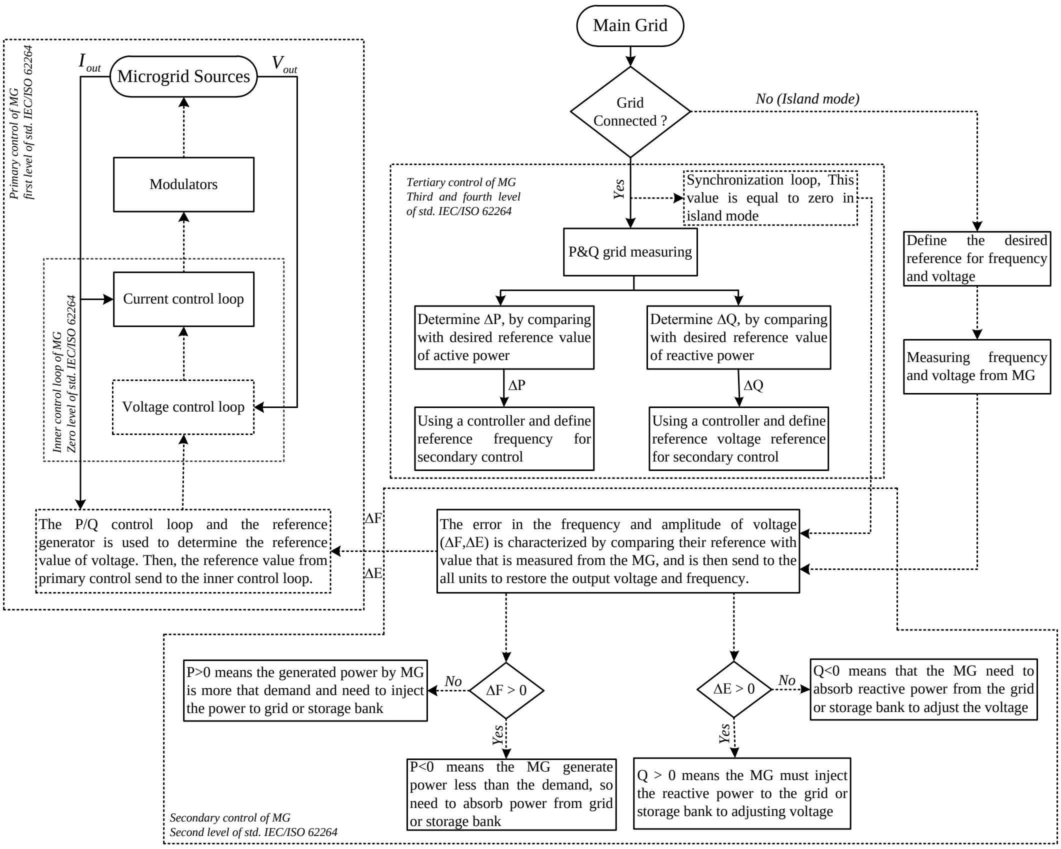


Figure 3.5 Hierarchical controls of MG and ESS based on std. *IEC/ISO 62264*

In *Publication III*, the authors proposed adapting the IEC/ISO62264 standard to MGs and storage systems. Moreover, *Publication IV* discusses some additional issues and develops operational concepts of MGs to have an impact on their participation in active network management and on the requirements for achieving targets. On the basis of the analysis in *Publication III*, the tertiary control level is disabled when the MG switches to island mode.

Since the technical focus of this doctoral dissertation is on the secondary control level, additional topics of MG—such as investigation of island-detection methods—are described in *Publication IV*. MGs can develop instability following planned or unplanned transitions to island mode. For this reason, *Publication IV* also addresses the principles of black-start operation, fault management, and protection systems, taking into account the IEC 62264 standard.

3.4 Summary of the chapter

In this chapter, a new standard has been adopted to the hierarchical control of MGs and ESSs. The IEC 62264 standard is an international standard that possesses the same level structure as the hierarchical control of MGs and ESS, with the same target in each level. In order to provide a complete solution, the hierarchical control strategy presented in Chapter 2 is summarized in a comprehensive flowchart (Figure 3.5) based on the standard adopted here.

4 DISTRIBUTED CONTROL STRATEGY FOR ENERGY STORAGE SYSTEMS

As discussed in the previous chapters, a decentralized control strategy for ESSs is needed to obtain coherence in MG control, especially with a distributed structure. On the basis of the research presented in Publication II (described in Chapter 2), the electrochemical storage method (battery) is the best storage technology for implementation in an MG. The energy levels in the storage units of a BESS are different, so when implementing a decentralized control method, sharing power between the storage units so that the overall performance of the system is maintained can be a challenge. This chapter proposes a decentralized control of ESSs that operates on the basis of the energy level of each storage unit. The DCS is applied to the secondary control level and, in the first stage, the storage units supply power (discharging mode). The ESSs are then combined with the DGs, which they also control in decentralized mode to determine the method to be employed during charging periods. The structure of the proposed system is shown in Figure 4.1.

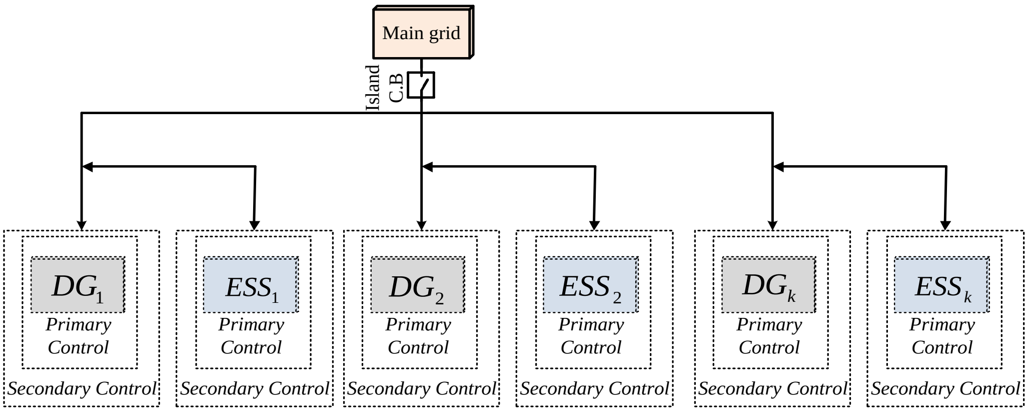
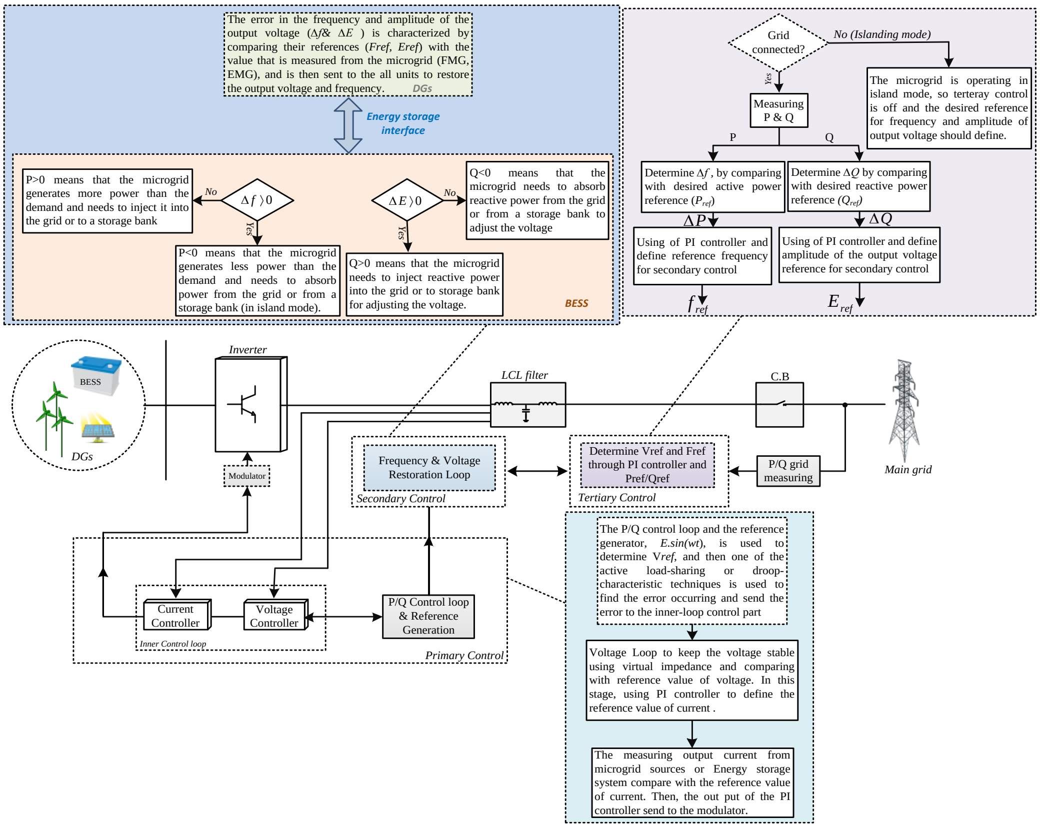


Figure 4.1 The structure of the proposed system

4.1 DG and ESS configuration

As mentioned in Chapter 2, the DGs and BESSs are power electronic control-based devices that contain several parts, each with a different responsibility. Figure 4.2 shows the configuration of the power electronics base sources (which may be a DG or a battery bank) and details of the hierarchical control and the responsibility of each control block. The details of the hierarchical control described in Chapter 2, and the distributed secondary control level used for the BESSs and DGs are discussed in the present chapter.



The error in the frequency and amplitude of the output voltage (Δf& ΔE) is characterized by comparing their references (*Fref, Eref*) with the value that is measured from the microgrid (FMG, EMG), and is then sent to the all units to restore the output voltage and frequency.

P>0 means that the microgrid generates more power than the demand and needs to inject it into the grid or to a storage bank

P<0 means that the microgrid generates less power than the demand and needs to absorb power from the grid or from a storage bank (in island mode).

Q>0 means that the microgrid needs to inject reactive power into the grid or to storage bank for adjusting the voltage.

Q<0 means that the microgrid needs to absorb reactive power from the grid or from a storage bank to adjust the voltage

The microgrid is operating in island mode, so terteray control is off and the desired reference for frequency and amplitude of output voltage should define.

Determine Δf , by comparing with desired active power reference (P_{ref})

Determine ΔQ by comparing with desired reactive power reference (Q_{ref})

Using of PI controller and define reference frequency for secondary control

Using of PI controller and define amplitude of the output voltage reference for secondary control

The P/Q control loop and the reference generator, *E.sin(wt)*, is used to determine V*ref*, and then one of the active load-sharing or droop-characteristic techniques is used to find the error occurring and send the error to the inner-loop control part

Voltage Loop to keep the voltage stable using virtual impedance and comparing with reference value of voltage. In this stage, using PI controller to define the reference value of current .

The measuring output current from microgrid sources or Energy storage system compare with the reference value of current. Then, the out put of the PI controller send to the modulator.

Figure 4.2 Configuration of power electronic based sources

As mentioned in *Publication V*, the second control level monitors and reacts to the system in order to keep deviations in the grid frequency and voltage within the permissible range of ± 0.2 Hz in UCTE (Continental Europe) and ± 0.1 Hz in Nordel (North of Europe), and -6% to +10% for the voltage (Guerrero, 2011; Morstyn, 2014). Such deviations are regulated toward zero by the BESS each time there is a load change or when any variation appears in the MG power generation. In the control method the frequency and voltage are measured at regular intervals (Shafiee, 2014). The strategies for DCS in DGs are executed based on a normal averaging method: the DCS uses the average value of frequency and voltage to eliminate the frequency deviation and to regulate the voltage of the MG. Since the voltage of the system is not the same at each sample time, the reactive power is also measured to regulate the set points that are provided when the power load is shared. The variations of reactive power and the restoration compensator for voltage and frequency are deduced from equations (4.1), (4.2), and (4.3) in the decentralized control method (Shafiee, 2014).

$$\begin{aligned}\Delta V_{BESU_k} &= G_{pv}(V_{BESU}^{ref} - \overline{V}_{BESU_k}) + G_{iv}\int (V_{BESU}^{ref} - \overline{V}_{BESU_k})dt \\ \overline{V}_{BESU_k} &= \frac{\sum\limits_{i=1}^{N} V_{BESU_i}}{N}\end{aligned} \tag*{4.1}$$

$$\begin{aligned}\Delta f_{BESU_k} &= G_{pf}(f_{BESU}^{ref} - \bar{f}_{BESU_k}) + G_{if}\int (f_{BESU}^{ref} - \bar{f}_{BESU_k})dt \\ \bar{f}_{BESU_k} &= \frac{\sum\limits_{i=1}^{N} f_{BESU_i}}{N}\end{aligned} \tag*{4.2}$$

$$\begin{aligned}\Delta Q_{BESU_k} &= G_{PQ}(\overline{Q}_{BESU_k} - Q_{BESU_K}) + G_{iQ}\int (\overline{Q}_{BESU_k} - Q_{BESU_k})dt \\ \overline{Q}_{BESU_k} &= \frac{\sum\limits_{i=1}^{N} Q_{BESU_i}}{N}\end{aligned} \tag*{4.3}$$

Where,

f_{BESU}^{ref}	Reference value of frequency in BESU
$\bar{f}_{BESU_k}$	The average frequency of BESU_k
Δf_{BESU_k}	Restoration values of the frequency
$\overline{Q}_{BESU_k}$	The average reactive power of BESU_k
Q_{BESU_k}	The reactive power of unit *k*
ΔQ_{BESU_k}	Restoration values of the reactive power
$\bar{V}_{BESU_k}$	The average voltage of BESU_k
V_{BESU}^{ref}	Reference value of voltage in BESU
ΔV_{BESU_k}	Restoration values of the voltage
$G_{p(v/f/Q)}$	Proportional gain for (voltage/frequency/reactive power) in secondary control
$G_{i(v/f/Q)}$	Integration gain for (voltage/frequency/reactive power) in secondary control

Due to the energy limitations in the storage system, the secondary control method for ESS, beside regulating the voltage, frequency, and reactive power, also needs to control the energy level of each storage unit. To achieve high performance in the distributed storage system, it is necessary to share power between the storage units on the basis of the energy level of each unit. Hence, in this doctoral dissertation, a new method for the control strategy is proposed and discussed in the following.

4.2 Decentralized energy control strategy for BESSs

With the battery energy storage technique, the operational voltage and current levels are generated through a series or a parallel connection of cells (Dunn, 2011). The amount of electrical charge in the cell from the fully charged state to the discharged state is called the capacity of the battery. The State of Charge (SoC) is the ratio between the remaining capacity and the full charge; this equals 100% at full charge and 0% at full discharge. The energy control in BESS involves two different approaches: Battery Management System (BMS) and Power Converter System (PCS). The SoC of each cell in a battery storage unit is monitored and balanced through BMS, while the output voltage, current, and load power sharing is implemented by PCS (Lu, 2015). This doctoral dissertation focuses on the PCS control and proposes a strategy for decentralized power sharing.

In the first step of the distributed control of ESS, it is necessary to determine an accurate SoC reference value. *Publications V* and *VI* presented a method for this, summarized here:

To obtain the reference value for energy, the SoC of each BESU (SoC_{BESU_k}) {k=1, 2,..., N} must be measured at each sample time and sent to the other units so as to calculate the average value of the state of charge ($So\bar{C}_{BESU}$), which is the sum of all the SoC values (SoC_{Total})divided by the number of BESUs (*N*):

$$So\overline{C}_{BESU} = \frac{SoC_{BESU_1} + SoC_{BESU_2} + \ldots + SoC_{BESU_N}}{N} \qquad 4.4$$

In the next step, to obtain the deviation of each BESU (ϑ_k), this average SoC value is compared with the SoC of the same BESU (SoC_{BESU_k}):

$$\vartheta_k = So\overline{C}_{BESU} - SoC_{BESU_k} \qquad 4.5$$

To determine the appropriate value of the SoC, a simple PI controller that is sufficiently fast to avoid full charge or discharge is added. The deviation of the SoC is amplified by the gain G_{PS} and integrated with the gain G_{iS}. Finally, in the secondary control level, the control signal for each sample period (δ_{SoC_k}) is considered follows:

$$\delta_{SoC_k} = G_{PS}\vartheta_k + G_{is}\int \vartheta_k dt \qquad 4.6$$

A control block diagram for the proposed distributed secondary control for BESS, designed on the basis of equations (4.1) to (4.6), is shown in Figure 4.3.

4.3 Droop control based on SoC

The reference value is used to determine the deviation of the SoC in the secondary control level and is sent to the primary control to restore this. In this doctoral dissertation, the primary level uses the *P/f-Q/V* droop control method to regulate the voltage and frequency in DGs and ESSs. However, as described in Chapter 2, with conventional droop control, the sharing of power between the different BESUs is based on power capacity, rather than energy levels.

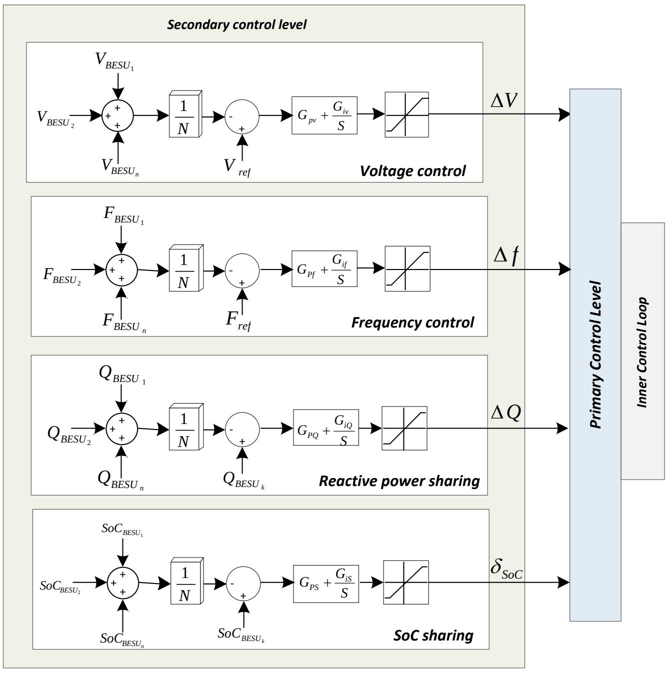


Figure 4.3 Decentralized secondary control for ESS

This type of power sharing can lead to some problems in the control system, where the storage units with lower energy level run out of energy earlier than the other units, causing frequency to be lost during discharge. Moreover, the storage units with the highest energy levels become full and drawing energy ceases to be possible even when the power demand is lower that the generated power—which would lead to renewable power potential being wasted due to unavailable storage capacity. Hence, to complete the distributed control of ESSs, a modification to the droop control is also required. To address this challenge, a modified droop control in primary level based on the SoC of the storage units is proposed here. The energy should be balanced during both the charging and discharging process, and their outputs or injected powers should be based on the SoC of the same BESU.

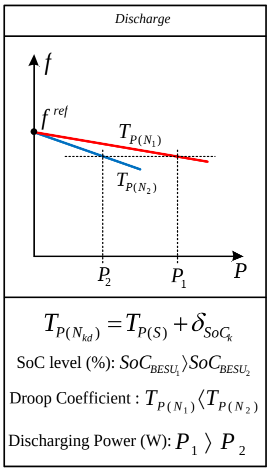


Figure 4.4 Modified droop control (discharging mode)

4.3.1 Discharging mode

The method used for distributed ESS when the storage units operate as a power supply (discharging mode) is evaluated in *Publication V*. In the droop control, the frequency and power are taken as reference values, so the modification cannot be applied to them. Hence, the variation should be controlled through the droop coefficient. To set the droop coefficients based on the energy level of each BESU, the output signal of the PI controllers (Equation 4.6) should be added to the traditional droop coefficient, presented in equation 2.5, so that the new droop coefficient value ($T_{P(N_{kd})}$) can be defined as:

$$T_{P(N_{kd})} = T_{P(S)} + \delta_{SoC_k} \qquad 4.7$$

Hence, by combining the traditional droop control (2.5) with (4.7), the modified droop control shown in equation (4.8) is obtained. Moreover, the new droop control for the discharging stage is illustrated in Figure 4.4.

$$f_k = f^{ref} - T_{P(N_{kd})}.(P_k - P^{ref}) \qquad 4.8$$

To equalize the energy storage discharge, the BESU with the lowest SoC should discharge slower than the others, in order to ensure the appropriate energy balance. The frequency is equal in each sample period and place and the variation is also within the acceptable range, so:

$$f_1 \approx f_2 \approx \ldots \approx f_N \tag{4.9}$$

By combining equation (4.8) with (4.9) is obtained:

$$P_1 T_{P(N_{1d})} = P_2 T_{P(N_{2d})} = \ldots = P_N T_{P(N_{Nd})} \tag{4.10}$$

Based on equations (4.7), (4.8), and (4.10), the droop coefficients at each BESU should be inversely proportional to the output power in order to achieve energy equalization. For instance, in a set of BESUs with different SoC levels, arranged as:

$$SoC_{BESU_1} > SoC_{BESU_2} > \ldots > SoC_{BESU_N} \tag{4.11}$$

Based on equations (4.6) and (4.7), the control signal and droop coefficients of each BESU can be defined as:

$$\delta_{SoC_{BESU_1}} < \delta_{SoC_{BESU_2}} < \ldots < \delta_{SoC_{BESU_N}} \tag{4.12}$$

$$T_{P(N_{1d})} < T_{P(N_{2d})} < \ldots < T_{P(N_{Nd})} \tag{4.13}$$

This means that the droop coefficient of the battery with the highest SoC is adjusted to the lowest value. Likewise, the BESU with the lowest SoC has the highest droop coefficient. It can be concluded from equations (4.10) and (4.13) that, if $SoC_i > SoC_j$ $\{i,j=1,2,\ldots,N\}$, then $P_i > P_j$.

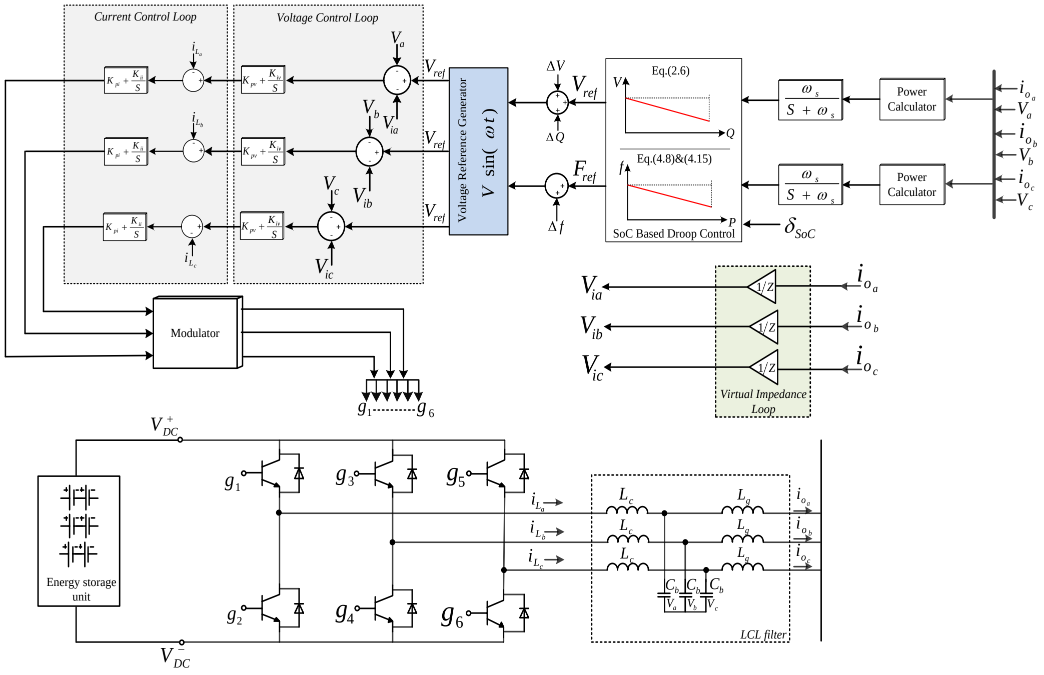


Figure 4.5 Primary level and inner control loop for ESS

The control block diagram of the modified droop control, as well as other parts of the primary control, are shown in Figure 4.5. Moreover, a flowchart of the distributed control strategy in discharge mode based on the proposed method with the modified *P/f* droop control is presented in Figure 4.6.

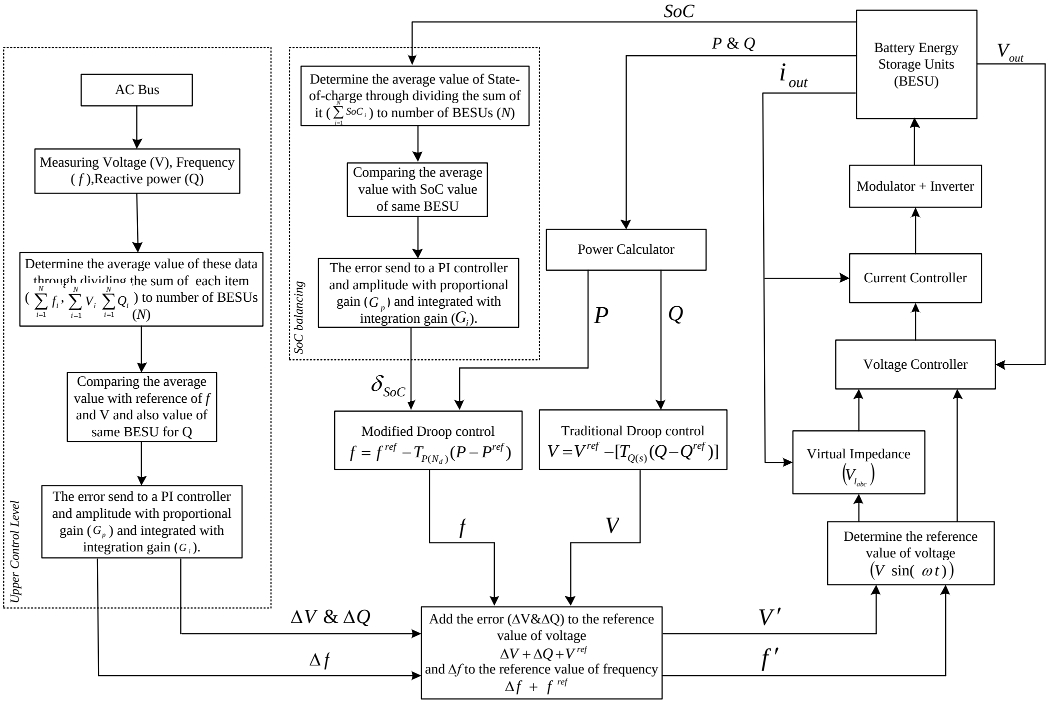


Figure 4.6 Flowchart of the proposed distributed control (discharging mode)

4.3.2 Charging mode

Also in the charging mode the objective of the control strategy is to set the droop control on the basis of the energy available in each storage unit. During the discharge process, the droop coefficient of the battery with the highest SoC is adjusted to the lowest value of the others. Likewise, the BESU with the lowest SoC is regulated to the highest droop coefficient. However, inverse proportionality cannot be used for the charging period, and the droop coefficient should be set to be proportional when the batteries absorb energy. The charging process for the proposed method is investigated in *Publication VI*. To achieve an optimum charging period, the output signal of the PI controllers (Equation 4.6) should be subtracted from the droop coefficients, so that new droop coefficient for the charging period ($T_{P(N_{kch})}$) is defined as:

$$T_{P(N_{kch})} = T_{P(S)} - \delta_{SoC_k} \tag{4.14}$$

Hence, by combining the traditional droop control (2.5) and (4.14), the modified droop control for charging mode shown in equation (4.15) is obtained. Moreover, the droop control for discharging mode (Figure 4.4) is extended to charging mode (see Figure 4.7).

$$f_k = f^{ref} - T_{P(N_{Kch})}.(P_k - P^{ref}) \qquad 4.15$$

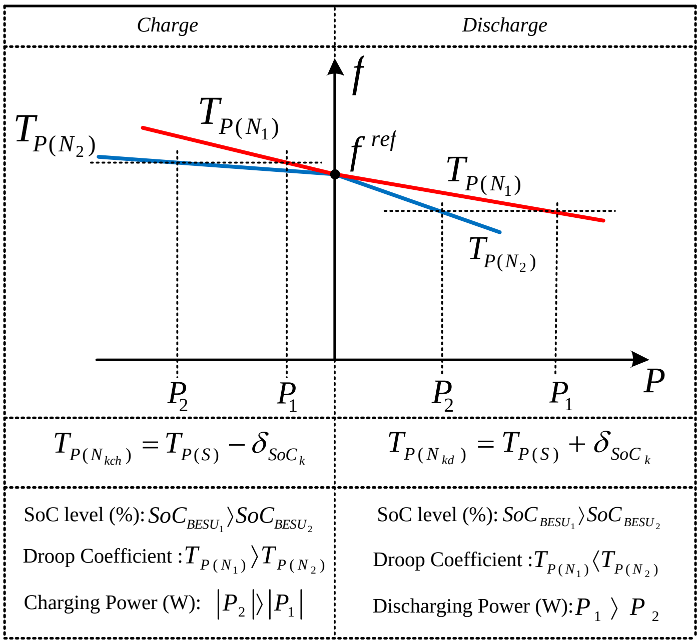


Figure 4.7 Modified droop control (charging and discharging mode)

To equalize the energy storage in charging mode, the BESU with the lowest SoC should charge faster than the others, in order to ensure energy balance. Taking into account equation (4.9) and applying equation (4.15):

$$P_1 T_{P(N_{1ch})} = P_2 T_{P(N_{2ch})} = \ldots = P_N T_{P(N_{Nch})} \qquad 4.16$$

To achieve energy equalization in the output power, based on equations (4.14), (4.15), and (4.16), the droop coefficients at each BESU should be proportional to the energy level during the charging mode. For the example of discharging mode with the order of the SoCs in equation (4.11), the BESU with the highest SoC absorbs the least energy while the most energy is injected into the storage unit with the lowest SoC level (if $SoC_i > SoC_j \, \{i,j=1,2,\ldots,N\}$, then $|P_i|<|P_j|$). A flowchart for the distributed control strategy based on the proposed method with the modified *P/f* droop control shown in Figure 4.6 is extended to charging mode in Figure 4.8.

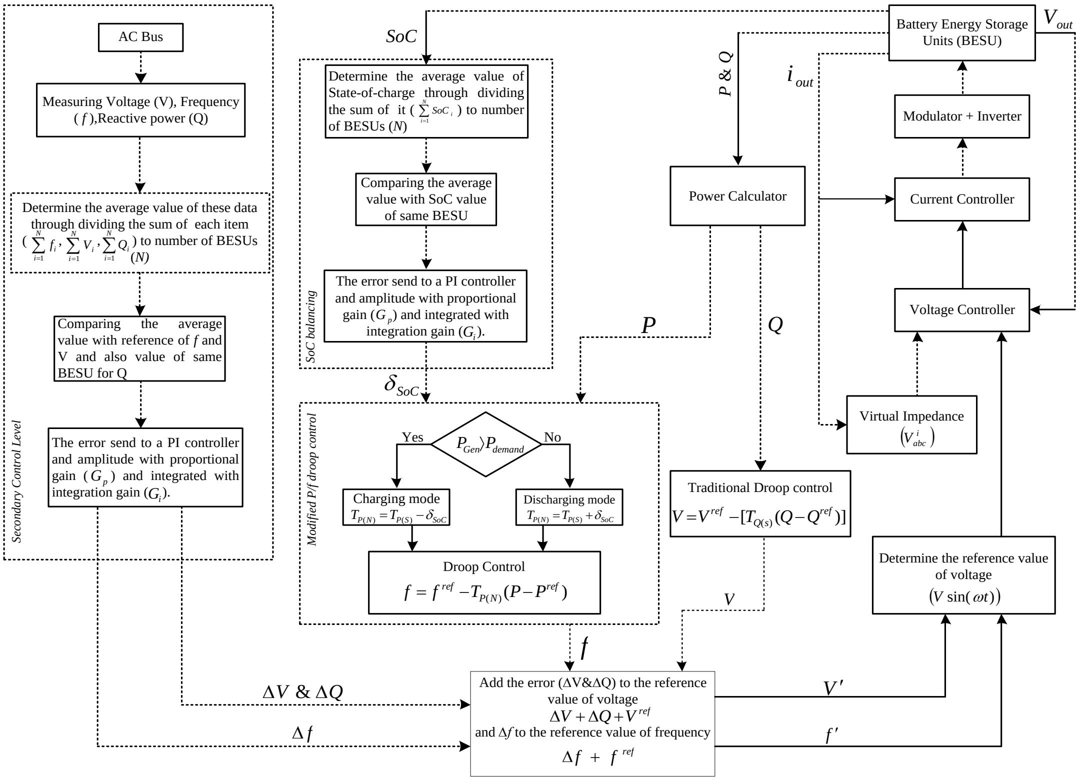


Figure 4.8 Flowchart of the proposed distributed control (Charging and discharging mode)

4.4 Summary of Chapter

In this chapter, a decentralized secondary control strategy for a distributed energy storage system, installed beside each DG, is proposed. More details about the method used are available in *Publication V* and *Publication VI*. Since the energy level of each storage unit is different, the main challenge in the distributed control strategy is to balance the energy. In this regard, a droop control method with the ability to share power based on the SoC of each battery is also employed: the droop coefficient is set to be inversely proportional during the discharging period and directly proportional during the charging period. Thus, the storage unit with the *highest* (*lowest*) energy level provides *more* (*less*) power to support the load when the storage unit operates as a power supplier, and absorbs *less* (*more*) power when the power generated exceeds the demand.

5 EVALUATION AND DISCUSSION

The proposed distributed cooperative control of BESSs and the decentralized control of DGs based on the modified droop control method are analyzed from a technical point of view in Chapter 4. The adopted standard for the hierarchical control of DGs and ESSs is presented in Chapter 3. This chapter ties these topics together by evaluating the proposed method using simulations and also investigating the result based on the adopted standard. The chapter summarizes the attached *Publications III*, *V*, *VI*, and *VII*.

5.1 Evaluation

To evaluate the proposed method for distributed cooperative control of BESSs, PSCAD/EMTDC software is used. The simulation system consists of three battery bank units connected to an AC bus through a power electronics interface. The AC bus supports two linear and one nonlinear load in a balanced three-phase system. Two resistors (R_{L1}, R_{L2}) are used as the linear loads while the nonlinear load is a diode rectifier loaded with a capacitor (C_{NL}) and a resistor load (R_{NL}). The different distances between the loads and the storage units are considered, so that the each load is *50 m* away from the AC bus and the interval distance storage units are *200 m*, *150 m*, and *100 m* for BESU_1 to BEUS_3; to model the distances and distribution lines, nominal *pi-sections* is used.

Firstly, the cooperative control for distributed BESSs is evaluated during the discharging period. During the time that these storage units operate as a power supply, the initial value of the SoC is adjusted by 5% difference, so that *Battery 1* is full (at 100%) when the SoC of *Batteries 2* and *3* are at 95% and 90%, respectively. Secondly, to charge these batteries, three DGs are used, one located beside each BESU, so that the distances from the DGs to the AC bus are also *200 m*, *150 m*, and *100 m*. As with discharging mode, the initial value of the SoC is also adjusted by 5% difference for charging time, so that that the SoC of *Battery 1* is at 20% while *Batteries 2* and *3* have SoCs of 15% and 10%, respectively. The configuration of the studied system is shown in Fig 5.1.

The equalization of the energy levels of each BESU for both discharging and charging periods is illustrated in Fig.5.2: this figure shows that the SoCs of these storage units, though they are different at the start, become closer to each other step by step, so that the 10% difference at the beginning of the simulation decreases to almost zero by the end of simulation.

Moreover, the absorption and injection of shared power is based on the SoC level of each storage unit during the discharging and charging modes. When the storage units operate as a power supply, to allow the BESUs to supply the loads, the battery with the highest SoC (*Battery 1*) provides more power than that with the lowest energy level (*Battery 3*). However, during charging mode, the storage unit with the highest energy level absorbs the lowest amount of power, while the storage unit with lowest energy level absorbs the highest power. The result of the power sharing of each BESU is illustrated in Fig.5.3 for the both discharging and charging process.

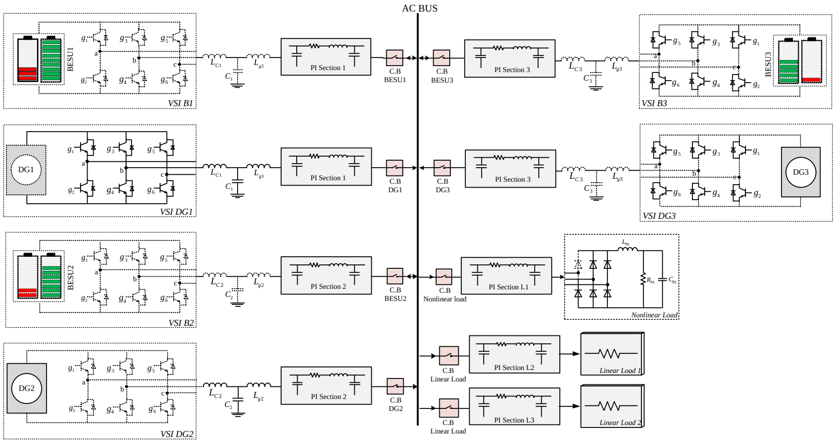
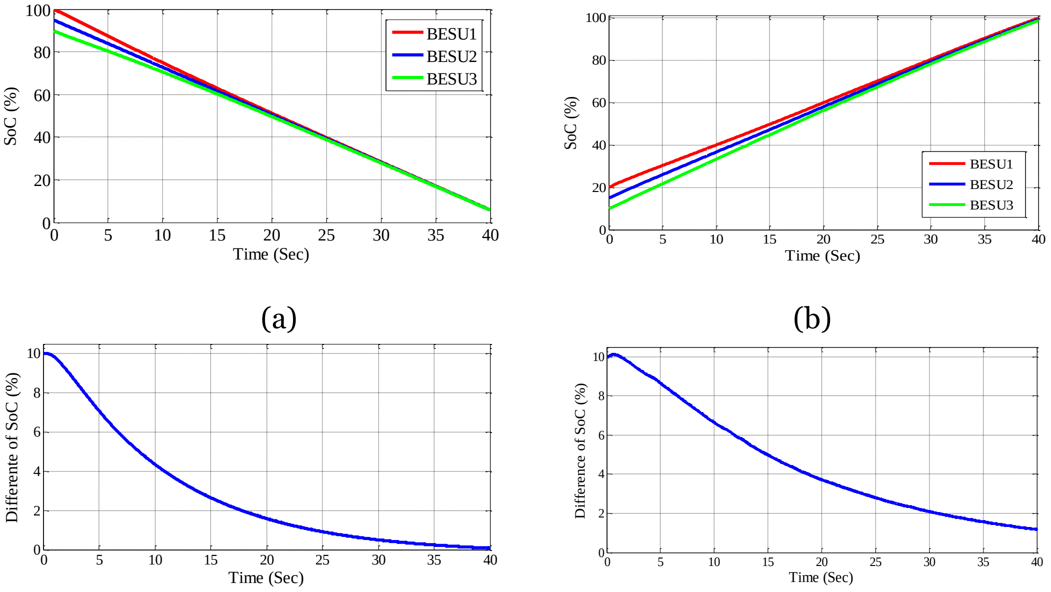


Figure 5.1 Configuration of the studied system



(a)

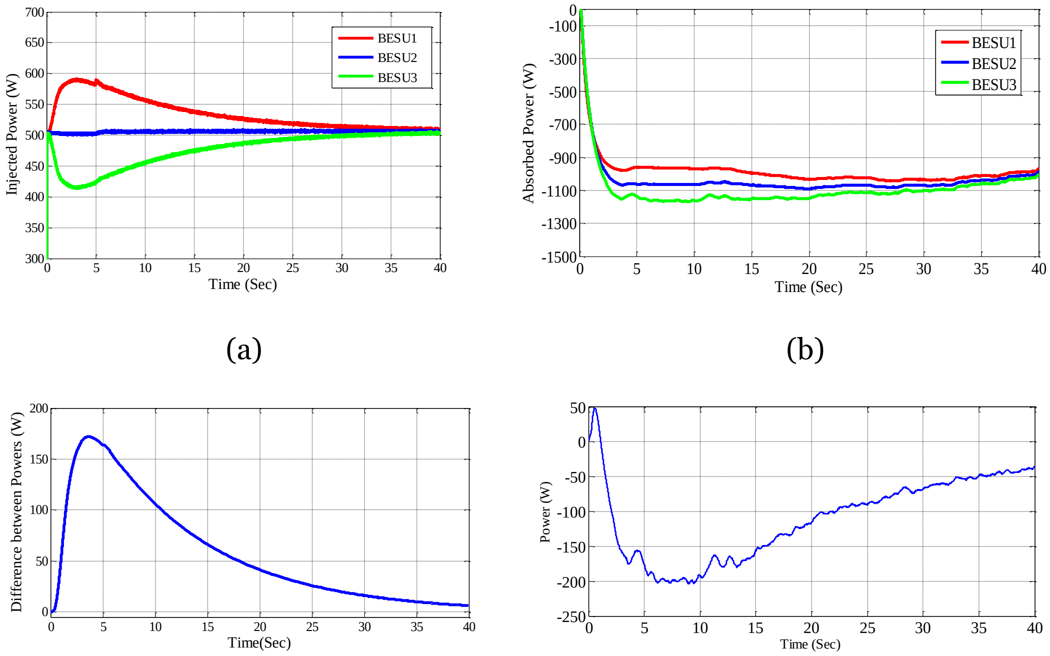
(b)

(c)

(d)

Figure 5.2 Energy balancing (a) discharging (b) charging & difference between unit 1 and unit 3 (c) discharging mode (d) charging mode

The total duration of the simulated period is *40 seconds* and, to better evaluate the power sharing based on the SoC modified droop control, two different time intervals are analyzed. The equalization of the power and SoC based on the two different time intervals is shown in Fig. 5.4 (discharging mode) and Fig.5.5 (charging mode). The initial difference in energy levels between the storage units with the largest differences (BESU$_1$ and BESU$_3$), is 10%, while by t = *20 s*, the difference has decreased to almost 2%.



(a) (b)

(c) (d)

Figure 5.3 Power sharing (a) discharging (b) charging & difference between unit 1 and unit 3 (c) discharging mode (d) charging mode

The difference continues to reduce step by step in the second time interval, almost reaching 0.1% by t = 40 s in discharging mode. This equalization is also illustrated in the absorbed and injected power, with the difference in injected power being almost 175 W during the discharging mode and 200 W in the charging process; at the end of the first time interval, the difference is 40 W for discharging and 100 W for charging. The differences drop below 40 W and 10 W at t = *40 s* for the charging and discharging modes, respectively. During both discharging and charging, the speed of convergence decreases with each time step on account of the decreasing error values between the SoC and the power sharing. Moreover, the fluctuation in power is higher during the charging process than during the discharging process because of the variation in output power of the DGs. The main parameters for the simulation are available in *Publications V* and *VI*.

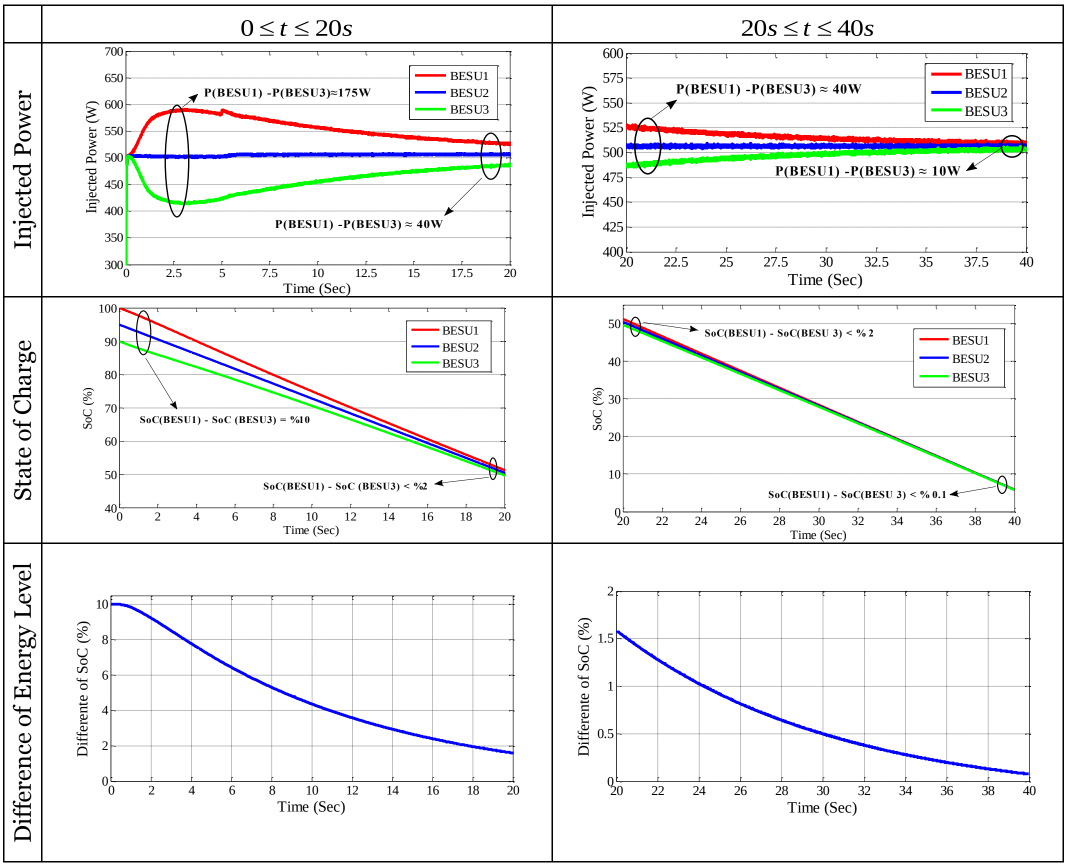


Figure 5.4 Analysis of discharging mode

5.2 Discussion

The different levels of IEC/ISO 62264 (described in Chapter 3), the hierarchical control of DGs and BESSs (described in Chapter 2), and the proposed decentralized control (describe in chapter 4) are treated together in *Publication VII*. The hierarchical control of MGs and ESSs has been considered in four different levels; the IEC 62264 standard also has five levels with the same objective as the hierarchical control at each level. The hierarchical control and adopted standard can be harmonized as follow:

- *Level zero of the IEC/ISO 62264 standard* considered the fundamental information on production units; the responsibility of the hierarchical control of DGs and BESSs in this level is to implement the *inner control loop* through voltage and current control loops so as to keep the power output at a given reference value.

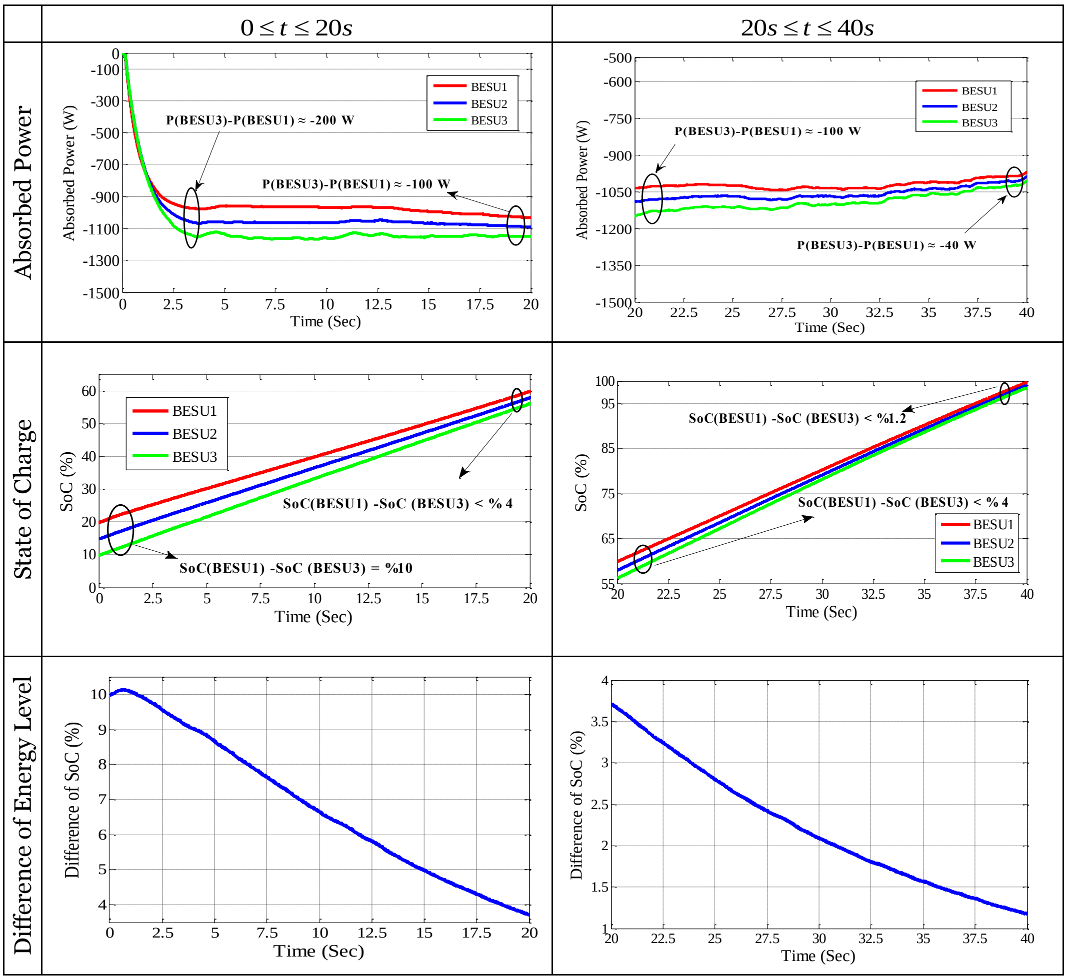


Figure 5.5 Analysis of charging mode

- The *first level of the IEC/ISO 62264 standard* detects any variation in the system and acts to cover it immediately by measuring the difference and transferring it to the upper control level. In the hierarchical control of DGs and BESSs, determining accurate reference values for voltage and frequency so as to maintain the optimum control of the power converter is the responsibility of the *primary control level.*

- The *second level of the IEC/ISO 62264 standard* monitors and supervises the system to keep it stable and under control; the *second control level in DG and BESS hierarchical control* covered by the standard level. Monitoring and supervising the variations in power, voltage, and frequency—as well as determining the reference value for the primary control based on the variation—are the responsibilities of the secondary control level.

- The duties of the *third level of the IEC/ISO 62264 standard* are to create a program to manage the coverage area and to produce an optimized strategy to support the subsystem, while the objectives of the *tertiary* *control level in DGs and BESSs* are power management of secondary control and also interfacing with main grid.

- Optimizing the set-point operation of the system from both the technical and economic points of view is another objective of the final level of control in the MG, with the *fourth level of the IEC/ISO 62264 standard* discussing the market structure and the business mode of system.

The adaptation of the decentralized control and the proposed standard are illustrated in Fig 5.6. Although the structure of the control is same for both DGs and BESSs, there are some differences in the responsibilities of hierarchical control between them. Hierarchical control is defined based on the type of the connection of the MG. As mentioned in previous chapters, the storage control does not have a tertiary control, but consists only of an inner control loop, primary, and secondary control levels, as it operates in island mode. The responsibility of the hierarchical control of BESSs, in addition to providing stable power, is to manage the energy levels of the energy storage system and to avoid the problems of overcharging and over discharging.

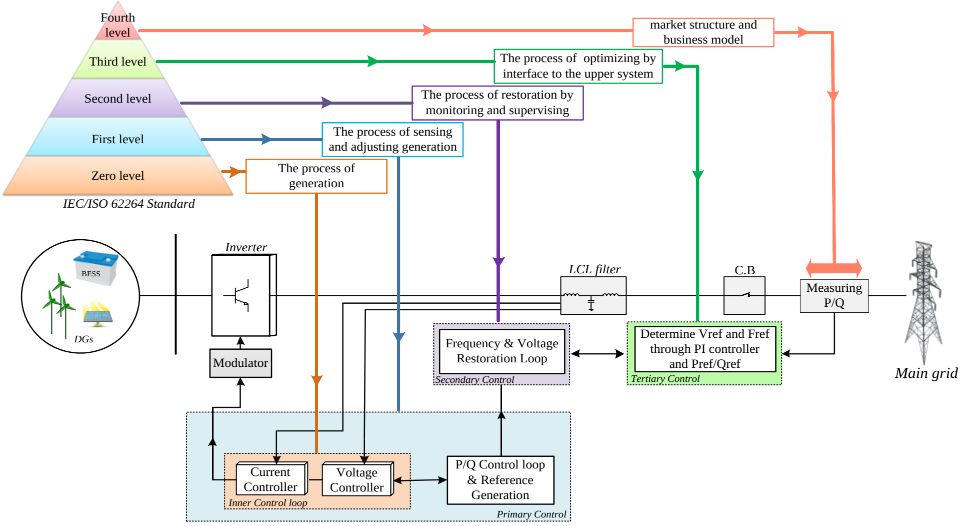


Figure 5.6 Microgrid (DGs and BESS) vs. IEC/ISO62264 Standard

The energy balancing method for energy storage systems operates with a hierarchical control strategy. Hence, the proposed decentralized control methodology for BESS can be matched with the adopted standard. An analysis of how the decentralized control of BESS could work with the IEC/ISO 62264 standard appears in *Publication VII* and is summarized in Table 5.1. Since the system is operated in island mode, the tertiary control level for DGs is disabled and only the zero, primary, and secondary control levels are included. The methodology is evaluated using only lithium-ion battery model but it is also applicable to all other batteries types. This is due to the fact that while the batteries differ in terms of their charging and discharging mode characteristics, this does not have impact the control method. Since the *P/f* droop method is used in primary control, the proposed method can only be implemented in AC MGs. The impossibility of using the method for DC MGs is one of the main limitations of the method.

5.3 Summary of the chapter

In this chapter, the proposed decentralized control strategy for BESS has been evaluated using simulations run in PSCAD/EMTDC. In the simulation, a hierarchical control level is also considered for power management. The proposed method has also been investigated on the basis of the standard adopted in this doctoral dissertation (IEC/ISO 62264). An analysis of how the decentralized control of BESS can work with the IEC/ISO 62264 standard appears in *Publication VII* and is summarized in Table 5.1.

Table 5.1 Summarize of responsibility of MGs and description of IEC/ISO62264 standard

	Levels	Description in IEC/ISO 62264	Responsibility in MG control	Levels	
Standardization	Zero	Process of manufacturing and fundamental information and management.	Manage the output power of the DGs and ESS which is accomplished through the current and voltage control.	Inner control loop	Decentralized Control strategy
	First	Specifies sensing, sensors, and actuators to monitor and regulate generation	Regulate the frequency and amplitude of the voltage references that feed the inner current and voltage control loops.	Primary control	
	Second	Monitoring and supervising the process in order to keep it stable.	Monitoring frequency, voltage, reactive power and energy level of each storage unit to restore the variation	Secondary control	
	Third	Connection between two different part of the control system.	The proposed method is operated in island mode. Hence, the tertiary control level is disabled.	Tertiary control	
	Fourth	Concerns the market structure and the business model of the system.	The tertiary control level is disabled.	Tertiary control	

6 CONCLUSION

The highlights of the approach of this doctoral dissertation—as well as its contributions to research and an introduction to future research opportunities and open research questions—are described in this final chapter.

6.1 Summary of research

This dissertation has focused on a method for the decentralized control of an island-mode AC MG, with special emphasis on energy storage systems with the aim of sharing power among batteries in a distributed approach based on the energy level of each unit. Moreover, an international standard is adapted to hierarchical control of MGs. The doctoral dissertation begins with a description of the reasons for implementing MGs and continued with a discussion of the role of ESSs in MGs. In Chapter 2, a comprehensive investigation into the hierarchical control of MGs is presented, and the technologies and applications of ESSs in MGs are reviewed. As part of the investigation of hierarchical control in Chapter 2, the principles of the inner control loop, primary, secondary, and tertiary control levels, and the relations between these control levels are presented. Based on the research, the technical solutions proposed for the inner control loop and the primary controls are sufficiently comprehensive to be implemented. However, in the secondary control level—especially when used with decentralized control methods—there are many research questions that need to be investigated in order to complete the control level. In the energy storage part of an MG, the different storage system technologies first need to be evaluated. To this end, Chapter 2 also presented a matrix of the relations between technologies and applications. Many different parameters—such as capacity, storage power, response time, discharge time, lifetime, efficiency, and others—are compared to produce the matrix. Based on the literature survey, electrochemical storage can cover most of the applications in MG; it is also a popular technique for implementing ancillary services in island MGs. Having presented the hierarchical control principle of MGs and ESSs arranged into four different levels in Chapter 2, Chapter 3 adapted an IEC standard to the hierarchical control levels. IEC/ISO 62264, which is considered for hierarchical control, has five levels: *level zero* (the generation process), *level one* (the process of sensing and adjusting generation), *level two* (monitoring and supervising), *level three* (maintenance and optimization), and *level four* (market structure and business model). Chapter 4 proposes a methodology for the decentralized control of BESSs and for balancing energy in the distributed BESS approach. In the first step, the methodology is investigated for the storage units operating as a power supply (discharging mode). For high-level control, a distributed ESS is then installed beside each DG, which is also controlled through a decentralized secondary control technique. The charging mode is then investigated. To achieve ideal power sharing, a modified droop control methodology is employed. In this strategy, the droop coefficient is set to be inversely proportional to the state of charge during the discharging period and directly proportional during the charging period. In Chapter 5, the proposed method is evaluated by simulation. The simulation demonstrating the performance of the proposed control approach has been carried out using PSCAD/EMTDC software and has been demonstrated that the storage unit with the *highest (lowest)* energy level provides *more (less)* power to support the load when the storage unit operates as a power supplier, and absorbs *less (more)* power when the power generated exceeds the demand. Finally, to advance the contributions made by this dissertation, the proposed method and the hierarchical control strategy used in the evaluated technique (based on the IEC/ISO 62264 standard) are also presented and discussed in Chapter 5.

This doctoral dissertation covers some open research questions in the modern grid, including:

- Standardization of the hierarchical control in DGs and ESSs;
- Decentralized control strategy in ESSs;
- Power sharing in distributed ESSs based on the energy level of each storage unit.

To investigate the equalization of energy levels in different storage units, a stable situation for charging and discharging period has been only considered in this dissertation. Hence, the sensitivity of the selected control method (droop control) in transient conditions and the significant parameters for stability in this control strategy needs more research. Moreover, since the proposed method for power sharing is based on a modified *P/f* droop control strategy, it cannot function in systems without frequency control, such as DC microgrids.

6.2 Contributions

The contributions of this dissertation are as follows:

- Development of a study of energy storage systems, providing a matrix of available technologies and applications. The assessment demonstrated that electrochemical energy storage technologies (batteries) are the most common type and are most suitable for implementing MGs; they can also serve in many related applications.

- The development of standard solution for controlling MGs and ESSs by adapting an international standard (IEC/ISO 62264) to the hierarchical control of such systems. The standard is based on a hierarchical control on four levels with the common objectives for each level.
- The development of distributed control strategies for energy storage systems to eliminate centralized control techniques. These strategies enhance the reliability of the system and also help achieve fully decentralized control of the MG. The method is evaluated for both charging and discharging modes.
- The development of a droop control method for power sharing between the different storage units on the basis of the energy level of each unit. The modified droop control is evaluated during the charging and discharging periods.
- Evaluating the proposed methodologies for decentralized control of BESSs and modifying the droop control to the adapted standard.

6.3 Future work

The techniques and contributions developed in this dissertation point to the following open research issues that can be studied in future:

- This dissertation has focused on a decentralized control method for MGs in island mode. The proposed method could thus also be analyzed in grid-connected mode, and this is an opportunity for future research.
- Analysis of the method proposed here for different ESS applications. The dissertation has only studied the possibility of the decentralized control of DGs and ESSs, along with energy balancing. Assessing different applications of ESS, as presented in Chapter 2, could also prove to be interesting research.
- Hierarchical control of DC MGs is another interesting topic for future research. The dissertation focused on AC MGs and implemented a modified P/f droop control on the primary level for sharing power among the ESSs on the basis of their energy levels. Since there is no need to control the frequency in DC MGs, the new droop control could be employed for power sharing.

- In modern grids, power quality remains an interesting open research question. Since this dissertation has focused on the main function of the secondary and primary controls in MGs and ESSs, research into other optional functions, such as power quality—especially if based on the proposed distributed control—is another attractive research topic.

References

ABB (Producer) (2014). Energy storage system solution, www.abbenergystoragesolutions.com.

Abu-Sharkh, S., Arnold, R., Kohler, J., Li, R., Markvart, T., Ross, J., Yao, R. (2006). Can microgrids make a major contribution to UK energy supply? *Renewable and Sustainable Energy Reviews, 10*(2), 78-127.

Ackermann, T., Andersson, G., Söder, L. (2001). Distributed generation: a definition. *Electric Power Systems Research, 57*(3), 195-204.

Akhil, A., Georgianne, H., Currier, B A., Rastler, K., Chen, S., Cotter, L., Bradshaw, D., Gauntlett, D. (2013). DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Albuquerque: Sandia National Laboratories.

Alto, P. (2012). Results from Case Studies of Pumped-Storage Plants. In I. 1023142 (Ed.), (Vol. ID 1023142). CA.USA: Electrical Power Research Institute.

Banerji, A., Sen, D., Bera, A. K., Ray, D., Paul, D., Bhakat, A., Biswas, S. K. (2013). *Microgrid: A review*. Paper presented at the Global Humanitarian Technology Conference: South Asia Satellite IEEE, GHTC-SAS.

Barnes, M., Kondoh, J., Asano, H., Oyarzabal, J., Ventakaramanan, G., Lasseter, R., Green, T. (2007). *Real-world microgrids-an overview*. Paper presented at International Conference on the System of Systems Engineering, IEEE SoSE'07.

Basso, T. S., DeBlasio, R. (2004). IEEE 1547 series of standards: interconnection issues. *Power Electronics, IEEE Transactions on, 19*(5), 1159-1162.

Basu, A. K. (2011). Microgrids: Energy management by strategic deployment of DERs—A comprehensive survey. *Renewable and Sustainable Energy Reviews*, 15 (9), 4348-4356.

Bidram, A., Davoudi, A. (2012). Hierarchical Structure of Microgrids Control System. *IEEE Transactions on Smartgrid, 3(4),1963-1976.*

Blaabjerg, F., Teodorescu, R., Liserre, M., Timbus, A. V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics, 53*(5), 1398-1409.

Blanc, C. R., Alfred. (2008). *Multiphysics and energetic modeling of a vanadium redox flow battery*. Paper presented at the International Conference on Sustainable Energy Technologies. .

Bradbury, K. (2010). Energy storage technology review. *Duke University*, 1-34.

Brown, P. D.,Pecas, J.A.,Matos, M.A. (2008). Optimization of pumped storage capacity in an isolated power system with large renewable penetration. *IEEE Transactions on Power Systems, , 23*(2), 523-531.

Carnegie, R.,Gotham, D.,Nderitu, D., Preckel, P.V. (2013). Utility Scale Energy Storage Systems (benefits, applications, and technologies): State Utility Forecasting Group.

Carrasco, J. M., Franquelo, L. G., Bialasiewicz, J. T., Galván, E., Guisado, R. P., Prats, M. A., Moreno-Alfonso, N. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on Industrial Electronics, 53*(4), 1002-1016.

Cavanagh, K.,Ward, J. K.,Behrens, S.,Bhatt, A.I., Ratnam, E.L., Oliver, E.,Hayward J. (2015). Electrical energy storage: technology overview and applications (Vol. EP154168). Australia. : CSIRO.

Chandorkar, M. C., Divan, D. M., Adapa, R. (1993). Control of parallel connected inverters in standalone ac supply systems. *IEEE Transactions on Industry Applications, 29*(1), 136-143.

Chiang, S., Chang, J. (2001). *Parallel control of the UPS inverters with frequency-dependent droop scheme*. Paper presented at 32nd Annual IEEE Conference on the Power Electronics Specialists, PESC.

Chowdhury, S., Chowdhury, S., Crossley, P. (2009). *Microgrids and active distribution networks*: Institution of Engineering and Technology (IET).

Chua, K. H., Lim, Y. S., Morris, S. (2013)Battery energy storage system for peak shaving and voltage unbalance mitigation. International Journal of Smart Grid and Clean Energy, 2 (3),357-363.

Cleveland, F. (2008). *IEC 61850-7-420 communications standard for distributed energy resources (DER)*. Paper presented at the Power and Energy Society IEEE General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century,.

Díaz-González, F.,Andreas, S., omis-Bellmunt, O.,Villafáfila-Robles, R. (2012). A review of energy storage technologies for wind power applications. *Renewable and Sustainable Energy Reviews, 16*(4), 2154-2171.

Dimeas, A. L., Hatziargyriou, N. D. (2005). Operation of a multiagent system for microgrid control. *IEEE Transactions on Power Systems, 20*(3), 1447-1455.

Divya, K., Østergaard, J. (2009). Battery energy storage technology for power systems—An overview. *Electric Power Systems Research, 79*(4), 511-520.

Dragicevic, T.,Guerrero, J.M.,Vasquez, J.C.,Skrlec, D. (2014). Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability. *IEEE Transactions on Power Electronics, , 29*(2), 695-706.

Dunn, B., Kamath, H., Tarascon, J.M. (2011). Electrical energy storage for the grid: a battery of choices. *Science, 334*(6058), 928-935.

Electrical Energy Storage. (December 2011): IEC.

Eyer, J., Corey, G. (2010). Energy storage for the electricity grid: Benefits and market potential assessment guide *SAND2010-0815*. Albuquerque, New Mexico: Sandia National Laboratories Report.

Farid, M. M., Khudhair, A.M., Razack, S.A.K., Al-Hallaj, S. (2004). A review on phase change energy storage: materials and applications. *Energy Conversion and Management, 45*(9), 1597-1615.

Galiana, F. D., Bouffard, F., Arroyo, J.M, Restrepo, J.F. (2005). Scheduling and pricing of coupled energy and primary, secondary, and tertiary reserves. *Proceedings of the IEEE, 93*(11), 1970-1983.

Gellings, C. W. (2009). *The smart grid: enabling energy efficiency and demand response* (1 ed.). Liburn- Unaited States: The Fairmont Press, Inc.

Gipe, P. (2004). Wind power. *Wind Engineering, 28*(5), 629-631.

Gu, W., Wu, Z., Bo, R., Liu, W., Zhou, G., Chen, W., Wu, Z. (2014). Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review. *International Journal of Electrical Power & Energy Systems, 54*, 26-37.

Guerrero, J., Loh, P., Chandorkar, M., Lee, T. (2013). Advanced Control Architectures for Intelligent MicroGrids, Part I: Decentralized and Hierarchical Control. *IEEE Transactions on Industrial Electronics, 60*(4), 1254-1262.

Guerrero, J. M., Berbel, N., Matas, J., Sosa, J. L., de Vicuna, L. G. (2007). *Droop control method with virtual output impedance for parallel operation of uninterruptible power supply systems in a microgrid.* Paper presented at the Twenty Second Annual IEEE Conference on Applied Power Electronics, APEC.

Guerrero, J. M., Hang, L., Uceda, J. (2008). Control of distributed uninterruptible power supply systems. *IEEE Transactions on Industrial Electronics, 55*(8), 2845-2859.

Guerrero, J. M., Vasquez, J. C., Matas, J., Castilla, M.,de Vicuna, L. G. (2009). Control strategy for flexible microgrid based on parallel line-interactive UPS systems. *IEEE Transactions on Industrial Electronics, , 56*(3), 726-736.

Guerrero, J. M., Vasquez, J.C., Matas, J.,de Vicuña, L.G.,Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization. *IEEE Transactions on Industrial Electronics, 58*(1), 158-172.

Gyuk, L.M.J., Vetarno, J., Lynn, K., Park, W., Honda, R. (2013). Grid Energy Storage: U S. Department of Energy.

Hadjipaschalis, I., Poullikkas, A., Efthimiou, V. (2009). Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews, 13*(6), 1513-1522.

Hatziargyriou, N. (2014). *Operation of Multi-Microgrids*: Wiley-IEEE Press.

Hatziargyriou, N., Asano, H., Iravani, R., Marnay, C. (2007). Microgrids. *Power and Energy Magazine, IEEE, 5*(4), 78-94.

Hirst, E., Kirby, B. (1999). Separating and measuring the regulation and load-following ancillary services. *Utilities Policy, 8*(2), 75-81.

Hotakainen, J. K. M. (2011). *Smart Power Generation*. Vaasa: Avain, Wartsila.

Huang, K.L., Li, X.,Liu, S., Tan, N. Chen, Li, Ch. (2008). Research progress of vanadium redox flow battery for energy storage in China. *Renewable Energy, 33*(2), 186-192.

Hyytinen, T. (2013). *Hybrid Power Generation Concept for Small Grids*. Master, University of Vaasa.

IEC. (2003). IEC 62264-1: Enterprise-Control System Integration, Part 1: Models and Terminology. *Bureau of Indian Standards (BIS), Industrial Process Measurement and Control (ETD 18).*

IEC Roadmap, (2010). SMB Smart Grid Strategic Group (SG3). *Application of Neural Network in Power system, A Review, World Academy of Science*.

IEEE. (2000). *IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems*: IEEE.

Jiayi, H., Chuanwen, J.,Rong, X. (2008). A review on distributed energy resources and MicroGrid. *Renewable and Sustainable Energy Reviews, 12*(9), 2472-2483.

Joerissen, L., Juergen, G.,Fabjan, Ch.,Tomazic, G. (2004). Possible use of vanadium redox-flow batteries for energy storage in small grids and stand-alone photovoltaic systems. *Journal of Power Sources, 127*(1), 98-104.

Justo, J. J., Mwasilu, F., Lee, J., Jung, J.W. (2013). AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renewable and Sustainable Energy Reviews, 24*, 387-405.

Kakigano, H.,Yushi, M.,Ise, T. (2013). Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique. *IEEE Transactions on Power Electronics, , 28*(5), 2246-2258.

Katiraei, F., Iravani, R., Hatziargyriou, N., Dimeas, A. (2008). Microgrids management. *IEEE Power and Energy Magazine, 6*(3), 54-65.

Katiraei, F.,Iravani, M.,Lehn, P.W. (2005). Micro-grid autonomous operation during and subsequent to islanding process. *IEEE Transactions on Power Delivery, , 20*(1), 248-257.

Kim, J.Y.,Kim, S.K.,Jeon, J.H. (2012). *Coordinated state-of-charge control strategy for microgrid during islanded operation*. Paper presented at the 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)

Kim, J.Y.,Joen, J.H.,Kim, S.K.,Cho, Ch.,Park, J.H.,Kim, H.M.,Nam, K.Y. (2010). Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation. *IEEE Transactions on Power Electronics, 25*(12), 3037-3048.

Kling, W., Slootweg, J. (2002). *Wind turbines as power plants.* Paper presented at the Proceedings of the IEEE/Cigré workshop on Wind Power and the Impacts on Power Systems.

Kroposki, B., Pink, C., DeBlasio, R., Thomas, H., Simões, M.,Sen, P. K. (2010). Benefits of power electronic interfaces for distributed energy systems. *IEEE Transactions on Energy Conversion, 25*(3), 901-908.

Kwasinski, A. (2011). Quantitative evaluation of DC microgrids availability: Effects of system architecture and converter topology design choices. *IEEE Transactions on Power Electronics, 26*(3), 835-851.

Laaksonen, H., Kauhaniemi, K. (2008). Stability of microgrid with different configurations after islanding due to fault in the utility grid. *International Review of Electrical Engineering (IREE), 3*(3).

Lasseter, R. H. (2002). *Microgrids.* Paper presented at the IEEE Power Engineering Society Winter Meeting, 2002.

Levron, Y., Shmilovitz, D. (2012). Power systems’ optimal peak-shaving applying secondary storage. *Electric Power Systems Research, 89*, 80-84.

Li, Ch.,Dragicevic, T.,Diaz, N.L,Vasquez, J.C.,Guerrero, J.M. (2014). *Voltage scheduling droop control for State-of-Charge balance of distributed energy storage in DC microgrids.* Paper presented at the IEEE International Energy Conference (ENERGYCON), 2014.

Li, C.,Dragicevic, T.,Plaza, M.G.,Andrade, F.,Vasquez, J.C.,Guerrero, J.M. (2014). *Multiagent based distributed control for state-of-charge balance of distributed energy storage in DC microgrids.* Paper presented at the 40th Annual Conference of the IEEE.on Industrial Electronics Society, IECON 2014

Li, W., Joos, G. (2007). *Comparison of energy storage system technologies and configurations in a wind farm.* Paper presented at the Power Electronics Specialists Conference, Orlando,FL.

Li, Y. W., Kao, C. N. (2009). An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid. *IEEE Transactions on Power Electronics, 24*(12), 2977-2988.

Logenthiran, T., Srinivasan, D.,Wong, D. (2008). *Multi-agent coordination for DER in MicroGrid.* Paper presented at the IEEE International Conference on Sustainable Energy Technologies, ICSET.

Lu, X., Sun, K., Guerrero, J. M., Vasquez, J. C., Huang, L. (2014). State-of-charge balance using adaptive droop control for distributed energy storage systems in

DC microgrid applications. *IEEE Transactions on Industrial Electronics, 61*(6), 2804-2815.

Lu, X., Sun, K., Guerrero, J. M., Vasquez, J. C., Huang, L. (2015). Double-Quadrant State-of-Charge-Based Droop Control Method for Distributed Energy Storage Systems in Autonomous DC Microgrids. *IEEE Transactions on Smart Grid, 6*(1), 147-157.

Lu, X., Sun, K., Guerrero, J. M., Vasquez, J. C., Huang, L., Teodorescu, R. (2012). *SoC-based droop method for distributed energy storage in DC microgrid applications*. Paper presented at the IEEE International Symposium on Industrial Electronics (ISIE).

Mackiewicz, R. (2006). *Overview of IEC 61850 and Benefits*. Paper presented at IEEE PES ,the Power Systems Conference and Exposition, PSCE'06.

Markvart, T. (2000). *Solar electricity*: John Wiley & Sons.

Martinez, M. T. (2004). Wind turbines for electrical power generation: Google Patents.

Mehrizi-Sanir, A., Iravani, R. (2009). Secondary control for microgrids using potential functions: Modeling issues. *Proc. CYGRE*, 181-189.

Morris, G. Y. (2012). A Framework for the Evaluation of the Cost and Benefits of Microgrids.

Morstyn, T., Branislav, H.,Agelidis, V. G. (2014). Distributed Cooperative Control of Microgrid Storage. *IEEE transactions on power systems, pp*(99), 1-10.

Nair, N. K. C.,Garimella, N. (2010). Battery energy storage systems: Assessment for small-scale renewable energy integration. *Energy and Buildings, 42*(11), 2124-2130.

Oberhofer, A. p. M. (2012). Energy Storage Technologies & Their Role in Renewable Integration. San Diego, US: Global Energy Network Institute.

Palizban, O., Kauhaniemi, K. (2015). Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode. *Renewable and Sustainable Energy Reviews, 44*, 797-813.

Palo Alto, A. (2009). Valve Regulated Lead Acid (VRLA) Battery Qualification Assessment (Vol. ID 1019216, pp. 26): Electrical Power Research Institute.

Parida, B., Iniyan, S., Goic, R. (2011). A review of solar photovoltaic technologies. *Renewable and Sustainable Energy Reviews, 15*(3), 1625-1636.

Piagi, P., Lasseter, R. H. (2006). *Autonomous control of microgrids*. Paper presented at the IEEE Power Engineering Society General Meeting, 2006.

Planas, E., Gil-de-Muro, A., Andreu, J., Kortabarria, I., Martínez de Alegría, I. (2013). General aspects, hierarchical controls and droop methods in microgrids: A review. *Renewable and Sustainable Energy Reviews, 17*, 147-159.

Pogaku, N., Prodanovic, M.,Green, T. C. (2007). Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. *IEEE Transactions on Power Electronics, 22*(2), 613-625.

Rebours, Y. G., Kirschen, D.S, Trotignon, M., Rossignol, S. (2007). A survey of frequency and voltage control ancillary services—Part I: Technical features. *IEEE Transactions on Power Systems, 22*(1), 350-357.

Ribeiro, P. F., Brian K.J., Crow, M.L., Arsoy, A., Liu, Y. (2001). Energy storage systems for advanced power applications. *Proceedings of the IEEE, 89*(12), 1744-1756.

Salameh, Z. (2014). *Renewable Energy System Design* (1 ed.): Academic Press,Science Direct, Elsevier.

Sao, C. K., Lehn, P. W. (2008). Control and power management of converter fed microgrids. *IEEE Transactions on Power Systems, 23*(3), 1088-1098.

Shafiee, Q. (2014). *Multi-Functional Distributed Secondary Control for Autonomous Microgrids.* Doctoral thesis, Aalborg University.

Shafiee, Q., Dragicevic, T., Vasquez, J. C.,Guerrero, J. M. (2014). Hierarchical control for multiple dc-microgrids clusters. *IEEE Transactions on Energy Conversion, 29*(4), 922-933.

Shafiee, Q., Vasquez, J. C., Guerrero, J. M. (2012). *Distributed secondary control for islanded MicroGrids-A networked control systems approach.* Paper presented at the 38th Annual Conference on IEEE Industrial Electronics Society IECON.

Shafiee, Q., Guerrero, J., Vasquez, J. (2014). Distributed secondary control for islanded microgrids—A novel approach. *IEEE Transactions on Power Electronics, , 29*(2), 1018-1031.

Sharma, A.,Tyagi, V.V.,Chen, C.R.,Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345.

Singh, G. (2013). Solar power generation by PV (photovoltaic) technology: A review. *Energy.*

Su, S.,Yinhong, L.,Zhong, X.D. (2009). Self-organized criticality of power system faults and its application in adaptation to extreme climate. *Chinese Science Bulletin, 54*(7), 1251-1259.

Tan, X.Li, Q.,Wang, H. (2013). Advances and trends of energy storage technology in microgrid. *International Journal of Electrical Power & Energy Systems, 44*(1), 179-191.

Tsikalakis, A. G., Hatziargyriou, N. D. (2011). *Centralized control for optimizing microgrids operation.* Paper presented at the IEEE Power and Energy Society General Meeting.

Tuladhar, A., Jin, H., Unger, T.,Mauch, K. (2000). Control of parallel inverters in distributed AC power systems with consideration of line impedance effect. *IEEE Transactions on Industry Applications, , 36*(1), 131-138.

Ustun, T. S., Ozansoy, C., Zayegh, A. (2011). Recent developments in microgrids and example cases around the world—A review. *Renewable and Sustainable Energy Reviews, 15*(8), 4030-4041.

Vandoorn, T., De Kooning, J., Meersman, B., Vandevelde, L. (2013). Review of primary control strategies for islanded microgrids with power-electronic interfaces. *Renewable and Sustainable Energy Reviews, 19*, 613-628.

Vandoorn, T. L., Vasquez, J. C., De Kooning, J., Guerrero, J. M.,Vandevelde, L. (2013). Microgrids: Hierarchical control and an overview of the control and reserve management strategies. *IEEE Industrial Electronics Magazine, 7*(4), 42-55.

Vasquez, J. C., Guerrero, J. M., Miret, J., Castilla, M.,De Vicuna, L. G. (2010). Hierarchical control of intelligent microgrids. *IEEE Industrial Electronics Magazine, 4*(4), 23-29.

Veszpremi, K. Schmidt, I. (2007). *Flywheel energy storage drive for wind turbines*. Paper presented at the 7th International Conference on power Electronics and Drive Systems.

Vuorinen, A. (2008). *Planning of optimal power systems* (1 ed.). Espoo, Finland: Ekoenergo Oy

Wu, D. (2015). *Decentralized coordinated control strategy of island microgrids*. Dotoral dissertation, Aalborg University.

Xu, Y.,Zhang, W.,Hug, G.,Kar, S.,Li, Z. (2015). Cooperative Control of Distributed Energy Storage Systems in a Microgrid. *IEEE Transactions on smart grid, 6*(1), 238-248.

Yang, Z., Zhang, J., Kintner-Meyer, M. C., Lu, X., Choi, D., Lemmon, J. P., Liu, J. (2011). Electrochemical energy storage for green grid. *Chemical Reviews, 111*(5), 3577-3613.

Zalba, B.,Marin, J.M.,Cabeza, L.F.,Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied thermal engineering, 23*(3), 251-283.

Zhang, Y.,Jie Jia, H.,Guo, L. (2012). *Energy management strategy of islanded microgrid based on power flow control.* Paper presented at the IEEE PES Innovative Smart Grid Technologies (ISGT).

Publication I

Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode

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Renewable and Sustainable Energy Reviews 44 (2015) 797–813

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Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode

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A R T I C L E I N F O

Article history:
Received 26 February 2014
Received in revised form
18 December 2014
Accepted 4 January 2015
Available online 28 January 2015

Keywords:
Distributed generation
Hierarchical control
Microgrid
Primary control
Secondary control
Tertiary control

A B S T R A C T

The hierarchical control structure of a microgrid can be described as having four levels responsible for processing, sensing and adjusting, monitoring and supervising, and maintenance and optimization. The responsibility of the hierarchical control level is to provide control over the production of power from renewable sources. This paper comprehensively investigates the principles of hierarchical control in microgrids from a technical point of view. In the first step, this article covers the control of the power generation using two popular renewable energy sources, namely wind turbines and photovoltaics. The synchronization and power flow between the microgrid and the main network is then investigated. Finally, some research questions are presented to improve the performance of the hierarchical control, especially in the secondary decentralized control and energy storage systems.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.01.008

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Nomenclature

DER	Distribution Energy Resource
DFIG	Double Fed Induction Generator
DG	Distributed Generation
DMS	Distribution Management System
f	frequency
$f^{\min}$	minimum value of frequency
f^{ref}	reference of frequency
f_{mg}^{ref}	reference of frequency for microgrid
f_{mg}	frequency in microgrid
f_{DG_i}	frequency in individual DG
$\overline{f}_{DG_k}$	average frequency for all DG units
FLL	Frequency locked loop
Δf	error of frequency
Δf_{DG_k}	control signal providing by $\mathrm{DG_k}$
G_i	integral gain
G_p	proportional gain
G_{if}	control parameters for frequency of secondary level compensator
G_{iv}	control parameters for voltage of secondary level compensator
G_{ip}	control parameters for active power of tertiary level compensator
G_{iQ}	control parameters for reactive power of tertiary level compensator
G_{pf}	control parameters for frequency of secondary level compensator
G_{pv}	control parameters for voltage of secondary level compensator
G_{pp}	control parameters for active power of tertiary level compensator
G_{PQ}	control parameters for reactive power of tertiary level compensator
HC	Harmonic compensator
HV	High voltage
LV	Low voltage
MG	Microgrid
MGCC	Microgrid Central Controller
MPPT	Maximum Power Point Tracking
MS	Microsource
MV	Medium voltage
P	active power
P^{ref}	reference of active power
$P^{\max}$	maximum value of active power
PV	Photovoltaic
PCC	Point of Common Coupling
PI	Proportional integral
PLL	Phase locked loop
PR	Proportional resonant
ΔP	error of active power
Q	reactive power
Q^{ref}	reference of reactive power
$Q^{\max}$	maximum value of reactive power
Q_{grid}^{ref}	reference of reactive power for main grid
$\overline{Q}_{DG_K}$	average reactive power for all DG units
Q_{DG_i}	reactive power in individual DG
Q_{grid}	reactive power of main grid
ΔQ	error of reactive power
ΔQ_{DG_K}	control signal providing by DG_k
R	Resistor
RES	Renewable energy source
$T_{P_{(S)}}$	transfer function of active power
T_{PI}^{abc}	transfer function of PI controller in *abc* frame
T_{PR}^{abc}	transfer function of PR controller in *abc* frame
T_{PI}^{dq}	transfer function of PI controller in *dq* frame
$T_{PR}^{\alpha\beta}$	transfer function of PR controller in stationary frame
$T_{Q_{(S)}}$	transfer function of Reactive power
V^{ref}	reference of voltage
$V^{\min}$	minimum value of voltage
V_{mg}^{ref}	reference of voltage for microgrid
V_{mg}	voltage in microgrid
V_{DG_K}	voltage in individual DG
$\overline{V}_{DG_K}$	average voltage for all DG units
VSC	Voltage source converter
ΔV	error of voltage
ΔV_{DG_K}	control signal providing by $\mathrm{DG_k}$
X	inductance

1. Introduction

Photovoltaic cells (PV) and wind power generation are the most popular of the energy sources that can be integrated into the main network in the form of Distributed Generators (DG) or Microgrids (MG). Indeed, MGs consist of a methodical organization of such DG systems [1–6]—an organization that leads to increase in system capacity and achieves high power quality [7].

From the control point of view, in a traditional system, distribution of electricity is managed with a multilayer process and connected to the main network [8]. However, in MG and DG systems (the modern approach), the management of electricity distribution is handled in different sectors for participation in active network management based on market terms [9–11].

As presented by Vandoorm et al. [12], in the modern approach, the control of generation units and systems—especially in island mode—have some significant conflicts with the conventional system, such as the lack of rotating inertia, the changes in the effect of line impedance on active and reactive power control, and the variations in power generation from RESs.

Since future distribution networks will require completely novel smart-grid concepts [13], it is necessary to conceive of flexible MGs that are capable of intelligently operating in both grid-connected and island modes. In this regard, the authors present a control algorithm for MGs participating in the active network management in [14,15]. Moreover, along with the control algorithm, these papers present a general standardization of MGs for hierarchical control. This research is, however, theoretical and investigates standardization from a standards point view, so the objective of the present paper is to investigate the control algorithm, both technically and from the point of view of microgrid control, from power generation using RESs (*zero level*) to synchronizing the MG with the main network (*third level*).

Based on the previous research, controlling the DGs and MGs is critical, and it is necessary to implement a hierarchical control system for them [16]. As shown in Fig. 1, the hierarchical control structure of MGs can be classified into four control levels. In the first step, the paper focuses on the principle of how the power is generated with the two most popular RESs, namely photovoltaic and wind turbine generation. The output voltage and current from the grid-side power converter of these sources are input data for the inner control loop (*level zero*). Then, to achieve high impact management, accurate references are required, which is the responsibility of the *primary control*. The strategy of the control level is an independent local control for increasing the reliability of the power system. On the next level, the approach of *Secondary*

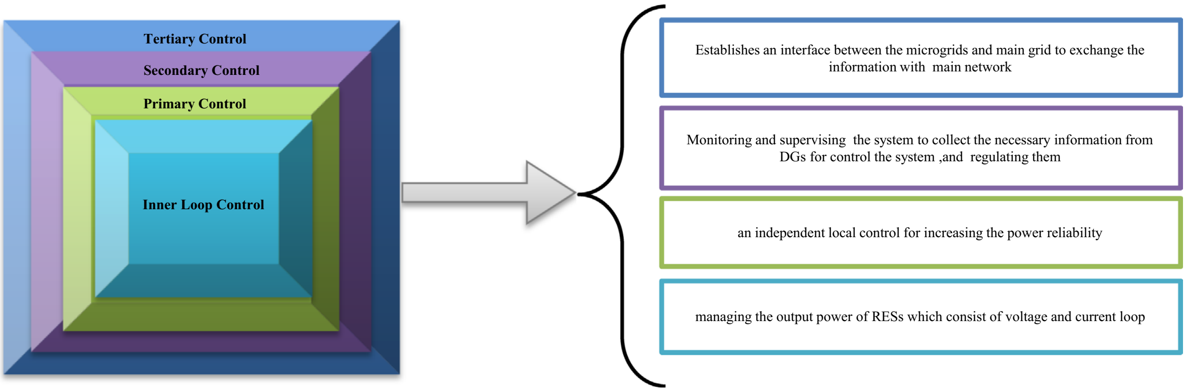

Fig. 1. The hierarchical control structure of MGs.

Control is to monitor the system and collect the necessary information from DGs to control the system in island mode, and to regulate them based on network data in grid connection mode. Finally, in the last step, the tertiary control level establishes an interface between the MGs and the main grid to exchange the secondary control's information with the network.

The present paper discusses the above issues, and employs the following organization: The inner control loop is discussed in Section 2. The structures of primary and secondary control in MG are investigated in Sections 3 and 4, respectively. The tertiary controls are discussed in Section 5. Finally, the conclusion is presented in Section 6.

2. Inner control loop

Managing the output power of microsources (MSs) is the main goal of this control level (*level zero*), and is generally accomplished through the inner current and voltage-control loop. Indeed, the first step in MG control is the source operating point control, using power electronic devices [17]. As mentioned above, wind power and PV are popular primary RESs, and the installation of such sources around the world is undergoing enormous growth due to the high potential, easy accessibility, and endless supply [18–20]. Hence, investigating their power generation and control strategies, as well as the inner current and voltage-control loop, is the first step in the control of MGs.

2.1. Wind power

Wind turbines convert kinetic energy into electricity [21,22], and there are many different classifications based on speed [23,24], control methods [25,26], and other factors. Indeed, the Doubly-fed Induction Generator (DFIG) is the most popular type of wind power generation used in MGs [27–31]. DFIGs are highly controllable and allow maximum extraction of power over a large range of wind speeds. Furthermore, control of the active and reactive power is fully decoupled via the independent control of the rotor currents [28,32]. A comparison of the control strategies and structures of other types of power generation with those of DFIGs is presented in [33,34].

2.1.1. DFIG

Doubly-fed induction-generators consist of two AC/DC (rotor side) and DC/AC (grid-side) converters, with a dc link that can either inject or absorb power from the grid, actively controlling voltage. The responsibility of the rotor side is to optimize the power generation from the source; on the other hand, control of the active and reactive power, as well as the dc link voltage, is the duty of the grid-side converter [35].

Fig. 2 shows the complete DFIG equivalent circuit, along with the control block diagrams for the wind turbine back-to-back voltage source converters for variable speed operation [36–38]. Indeed, in the rotor-side converter, the voltage of the rotor is achieved by comparing the stator power with its reference. The issue here, however, is in defining the active and the reactive reference values, respectively determined in the dc link and in the block controlling the reactive power. Moreover, defining the reference value for amplitude voltage and frequency in this figure is the responsibility of the primary and secondary control, which will be discussed in Sections 3 and 4, respectively. The other block diagram presents the grid-side converter controller. The input to the grid-side controller is the set of values for the currents flowing to the network through the Voltage Source Converter (VSC).

The capacitor in the dc link is an energy storage device, and the energy time derivative in this capacitor depends on the difference between the power delivered to the grid filter and the power provided by the DFIG rotor circuit [36,39]. Indeed, the power factor in island-mode MGs is very sensitive; any changes will cause large load variations, destabilizing the ac side. Hence, use of energy storage for system support is recommended if power quality and reliability is to be increased in these systems [40,41].

2.2. Photovoltaic system

The whole of the PV system has an impact on the output power performance; however, the functions of the control system and the construction of the power electronics are more significant. In [42–44] different techniques to develop the inverter of the photovoltaic system are presented, and in [45] different types of PV arrangement along with the inverters are discussed [46].

Fig. 3 presents a block diagram of the PV module with its controller structure. The simplified equivalent circuit of a PV cell, as illustrated by this figure, consists of four different parameters: light current (I_L), series resistance (R_s), saturation current (I_o), and the thermal voltage timing completion factor (α) [47,48]. Indeed, the voltage–current and of current–power characteristics [49,50] are crucial in achieving maximum power in a PV system. The actual solar cell is clearly much more complex than that indicated by the equation. But setting the parameters to be functions of temperature, solar irradiation, or load current should suffice for our purposes. The light current (I_L) and saturation current (I_o) depend on solar temperature and radiation [51]; the thermal voltage timing completion factor (α) depends on temperature; and the series resistance (R_s) can be calculated in several ways [52,53], and is also provided by some manufacturers.

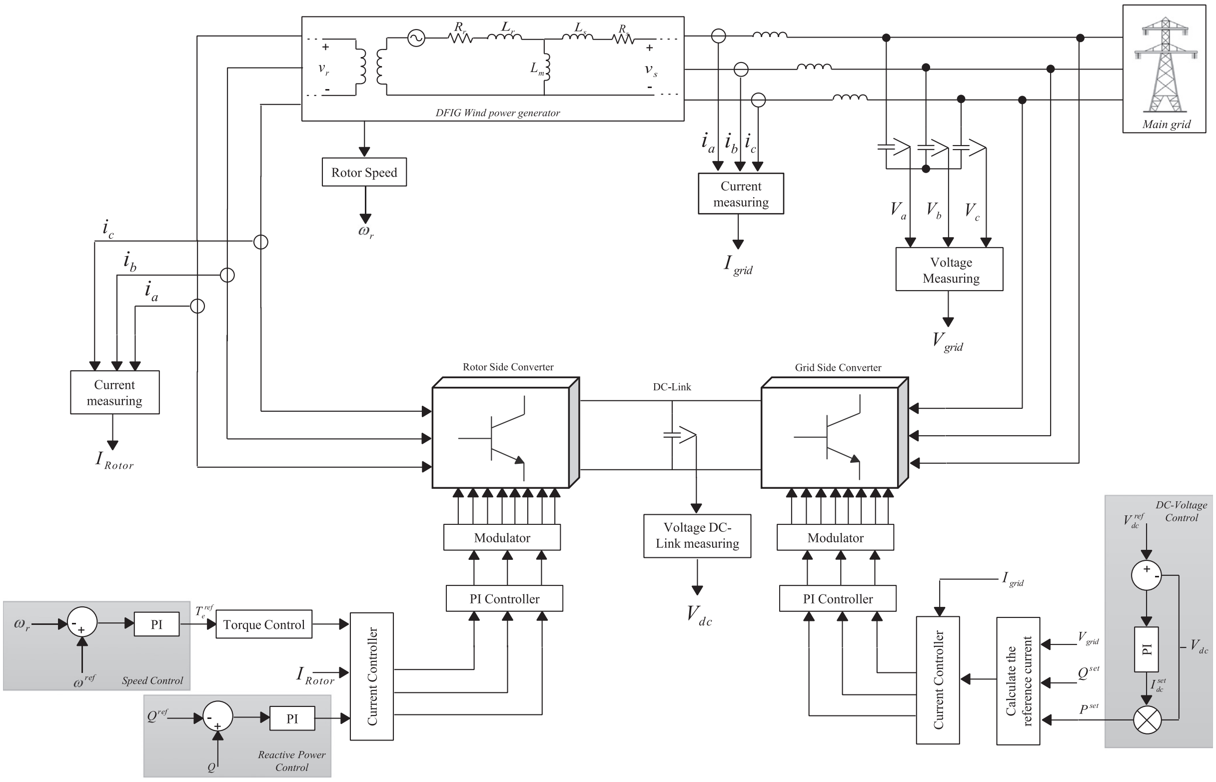

Fig. 2. DFIG equivalent circuit, and its control block diagrams.

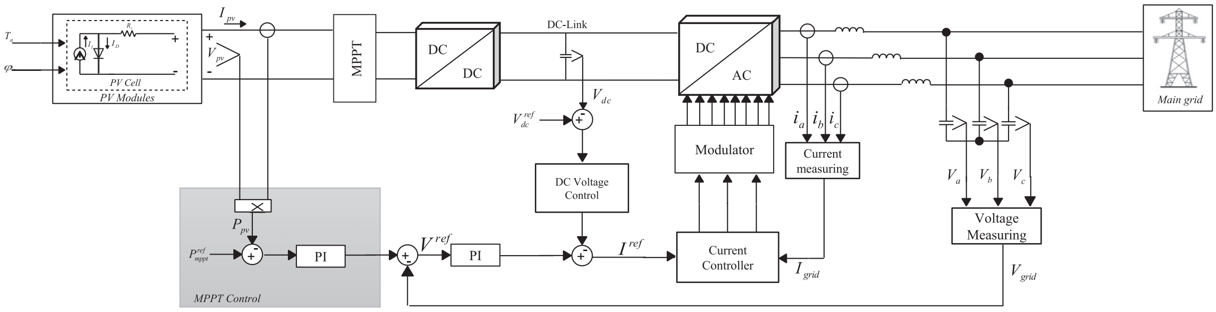

Fig. 3. The PV module with its controller structure.

With PV panels being costlier than other types of RES devices, the maximum product effectiveness is very important. A certain point of current and voltage defines the Maximum Power Point Tracking (MPPT) during connection to the grid; however, the operating point when the load is connected to the PV panel directly depends on the load demand, and may be less than the MPP. Indeed, MPPT depends on temperature and irradiation in a nonlinear way, and there is no priority in it. One control method for transferring maximum array power is perturbation and observation (P&O), which transfers the operating voltage with respect to the MPP and periodically increases or decreases the array voltage [54–56]. The technique works at the optimum point where insolation varies rapidly in time; however, there are some oscillations around the MPP. Another method is voltage feedback, which regulates the voltage base on the basis of a comparison of output with the reference value. The method is simple to implement, but is not suitable when there are variations in temperature. The third method is model-based computation, which has two major categories: CMPPT (current-based) and VMPPT (voltage-based). There are also many other methods, such as the measure method [57,58], the linear approach [59] and incremental conductance [60,61].

Based on the comprehensive research presented by Hohm and Ropp [62] and Alanen [46], the first method (P&O) is currently the most commonly used algorithm in commercial converters and has the potential for optimization.

As shown in Fig. 3, after the PV module and the MPPT hardware structure of the system come the dc–dc converters and inverters, whose responsibility is to create optimum conditions to support the normal customer load or send power into the network in

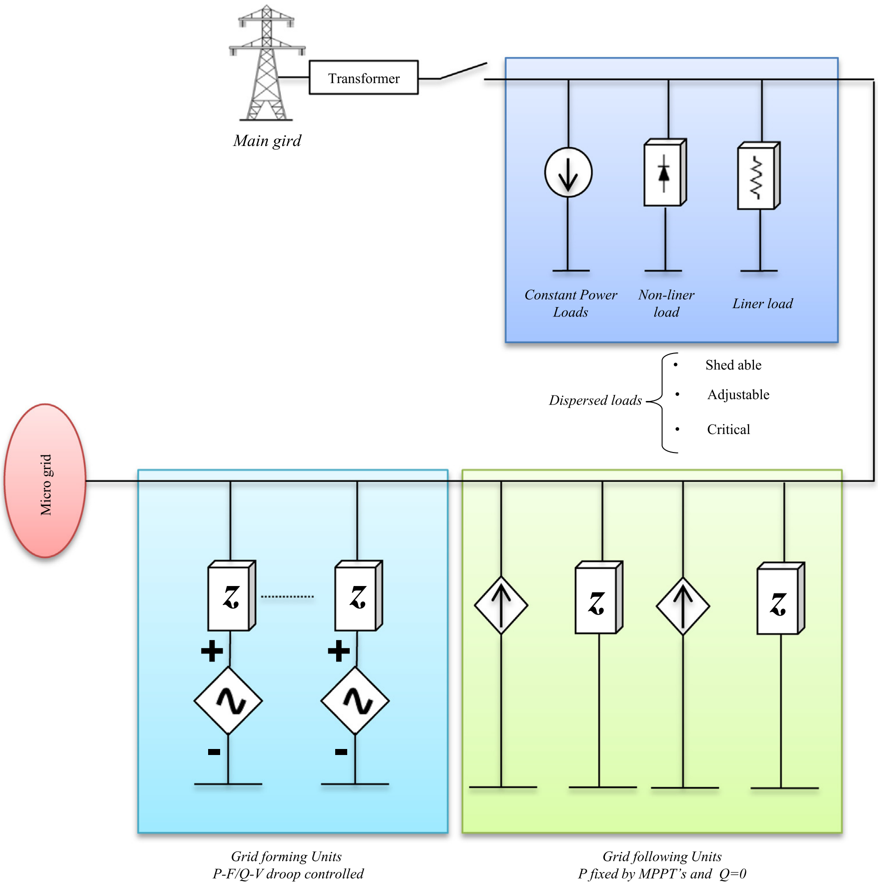

Fig. 4. Equivalent circuit diagram of converter connected to MG.

grid-connection mode. In a photovoltaic system, the reference value for voltage and frequency is defined through the primary and secondary control, just as in wind turbine control.

2.3. Voltage and current-control loop discussion

After stabilizing the generation of power from RESs, the active and reactive power set value determine the current and voltage loop through the grid-side power converter. Indeed, the definition of the reference value is dependent on the state of the MG connection, which means that the purpose of the power electronics interface in voltage control mode is to manage the frequency and voltage inside the MG when the system is in island mode, and to operate based on active and reactive power control mode in grid-connection mode [63–65].

Moreover, based on the operation modes, the power converter in a MG can be classified as grid-following or grid-forming [66]. Recently, comprehensive research into this classification has been presented by Rocabert et al. [67] and Rodriguez et al. [68]. As shown in Fig. 4, the simplified arrangement of the power converters is presented based on an ideal ac voltage and current source with low and high output impedance, respectively, for grid-forming and grid-following converters. To determine the reference value for voltage and frequency, a proper voltage and current-control loop is required. Dong [69] and Tarasantisuk et al. [16] present a complete modeling and control design methodology for converters and discuss the current and voltage-control loops. Grid-forming power converters operate on the basis of voltage, while grid-following convertors are based on current; the determination of the reference values in the different models of these categories will be discussed in Section 3.

3. Primary control

The target of this control level (*level one*) is to adjust the frequency and amplitude of the voltage references that feed the inner current and voltage-control loops, and to reduce the circulating currents. The primary control should have the fastest response to any variation in sources or demand (on the order of milliseconds), which can be assisted to improve the power reliability.

Primary control in conventional grids for maintaining the power within desired parameters is based on rotating inertia in the system. However, in MGs, on account of their use of power electronics interfaces, this significant feature is lacking [12]; the principle of this control level in MGs is shown in Fig. 5. As mentioned previously, power converters for DG unit are classified into two general categories: grid-forming and grid-following. A comprehensive review of primary control in grid-forming strategies is presented by Vandoorm et al. [70] and grid-following techniques are discussed by Blaabjerg et al. [71]. With respect to this classification, Fig. 6 shows a complete overview of different techniques of primary control.

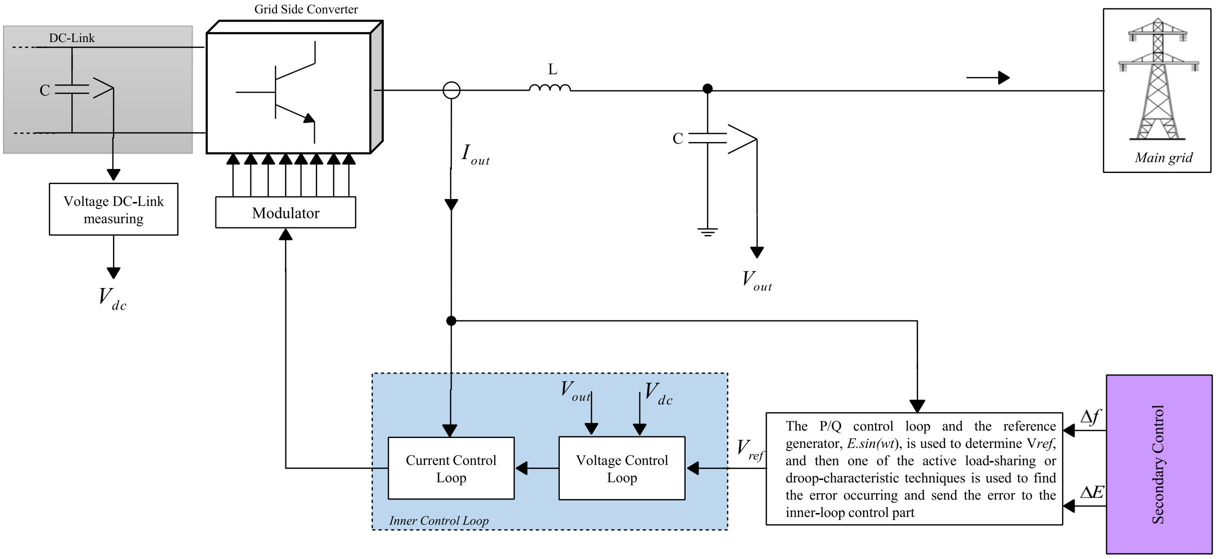

Fig. 5. The principle of primary control in MGs.

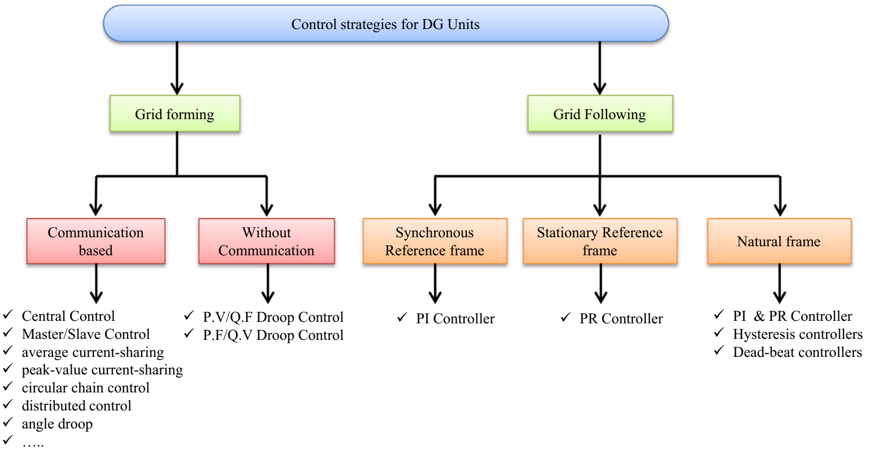

Fig. 6. Techniques of primary control.

3.1. *Primary control based on grid-forming*

Grid-forming control strategies are based on voltage control, and in island mode of a MG, at least one of the converters must operate in this mode to provide the voltage reference for other converters [72]. As shown in Fig. 6, the primary control in grid-forming is divided into two different parts that operate with and without a communications link. Such a communications link can increase the investment cost of MGs over no-communication techniques; however, power sharing and voltage adjustment is very accurate with this method [70].

3.1.1. *Control methods with communication*

The first strategy based on communication is the concentrated method, in which active and reactive power is managed using a central controller. A requirement for such strategies is that a communications link exists between the central control and other units. The concentrated method has two versions, *central limit control* [73,74] and *power deviation* [75]. Central limit control consists of a voltage controller that provides the voltage reference and a controller for defining current reference value for other units. The current reference value depends on variation in the load and the number of units. Indeed, the power quality of this method is high, as it can manage power even during transients, but requires a high-bandwidth communications link.

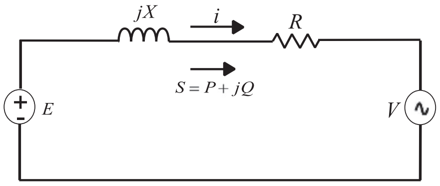

Fig. 7. Equivalent circuit of power converter connection to the grid [67].

As will be explained in the next section of this paper, active and reactive power are defined based on the phase angle and voltage amplitude, respectively, in inductive networks, and vice versa in resistive networks [76]. The principle of the power deviation technique is based on this. The second control method based on communication is a master–slave strategy [77–79], which again has two variants.

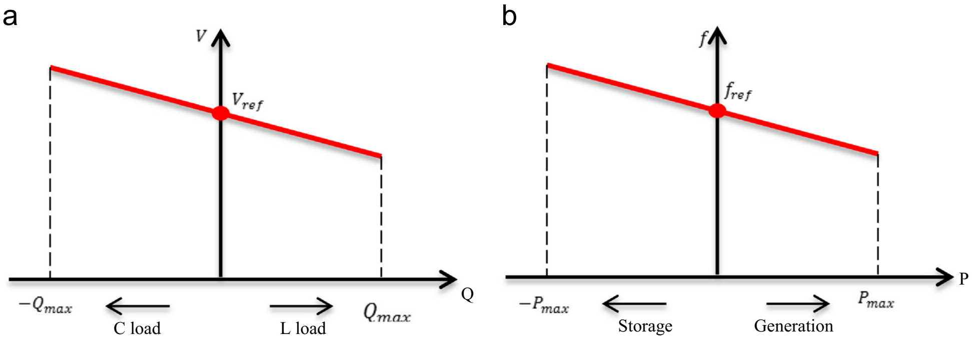

Fig. 8. Voltage and frequency versus active and reactive power [64].

The master unit consists of a voltage controller for regulating the output voltage; it assigns the current reference for the other units that follow the master—the slave units. The master unit may be central [80,81] or decentralized [82–84], and that choice is made based on the fixed module, arbitrarily, or based on maximum current. In grid-connection mode with this method and a central controller, the grid is defined as the master, so there is no need for any special control for grid connection and island detection operation. The third strategy is based on average current-sharing, without a master unit. The reference value of current and voltage are determined individually in each module using a common current-sharing bus and voltage-reference synchronization.

The fourth strategy is also based on current-sharing. In this method, the reference values for current and voltage are determined based on the peak-value calculation of voltage amplitude and phase angle; the method is thus called the peak-value current-sharing technique [85,86]. Indeed, during island-mode operation, there is one voltage-based control converter used to obtain the reference value, and other converters only operate with the current-control loop.

Other primary control methods based on communication are *circular chain control* [87], *distributed control* [88]**,** and *angle droop* [89] (this method has the same principle as the droop control method and uses GPS signals to determine the reference angle).

3.1.2. Control methods without communication

Taking Fig. 6 into account, the other category of primary control strategies that operate without communications links is based on droop control. This type of control is more reliable and of lower cost than communication methods, and is usually implemented in projects with long distance [70].

3.1.2.1. Droop control. Droop control methods depend on the types of generators and power system, of which an equivalent circuit is shown in Fig. 7. There are three types which the droop control method varies for each of these types of system [90]:

- Group 1: *large systems* (HV) with high dispersion, where resistance is negligible and impedance is approximately inductive.
- Group 2: *medium systems* (MV), where the impedance is also inductive but has some significant resistive part, which helps to maintain the voltage amount from different sources.
- Group3: *small systems* (LV), in which inductance is negligible and the impedance are more resistive.

3.1.2.1.1. (P/f, Q/V) & (P/V, Q/f) droop control. The principle of droop control for the first and second groups (HV and MV) is based on the control of synchronous generators [64,70]. The significant difference between a converter-based MG and the synchronous generator for controlling the system is inertia. The lack of inertia in MGs means that the active and reactive power strategy is based on line characteristics [12]. Power-frequency droop control is discussed in [91–95]. Active and reactive power is defined as in (1) and (2) [70].

$$P=\frac{E}{R^2+X^2}[R(E-V\ \cos\ \theta)+XV\ \sin\ \theta] \tag{1}$$

$$Q=\frac{E}{R^2+X^2}[-RV\ \sin\ \theta+X(E-V\ \cos\ \theta)] \tag{2}$$

In both high and medium voltage systems, line impedance is almost inductive, so the resistive part of the above equation can be removed without creating any inaccuracy. For this reason θ is also very small and it can be supposed that ($\sin\ \theta=\theta$, and $\cos\ \theta=1$); therefore, (1) and (2) can be summarized as in (3) and (4)

$$P\approx\frac{EV\theta}{X} \tag{3}$$

$$Q=\frac{E^2-V}{X}. \tag{4}$$

The principle of the droop control *(P/f, Q/V)* is then descripted in Fig. 8 [96,97]. The figure illustrates that the operational voltage is regulated by a local voltage set-point value, taking into account the inductive and capacitive reactive current generated by the MSs. In inductive situations, voltage operation increases, and to adjust this, the voltage set point must decrease. In capacitive mode, however, the set-point value increases. The limitations of the reactive current variability are based on the maximum reactive power [98,99].

Generally, the frequency and voltage of droop control for large and medium systems can be determined thus [70]:

$$f=f^{ref}-T_{p(s)}\ (P-P^{ref}) \tag{5}$$

$$V=V^{ref}-T_{Q(s)}\ (Q-Q^{ref}) \tag{6}$$

$$T_{p(s)}=\frac{\overbrace{f^{ref}-f^{\min}}^{\Delta f}}{\underbrace{P^{ref}-P^{\max}}_{\Delta P}}\langle 0,\quad T_{Q(s)}=\frac{\overbrace{V^{ref}-V^{\min}}^{\Delta V}}{\underbrace{Q^{ref}-Q^{\max}}_{\Delta Q}}\langle 0. \tag{7}$$

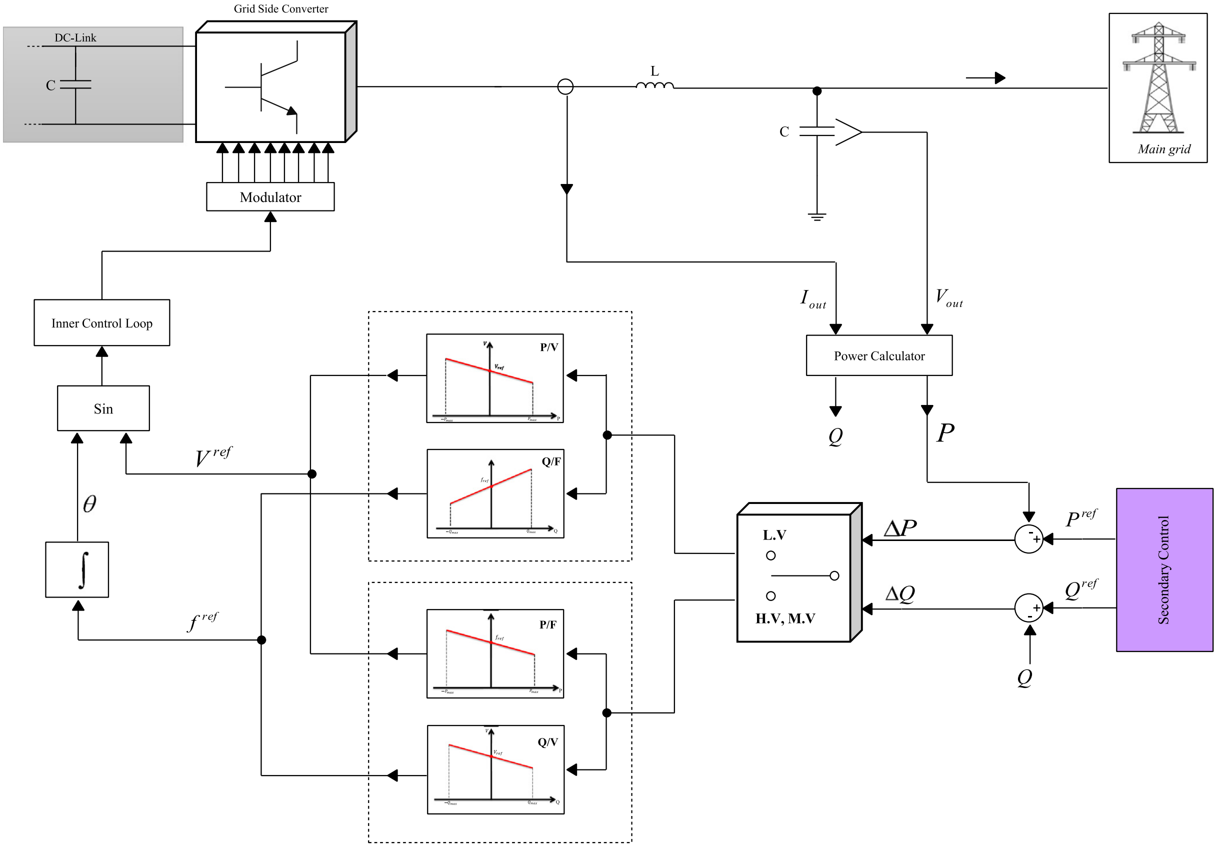

Fig. 9. Principle of the droop control strategy in primary control.

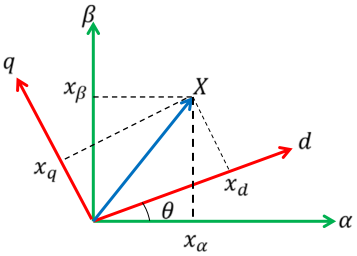

Fig. 10. Difference between the natural, synchronous, and stationary framework.

On the other hand, due to the coupling of active and reactive power in DG units when inductance is not present, the implementation of this method can create a particular problem for the third group (low voltage) [7]. Hence, unlike with the two first groups, the inductance in the impedance is negligible when compared to the resistance, so the impedance is more resistive. Hence, taking (1) and (2) with this assumption on the phase angle ($\sin\ \theta = \theta$ and $\cos\ \theta = 1$),

$$V = V^{ref} + T_{p(s)}(P^{ref} - P) \tag{8}$$

$$f = f^{ref} + T_{Q(s)}(Q^{ref} - Q). \tag{9}$$

The active and reactive powers in the group three (small system) are thus controlled based on variations in the voltage's amplitude and frequency, respectively. Fig. 9 illustrates the comprehensive control principle of the droop control strategy in primary control.

There are many different approaches for supporting the system based on droop control. As mentioned, decoupling the voltage and frequency-droop controls by analysing and compensating for the effect of line impedance on active and reactive power flow is the main approach to addressing the effect of interconnecting line impedance on droop-based control [90]. A complete and extensive review and technical investigation into the control strategy is provided by Guerrero et al. [90] and Bidram and Davoudi [17].

3.2. *Primary control based on grid-following*

Grid-following power convertors operate based on current control. As shown in Fig. 6, this type of primary control includes of three different references frameworks: *natural* (*abc*), *synchronous* (*dq*), and *stationary* ($\alpha\beta$) [100]. The principles of these frameworks and the difference between them are shown in Fig. 10 and discussed by Blaabjerg et al. [71] and Hassaine et al. [101].

3.2.1. *Natural framework*

The natural reference framework is based on current control for each grid phase. However, two current controllers suffice for the control type and for the third phase control, using Kirchhoff law. Generally, current control based on natural reference is used where the system is high dynamic and control is nonlinear. Both the Proportional Integral (PI) and Proportional Resonant (PR) controller [102] can be implemented in this method. The structure

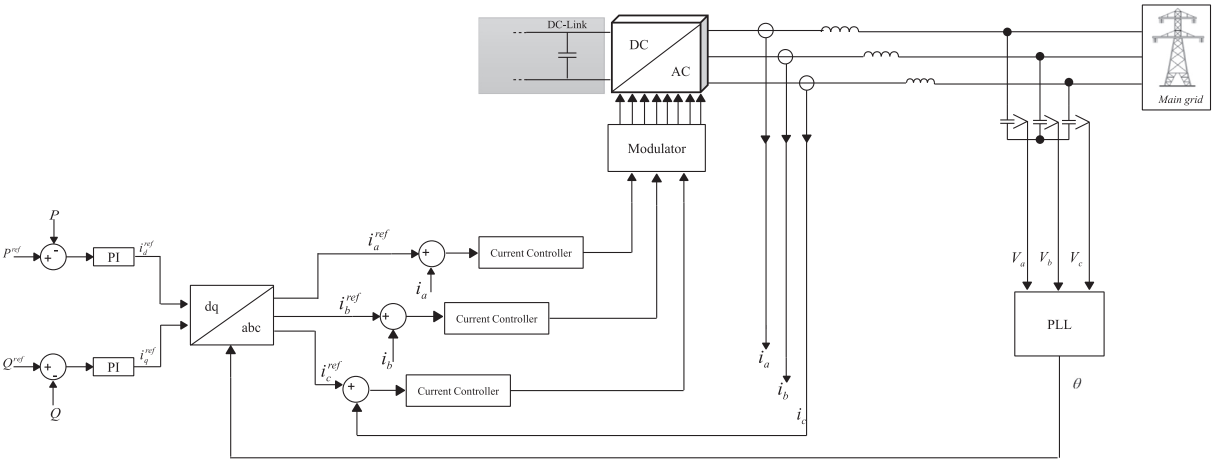

Fig. 11. Structure of the natural frame-control technique.

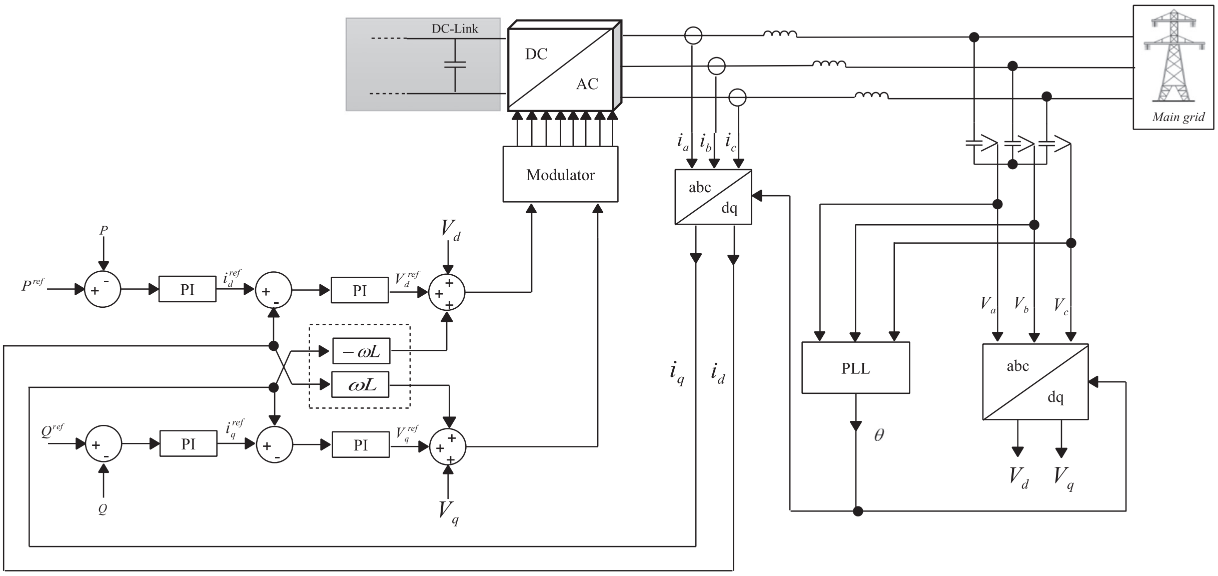

Fig. 12. Structure of the synchronous frame-control technique.

of the frame-control technique is shown in Fig. 11, and the transfer function of the PI and PR controller in the natural framework are shown in (10) and (11), respectively [71].

Based on the provided control structure, in the first step, the current reference values are created by measuring the active and reactive set values and phase angles of the grid voltage. Then, the errors in comparing the reference value and measuring the current act as input for the controller. There are two other controller types for implementation based on the natural frame reference: namely, hysteresis controllers [103–106] and dead-beat controllers [107,108].

$$T_{PI}^{abc}(s)=\frac{2}{3}\begin{bmatrix} G_p+\frac{G_i s}{s^2+f^2} & -\frac{G_p}{2}-\frac{G_i s+\sqrt{3}G_i f}{2\left(s^2+f^2\right)} & -\frac{G_p}{2}-\frac{G_i s-\sqrt{3}G_i f}{2\left(s^2+f^2\right)} \\ -\frac{G_p}{2}-\frac{G_i s-\sqrt{3}G_i f}{2\left(s^2+f^2\right)} & G_p+\frac{G_i s}{s^2+f^2} & -\frac{G_p}{2}-\frac{G_i s+\sqrt{3}G_i f}{2\left(s^2+f^2\right)} \\ -\frac{G_p}{2}-\frac{G_i s+\sqrt{3}G_i f}{2\left(s^2+f^2\right)} & -\frac{G_p}{2}-\frac{G_i s-\sqrt{3}G_i f}{2\left(s^2+f^2\right)} & G_p+\frac{G_i s}{s^2+f^2} \end{bmatrix} \tag{10}$$

$$T_{PR}^{abc}(s)=\begin{bmatrix} G_p+\frac{G_i s}{s^2+f^2} & 0 & 0 \\ 0 & G_p+\frac{G_i(s)}{s^2+f^2} & 0 \\ 0 & 0 & G_p+\frac{G_i(s)}{s^2+f^2} \end{bmatrix} \tag{11}$$

PI and PR controllers are used only to create the reference signals for the PWM controller, which is a modulator needed to produce the final switching pattern. However, in hysteresis and dead-beat controllers, the switching of the power converter uses switching states, so a separate modulator is not needed for them [71].

3.2.2. *Synchronous framework*

In practice, it is clear that controlling and filtering can make simpler by reduced the control items. For this reason, rotating references are usually more popular in current-based power converters. Indeed, the natural voltage and current waveform

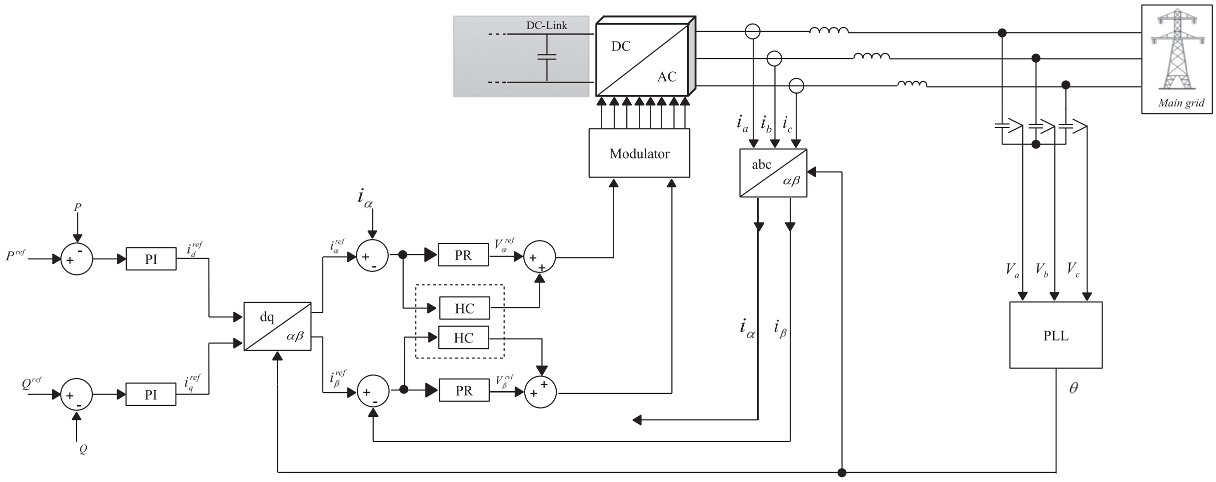

Fig. 13. Structure of the stationary frame-control technique.

(*abc*) translates to a synchronous frame (*dq*) with the voltage of the main network by phase locked loop and the park vector [109–113]. This control method uses a PI controller, whose transfer function is described in (12); the structure of the control strategy is shown in Fig. 12 [71].

As illustrated in that figure, the measured current is compared with the reference value, which is arrived at using the active and reactive power set point and the PI controller. Moreover, due to the increase in the performance of the controller, the cross coupling terms and feed-forward of the voltage are established [114–116]

$$T_{PI}^{dq}(s) = \begin{bmatrix} G_p + \frac{G_i}{s} & 0 \\ 0 & G_p + \frac{G_i}{s} \end{bmatrix}. \tag{12}$$

3.2.3. Stationary framework

The final method to reduce the control items is to translate the natural waveform to stationary form ($\alpha\beta$) and to use a frequency-locked loop (FLL) to implement this controller [117,118]. Since the PI controller is not suitable for sinusoidal waveforms, and because of the dynamic characteristic of the PR controller, this controller is used for the stationary method. Refs. [115,116,119] presented a comprehensive investigation of this type of controller.

The transfer function is described in (13), and the control methodology is shown in Fig. 13. In this control framework, the use of voltage feed-forward is not required [120], and the PR controller is operated based on infinite gain at the resonant frequency to eliminate the steady state error between the reference value and the control signal [71,101]

$$T_{PR}^{\alpha\beta}(s) = \begin{bmatrix} G_p + \frac{G_i s}{s^2+f^2} & 0 \\ 0 & G_p + \frac{G_i s}{s^2+f^2} \end{bmatrix}. \tag{13}$$

3.3. Primary control discussion

As mentioned above, this control level is the first step in the hierarchical control of the MG, and aims at the following targets to improve the reliability of MGs:

- to give the fastest response to each variation,
- to reduce circulating currents,
- to regulate the voltage amplitude and the frequency, and
- to provide reference values to feed the current and voltage control loops.

Grid-forming and grid-following are the main types of this control level. As is well known, the control of MGs is based on voltage and frequency during the island mode, but on active and reactive power in grid-connection mode. Moreover, grid-forming and grid-following operate on the basis of voltage and current, respectively. Hence, in grid-forming, power converters are able to control the MG individually, whereas grid-following power converters can only operate correctly in grid-connection mode.

On the basis of the above discussion, the requirements of this control level are as follows:

- In Island mode: using at least one of the grid-forming power converters to determine the voltage reference for the other grid-following power converters is mandatory.
- In grid-connection mode: because the control is based on active and reactive power, and because their reference values are determined through the main grid, the inverter type is not important.

A comparison of the different primary control methods based on their advantages and disadvantages is presented in Table 1, along with a brief summary of the topic.

Generally, a mechanism should be in place to restore the system frequency and voltage to nominal values following a load change [121,122]. In electric power system control, this restoration mechanism is called the secondary control of voltage and frequency, and will be explained in Section 4.

4. Secondary control

The responsibility of second level control is to supervise and monitor the system, to adjust for deviations in both voltage and frequency. Indeed, the secondary control ensures that the frequency and voltage deviations are regulated towards zero following each load change or generation in the MG, and serves power systems by correcting grid frequency deviations within allowable limits—for example by ±0.1 Hz in Nordel (North of Europe) or ±0.2 Hz in UCTE (Continental Europe) [64]. The principle of the control level in MGs is shown in Fig. 14. In practice, the secondary control has slower dynamic response to variation, as compared to

Table 1
Summary of primary control.

	Summarized information		Potential advantage	Potential disadvantage
Grid forming	These power converters operate based on voltage control and the equivalent circuit is composed of a voltage source and low series impedance.	Communication methods	Regulation of voltage and power sharing is very accurate	Economically not affordable
	The power converter is able to operate independently in island microgrid. Hence, for making the reference voltage for grid following converters, at least one the them must be operated based on grid forming method in island mode.		The output values of the control parameters are very close to their reference values	For the long distance, the reliability of the system is not high due to the communication link vulnerability
	A standby UPS can be a practical sample of this method, means during the grid failure, this power converter procedures the grid voltage.			Possibilities to the system development are limited
		Without communication methods	Accurate centralized control is not required Implementation of the system is simple as well as development The system reliability is high and it is also affordable from economic point view when comparing to the system based on communication method	The system control conditions are proportional to line impedance There are some tendency to unbalance in sharing of harmonic current Responding to the transient variation is slow when comparing to the methods based on communication link
Grid following	These Power converters operate based on Current control and the equivalent circuit is composed of a current source and high parallel impedance.	Natural frame		The complexity of the implementation of the transfer function is high.
	These power converters are not able to operate in island mode when there is no connection to the main grid, grid forming power converter or local synchronous generator to regulate the frequency and the voltage amplitude.	Stationary frame	The structure implementation is simple with using of PR controllers when comparing the use of natural and synchronous frame There is no error in steady state condition when using PR controller	The power factor is not fully controllable
	An upper level controller such as MPPT or power plant controller is required for adjusting the reference value of voltage, as well as active and reactive power.	Synchronous frame	Controlling and filtering the system is simpler because of reduced number of the control variables	Voltage feed forward and cross coupling is required
				In PI controller, the capacity of harmonic compensation is very low

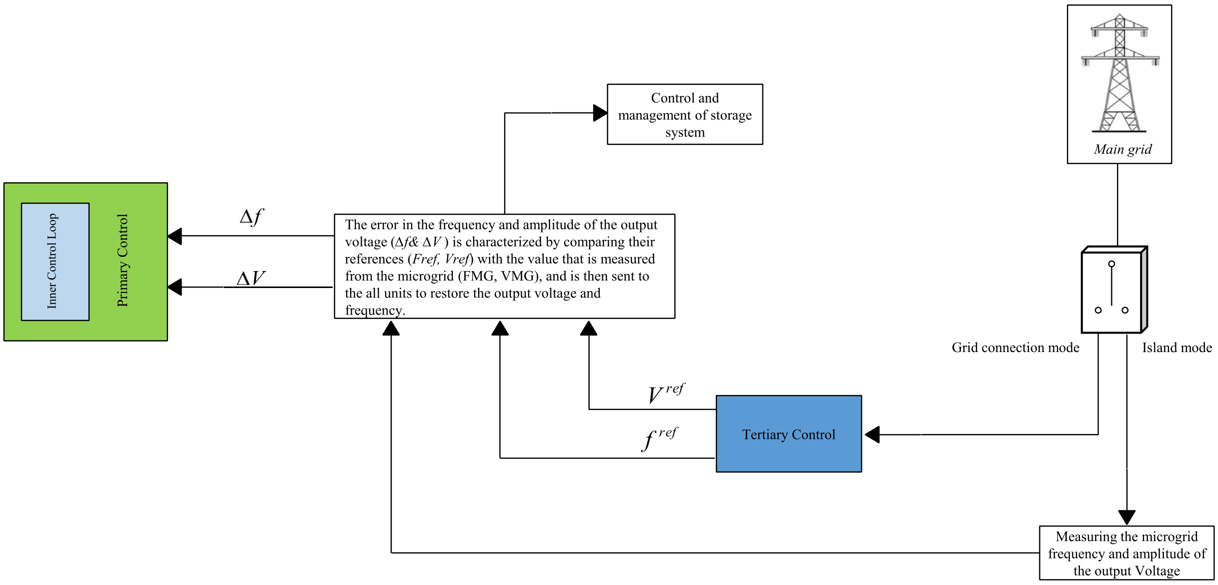

Fig. 14. Principle of the secondary control in Microgrids.

the primary control level [17]. This control level can be divided into centralized and decentralized control. By far the largest body of research on MG control has been performed by Chandorkar et al. [123] and Guerrero et al. [64], who have presented comprehensive research into centralized control. Moreover, a novel approach to decentralizing control based on communications links is presented in [124].

4.1. Centralized control

The MG controllers in centralized method are based on principles similar to those of the inner loop controllers, as explained in Section 2. In this technique, there is a central controller—called the Microgrid Central Controller (MGCC)—that allows each MG to interface with the Distribution Management System (DMS). This type of control is very suitable for certain small manually controlled MGs, as well as for MGs with common goals and those pursuing cooperation [99]. Indeed, the definition of centralization or decentralization is based on the position of the MGCC. The control structure of centralized secondary control is shown in Fig. 15. Based on the previous investigations, the outputs of the MGCC are sent to the primary and inner control loop through a communications link in order to regulate the reference values of voltage and frequency [125].

In centralized control, the frequency and voltage amplitude of DER is measured and compared with the reference value received from the main network (if the MG is in grid-connection mode). Thus, the droop control (5) and (6) can be replaced by (14) and (15), using Park's transformation [64].

$$f = f^{ref} - T_{p(s)}\left[(P-P^{ref})\sin\theta - (Q-Q^{ref})\cos\theta\right] \quad (14)$$

$$V = V^{ref} - T_{Q(s)}\left[(P-P^{ref})\cos\theta + (Q-Q^{ref})\sin\theta\right] \quad (15)$$

The measurement error will then be sent to primary control to restore the voltage and frequency; the restoration compensator can be defined through (16) and (17).

$$\Delta f = G_{pf}(f_{mg}^{ref} - f_{mg}) + G_{if}\int (f_{mg}^{ref} - f_{mg})dt + \delta f_s \quad (16)$$

$$\Delta V = G_{pv}(V_{mg}^{ref} - V_{mg}) + G_{iv}\int (V_{mg}^{ref} - V_{mg})dt \quad (17)$$

In order to connect a MG to the grid, the frequency and voltage of the grid must be measured. These values will serve as references to the secondary control loop. The phase angle between the grid and MG will be synchronized by means of a synchronization control loop, which is disabled in the absence of the grid ($\delta f_s = 0$) [64]. However, in grid-connection mode, the synchronization is present through a PLL module, which is needed for measuring the voltage angle needed for the inverter control [126,127].

4.2. Decentralized control

The main duty of decentralized control is to specify the maximum power generated by a microcontroller, while at the same time taking into account the MG's capability to support the consumer and increase power exports to the grid for market participation. As shown in Fig. 15 the secondary control in the central control method is located after the primary control and the communications link. In this method, the result of the secondary control (the error) is distributed to all the primary controllers. However, Shafiee et al. [124] have proposed a distributed secondary control method in which the secondary control is located before the communications link and beside each primary control. In other words, the method moved the role of the MGCC to controlling and supporting the primary control. The control structure of the decentralized secondary control is shown in Fig. 16. In this case, the voltage amplitude and frequency are measured over the communications link. Then, the average of the measured values is sent with the measurement errors to primary control so that the voltage and frequency may be restored. Thus, (18) and (19) can be replaced in decentralized control as follows [124]:

$$\Delta V_{DG_k} = G_{pv}(V_{mg}^{ref} - \overline{V}_{DG_k}) + G_{iv}\int (V_{mg}^{ref} - \overline{V}_{DG_k})dt$$
$$\overline{V}_{DG_k} = \frac{\sum_{i=1}^{N} V_{DG_i}}{N} \quad (18)$$

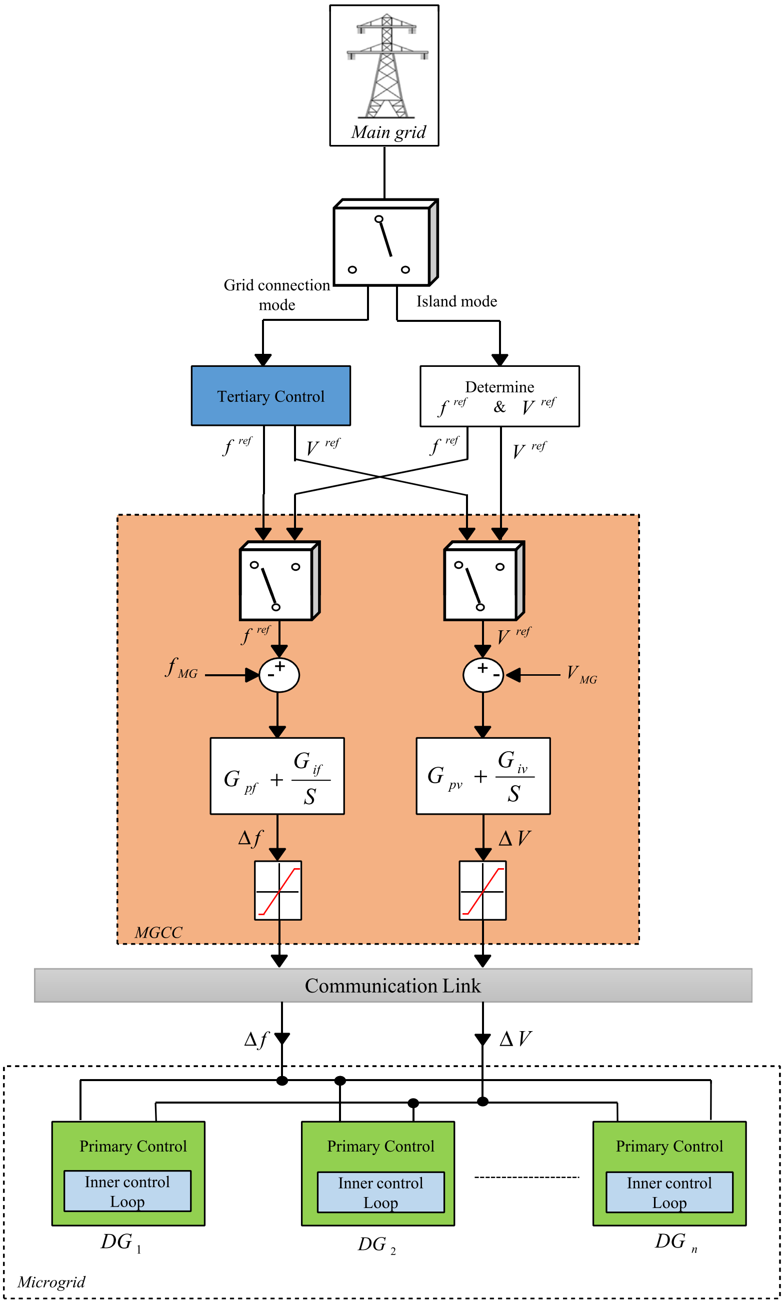

Fig. 15. Control structure of centralized secondary control.

$$\Delta f_{DG_k} = G_{pf}(f_{mg}^{ref} - \bar{f}_{DG_k}) + G_{if}\int(f_{mg}^{ref} - \bar{f}_{DG_k})dt$$
$$\bar{f}_{DG_k} = \frac{\sum\limits_{i=1}^{N} f_{DG_i}}{N} \qquad (19)$$

According to the discussion in Section 3, primary control improves reactive power through many different methods. However, due to variation in the voltage at different points of the MG (as opposed to the frequency, which is constant in the network), in the decentralized control method, the reactive power also needs to be measured for each DG and shared with other DGs, as with voltage and frequency. Hence, the variation in each reactive power can be calculated through (20)

$$\Delta Q_{DG_k} = G_{PQ}(\bar{Q}_{DG_k} - Q_{DG_K}) + G_{iQ}\int(\bar{Q}_{DG_k} - Q_{DG_k})dt$$
$$\bar{Q}_{DG_k} = \frac{\sum\limits_{i=1}^{N} Q_{DG_i}}{N}. \qquad (20)$$

This type of control is ideally utilized in MGs with different suppliers, where there is a need to make decisions separately

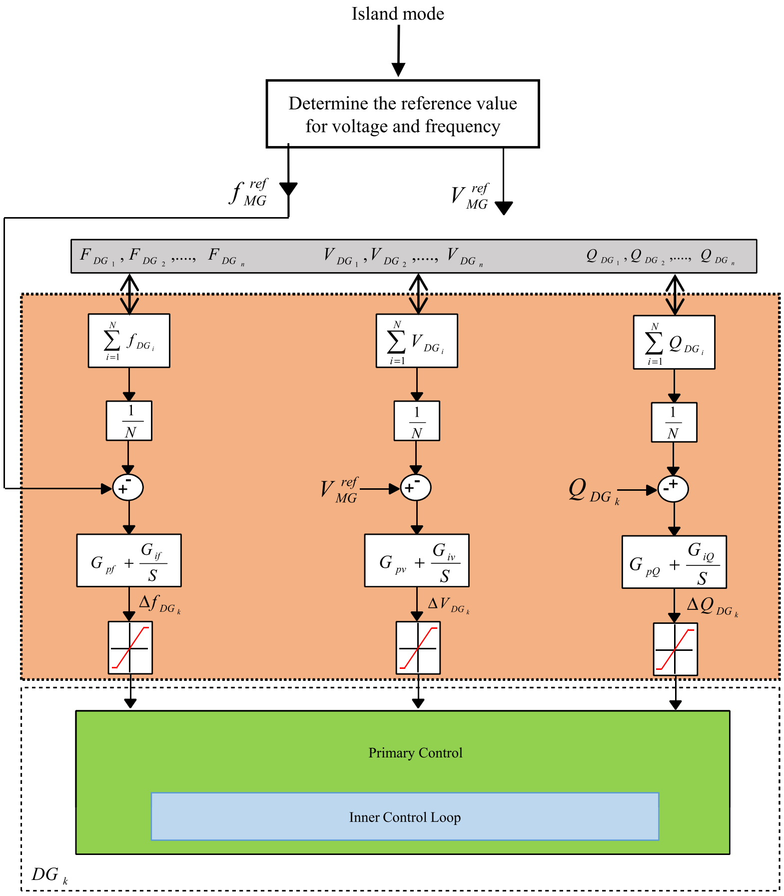

Fig. 16. Control structure of the decentralized secondary control [124].

regarding individual situations, and also for MGs with active roles in an electrical market environment; such MGs should possess an intelligent control for each unit. MSs with responsibilities other than power generation should also be considered here [99].

4.3. Secondary control discussion

Secondary control is used in MGs in order to achieve secure output through the links established between different DG units and targets of the level control list, as detailed here:

- supervising and monitoring the microgrids;
- interfacing between DGs and the energy storage system (master units); and
- adjusting frequency- and voltage-following of each load variation.

As discussed, in centralized techniques, the output voltage of each DG is measured using remote sensing and sent to the MGCC, while in decentralized control, the sensing and measurement of the voltage is performed at the terminal of each DG unit. A disadvantage of using an MGCC in secondary control is that it may malfunction, which can affect the reliability of the MG. Although MGCCs in MGs are being replaced by decentralized control methods, they are still required for management of DG units when a black start happens and for other coordination functions [124,128].

In this control level, there are some different requirements in island and grid connection mode, namely:

Grid-connection mode: the secondary control in centralized techniques will act as an interface between the MG and the main network. The power converter can also operate based on the grid-forming and following methods.

Island mode: secondary control establishes the reference value for voltage and frequency and the power converter must operates according to grid-forming method. [67]

5. Tertiary control

The purpose of the level control is to manage power flow by regulating amplitude voltage and frequency when the MG is in grid-connected mode. By measuring the *P*/*Q* ratio through the PCC, the grid's active and reactive power can be compared against the desired reference. Indeed, the frequency and voltage reference defined in (21) and (22) are used for (14) and (15) in secondary control [64].

$$f^{ref} = G_{pp}(P^{ref}_{grid} - P_{grid}) + G_{ip}\int (P^{ref}_{grid} - P_{grid})dt \tag{21}$$

$$V^{ref} = G_{PQ}(Q^{ref}_{grid} - Q_{grid}) + G_{iQ}\int (Q^{ref}_{grid} - Q_{grid})dt \tag{22}$$

This control level is the final and slowest. Fig. 17 shows a scheme of this level control. Indeed, tertiary control involves the

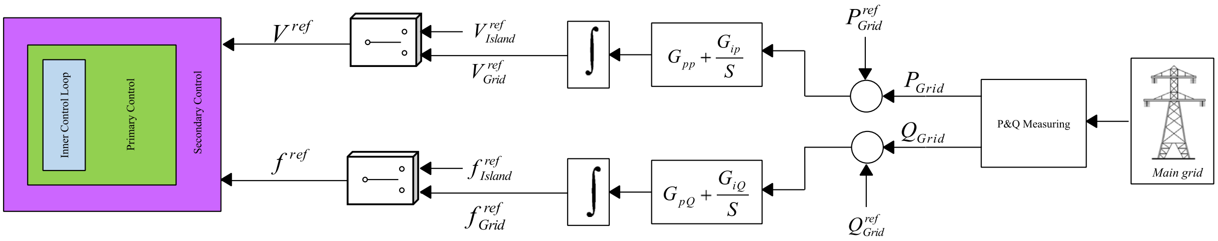

Fig. 17. Structure of tertiary control in microgrids.

optimal operation of the MG in the economic part as well as the technical part [17]. The tertiary control provides an economically optimal operation through grid-following power converters [67] or by using a gossiping algorithm, as discussed in [17]. Technically, if a fault or any non-plane islanding issue arises for the MG, the tertiary control attempts to absorb *P* from the grid such that, if the grid is not present, the frequency will start decreasing. When the expected value is surpassed, the MG is disconnected from the grid for safety, and the tertiary control is disabled [90].

6. Conclusion

Controlling MGs is critical due to the variation in generation of renewable energy sources. To optimize microgrid control, hierarchical control schemes have been presented by many researchers over the last decade. This paper has presented a comprehensive technical structure for hierarchical control—from power generation, through RESs, to synchronization with the main network or support customer as an island-mode system. The control strategy presented alongside the standardization can enhance the impact of control and energy management issues in microgrids. Hence, the optimal control strategy provides a strong motivation for customers to use RESs, and particularly, wind, and PV panels, in power generation. The increase in the consumption of energy from RESs is equal to the decrease in greenhouse gas release—an energy target that is established in many countries.

The technical solutions proposed for inner control loop and primary control are sufficiently comprehensive to be implemented by industry. However, there are many research questions that need to be answered and many gaps that need to be filled in order to complete the secondary level, especially with the decentralized method. The first important matter is reducing the role of the microgrid central control (MGCC) from the secondary control level. There are some methods of decentralizing control, but they are only partial. Secondly, an effort is needed to extend decentralized control to the energy storage system and to obviate the need for a master unit in microgrid control, which can recover from unplanned interruptions.

Acknowledgment

The authors would like to acknowledge the financial support provided by the Finnish Funding Agency for Technology and Innovation, Tekes, to the Smart Grids and Energy Markets (SGEM) research program.

References

[1] Lasseter RH. Microgrids. In: Proceedings of the IEEE power engineering society winter meeting; 2002. p. 305–8.
[2] Barnes M, Ventakaramanan G, Kondoh J, Lasseter R, Asano H, Hatziargyriou N, et al. Real-world microgrids-an overview. In: Proceedings of the IEEE international conference on system of systems engineering, SoSE'07; 2007. p. 1–8.
[3] Pogaku N, Prodanovic M, Green TC. Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. IEEE Trans Power Electron 2007;22:613–25.
[4] Gu W, Wu Z, Bo R, Liu W, Zhou G, Wu C, et al. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Int J Electr Power Energy Syst 2014;54:26–37.
[5] Logenthiran T, Srinivasan D, Wong D. Multi-agent coordination for DER in MicroGrid. In: Proceedings of the IEEE international conference on sustainable energy technologies, ICSET; 2008. p. 77–82.
[6] Ackermann T, Andersson G, Söder L. Distributed generation: a definition. Electr Power Syst Res 2001;57:195–204.
[7] Li YW, Kao CN. An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid. IEEE Trans Power Electron 2009;24:2977–88.
[8] Wood AJ, Wollenberg BF. Power generation, operation, and control. John Wiley & Sons; 2012.
[9] Katiraei F, Iravani R, Hatziargyriou N, Dimeas, A. Microgrids management. IEEE Power Energy Mag 2008;6:54–65.
[10] Guerrero JM, Matas J, de Vicuña LG, Castilla M, Miret J. Wireless-control strategy for parallel operation of distributed-generation inverters. IEEE Trans Ind Electron 2006;53:1461–70.
[11] Vandoorn TL, Meersman B, Degroote L, Renders B, Vandevelde L. A control strategy for islanded microgrids with dc-link voltage control. IEEE Trans Power Deliv 2011;26:703–13.
[12] Vandoorn TL, Guerrero JM, de Kooning DM, Vasquez JC, Vandevelde L. Decentralized and centralized control of islanded microgrids including reserve management. IEEE Ind Electron Mag 2013:1–14.
[13] Farhangi H. The path of the smart grid. IEEE Power Energy Mag 2010;8: 18–28.
[14] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management—Part I: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014.
[15] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management—Part II: system operation, power quality and protection,. Renew Sustain Energy Rev 2014;36:440–51.
[16] Tarasantisuk C, Chunkag V, Thounthong P. Control of parallel-connected AC to DC converter with droop technique for DC microgrid application. Energy Proc 2013;34:351–61.
[17] Bidram A, Davoudi A. Hierarchical structure of microgrids control system. IEEE Trans Smartgrid 2012;3:1963–76.
[18] Patel MR. Wind and solar power systems: design, analysis, and operation. CRC Press; 2005.
[19] Kalogirou SA. Solar energy engineering: processes and systems. Academic Press, an imprint of Elsevier; 2009.
[20] Armaroli N, Balzani V. The future of energy supply: challenges and opportunities. Angew Chem Int Ed 2007;46:52–66.
[21] Lu X, McElroy MB, Kiviluoma J. Global potential for wind-generated electricity. Proc Natl Acad Sci 2009;106:10933–8.
[22] Mauricio JM, Marano A, Gómez-Expósito A, Martinez Ramos JL. Frequency regulation contribution through variable-speed wind energy conversion systems. IEEE Trans Power Syst 2009;24:173–80.
[23] Miller A, Muljadi E, Zinger DS. A variable speed wind turbine power control,. IEEE Trans Energy Convers 1997;12:181–6.
[24] Yingcheng X, Nengling T. Review of contribution to frequency control through variable speed wind turbine. Renew Energy 2011;36:1671–7.
[25] Bianchi F, De Battista H, Mantz R. Wind turbine control systems: principles, modelling and gain-scheduling design (advances in industrial control), Lavoisier Ed.; 2006.
[26] Boukhezzar B, Lupu L, Siguerdidjane H, Hand M. Multivariable control strategy for variable speed, variable pitch wind turbines. Renew Energy 2007;32:1273–87.
[27] Ackermann T. Wind Power in Power Systems; November/December 2013.
[28] Palizban O, Mekhilef S. Hybrid systems control, with renewable energy sources. Lap Lambert: German Academic Publishing; 2012.
[29] Ko HS, Yoon GG, Kyung NH, Hong WP. Modeling and control of DFIG-based variable-speed wind-turbine. Electr Power Syst Res 2008;78:1841–9.

[30] Lei Y, Mullane A, Lightbody G, Yacamini R. Modeling of the wind turbine with a doubly fed induction generator for grid integration studies. IEEE Trans Energy Convers 2006;21:257–64.

[31] Hughes FM, Anaya-Lara O, Jenkins N, Strbac G. Control of DFIG-based wind generation for power network support. IEEE Trans Power Syst 2005;20:1958–66.

[32] Junyent-Ferré A, Gomis-Bellmunt O, Sumper A, Sala M, Mata M. Modeling and control of the doubly fed induction generator wind turbine. Simul Model Pract Theory 2010;18:1365–81.

[33] Ekanayake J, Jenkins N. Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. IEEE Trans Energy Convers 2004;19:800–2.

[34] Holdsworth L, Wu X, Ekanayake J, Jenkins N. Comparison of fixed speed and doubly-fed induction wind turbines during power system disturbances. IEE Proc—Gener, Transm, Distrib 2003;150:343–52.

[35] Palizban O. Active and reactive power control for hybrid system with renewable energy sourses. Kualalumpur: University of Malaya; 2011 (Master, Electrical).

[36] Ko HS, Yoon GG, Hong WP. Active use of DFIG-based variable-speed wind-turbine for voltage regulation at a remote location. IEEE Trans Power Syst 2007;22:1916–25.

[37] Ledesma P, Usaola J. Doubly fed induction generator model for transient stability analysis. IEEE Trans Energy Convers 2005;20:388–97.

[38] Makinen AS, Raipala O, Repo S, Tuusa, H. Influence of DFIG reactive current injection during a voltage dip on the operation of wind turbine circuit breaker. In: Proceedings of the IEEE 8th international conference on power electronics and ECCE Asia (ICPE & ECCE); 2011. p. 88–95.

[39] Hong WP. Active use of DFIG-based variable-speed wind-turbine for voltage control in power system operation. J Electr Eng Technol 2008;3:254–62.

[40] Tan X, Li Q, Wang H. Advances and trends of energy storage technology in microgrid. Int J Electr Power Energy Syst 2013;44:179–91.

[41] Rabiee A, Khorramdel H, Aghaei J. A review of energy storage systems in microgrids with wind turbines. Renew Sustain Energy Rev 2013;18:316–26.

[42] Teodorescu R, Rodriguez P, Liserre, M. Power electronics for PV power systems integration. In: Proceedings of the IEEE international symposium on industrial electronics (ISIE); , 2010. p. 4532–614.

[43] Braun M. Grid-Friendly Local Consumption of PV Energy. In: Proceedings of the 5th IRES; 2010.

[44] Selvaraj J, Rahim NA. Multilevel inverter for grid-connected PV system employing digital PI controller. IEEE Trans Ind Electron 2009;56:149–58.

[45] Kjaer SB, Pedersen JK, Blaabjerg F. A review of single-phase grid-connected inverters for photovoltaic modules. IEEE Trans Ind Appl 2005;41:1292–306.

[46] Alanen R. Nordic photovoltaic design systems. Functions, requirements and review of current PV system design tools. Finland: VTT; 2012.

[47] Pandiarajan N, Muthu R. Mathematical modeling of photovoltaic module with Simulink. In: Proceedings of the 1st international conference on electrical energy systems (ICEES); 2011. p. 258–63.

[48] Benmessaoud M, Zerhouni F, Zegrar M, Boudghene Stambouli A, Tioursi M. New approach modeling and a maximum power point tracker method for solar cell. Comput Math Appl 2010;60:1124–34.

[49] Khaligh A, Onar OC. Energy harvesting: solar, wind, and ocean energy conversion systems. CRC Press Inc.; 2010.

[50] Van Dyk E, Gxasheka A, Meyer E. Monitoring current–voltage characteristics and energy output of silicon photovoltaic modules. Renew Energy 2005;30:399–411.

[51] Datta M, Senjyu T, Yona A, Funabashi T, Kim CH. A frequency-control approach by photovoltaic generator in a PV–diesel hybrid power system. IEEE Trans Energy Convers 2011;26:559–71.

[52] Villalva MG, Gazoli JR. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans Power Electron 2009;24:1198–208.

[53] Wang C. Modeling and control of hybrid wind/photovoltaic/fuel cell distributed generation systems. Bozeman: Montana State University; 2006.

[54] Palizban O, Mekhilef S. Modeling and control of photovoltaic panels base perturbation and observation MPPT method. IEEE; 25–27 November, 2011.

[55] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans Energy Convers 2007;22:439–49.

[56] Salas V, Olias E, Barrado A, Lazaro A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. Sol Energy Mater Sol Cells 2006;90:1555–78.

[57] Coelho RF, Concer FM, Martins DC. A MPPT approach based on temperature measurements applied in PV systems. In: Proceedings of the 9th IEEE/IAS international conference on industry applications (INDUSCON); 2010. p. 1–6.

[58] Haeberlin H, Borgna L. A new approach for semi-automated measurement of PV inverters, especially MPP tracking efficiency, using a linear PV array simulator with high stability, vol. 24; 2004. p. 32.

[59] Moura S, Hiskens I. A switched extremum seeking approach to maximum power point tracking in photovoltaic systems. Grid Integration of Alternative Energy Sources, vol. 4; 2009.

[60] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using Cuk converter. IEEE Trans Ind Electron 2011;58:1154–61.

[61] Liu B, Duan Sh, Liu F, Xu P. Analysis and improvement of maximum power point tracking algorithm based on incremental conductance method for photovoltaic array. In: Proceedings of the 7th international conference on power electronics and drive systems, PEDS'07; 2007. p. 637–41.

[62] Hohm D, Ropp ME. Comparative study of maximum power point tracking algorithms. Prog Photovolt: Res Appl 2003;11:47–62.

[63] Palizban O, Mekhilef S. Power optimization and static performance investigation of an island-mode doubly-fed induction generator (DFIG). In: Proceedings of the IEEE international conference oncontrol system, computing and engineering (ICCSCE); 2011. p. 399–403.

[64] Guerrero JM, Vasquez JC, Matas J, de Vicuña LG, Castilla M. Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization. IEEE Trans Ind Electron 2011;58:158–72.

[65] Palizban O, Mekhilef S. Modeling and control of photovoltaic panels base perturbation and observation MPPT method. In: Proceedings of the IEEE international conference on control system, computing and engineering (ICCSCE); 2011. p. 393–8.

[66] De Brabandere K, Bolsens B, Vanden Keybus J, Woyte A, Driesen J, Belmans R. A voltage and frequency droop control method for parallel inverters. IEEE Trans Power Electron 2007;22:1107–15.

[67] Rocabert J, Luna A, Blaabjerg F, Rodriguez P. Control of power converters in AC microgrids. IEEE Trans Power Electron 2012;27:4734–49.

[68] Rodriguez P, Candela I, Citro C, Rocabert J, Luna A. Control of grid-connected power converters based on a virtual admittance control loop. In: Proceedings of the 15th European conference on power electronics and applications (EPE); 2013. p. 1–10.

[69] Dong D. Modeling and control design of a bidirectional PWM converter for single-phase energy systems. MS Thesis in Electrical Engineering, Virginia Polytechnic Institute and State University; 2009.

[70] Vandoorn T, De Kooning J, Meersman B, Vandevelde L. Review of primary control strategies for islanded microgrids with power-electronic interfaces. Renew Sustain Energy Rev 2013;19:613–28.

[71] Blaabjerg F, Teodorescu R, Liserre M, Timbus A. Overview of control and grid synchronization for distributed power generation systems. IEEE Trans Ind Electron 2006;53:1398–409.

[72] Green T, Prodanović M. Control of inverter-based micro-grids. Electr Power Syst Res 2007;77:1204–13.

[73] Wu T, Siri K, Banda J. The central-limit control and impact of cable resistance in current distribution for parallel-connected DC–DC converters. In: Proceedings of the 25th annual IEEE power electronics specialists conference, PESC'94 Record; 1994. p. 694–702.

[74] Banda J, Siri K. Improved central-limit control for parallel-operation of dc-dc power converters. In: Proceedings of the 26th annual IEEE power electronics specialists conference, PESC'95 Record; 1995. p. 1104–10.

[75] Kawabata T, Higashino S. Parallel operation of voltage source inverters. IEEE Trans Ind Appl 1988;24:281–7.

[76] Colet-Subirachs A, Ruiz-Alvarez A, Gomis-Bellmunt O, Alvarez-Cuevas-Figuerola F, Sudria-Andreu A. Centralized and distributed active and reactive power control of a utility connected microgrid using IEC61850. IEEE Syst J 2012;6:58–67.

[77] He Z, Xing Y. Distributed control for UPS modules in parallel operation with RMS voltage regulation. IEEE Trans Ind Electron 2008;55:2860–9.

[78] Pascual M, Garcera G, Figueres E, Gonzalez-Espin F. Robust model-following control of parallel UPS single-phase inverters. IEEE Trans Ind Electron 2008;55:2870–83.

[79] Low K-S, Cao R. Model predictive control of parallel-connected inverters for uninterruptible power supplies. IEEE Trans Ind Electron 2008;55:2884–93.

[80] Chen J-F, Chu C-L. Combination voltage-controlled and current-controlled PWM inverters for UPS parallel operation. IEEE Trans Power Electron 1995;10:547–58.

[81] Emadi A, Nasiri A, Bekiarov S. Uninterruptible power supplies and active filters. CRC Press; 2004.

[82] Cai N, Mitra J. A decentralized control architecture for a microgrid with power electronic interfaces. In: Proceedings of the North American power symposium (NAPS); 2010. p. 1–8.

[83] Guerrero JM, Hang L, Uceda J. Control of distributed uninterruptible power supply systems. IEEE Trans Ind Electron 2008;55:2845–59.

[84] Ramos R, Biel D, Guinjoan F, Fossas E. Master-slave sliding-mode control design in parallel-connected inverters. AUTOMATIKA: časopis za automatiku, mjerenje, elektroniku, računarstvo i komunikacije 2001;42:37–44.

[85] Chen C, Wang Y, Lai J, Lee Y, Martin D. Design of parallel inverters for smooth mode transfer microgrid applications. IEEE Trans Power Electron 2010;25:6–15.

[86] Vandoorm BZTL, De Kooning JDM, Meersman B, Vandevelde L. Smart Microgrids and Virtual Power Plants in a Hierarchical Control Structure. Presented at the 2nd IEEE PES International Conference and Exhibition; 2011.

[87] Wu T, Chen Y, Huang Y. 3C strategy for inverters in parallel operation achieving an equal current distribution. IEEE Trans Ind Electron 2000;47:273–81.

[88] Prodanovic M, Green TC. High-quality power generation through distributed control of a power park microgrid. IEEE Trans Ind Electron 2006;53:1471–82.

[89] Majumder R, Chaudhuri B, Ghosh A, Ledwich G, Zare F. Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop. IEEE Trans Power Syst 2010;vol. 5:796–808.

[90] Guerrero J, Loh P, Chandorkar M, Lee T. Advanced Control Architectures for Intelligent MicroGrids, Part I: Decentralized and Hierarchical Control; 2013.

[91] Sao CK, Lehn PW. Control and power management of converter fed micro-grids. IEEE Trans Power Syst 2008;23:1088–98.

[92] Piagi P, Lasseter RH. Autonomous control of microgrids. In: Proceedings of the IEEE power engineering society general meeting; 2006. p. 8.

[93] Guerrero JM, Berbel N, Matas J, Sosa J, de Vicuna L.G. Droop control method with virtual output impedance for parallel operation of uninterruptible power supply systems in a microgrid. In: Proceedings of the 22nd Annual IEEE applied power electronics conference, APEC; 2007. p. 1126–32.

[94] Planas E, Gil-de-Muro A, Andreu J, Kortabarria I, Martínez de Alegría I. General aspects, hierarchical controls and droop methods in microgrids: a review. Renew Sustain Energy Rev 2013;17:147–59.

[95] Chiang S, Chang J. Parallel control of the UPS inverters with frequency-dependent droop scheme. In: Proceedings of the IEEE 32nd annual power electronics specialists conference, PESC; 2001. p. 957–61.

[96] Laaksonen H, Kauhaniemi K. Stability of microgrid with different configurations after islanding due to fault in the utility grid. Int Rev Electr Eng (IREE) 2008;3.

[97] Guerrero JM, Vasquez JC, Matas J, Castilla M, de Vicuna L. Control strategy for flexible microgrid based on parallel line-interactive UPS systems. IEEE Trans Ind Electron 2009;56:726–36.

[98] Laaksonen H, Kauhaniemi K. Synchronized re-connection of island operated LV microgrid back to utility grid. In: Proceedings of the IEEE PES innovative smart grid technologies conference, Europe (ISGT Europe); 2010. p. 1–8.

[99] Zamora R, Srivastava AK. Controls for microgrids with storage: review, challenges, and research needs. Renew Sustain Energy Rev 2010;14:2009–18.

[100] Rafiei S. Application of distributed generation sources for micro-grid power quality enhancement. (Master dissertation). Queen's University; 2014.

[101] Hassaine L, OLias E, Quintero J, Salas V. Overview of power inverter topologies and control structures for grid connected photovoltaic systems,. Renew Sustain Energy Rev 2014;30:796–807.

[102] Twining E, Holmes DG. Grid current regulation of a three-phase voltage source inverter with an LCL input filter. IEEE Trans Power Electron 2003;18:888–95.

[103] Ciobotaru M, Teodorescu R, Blaabjerg F. Control of single-stage single-phase PV inverter. In: Proceedings of the European conference on power electronics and applications; 2005. p. 10.

[104] Malesani L, Mattavelli P, Tomasin P. Improved constant-frequency hysteresis current control of VSI inverters with simple feedforward bandwidth prediction. IEEE Trans Ind Appl 1997;33:1194–202.

[105] Sonaglioni L. Predictive digital hysteresis current control. In: Proceedings of the conference record of the IEEE industry applications conference. Thirtieth IAS Annual Meeting, IAS'95; 1995. p. 1879–86.

[106] Bose BK. An adaptive hysteresis-band current control technique of a voltage-fed PWM inverter for machine drive system. IEEE Trans Ind Electron 1990;37:402–8.

[107] Mattavelli P, Spiazzi G, Tenti P. Predictive digital control of power factor preregulators with input voltage estimation using disturbance observers. IEEE Trans Power Electron 2005;20:140–7.

[108] Ito Y, Kawauchi S. Microprocessor based robust digital control for UPS with three-phase PWM inverter. IEEE Trans Power Electron 1995;10:196–204.

[109] Danneels H, Coddens K, Gielen G. An enhanced, highly linear, fully-differential PLL-based sensor interface. Proc Eng 2011;25:1597–600.

[110] Kiyose M. Phase-locked loop. Google Patents; 2001.

[111] Hsieh G-C, Hung JC. Phase-locked loop techniques. A survey. IEEE Trans Ind Electron 1996;43:609–15.

[112] Golestan S, Monfared M, Freijedo F.Design-oriented Study of Advanced Synchronous Reference Frame Phase-locked Loops; 2013.

[113] Rodriguez P, Pou J, Bergas J, Candela JI, Burgos R, Boroyevich D. Decoupled double synchronous reference frame PLL for power converters control. IEEE Trans Power Electron 2007;22:584–92.

[114] Teodorescu R, Iov F, Blaabjerg F.Flexible development and test system for 11 kW wind turbine. In: Proceedings of the IEEE 34th annual power electronics specialist conference, PESC'03; 2003. p. 67–72.

[115] Zmood DN, Holmes DG. Stationary frame current regulation of PWM inverters with zero steady-state error. IEEE Trans Power Electron 2003;18: 814–22.

[116] Fukuda S, Yoda T. A novel current-tracking method for active filters based on a sinusoidal internal model [for PWM invertors]. IEEE Trans Ind Appl 2001;37:888–95.

[117] A.V. Tsyrganovich. Frequency locked loop. Google Patents; 2006.

[118] Rodriguez P, Luna A, Candela I, Mujal R, Teodorescu R, Blaabjerg F. Multi-resonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions. IEEE Trans Ind Electron 2011;58:127–38.

[119] Teodorescu R, Blaabjerg F. Proportional-resonant controllers. A New Breed of Controllers Suitable for Grid-Connected Voltage-Source Converters; 2004.

[120] Pregelj A, Begovic M, Rohatgi A. Impact of inverter configuration on PV system reliability and energy production. In: Proceedings of the conference record of the 29th IEEE photovoltaic specialists conference; 2002.p. 1388–91.

[121] Chandorkar M, Divan D. Decentralized operation of distributed UPS systems. In: Proceedings of the international conference on power electronics, drives and energy systems for industrial growth; 1996. p. 565–71.

[122] Katiraei F, Iravani M. Power management strategies for a microgrid with multiple distributed generation units. IEEE Trans Power Syst 2006;21: 1821–31.

[123] Chandorkar MC, Divan DM, Adapa R. Control of parallel connected inverters in standalone ac supply systems. IEEE Trans Ind Appl 1993;29:136–43.

[124] Shafiee Q, Guerrero JM, Vasquez J. Distributed Secondary Control for Islanded MicroGrids—A Novel Approach. IEEE Trans Power Electron 2014;29:1018–31.

[125] Justo JJ, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew Sustain Energy Rev 2013;24:387–405.

[126] McGrath BP, Holmes DG, Galloway JJH. Power converter line synchronization using a discrete Fourier transform (DFT) based on a variable sample rate. IEEE Trans Power Electron 2005;20:877–84.

[127] Jovcic D. Phase locked loop system for FACTS. IEEE Trans Power Syst 2003;18:1116–24.

[128] Shafiee Q, et al. Distributed secondary control for islanded MicroGrids—a networked control systems approach. In: Proceedings of the 38th annual conference on IEEE industrial electronics society, IECON; 2012. p. 5637–42.

Publication II

Energy storage systems in modern grids—Matrix of technologies and applications

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Journal of Energy Storage 6 (2016) 248–259

Journal of Energy Storage 6 (2016) 248–259

Contents lists available at ScienceDirect

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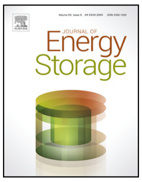

Energy storage systems in modern grids—Matrix of technologies and applications

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form 1 February 2016
Accepted 2 February 2016
Available online 13 February 2016

Keywords:
Applications of energy storages
Energy storage system
Modern grid
Renewable energy source
Energy storage technologies

ABSTRACT

Energy storage technologies are used in modern grids for a variety of applications and with different techniques. The range of applications and technologies is very broad, and finding the right storage solution for the job at hand can be difficult. In order to simplify the selection, this paper presents a matrix of the available technologies and applications. Along with proposing the matrix, the technologies and applications of Energy Storage Systems (ESSs) are described thoroughly and are compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, and life time. Moreover, the structure of energy storage, which is constituted of different steps and parts, is investigated. Since the implementing of an ESS is expensive, this paper also analyzes the possibility of integrating different types of ESSs and presents a comprehensive diagram to show the ESS technologies that can be integrated together in order to provide the needed performance in a cost-optimal way. Finally, the key results of this comprehensive study are summarized in a number of tables.

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http://dx.doi.org/10.1016/j.est.2016.02.001
2352-152X/

1. Introduction

Power management and stability assurance are critical tasks in modern grids because of the variables involved in generation and on the demand side. There are many different methods of approaching these problems, such as de-loading the operation of Renewable Energy Sources (RESs) when the generation of power is greater than demand and load shedding during power shortages [1–5]. However, the absorption and injection of energy by energy storage systems may be the best solution for managing this issue well [6–9]. Investigations of the challenges and barriers to power systems indicate that ESSs should aim at the following three targets [10–12]:

- Enhancing the reliability of renewable energy sources;
- Improving the resilience of the grid and resolving its issues;
- Realizing the benefits of smart grids and optimizing generation to suit demand.

Indeed, by storing energy when it is easily available and dispatching it during shortages, the combination of energy storage technology and RESs can help to stabilize power output while also enhancing the reliability of RESs. Moreover, energy storage can increase the resilience of systems during weather variations, natural disasters, and so on [13–16].

In fact, determining the best arrangement of ESS can be the first critical issue in designing a system. From this point of view, storage systems may be either distributed or aggregated. In distributed arrangements, the energy storage systems are connected via individual power electronic interfaces to each RES. In this method, each storage system has responsibility for the control and optimization of the power output of the source to which it is connected [17–19]. The aggregated model operates so that the whole system—for example, a microgrid (MG)—is supported through a central energy storage system. Depending on the arrangement, such a system may be connected to the DC bus either directly or through a power-electronic interface [20–22].

The second critical issue for storage systems may be the control of each application and of the optimum storage type. Indeed, in implementing an optimum storage project, three different steps need to be considered:

- Investigating the type and size of the storage system and selecting the one that is best for the system.
- Defining the best control strategy for the application considering the selected storage system.
- Investigating the net present value of the storage system.

In the second step, control methodologies for ESSs can be classified as either central or decentralized and can cover both of the arrangements. Indeed, the control methodologies of storage units, and also the power-electronics interfaced DG system with them, are investigated in [23–25] for centralized methods and in [26–31] for decentralized methods. Moreover, the control strategy is comprehensively discussed by the authors in [32,33].

In recent years, there has been much interest in investigations into technologies and applications of ESS. Researchers have produced comprehensive reviews in this area, such as those by Tan et al. [17], Carnegie et al. [34], Bradbury et al. [35], and Cavanagh et al. [36] The first objective of the present paper is thus to cover the first step by creating a matrix of different storage technologies and their applications. Such a matrix may be beneficial in allowing industry and researchers to quickly determine the optimum storage technique for a given application. The second objective of this paper is to analyze the possibility of integrating different ESS technologies. Indeed, such an analysis can help to obviate the high cost of storing energy in certain applications.

The present paper is organized as follows: The structure of energy storage is discussed in Section 2. The energy storage technologies and applications are investigated in Sections 3 and 4, respectively. A comparison of these two issues and the matrix appear in Section 5. The possibility of integrating ESS is discussed in Section 6. Finally, the conclusion is presented in Section 7.

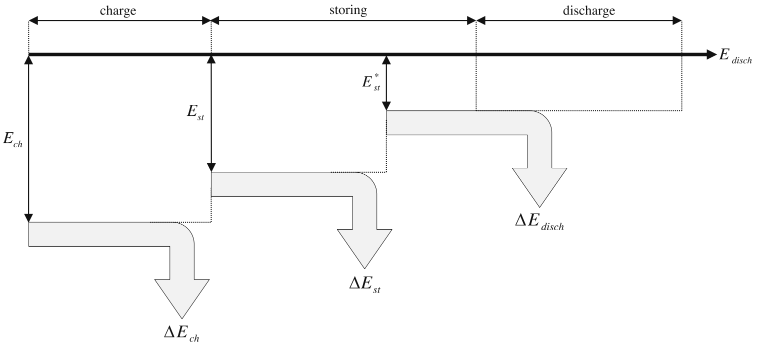


Fig. 1. Energy equilibrium in ESS.

2. Structure of energy storage

To store the generated power, it is necessary to convert it into other forms of energy, such as chemical or mechanical energy. As was presented by Gazarian[37], and based on the above definitions, energy storage consists of three different steps: *charge*: absorbing electrical energy from sources; *storage*: converting electrical energy to other types of energy and storing it and *discharge*: injecting the stored electrical energy back into the system. Moreover, storage systems can be divided into three different parts: *central storage*, the repository in which the energy is stored after conversion; *power transformation*, the interface between the central storage and the power system with bidirectional transfer; and *control*, which uses sensors and other measuring devices to determine the level of charge or discharge of the stored energy. Since energy storage is not an ideal energy source, but just a repository of energy, there are always losses at each step of the storage process. The energy generated by the sources given the energy delivered to the system during shortages is described by Eq. (1),

$$E_{generate} - \Delta E_{loss} = E_{out} \tag{1}$$

And the energy losses in this process are explained by Eq. (2).

$$\Delta E_{loss} = \Delta E_{ch} + \Delta E_{st} + \Delta E_{disch} \tag{2}$$

Indeed, a significant parameter in electrical storage is the efficiency of each step. Taking into account Fig. 1, which shows the energy flow in a storage system, the efficiency of the charge step can be calculated as

$$\eta_{ch} = \frac{E_{st}}{E_{ch}} \tag{3}$$

The storage period can be expressed as

$$\eta_{st}(t) = \frac{E^*_{st}}{E_{st}} \tag{4}$$

Regarding Eq. (4), it should be noted that the energy losses, and also the efficiency of the storage, depend on the storage time; for this reason, the time t between charging and discharging need to be considered. Finally, the discharge steps can be obtained:

$$\eta_{dish} = \frac{E^*_{st}}{E_{disch}} \tag{5}$$

Moreover, the total energy storage efficiency (η^{total}_{st}) is shown in Eq. (6) [37].

$$\eta^{total}_{st} = \frac{E_{out}}{E_{generate}} = \eta_{ch} \times \eta_{st}(t) \times \eta_{disch} \tag{6}$$

In these equations and Fig. 1, the losses of energy are shown by $\Delta E_{loss}$and the energy losses during storage, charge, and discharge are presented asΔE_{st},ΔE_{ch} and ΔE_{disch}respectively. The stored energy in the central part, represented by E_{st} andE^*_{st}, is the existing energy from this part.$E_{generate}$,E_{out},E_{ch}, and $E_{disch}$are the generated, output, charging, and discharging energy respectively. The efficiencies of charging, discharging, and storage are represented byη_{ch},η_{disch}, and, η_{st}.

3. Energy storage technologies

As mentioned earlier, energy storage can be achieved by converting electrical energy into another form. A complete classification of ESS types is presented in Fig. 2.

3.1. Electrochemical storage

In this technology, the chemical energy contained in the active material is converted directly into electrical energy [38,39]. Batteries are an advanced technique for storing electrical energy in electrochemical form. The possibility of using batteries in a wide range of different sizes is the main advantage of this technique [40,41].

Indeed, the operational voltage and current levels are generated through series or parallel connections of cells [43]. A simplest equivalent circuit of a battery and an explanation of its operation is presented by Patel [42], and shown in Fig. 3. The operating point is the intersection of the source line, which has the terminal voltage drop (V_b), and the load line (V_L). The quantity of electrical charge in the cell from the fully charged state to the discharged state is called

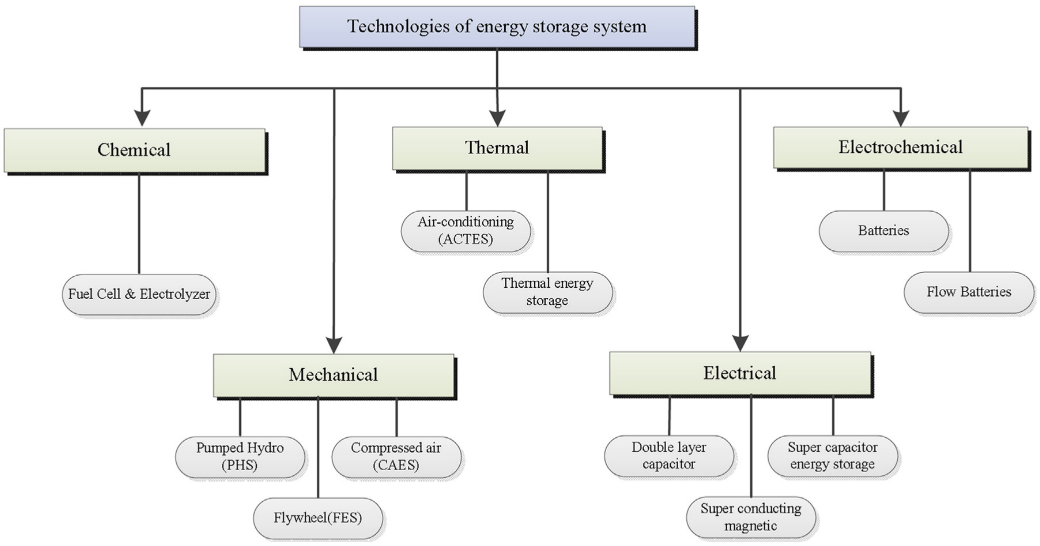


Fig. 2. Classification of ESS Technologies.

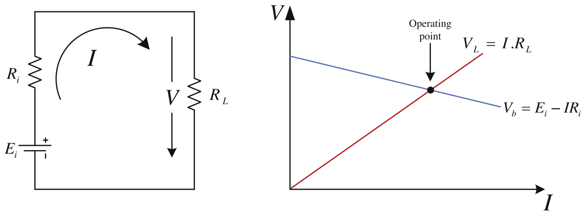


Fig. 3. Equivalent circuit of a battery and its operating point [42].

the capacity of the battery. Moreover, the state of charge (SoC) is the ratio between remaining capacity and the full charge, equal to 100% for full charge and 0% for full discharge. The variation in SoC (dSoC) is based on time and its relation to capacity (C_i) is outlined in Eq. (7).

$$d\text{SoC} = \frac{idt}{C_i}$$

$$\text{SoC} = \text{SoC} - \int \frac{idt}{C(i)} \tag{7}$$

Lead–acid batteries [44,45] are available in large quantities and in a variety of sizes and designs. They have high performance and possess the highest cell voltages of all aqueous electrolyte battery technologies. For MGs (especially when large), they are the most economic option [38,46]. Despite their suitability for a wide range of applications, they cannot equal the storage capacity of pumped hydro [47]. Nickel–Cadmium (NiCd) [48,49] and Nickel–Metal Hydride (NiMh) [50–52] batteries are much more expensive to implement than lead-acid batteries, but they provide good charge retention and energy density. They also have a long life cycle. Lithium-ion batteries [53] have rapid charge capability and high energy density. They need no maintenance during operation, and their energy loss is very low (5% per month). On the other hand, their performance decreases at high temperatures and protective circuitry is needed [54–56]. Sodium sulfur (NaS) is a type of electrochemical energy storage [57,58] that needs to operate at high temperature (350 °C/623 K) in order to ensure that the sodium is liquid. This condition leads to some difficulty and increases the cost of implementation [48,59,60]. However, the energy efficiency is high and these systems have very flexible operation [60]. Finally, flow batteries are another type of storage method; this is a class of electrochemical energy storage that uses ions dissolved into liquid electrolytes [61–63]. There exist both redox and hybrid flow batteries. Hybrid flow batteries include zinc–bromine models, while vanadium batteries are a good example of the redox type. This method is characterized by its long life cycle (around 40 years) and its adaptability: increasing the tank sizes and adding more electrolytes allows the capacity to be increased [47,64,65]. However, further development is still needed; these batteries are expensive to use and an external power is also required to operate [36].

3.2. Mechanical storage

Electrical energy can also be stored in the form of mechanical energy. Some major methods of this type are described in the following:

3.2.1. Flywheel energy storage (FES)

This technique employs the mechanical energy of a spinning rotor to store energy. There are two types of FES: low speed (under 10,000 rpm) and high speed (above 10,000 rpm). Low-speed systems are much more popular in industry [66–68]. FES systems have low maintenance, long life cycles of up to 20 years, no carbon emissions, no toxic components, and very fast response. However, they suffer from high rates of self-discharge (3–20% percent per hour), low storage capacity, and high cost. The available range of energy storage for a FES system is 0.2–25 kWh; however, this is expected to increase to 200 Wh/kg and 30 kW/kg respectively over the next few decades [42]. The energy stored by a flywheel (E) can be calculated using (8). This equation shows that the total mass of the flywheel (m) and the angular velocity (ω) squared have a direct impact on the energy stored by this device. In this equation, the radius of flywheel is shown by (r).

$$E = \frac{1}{2}\text{mr}^2\omega^2 \tag{8}$$

As presented by Östergård [69], a model of a general FES system consists of two voltage source converters (VSC), an electrical machine, a step-up transformer, and a main network. Indeed, the frequency decreases as the flywheel slows down. For this reason, the generation of AC power by the FES system should be converted to DC (constant frequency)—hence the use of the VSCs, for two back-to-back converters. The controller operation of these converters varies depending on the requirements of the FES application. For example, control of both active and reactive power may be needed for a FES system connected to an AC grid.

3.2.2. Pumped hydro storage

Electrical energy may be stored through pumped-storage hydroelectricity, in which large amounts of water are pumped to an upper level, to be reconverted to electrical energy using a generator and turbine when there is a shortage of electricity. The infinite technical lifetime of this technique is its main advantage [70], and its dependence on topographical conditions and large land use are the main drawbacks [43,71]. Pump storage projects throughout the world are significantly contributing to balancing the massive increase in future volatile regenerative energy production (wind and solar). The technology is well-established and commercially available on a large scale (sized up to 4000 MW), and the efficiency of the storage type is usually around 70–85%. [37]. The energy stored by this technique can thus be calculated through (9); the general equation for the output power (P) is shown in Eq. (10) [47].

In these equations, Q is the volume flow rate passing the turbine $[\text{m}^3/\text{S}]$,ρ is density of the water $[\text{kg}/\text{m}^3]$, and η is the hydraulic efficiency of the turbine [%]. Gravitational acceleration and height are shown by g $[\text{m}/\text{s}^2]$ and h [m] respectively.

$$W = \text{mgh} \tag{9}$$

$$P = Qh\eta g\rho \tag{10}$$

3.2.3. Compressed air energy storage

Compressing air to a pressure of around 70 bar is used to store electrical energy in the technology called compressed air energy storage (CAES). The method is, however, very expensive. In practice, large volumes of cheap natural storage, such as aquifers, salt caverns, and hard rock caverns, are used. An expansion turbine and generator are used to reconvert the compressed air to electrical energy [67]. CAES systems have typical capacities of about 50–300 MW and can store energy for longer than other methods—typically for more than a year—due to the very low losses involved. Like the pumped hydro method, CAES systems are capable of storing large amounts of energy. The efficiency of CAES is also similar to that technique (at around 70%). Moreover, the response time of the method is very high, but the technology is still not fully developed [47].

3.3. Electrical storage

Electric double-layer capacitors and superconducting magnetic energy storage (SMES) are electrical storage types discussed in the following:

3.3.1. Double layer capacitor (DLC)

In double-layer capacitor storage—which is also called ultra-capacitor or super-capacitor storage—the dielectric gap between two conductors is employed. This technique has a high energy storage capability due to its high power ability [72]. As presented in Ref. [37], based on a simple series RC circuit and the total energy which can be stored in a capacitor by this technique is calculated with (11). In fact, the energy stored in a capacitor is divided into two different parts: one part is retained in the capacitor, while the other is converted to heat and is wasted. The electrical energies stored in capacitors must be used very quickly, because the self-discharge rate of this method of energy storage is around 5% per day [54]. In this equation, Qis the charge stored in the capacitor [C], V_q is voltage across the capacitor [V], and C is its capacitance [F].

$$W = \int_0^Q V_q dq = \frac{CV^2}{2} \qquad (11)$$

3.3.2. Superconducting magnetic energy storage

The SMES technique involves a cryogenic refrigerator, a superconducting coil, a helium vessel, and a power conditioning system which is presented by Salameh in Ref. [73]. In this method the voltage is stored in the superconducting coil after being switched to DC by an AC–DC convertor. The temperature of the coil is kept low in order to avoid resistive loss. With this method, the current is stored in the coil until it is injected into the system. The responsibility of the power conditioning system is to control the stored energy and to inject power into the system.

A simple diagram of an SMES system is usually equal to the series RL circuit. Hence, the principle of the mathematical model is similar to the double layer capacitor (DLC), and the amount of energy stored by SMES per coil volume [J/m^3] can be calculated by Eq. (12) [37]. In this equation, B is the magnetic flux density [T] and μ is the permeability [H/m].

$$W = \frac{1B^2}{2\mu} \qquad (12)$$

3.4. Thermal storage

The thermal storage method is based on converting the energy to ice or hot water. There are many different approaches to use such thermal energy storage, a comprehensive review of which is presented in Refs. [74–76]. The most common version of a thermal energy storage system stores ice during the night and use the water to cool an air conditioning system during the day, thus reducing the use of power from the main grid or microgrid. On the other hand, the heat storage method can also use water to store heat energy and inject this energy into the system whenever it is needed [34]. There are many other thermal methods, such as geothermal energy systems, solar thermal energy conversion systems, and phase-changing materials, which are discussed in more detail in Refs. [77–79].

4. Energy storage applications in the power system

The principle of system control that classifies loads by priority and employs load shedding is not suitable for achieving high reliability in modern systems. Hence, one benefit of ESSs may be that they result in improved reliability for these systems. Akhil et al. [79] and Eyer et al. [80] have presented different applications that can be provided with ESS. The applications of ESS to MG are classified into four different groups, which are shown in Fig. 4 and discussed in the following.

4.1. Bulk energy applications

Bulk energy is a key application for integrating a large amount of variation in modern grids. The two major types are represented in the following:

4.1.1. Energy arbitrage

Energy generation is very expensive, and storing the energy can both increase the efficiency of a system and optimize it economically. Storage of energy when the price is low and selling energy at peak times when electricity is expensive is the main goal of the application. In a MG with RESs, the application also stores energy when the amount generated exceeds demand and inject power during shortages [81].

4.1.2. Peak shaving

The principle of peak shaving is very similar to energy arbitrage. The difference is that peak shaving is installed to cover the peak load, and does not have an economic target, as energy arbitrage does [82]. The application helps to improve the system design, based on a normal capacity and supporting the peak demand

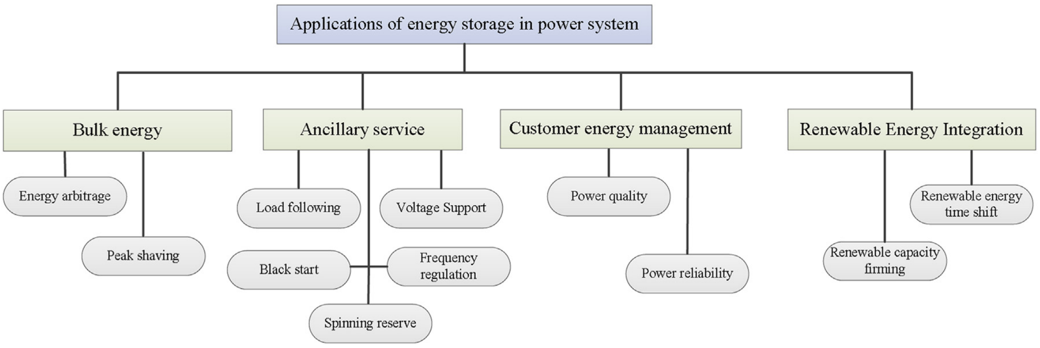


Fig. 4. Classification of ESS applications.

through the ESS. The peak shaving application is usually installed at the consumer, whereas energy arbitrage is used on the supply side [80,83].

4.2. Ancillary service applications

In modern grids, providing support to the system during the transmission of power from its generation to the consumer can be referred to as an ancillary service and involves adjustments and flexible reserves. The different approaches to this application are discussed below:

4.2.1. Load following

As compared to generation types, ESSs have a rapid response to changes in load [84]. Since the load can undergo frequent variations, energy storage is more suitable for load-following applications. In fact, in this application, the responsibility of energy storage is to create a balance between the generation part and the load [85]. Another reason for supporting load changing using energy storage is so that the system can cover both sides of the variations, following the load both up and down [80].

4.2.2. Spinning reserve

As mentioned by Gonzalez et al. in Ref. [58], the spinning reserve is a part of the capacity of the source that is not used in normal operation. However, the source can cover a power shortage in the system by injecting power for specific period. Indeed, the power shortage thus is covered by sources operating in this extra operations mode. Since power generation must continue until the backup system reaches its nominal value, the storage system in this application must be able to discharge over a long time (at least one hour) [83,86].

4.2.3. Voltage support

Stability is an important issue in the power system, and can be achieved through maintaining the voltage within the permissible limits. As discussed in Ref. [79], the management of reactive power is a requirement for achieving this, and can regulate accurately with an ESS as a voltage support resource. As reactive power cannot reasonably be transferred over long distances, a voltage support application is used locally to manage the problem [79,80].

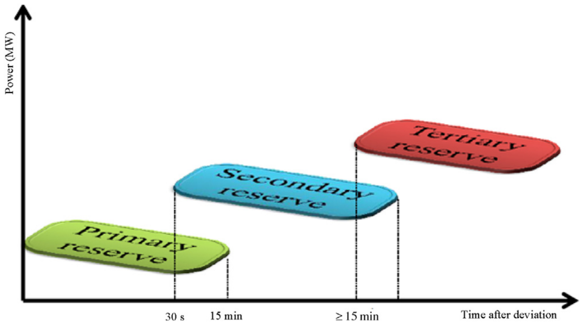


Fig. 5. Operating areas of the different levels of frequency control.

4.2.4. Black start

Unplanned events can lead to interruptions in power throughout the whole system or in a single part [87]. The result of this may be a black out [88], compromising the stability of the system [89–91]. The system is restored through a process called a black start, the responsibilities of which are power management, voltage control, and balancing. In this application, the energy storage system generates active power that can be used for energizing distribution lines or as start up power for large power plants [79].

4.2.5. Frequency regulation

Frequency control is crucial in power systems for dealing with the many small variations that occur. The energy storage system in a frequency regulator serves power systems by correcting the frequency deviations to within the permissible limits—for example to ±0.1 Hz in Nordel (North of Europe) or ±0.2 Hz in UCTE (Continental Europe) [92–94]. As mentioned in Refs. [95,96], there are three types of frequency regulation: primary, secondary, and tertiary. These are shown in Fig. 5. The responsibility of the *primary reserve* control is to create a balance between generation and demand and to restore the frequency within 5–30 s for the generator control [39,95–97]. The *secondary reserve* has two objectives: it serves as a backup for primary regulation and ensures that the frequency is set to 50 Hz, while also avoiding any imbalance in the interconnection. This control level reacts to the primary control reserves for 5–15 min, and should then be ready for frequency correction to within the permitted limits [96–98]. In the last level, *Tertiary reserve* has the same objective as the secondary reserve and also aims to balance load, generation, and sales, thus helping to keep the system synchronized. This reserve level is operated manually, and should reach its target in 15–60 min, depending on the country [96].

4.3. Customer energy management applications

Energy management applications are based on the quality and reliability of power delivery to the consumer which are discussed as follow:

4.3.1. Power quality

It is clear that there are some variations in generation and in energy sources, especially when it comes to RESs, which are dependent on environmental conditions [99–101]. Indeed, the fluctuations in power generation systems lead to concerns about power quality, especially in terms of voltage harmonics and voltage variation [102]. To manage this problem, energy storage is the first alternative to cover the variation. The application helps to protect downstream loads against short-duration events and to improve the quality of delivered power [83].

4.3.2. Power reliability

The principle of power reliability is similar to power quality [103,104], but power reliability follows power quality in sequence. This means that the time for restoring power with this application is longer than the time taken by the power quality application. The energy storage system in this application should have high reliability power with the best quality. Moreover, the power reliability application is under customer control and is installed in customer locations [105].

4.4. Renewable energy integration applications

There are many fluctuations in the power generated by RESs which can be covered by ESS. These applications are divided in two

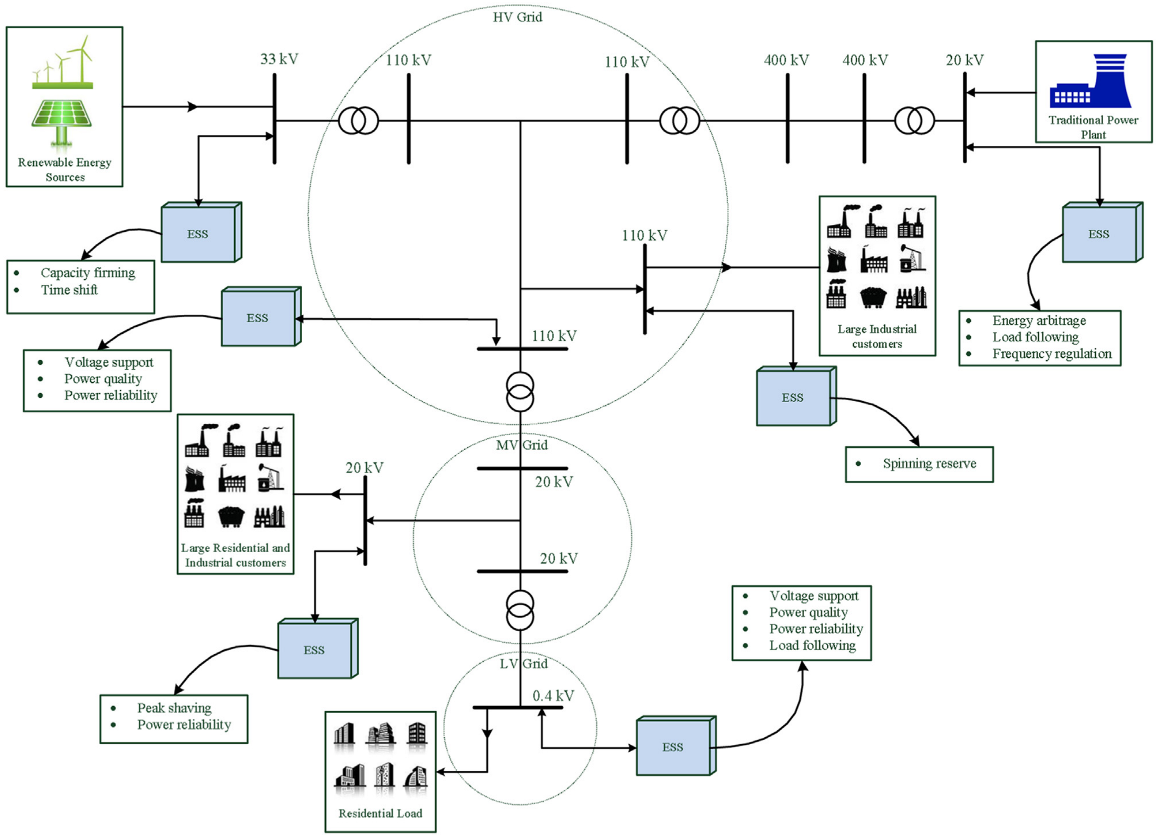


Fig. 6. Location of each ESS application in power system.

different categories: time shifting and capacity firming. The time-shift application manages the problem through different energy storage techniques [11]. It stores energy when demand is lower than generation, and injects this power into the system during shortages. In this application, energy storage can be installed anywhere in the system, whether near to the source or to the load [106–108]. The responsibility of the capacity firming application is to smooth the power and voltage output from renewable energy over a short period using an ESS [40]. The output power from RESs is added to the energy storage and supports the load. This mixing also can help to improve power quality.

4.5. Location of each application

In optimizing the amount of stored energy, the utilization of the energy storage system is important, as is its application in related

Table 1
Characteristics of energy storage applications in modern grids.

Applications			Storage power (MW)	Response time	Discharge time	Cycle	Desired life time (years)	Recommendation grid
Bulk energy	Energy arbitrage		≤ 500	minutes	≤ 10 h	300–400/yr	≤ 20	MV
	Peak shaving		≤ 500		≤ 6 h	50–250/yr	≤ 20	MV
Ancillary service	Load following		≤ 100		≤ 4 h	N/A	≤ 20	MV, LV
	Spinning reserve		≤ 100	≤ 4 h	≤ 5 h	N/A	≤ 20	HV
	Voltage support		≤ 10	≤ 100 ms	≤ 1 h	5000/yr	≤ 20	HV
	Black start		≤ 50	≤ 2 h	≤ 16 h	10–20/yr	≤ 25	HV, MV
	Frequency regulation	Primary	≤ 40	Instantaneous	30 min $\geq t \geq$ 15 min	8000/yr	≤ 15	MV
		Secondary	≤ 40	minute	1 h $\geq t \geq$ 30 min			MV
		Tertiary	≤ 100		≥ 1 h			MV
Customer energy management	Power quality		≤ 10	≤ 200 ms	≤ 2 h	50/yr	≤ 10	HV, MV, LV
	Power reliability		≤ 10	minutes	≤ 4 h	≤ 400/yr	≤ 15	MV, LV
Renewable energy integration	Time shift		≤ 500	≤ 30 min	≤ 5 h	≤ 4000/yr	≤ 15	MV
	Capacity firming		≤ 500	≤ 30 min	≤ 4 h	300–500/yr	≤ 20	MV

Table 2
Characteristics of energy storage technologies in modern grids.

Technologies				Capacity (MWh)	Power (MW)	Response time	Discharge time	Maturity	Life time (Years)	Efficiency (%)	Advantage	Disadvantage
Electrochemical	Lead–acid			0.25 ~ 50	≤100	millisecond	≤4 h	Demo ~ Commercial	≤20	≤85	Inexpensive High recyclable Reality available	Very heavy Limited usable energy Poor energy density
	Lithium-ion			0.25 ~ 25	≤100		≤1 h	Demo	≤15	≤90	High capacity Great stability in calendar and cycle life	
	NaS			≤300	≤50		≤6 h	Commercial	≤15	≤80	High storage capacity Inexpensive	Working only when the sodium and sulfur are liquids 290 ~ 390 °C
	Vanadium Redox			≤ 250	≤50	≤10 min	≤8 h	Demo	≤10	≤80	Possible to use for many different renewable energy sources	
Mechanical	FES			≤10	≤20	≤10 ms	≤1 h	Demo ~ Mature	≤20	≤85	High power density Nonpolluting High efficiency	Not enough safe Noisy High speed operation let to vibration
	PHS	small		≤5000	≤500	sec ~ min	6 ~ 24 h	Mature	≤70	≤85	Remote operation is possible Low man power factor Relatively low maintenance	Silt build-up Impedance to the movement of environmental issues
		large		≤14000	≤1400	sec ~ min						
	CAES	underground	small	≤1100	≤135	≤ 15 min	≤8 h	Demo ~ Commercial	≤40	≤85	High power capacity Low losses(can be storage energy for more than a year) Fast startup	It is not possible to install everywhere and the location is depend on a geological structure
			large	≤2700	≤135	≤ 15 min	≤20 h					
		above ground		≤250	≤50	≤15 min	≤5 h	Demo				
Electrical	DLC			0.1 ~ 0.5	≤1	≤10 ms	≤1 min	Commercial	≤40	≤95	High power density Low resistance high efficiency	Low energy density Low voltage per cell Incomplete capacity utilization
	SMES			1 ~ 3	≤10	≤10 ms	≤1 min	Commercial	≤40	≤95	High power High efficiency Environmentally safe	For sizing of high energy storage need to long loop Cooling system in needed expensive
Thermal				≤350	≤50	≤10 min	N/A	Mature	≤30	≤90	Nonpolluting Unlimited energy source	Expensive Depend on a geological structure

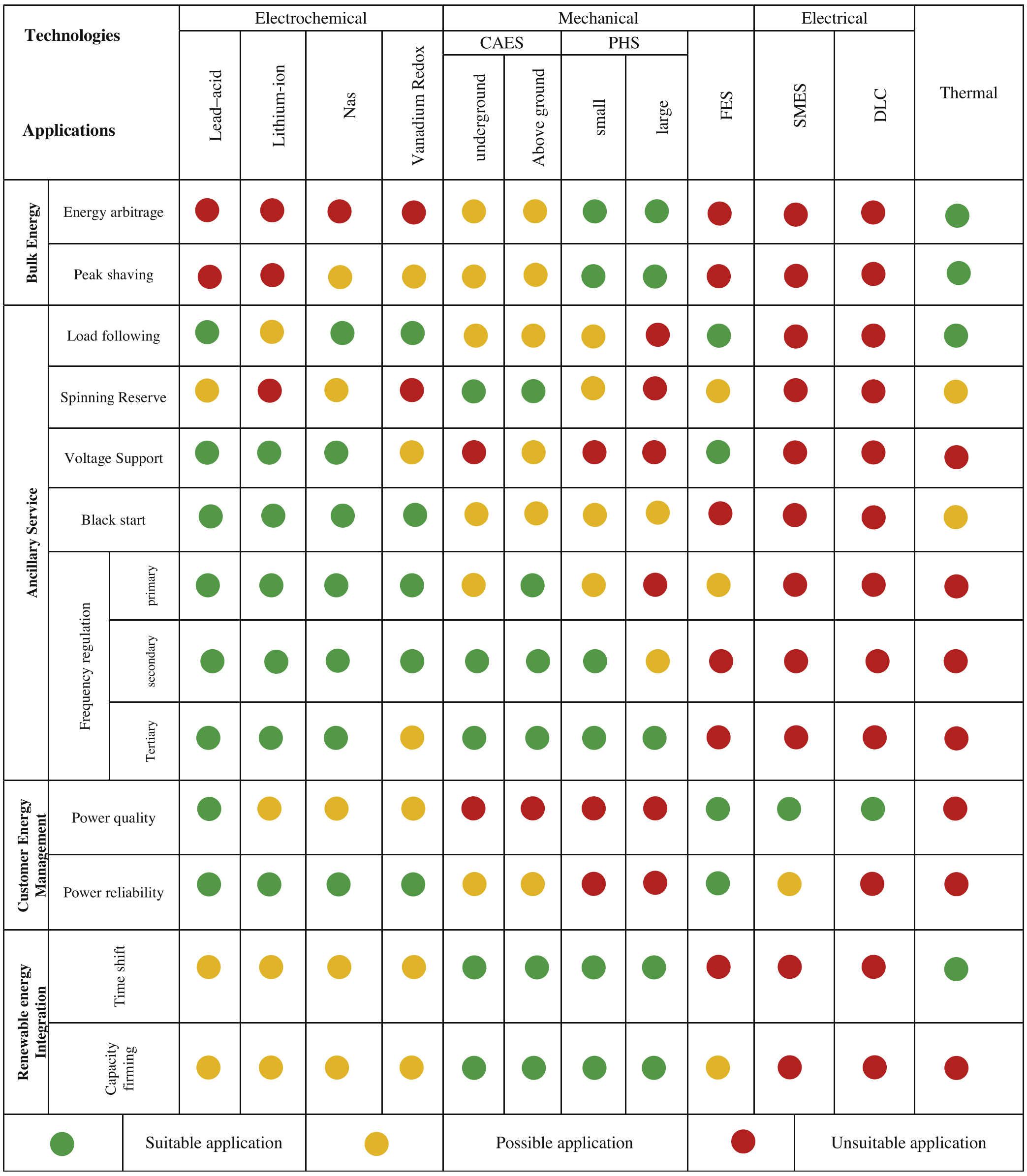
parts. There are several applications which can be used in different parts of a power system. Fig. 6 demonstrates the locations of each energy storage application in power system, from the point of generation to the customer.

5. Technologies and applications

As aforementioned, there are many different options for using energy storage in conventional or modern grids (DG, MG, Smart grid). As is well known, the choice of energy storage technique directly depends on the applications [106]. To correctly choose storage techniques, it is first necessary to distinguish two important parameters: energy (kWh) and power (kW) [34]. Thus, to design the ideal ESS, the power and energy of the system should be determined in the first instance. In Table 1, the discharge and response times, as well as the power and desired life cycles, are presented for each application separately. Indeed, the important parameter for energy storage applications is the length of discharge, which can be divided into three different categories: second–minute, minute–hour, hours. It is clear that the two first categories are related to customer energy management and to the ancillary services of energy storage application. The *hours* category can be used for long-term storage and discharge, such as for bulk energy, or in renewable energy integration applications [106]. In Table 2 presents comprehensive information regarding these energy storage techniques, such as their capacity, power, response and discharge time, life time, and efficiency. Taking into account the objective of this paper, and the contents of Tables 1 and 2, Table 3has been developed on the basis of [10,34] to provide a matrix of the relationships between the available energy storage technologies and their application in ESSs. As shown in the matrix, battery technologies come in different shapes and sizes and can be used in many different applications.

There are three major parameters that are important in defining the battery types suitable for an application: the high or low rate service, the response and discharge times, and the environmental matching. As shown in Table 3, the battery's energy storage can support the system in ancillary service and customer energy

Table 3
Technologies vs. applications.



Technologies			Electrochemical				Mechanical					Electrical		Thermal
							CAES		PHS					
Applications			Lead–acid	Lithium-ion	Nas	Vanadium Redox	underground	Above ground	small	large	FES	SMES	DLC	
Bulk Energy	Energy arbitrage		🔴	🔴	🔴	🔴	🟡	🟡	🟢	🟢	🔴	🔴	🔴	🟢
	Peak shaving		🔴	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🔴	🔴	🔴	🟢
Ancillary Service	Load following		🟢	🟡	🟢	🟢	🟡	🟡	🟡	🔴	🟢	🔴	🔴	🟢
	Spinning Reserve		🟡	🔴	🟡	🔴	🟢	🟢	🟡	🔴	🟡	🔴	🔴	🟡
	Voltage Support		🟢	🟢	🟢	🟡	🔴	🟡	🔴	🔴	🟢	🔴	🔴	🔴
	Black start		🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🟡
	Frequency regulation	primary	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🔴	🟡	🔴	🔴	🔴
		secondary	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🔴	🔴	🔴
		Tertiary	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴
Customer Energy Management	Power quality		🟢	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🔴
	Power reliability		🟢	🟢	🟢	🟢	🟡	🟡	🔴	🔴	🟢	🟡	🔴	🔴
Renewable energy Integration	Time shift		🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🟢
	Capacity firming		🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🔴	🔴	🔴

🟢 Suitable application 🟡 Possible application 🔴 Unsuitable application

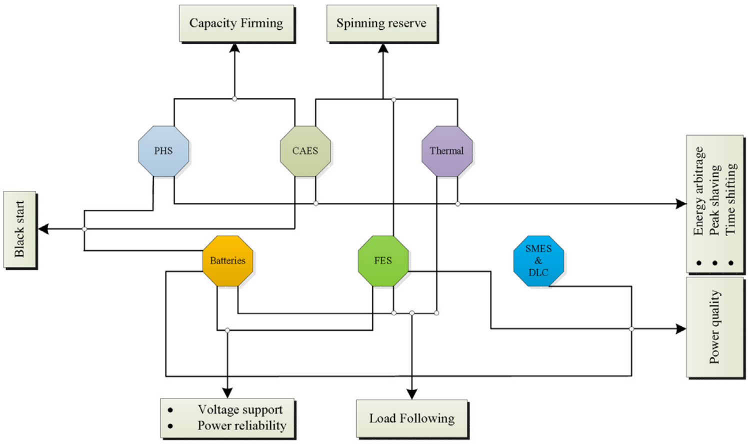


Fig. 7. Possibility of integrating ESS.

management applications. The technique is also possible for renewable energy integration, such as time shifting and capacity firming, while the technique cannot support the system in bulk energy applications. Another technique that has been described is the flywheel; this is used for low-energy applications, emergency devices, and load levelers. It cannot be used on the large scale, but it may be useful when it gives an economic advantage [73]. The other mechanical energy storage techniques (CAES, PHS) are also suitable for most of the applications expected of customer management and voltage support in ancillary service categories. Electrical energy storage techniques can be used just for emergency devices and applications that need very rapid responses.

6. The integration of energy storage technologies

The cost of the energy storing process is high. However, because of the variation in generation and the need to balance power and regulate voltage and frequency, the use of energy storage systems is unavoidable in the modern grid. One solution to the problem of the high cost of energy storage may be the integration of different technologies for implementing specific application. To cover this methodology, the characteristics of each technology should be analyzed. Table 2 shows specific information on energy storage technologies—namely, the minimum and maximum capacities and powers, the high and low response rates, and the discharge times. The requirement characteristics for implementation of each application are shown in Table 1. Finally, the agreement of these data with each other (shown in Table 3 as a matrix) can be used to create a categorization of energy storage systems that can be integrated together. Based on the results of this work in Tables 1–3, Fig. 7 is a comprehensive diagram of technologies and applications that can be integrated together. Based on the provided figure, batteries and FES can integrate together to cover the system for voltage support and power reliability applications. Moreover, power quality application can be supported by integrating electrical energy storage with batteries and FES. Mixing CAES with PHS and thermal techniques can cover capacity firming and spinning reserve, respectively and using these three methods (PHS, CAES, and Thermal) can maintain energy arbitrage, peak shaving, and time shifting. Finally, the black start application can be managed by combining PHS, CAES, and batteries.

7. Conclusion

To design an optimum energy storage system, selecting the ESS type most closely related to the application is the most significant issue, but control methodologies should not be neglected either. There are many different characteristics of energy storage systems that can help to match the different techniques with applications. This paper provides a matrix of the relations between these, along with a comprehensive diagram of ESS solutions that can be integrated together. To provide the matrix, storage technologies and application have been compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, life time, efficiency, cycle life, and maturity. Electrical energy storage techniques have only a limited number of potential applications, focusing on power system transient issues, such as improving power quality. On the other hand, electrochemical storage is the most commonly used technique and covers many applications, such as voltage support, black start, and frequency regulation. Mechanical storage techniques can also be useful for bulk energy applications and for supporting renewable integration on a large scale. Finally, based on the provided integration of ESS, the integration between thermal, CAES, and PHS is most supportive as cover energy arbitrage, peak shaving, and time shifting. Moreover, the integration of batteries and FES is another method that can cover voltage support and power reliability applications.

Since the integration of ESS with the aim of reducing the cost has been investigated in this paper only from the technical point of view, analyzing it from the economics side, as well as the issue of determining the precise energy and cost savings, remains a good research question for future work.

References

[1] Y. Xu, W. Zang, G. Hug, S. Kar, Z. Li, Cooperative control of distributed energy storage systems in a microgrid, IEEE Trans. Smart Grid 6 (2015) 238–248.
[2] Y. Xu, W. Zhang, W. Liu, X. Wang, et al., Distributed subgradient-based coordination of multiple renewable generators in a microgrid, IEEE Trans. Power Syst. 29 (2014) 23–33.
[3] S.A. Pourmousavi, M. Hashem, Real-time central demand response for primary frequency regulation in microgrids, IEEE Trans. Smart Grid 3 (2012) 1988–1996.
[4] O. Palizban, K. Kauhaniemi, Distributed cooperative control of battery energy storage system in AC microgrid applications, J. Energy Storage 3 (2015) 43–51.
[5] R.M. Nejad, A survey on performance of photovoltaic systems in Iran, Iranica J. Energy Environ. 6 (2015) 77–85.
[6] H. Jiayi, J. Chuanwen, X. Rong, A review on distributed energy resources and MicroGrid, Renew. Sustain. Energy Rev. 12 (2008) 2472–2483.

[7] O. Palizban, K. Kauhaniemi, Microgrid control principles in island mode operation, IEEE Intertational Conference PowerTech Grenoble (2013) 1–6.

[8] J.M. Guerrero, L. Hang, J. Uceda, Control of distributed uninterruptible power supply systems, IEEE Trans. Ind. Electron. 55 (2008) 2845–2859.

[9] C.W. Gellings, The Smart Grid: Enabling Energy Efficiency and Demand Response, 1st ed., The Fairmont Press, Liburn- United States, 2009.

[10] M.J. Imre Gyuk, J. Vetarno, K. Lynn, W. Park, R. Honda, Grid Energy Storage, U S. Department of Energy, 2013 December.

[11] R.M. Strzelecki, Power Electronics in Smart Electrical Energy Networks, 1st ed., Springer, Verlag London, 2008.

[12] H. Zhao, Q. Wu, Sh. Hu, H. Xu, C.N. Rasmussen, Review of energy storage system for wind power integration support, Appl. Energy 137 (2015) 545–553.

[13] J. Han, S.K. Solanki, J. Solanki, Coordinated predictive control of a wind/ battery microgrid system, IEEE J. Emerg. Sel. Top. Power Electron. 1 (2013) 296–305.

[14] B. Kroposki, T. Basso, R. DeBlasio, Microgrid standards and technologies, Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century (2008) 1–4.

[15] O. Palizban, M.A. Rezaei, S. Mekhilef, Active and reactive power control for a hybrid system with photovoltaic panel, wind turbine, fuel cells, electrolyzer and super capacitor in off-grid mode, International Conference on Control System, Computing and Engineering (2011) 404–408.

[16] S. Sabihuddin, A. Kiprakis, M. Mueller, A numerical and graphical review of energy storage technologies, Energies 8 (2014) 172–216.

[17] X. Tan, Q. Li, H. Wang, Advances and trends of energy storage technology in microgrid, Int. J. Electr. Power Energy Syst. 44 (2013) 179–191.

[18] H. Laaksonen, K. Kauhaniemi, New concept for power quality management in microgrid with energy storage based power quality compensator, Int. J. Distrib. Energy Res. (DER Journal) 4 (2008).

[19] O. Palizban, Active and reactive power control for hybrid system with renewable energy sources, Master, M.S. Degree, Electrical, University of Malaya, Kualalumpur, 2011.

[20] W. Li, G. Joos, Comparison of energy storage system technologies and configurations in a wind farm, Power Electronics Specialists Conference, Orlando, FL, 2007, pp. 1280–1285.

[21] O. Palizban, S. Mekhilef, Power optimization and static performance investigation of an island-mode doubly-fed induction generator (DFIG), IEEE International Conference on Control System, Computing and Engineering (ICCSCE) (2011) 399–403.

[22] O. Palizban, S. Mekhilef, Modeling and control of photovoltaic panels base perturbation and observation MPPT method, IEEE International Conference on Control System, Computing and Engineering (ICCSCE) (2011) 393–398.

[23] P. Thounthong, S. Rael, B. Davat, Analysis of supercapacitor as second source based on fuel cell power generation, IEEE Trans. Energy Convers. 24 (2009) 247–255.

[24] J.Y. Kim, J.H. Jeon, S.K. Kim, et al., Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation, IEEE Trans. Power Electron. 25 (2010) 3037–3048.

[25] Y. Li, D.M. Vilathgamuwa, P.C. Loh, 'Design, analysis, and real-time testing of a controller for multibus microgrid system', IEEE Trans. Power Electron. vol. 19 (2004) 1195–1204.

[26] Y. Zhang, H.J. Jia, L. Guo, Energy management strategy of islanded microgrid based on power flow control, IEEE PES Innovative Smart Grid Technol. (ISGT) (2012) 1–8.

[27] T. Dragicevic, J.M. Guerrero, J.C. Vasquez, D. Skrlec, Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability, IEEE Trans. Power Electron. 29 (2014) 695–706.

[28] X. Lu, K. Sun, J.M. Guerrero, J.C. Vasquez, et al., SoC-based droop method for distributed energy storage in DC microgrid applications, IEEE International Symposium on Industrial Electronics (ISIE) (2012) 1640–1645.

[29] H. Kakigano, Y. Miura, T. Ise, Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique, IEEE Trans. Power Electron. 28 (2013) 2246–2258.

[30] C. Li, T. Dragicevic, N.L. Diaz, J.C. Vasquez, J.M. Guerrero, Voltage scheduling droop control for State-of-Charge balance of distributed energy storage in DC microgrids, IEEE International Energy Conference (ENERGYCON) (2014) 1310–1314.

[31] C. Li, T. Dragicevic, M.G. Plaza, F. Andrade, et al., Multiagent based distributed control for state-of-charge balance of distributed energy storage, DC microgrids in 40th Annual Conference of the IEEE Industrial Electronics Society, IECON (2014) 2180–2184.

[32] O. Palizban, K. Kauhaniemi, J.M. Guerrero, Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation, Renew. Sustain. Energy Rev. vol. 36 (2014) 428–439.

[33] O. Palizban, K. Kauhaniemi, J.M. Guerrero, Microgrids in active network management? part II: system operation, power quality and protection, Renew. Sustain. Energy Rev. vol. 36 (2014) 440–451.

[34] R. Carnegie, D. Gothm, D. Nderitu, P.V. Preckel, Utility Scale Energy Storage Systems (benefits, applications, and technologies) State Utility Forecasting Group (2013).

[35] K. Bradbury, Energy Storage Technology Review, Duke University, 2010, pp. 1–34.

[36] K. Cavanagh, J.K. Ward, S. Behrens, A.I. Bhatt, et al., Electrical Energy Storage: Technology Overview and Applications, CSIRO, Australia, 2015.

[37] A. Ter-Gazarian, Energy Storage for Power System, 2 ed., Institution of Engineering and Technology, London, UK, 2012.

[38] K. Divya, J. Østergaard, Battery energy storage technology for power systems—an overview, Electr. Power Syst. Res. 79 (2009) 511–520.

[39] P.F. Ribeiro, B.K. Johnos, M.L. Crow, et al., Energy storage systems for advanced power applications, Proceedings of the IEEE 89 (2001) 1744–1756.

[40] M. Beaudin, H. Zareipour, A. Schellenberglabe, W. Rosehart, Energy storage for mitigating the variability of renewable electricity sources: an updated review, Energy Sustain. Dev. 14 (2010) 302–314.

[41] A. Evans, V. Strezov, T.J. Evans, Assessment of utility energy storage options for increased renewable energy penetration, Renew. Sustain. Energy Rev. 16 (2012) 4141–4147.

[42] M.R. Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd ed., CRC Press, Taylor and Francis Group, Florida,United States, 2012.

[43] B. Dunn, H. Kamath, J.M. Tarascon, Electrical energy storage for the grid: a battery of choices, Science 334 (2011) 928–935.

[44] A.P. Alto, Valve Regulated Lead Acid (VRLA) Battery Qualification Assessment Electrical Power Research Institute (2009).

[45] D.A.J. Rand, P.T. Moseley, J.Garcher, C.D. Parker, Valve-regulated lead-acid batteries: Access Online via Elsevier (2004).

[46] L. Dusonchet, M.G. Ippolito, E. Telaretti, G. Graditi, Economic impact of medium-scale battery storage systems in presence of flexible electricity tariffs for end-user applications, 9th International Conference on the European Energy Market (EEM) (2012) 1–5.

[47] A. Oberhofer, P. Meisen, 'Energy Storage Technologies & Their Role in Renewable Integration', Global Energy Network Institute, San Diego, US, 2012.

[48] J. Baker, New technology and possible advances in energy storage, Energy Policy vol. 36 (2008) 4368–4373.

[49] C.J. Rydh, M. Karlström, Life cycle inventory of recycling portable nickel–cadmium batteries, Res. Conserv. Recycl. 34 (2002) 289–309.

[50] J. Dunbar, 'High Performance Nickel Metal Hydride Batteries', Idea/ Microelectron, Anaheim, CA, 1994, pp. 236–241.

[51] T.P. Crompton, Battery Reference Book, 3rd ed., Newnes, Burlington, U. S. A, 2000.

[52] M. Verbrugge, E. Tate, Adaptive state of charge algorithm for nickel metal hydride batteries including hysteresis phenomena, J. Power Sources 126 (2004) 236–249.

[53] N.K.C. Nair, N. Garimella, Battery energy storage systems: Assessment for small-scale renewable energy integration, Energy Build. 42 (2010) 2124–2130.

[54] H. Ibrahim, A. Llinca, J. perron, Energy storage systems—characteristics and comparisons, Renew. Sustain. Energy Rev. 12 (2008) 1221–1250.

[55] S. i. Tobishima, K. Takei, Y. Sakurai, J.I. Yamaki, Lithium ion cell safety, J. Power Sources vol. 90 (2000) 188–195.

[56] A.D. Robertson, A.R. West, A.G. Ritchie, Review of crystalline lithium-ion conductors suitable for high temperature battery applications, Solid State Ionics vol. 104 (1997) 1–11.

[57] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications, Renew. Sustain. Energy Rev. 13 (2009) 1513–1522.

[58] F.D. González, A. Sumper, O. Gomis-Bellmunt, R. Villafáfila-Robles, A review of energy storage technologies for wind power applications, Renew. Sustain. Energy Rev. 16 (2012) 2154–2171.

[59] C.J. Rydh, B.A. Sandén, Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements, Energy Convers. Manage. 46 (2005) 1957–1979.

[60] P.J. Hall, E.J. Bain, Energy-storage technologies and electricity generation, Energy Policy 36 (2008) 4352–4355.

[61] L. Joerissen, J. Garche, C.H. Fabjan, G. Tomazic, Possible use of vanadium redox-flow batteries for energy storage in small grids and stand-alone photovoltaic systems, J. Power Sources 127 (2004) 98–104.

[62] K.L. Huang, X. Li, S. Liu, N. Tan, L. Chen, Research progress of vanadium redox flow battery for energy storage in China, Renew. Energy 33 (2008) 186–192.

[63] C. Blanc, A. Rufer, Multiphysics and energetic modeling of a vanadium redox flow battery, International Conference on Sustainable Energy Technologies (2008) 696–701.

[64] P. Poizot, F. Dolhem, Clean energy new deal for a sustainable world: from non-CO_2 generating energy sources to greener electrochemical storage devices, Energy Environ. Sci. 4 (2011) 2003–2019.

[65] R. Baxter, Energy Storage: A Nontechnical Guide, PennWell Books, 2006.

[66] K. Veszpremi, I. Schmidt, Flywheel energy storage drive for wind turbines, 7th International Conference on power Electronics and Drive Systems (2007) 916–923.

[67] J. Klimstra, M. Hotakainen, Smart Power Generation, Avain, Wartsila, Vaasa, 2011.

[68] T. Hyytinen, Hybrid power generation concept for small gridsmaster, M.S., Degree, Electrical and Energy Engineering, University of Vaasa, 2013.

[69] R. Östergård, Flywheel energy storage: a conceptual study Master, Master degree in Electrical, Uppsala University, 2011.

[70] P. Alto, Results from Case Studies of Pumped-Storage Plants, Electrical Power Research Institute, CA, USA, 2012.

[71] H. Chen, T.N. Cong, W. Yang, Ch. Tan, et al., Progress in electrical energy storage system: a critical review, Prog. Nat. Sci. 19 (2009) 291–312.

[72] Electrical Energy Storage, IEC, December 2011.

[73] Z. Salameh, Renewable Energy System Design, 1st ed., Academic Press, Science Direct, Elsevier, 2014.
[74] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. vol. 13 (2009) 318–345.
[75] M.M. Farid, A.M. Khudhair, S.A.K. Razack, S. Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Convers. Manage. 45 (2004) 1597–1615.
[76] B. Zalba, J.M. Marı'n, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Appl. Therm. Eng. vol. 23 (2003) 251–283.
[77] L. Fan, J.M. Khodadadi, hermal conductivity enhancement of phase change materials for thermal energy storage: a review, Renew. Sustain. Energy Rev. vol. 15 (2011) 24–46.
[78] S. Hasnain, Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques, Energy Convers. Manage. 39 (1998) 1127–1138.
[79] A.A. Akhil, G. Huff, A.B. Currier, B.C. Kaun, et al., DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA Sandia National Laboratories, Albuquerque (2013).
[80] J. Eyer, G. Corey, Energy storage for the electricity grid: Benefits and market potential assessment guide Sandia National Laboratories Report, Albuquerque, New Mexico (2010).
[81] M. Bragard, N. Soltau, S. Thomas, R.W. De Doncker, The balance of renewable sources and user demands in grids: Power electronics for modular battery energy storage systems, IEEE Trans. Power Electron. (2010) 3049–3056.
[82] J. Makansi, J. Abboud, Energy Storage Energy Storage Council White Paper (2002).
[83] ABB, "Energy storage system slloution, www.abb-energystoragesolutions.com," ed. (2014).
[84] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, D. Morton, 'Challenges in integrating distributed energy storage systems into future smart grid', International Symposium on Industrial Electronics (2008) 1627–1632.
[85] E. Hirst, B. Kirby, Separating and measuring the regulation and load-following ancillary services, Util. Policy 8 (1999) 75–81.
[86] P.D. Brown, J.A.P. Lopes, M.A. Matos, Optimization of pumped storage capacity in an isolated power system with large renewable penetration, IEEE Trans. Power Syst. vol. 23 (2008) 523–531.
[87] F. Katiraei, M.R. Iravani, P.W. Lehn, Micro-grid autonomous operation during and subsequent to islanding process, IEEE Trans. Power Delivery 20 (2005) 248–257.
[88] E.V. der Vleuten, V. Lagendijk, Transnational infrastructure vulnerability: the historical shaping of the 2006 European 'Blackout', Energy Policy vol. 38 (2010) 2042–2052.
[89] J.W. Feltes, C.G. Moran, Black start studies for system restoration, Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century (2008) 1–8.
[90] H. Laaksonen, K. Kauhaniemi, Control Principles for Blackstart and Island Operation of Microgrid, Nordic Workshop on Power and Industrial Electronics (NORPIE), Espoo, Finland, 2008.
[91] W. Sun, Ch. Ching Liu, Sh. Liu, Black start capability assessment in power system restoration', Power and Energy Society General Meeting (2011) 1–7.
[92] J.M. Guerrero, J.C. Vasquez, J. Matas, L.G. de Vicuña, Hierarchical control of droop-controlled AC and DC microgridsña general approach toward standardization, IEEE Trans. Ind. Electron. vol. 58 (2011) 158–172.
[93] J.M. Guerrero, M. Chandorkar, T. lee, P.H. Loh, Advanced control architectures for intelligent microgrids, Part I: decentralized and hierarchical control, IEEE Trans. Ind. Electron. 60 (2013).
[94] J.M. Guerrero, P.C. Loh, T. Lee, M. Chandorkar, Advanced control architectures for intelligent microgrids—Part II: power quality, energy storage, and AC/DC microgrids, IEEE Trans. Ind. Electron. vol. 60 (2013) 1263–1270.
[95] Ancillary services to be delivered in Denmark Tender conditions, Energinet, DK, Fredericia (2012).
[96] A. Vuorinen, Planning of Optimal Power Systems, 1st ed., Ekoenergo Oy, Espoo, Finland, 2008.
[97] F.D. Galiana, F. Bouffard, J.M. Arroyo, J.F. Restrepo, Scheduling and pricing of coupled energy and primary, secondary, and tertiary reserves, Proceedings of the IEEE vol. 93 (2005) 1970–1983.
[98] Y.G. Rebours, D.S. Kirschen, M. Trotignon, S. Rossignol, A survey of frequency and voltage control ancillary services—Part I: technical features, IEEE Trans. Power Syst. vol. 22 (2007) 350–357.
[99] G. Boyle, Renewable Energy, 3rd ed., OXFORD university, UK, 2004.
[100] H. Bevrani, A. Ghosh, G. Ledwich, Renewable energy sources and frequency regulation: survey and new perspectives, IET Renew. Power Gener. 4 (2010) 438–457.
[101] Y.M. Atwa, E.F. El-Saadany, M.M.A. Salama, R. Seethapathy, Optimal renewable resources mix for distribution system energy loss minimization, IEEE Trans. Power Syst. vol. 25 (2010) 360–370.
[102] J. Mundackal, A. Varghese, P. Sreekala, V. Reshmi, rid power quality improvement and battery energy storage in wind energy systems, Annual International Conference on Microelectronics, Communications and Renewable Energy (2013) 1–6.
[103] R.E. Brown, Electric Power Distribution Reliability, 2 ed., CRC Press, Taylor and Francis Group, 2008.
[104] A. Moreno-Munoz, Power Quality, Mitigation Technologies in a Distributed Environment, Springer, London, 2007.
[105] J.M. Carrasco, L.G. Franquelo, J.T. Bialasiewicz, E. Galvan, et al., Power-electronic systems for the grid integration of renewable energy sources: a survey, IEEE Trans. Ind. Electron. vol. 53 (2006) 1002–1016.
[106] P. Denholm, E. Ela, B. Kirby, M. Milligan, The role of energy storage with renewable electricity generation, A national laboratory of the U.S department of energy office of energy effiecient and renewable energy (2010).
[107] C.A. Hill, M.C. Such, D. Chen, J. Gonzalez, W. Mack Grady, Battery energy storage for enabling integration of distributed solar power generation, IEEE Trans. on Smart Grid vol. 3 (2012) 850–857.
[108] J.P. Barton, D.G. Infield, Energy storage and its use with intermittent renewable energy, IEEE Trans. Energy Convers. vol. 19 (2004) 441–448.

Publication III

Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation

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Renewable and Sustainable Energy Reviews 36 (2014) 428–439

Renewable and Sustainable Energy Reviews 36 (2014) 428–439

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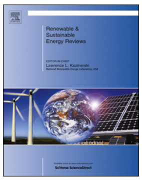

Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation

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ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form
5 December 2013
Accepted 4 January 2014
Available online 22 January 2014

Keywords:
Energy storage
Hierarchical control
IEC/ISO 62264 standards
Microgrid
Market structure
Virtual power plant

ABSTRACT

The microgrid concept has been closely investigated and implemented by numerous experts worldwide. The first part of this paper describes the principles of microgrid design, considering the operational concepts and requirements arising from participation in active network management. Over the last several years, efforts to standardize microgrids have been made, and it is in terms of these advances that the current paper proposes the application of IEC/ISO 62264 standards to microgrids and Virtual Power Plants, along with a comprehensive review of microgrids, including advanced control techniques, energy storage systems, and market participation in both island and grid-connection operation. Finally, control techniques and the principles of energy-storage systems are summarized in a comprehensive flowchart.

Contents

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1364-0321/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2014.01.016

Nomenclature

CSI	current source inverter
DER	distributed energy resource
DG	distribution generation
DMS	distribution management system
ESS	energy storage system
FES	flywheel energy storage
LC	local control
LV	low voltage
MGs	microgrids
MGCC	microgrid central controller
MMS	microgrid management system
MPPT	maximum power point tracking
MSs	micro sources
PCC	point of common coupling
PI	proportional integral
P/Q	active and reactive power
PV	photovoltaic
RESs	renewable energy sources
SMES	superconducting magnetic energy storage
SOC	state of charge
UPS	uninterruptible power supply
VSC	voltage source converter
WT	wind turbine

1. Introduction

Microgrids and virtual power plants (VPPs) are two LV distribution network concepts that can participate in active network management of a smart grid [1]. With the current growing demand for electrical energy [2], there is an increasing use of small-scale power sources to support specific groups of electrical loads [3]. The microgrids (MGs) are formed of various renewable sources of electrical energy, such as wind turbines [4–6] or photovoltaic cells [7–9] with storage (e.g., batteries or super capacitors) [10], which operate in either island mode or grid-connection mode [11,12]. Such implemented projects of MGs have demonstrated their efficiency in very different applications. Lidula et al. [13] presented some existing microgrid networks from North America, Europe, and Asia. Indeed, MGs have attracted great interest due to their tremendous application potential in remote areas, where power provision presents a challenge in terms of transmission or distribution [14].

There are three different classes of benefits associated with MGs: Technical, Economical and Environmental. In [15,16] some of the benefits are presented from a technical point view, such as supporting the power of remote communities, higher energy efficiency, the lack of vulnerability of large networks, and power blackouts reduction. The economic benefits have been reviewed comprehensively by Basu et al. [17], and consist of reductions in emissions, line losses, and interruption costs for the customer, minimization of fuel cost, ancillary services, etc. The environmental benefits of MGs are discussed in [18], out of which the following provides some samples: MGs may result in lower emissions of pollutants and greenhouse gases; the generation system, also requires a smaller physical footprint; MG usage can increase the number of clean energy sources incorporated into the grid; and it offers decreased reliance on external fuel sources.

The other main concept in the active distribution network is the VPP, which manages the energy of the system and is tasked with aggregating the capacity of distributed generation (DG), the Energy Storage System (ESS), and dispatchable loads (DLs) [19]. Indeed, the first idea for creating VPPs appeared in 1997 [20], and their modular structure is considered to be a great advantage [21].

Since future distribution networks will require completely novel smart-grid concepts [22], it is necessary to conceive of flexible MGs that are capable of intelligently operating in both grid-connected and island modes. As discussed by Zeng et al. [23], experts and researchers are currently working on simulation and modeling [24–26], the optimization of power quality [27], power management and stability [28], control of generation units and systems, and so on.

Over the last several years, researchers have been also working on attaining approval for standards for the most suitable overall MG design. In [29] a summary of the European and American standards applicable to MGs is presented. The IEEE 1547 and UL 1541 (in the US) standards are the most important guides for operation, design, and connection of distribution resources with electric power systems [13]. Indeed, there are no exact standards which have been developed for adapting MGs, but some Distributed Energy Resource (DER) standards can be adapted to them [29]. IEEE P1547.4 can be adapted for the connection of DERs and specifically it covers some topics missing from IEEE Std 1547, such as frequency, power quality, and the impact of voltage [30,31]. The other standards which can be adapted to MGs to cover low-voltage distortion and power quality interference are EN50160 and the IEC61000 [32–34].

In recent years, several control devices have also been developed for improving the integration of MGs in island and grid-connection modes. Therefore, the variation of power generation and interconnection, as well as the electrical interface between different sources, energy storage, and the main grid may be the barriers for achieving a common standard for connecting DERs to the grid [29].

In order to deal with the above issues, this paper proposes the IEC/ISO 62264 international standard to be applied to MGs and VPP, which are considered here from hierarchical control, energy storage, and marketing perspectives. The objective of IEC/ISO 62264 is to offer consistent terminology for supplier and manufacturer communications, and to thus serve as a foundation for clarifying applications and information. The standard can be explained at five levels: *level zero* (the generation process), *level one* (the process of sensing and adjusting generation), *level two* (monitoring and supervising), *level three* (maintaining and optimizing), and *level four* (market structure and business model) [35,36]. Fig. 1 illustrates the adaptation of the standards to MGs. The present paper includes a comprehensive literature survey to provide information on the detailed status of advances in MG principles from the viewpoints of both island and grid connected mode of operation, on the basis of the proposed standard. The MG control hierarchy is discussed in Section 2. Energy storage issues and the microgrid market structure are discussed in Sections 3 and 4, respectively. The virtual power plant hierarchical controls are discussed in Section 5. The literature survey concludes in Section 6.

2. Microgrid control principle

As a result of the recent widespread application of power-electronics devices [37], the operation of an MG requires both energy management and the classification of a control strategy. Power flow control, resynchronization between the MG and the

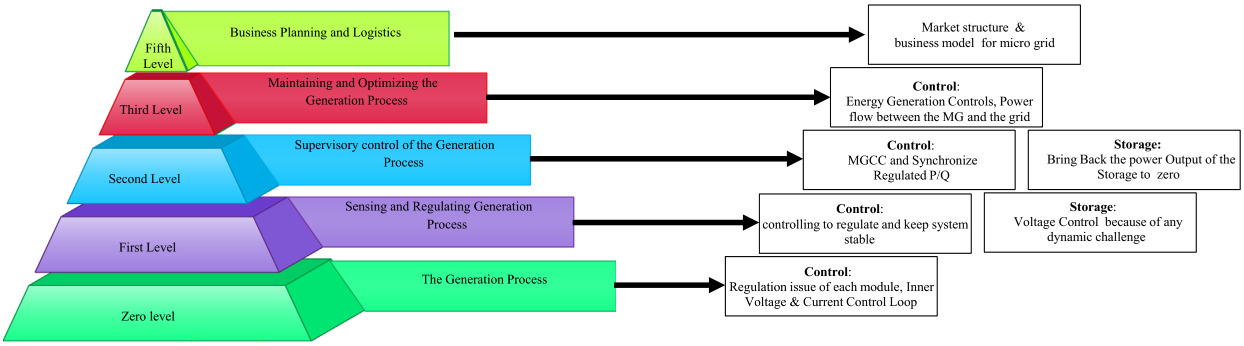

Fig. 1. IEC/ISA 62264 std. levels and applied in microgrid context.

main grid, adjustments of voltage and frequency in both modes, and improvements to MG efficiency together comprise the key principles of MG control structure [38,39]. The Union for the Coordination of Transmission of Electricity (UCTE) in continental Europe has defined a hierarchical control for large power systems, presented in [36]. The most suitable control design should certainly cover all the responsibilities of MG controllers, which [40] defined thus: the system should function at predefined operating points, or within satisfactory operating limits; active and reactive power must be transferred by optimal means; system stability should be maintained; processes of disconnection and reconnection should run seamlessly; local Micro sources (MS) production should be optimized for best market participation and power exchanges with the utility; loads must be classified according to sensitivity, from highest to lowest (e.g. medical equipment is the highest priority consumer); if a general failure occurs, the MG should be able to operate through a black start; and finally, ESS should support the MG and increase the system′s reliability and efficiency. Justo et al. [41] investigate some different energy management and control strategies of the MG system which are published relying on the most current research works.

With respect to the above-mentioned requirement, and based on the IEC/ISO 62264 standard, microgrid hierarchical controls are defined on four levels (*zero to three*), which also are shown in Fig. 1. Level zero is the inner control loop for controlling the output voltage and current from the sources. The reference value for the inner control loop is generated by primary control (*level one*). Then, secondary control in the next step monitors and supervises the system with different methods. Finally, the last level is tertiary control which manages the power follow and interface between the MG and main network. In the rest of this paper, the four levels above the control level are discussed.

2.1. *Internal control loop*

The target of this control level (*level zero of the IE/ISO 62264 std.*) is to manage the power of MSs. Generally, the first step of the MG control is the source operating point control, using power electronic devices in current or voltage control modes [38]. The purpose of the power electronic interface in voltage control mode is to manage frequency and voltage inside the microgrid while the system is connected to energy storage devices (island mode) [42]. On the other hand, in current control mode, where the system is often joined to the main grid (grid connection mode) [43], management of the active and reactive power is the main target [36,44]. Indeed, the inner control loop for wind and solar power which are most common Renewable Energy Sources (RESs), is in practice created by the power converter. For instance, a Doubly-Fed Induction-Generator (DFIG) wind turbine consists of two AC/DC (rotor side) and DC/AC (grid side) converters with a DC-link that can either inject or absorb power from the grid, actively controlling voltage [45]. The responsibility of the rotor side is to optimize power generation from the source, while providing control of active and reactive power and maintaining the DC link voltage is the duty of the grid-side converter [46–49]. Moreover, based on the hardware structure of the PV system, after the PV module and MPPT, the system includes dc–dc converters and inverters, whose responsibility is to create the optimum conditions to support the normal customer load in island mode, or to send power into the network in grid-connection mode [49].

The optimization and inner controls need to have accurate reference values for the frequency and voltage amplitude, and this is the duty of the primary control.

2.2. *Primary control*

As aforementioned, the target of this control level (*level one of IEC/ISO 62264 std.*) is to adjust the frequency and amplitude of the voltage references that are fed to the inner current and voltage control loops. The primary control should have the fastest response to any variation in the sources or the demand (on the order of milliseconds) [50], which can help to increase the power system stability. Furthermore, the primary control can be used to balance energy between the DG units and the energy storage elements, such as batteries. In this situation, depending on the batteries′ state of charge (SoC), the contribution of active power can be adjusted in line with the availability of energy from each DG unit [51]. In other words, to achieve optimal performance of the primary control, especially in island mode, it is necessary to control the SoC [52]—an idea that will be developed further in Section 4. A complete and extensive review and technical investigation into the control strategy and hierarchy is provided by Guerrero et al. [53] and Bidram and Davoudi [38].

The DG power converter control techniques in ac MGs are classified into two different methods: grid-following and grid-forming [54,55]. Grid-forming converters are voltage-control based and an equivalent circuit for them includes a voltage source and series low impedance. Creating a reference value for voltage and frequency by using a proper control loop is the duty of this type of power converter [54]. On the other hand, grid-following power converters are designed as control-based and can be represented by a current source with high parallel impedance. In addition, power delivery to the main network in grid-connection mode is the responsibility of the grid-following power converter [56]. It should be noted here that one of the power converters in island mode must be of the grid-forming model in order to determine the voltage reference value. In other words, a grid-following converter cannot control the MG in island mode.

The differences between these connections are shown in Fig. 2. A comprehensive review of primary control in grid-forming strategies is presented by Vandoorn et al. [57]; grid-following techniques are discussed by Rocabert et al. [58] and Blaabjerg et al. [49].

2.2.1. *Droop control and active load sharing*

The main idea of the primary control level is to mimic the behavior of a synchronous generator by reducing the frequency when the active power increases [59]. This principle can be applied to Voltage Source Converters (VSCs) by employing the well-known *P*/*Q* droop method [60]. The principle of the droop control method for MGs is the same as that for an equivalent circuit of a VSC connected to an AC bus (Fig. 2) [38]. On the other hand, the principle of active load sharing involves using a parallel converter configuration based on a communication link [61,62]. The accretion of voltage regulation and power sharing in the control methods based on a communication link is better than with droop control methods. However, over long distances, communication lines are vulnerable and expensive [57]. There are some different methods based on communication links which researchers have proposed, such as concentrated control [63,64], master/slave [65,66], instantaneous current sharing [67,68], and circular chain control methods [69].

Since a communication link is not necessary for droop control, it is more reliable than active load sharing, However, the method does have certain drawbacks [53,70,71]: it is one-dimensional and can only support one control objective; In an LV distribution line, there is resistive effective impedance between the power electronic devices and the AC bus, so the phase difference is zero, meaning that it is not possible to apply the frequency and voltage droop characteristics to determine the desired voltage references; since voltage in MGs is not found to the same exact degree as frequency, reactive power control may negatively affect the voltage adjustment for critical loads; the conventional droop method cannot differentiate between load current harmonics and circulating current in nonlinear loads; and the droop method has its load-dependent frequency and amplitude deviations. A number of researchers have attempted to propose different solutions to these issues, such as load sharing and voltage and frequency regulation tradeoffs [57], line impedance [72], virtual frame transformation [73–75], coupling inductance [76–78], etc. The ideas are extensively discussed in [38], and [29] along with their advantages and disadvantages.

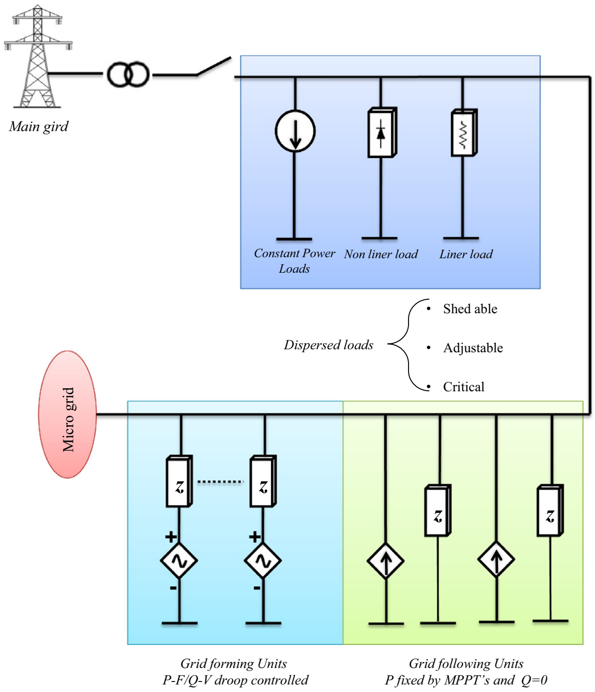

Fig. 2. Equivalent circuit diagram of converters connected to MG.

The droop is based on voltage-reactive power and frequency-active power controls (*P–f, Q–V*) in high voltage (HV) and medium voltage (MV) systems, a description of which is given in Fig. 3 [79,80]. The figure illustrates that the operational voltage is regulated by a local voltage set-point value, taking into account the inductive and capacitive reactive current generated by the suppliers. In inductive situations, voltage operation increases, and in order to adjust this, the voltage set-point must decrease. In capacitive mode, however, the set-point value increases. The limitations of the reactive current variability are based on the maximum reactive power [40,81,82].

In low voltage (LV) systems, however, the circuit is more resistive and so the droop control should be based on active power–voltage and reactive power–frequency (*P–V, Q–f*) [73,83] If MG sources are to conform to IEEE Standard 1547–2003 [84], then a mechanism should be in place to restore the system frequency and voltage to nominal values following a load change [85,86]. As in the case of the electrical power system controls, this restoration mechanism is referred to as *secondary control* of voltage and frequency.

2.3. *Secondary control*

The hierarchical control system – in particular, the secondary control section (*second level of IEC/ISO 62264 std.*) – works to compensate for voltage and frequency errors and to regulate the value in the operational limitations of the microgrid. In other words, the secondary control ensures that the frequency and voltage deviations are regulated toward zero following each load or generation change in the MG. The secondary control serves power systems by correcting the grid-frequency deviations within allowable limits, for example by ±0.1 Hz in Nordel (North of Europe) or ±0.2 Hz in UCTE (Continental Europe) [36]. The response speed of the secondary control is slower than the first control level because of some limitations, such as availability of primary sources and battery capacity [58]. This control level can be divided into centralized [87] and decentralized controls [53]. By far the largest body of research and work on decentralized MG control has been performed by [88]. Additionally, novel general approaches to centralized control base on droop control and decentralized control based on communication links is presented by Guerrero et al. [36] and shafiee et al. [89], respectively.

2.3.1. *Centralized control*

The microgrid controllers in centralized control are based on principles similar those of the inner loop controllers explained in the previous part. A Microgrid Central Controller (MGCC) is available for each microgrid to interface with the Distribution Management System (DMS). Indeed, the definition of centralization or decentralization is based on the position of the MGCC. This type of control is very suitable for certain small manually controlled MGs, as well as for MGs with common goals and those pursuing cooperation [40].

2.3.2. *Decentralized control*

The main duty of decentralized control is to specify the maximum power generated by MSs, while at the same time taking into account the microgrid's capability to support the consumer

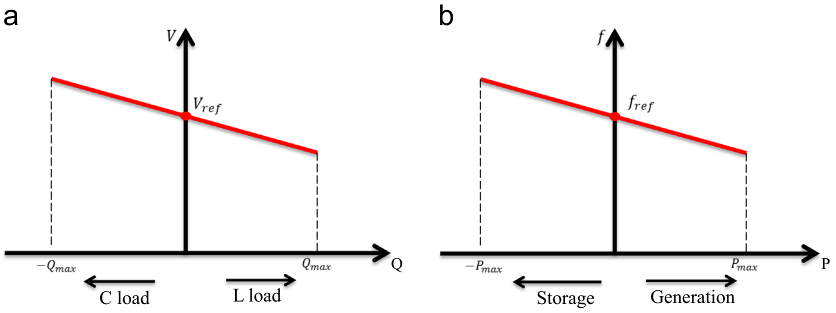

Fig. 3. Voltage and frequency versus active and reactive power.

and increasing power exports to the grid for market participation. This type of control is ideally utilized in the MGs of different suppliers, where there is a need to make decisions separately regarding individual situations, and for MGs with active roles in an electrical market environment—such MGs should possess an intelligent control for each unit, in addition to MSs with responsibilities other than power generation [40].

In order to connect a MG to the grid, the frequency and voltage of the grid must be measured. These values will serve as references for the secondary control loop. In the case of MG controls, this restoration of references is the duty of the tertiary control. Indeed, the phase angle between the grid and MG will be synchronized by means of a synchronization control loop, which is disabled in the absence of the grid.

2.4. *Tertiary control*

The purpose of this control level (*level three of IEC/ISO 62264 std.*) is to manage the power flow by regulating the voltage and frequency when the MG is in grid-connected mode. By measuring the P/Q through the PCC, the grid′s active and reactive power may be compared against the desired reference. Hence, grid active power can be controlled by adjusting the MG′s reference frequency. This control level is the last and slowest level of control, and ensures optimal operation of the microgrid, not only technically, but also economically [38]. Technically, if a fault or any nonplane islanding issue arises for the MG, then the tertiary control will attempt to absorb P from the grid in such a way that, if the grid is not present, the frequency will begin to decrease. When the expected value is surpassed, the MG will be disconnected from the grid for safety, and the tertiary control disabled [53]. Islanding detection is also a very important issue in disconnecting the MG from the main grid in tertiary control, and this is discussed in the second part of this paper.

2.5. *Discussion of the hierarchical control of microgrids*

Advanced microgrid control techniques under the IEC/ISO 62264 standard are summarized by the flowchart in Fig. 4. As discussed in this section, and based on the proposed standard, to achieve the optimum level of adjustment of the operational reference value, the control of the MG can be divided into four different levels. The foundational control level is the inner control loop: active and reactive power management inside the sources and control of voltage in the DC-link are its responsibility. Additionally, the inner control loop is implemented by fast voltage and current control loops. An accurate reference value for voltage and frequency for control of the power converters can be obtained through primary control by different methods. In the next step, there are two different approaches to secondary control: grid connection and island mode. During grid-connection mode, the microgrid operates based on active and reactive power controls, whereas in island operation, the secondary control acts as voltage and frequency based. As shown in Fig. 4, the reference value for sending the deviation of voltage and frequency to the primary control are determined basing on the variation of active and reactive power received from the main network. Power management and the reinstatement of the secondary control is the objective of the tertiary control level. Moreover, optimizing the set-point operation of the system from both technical and economic points view is the other objective of the last level of control in the MG.

3. Principle of the energy storage system

Managing power balance and stability is a challenging task, as these depend on a number of variables. Energy storage plays a crucial role in mitigating the problem [8]. In fact, by combining energy storage with renewable power generators, output power may be stabilized by storing surplus energy during periods of high obtainability, and dispatching it in case of power shortage [90]. As mentioned earlier in this paper, the principles of MG are almost the same in both island and grid-connection modes. There are, however, some fundamental contradictions between the two modes in terms of storage systems. Frequency regulation, the integration with renewable energy production, and the large capacity for power density and energy are the main applications of a storage system in grid-connection mode. However, enhancing power quality, stability, and quick response times to transient faults are the main responsibilities of a storage system when the microgrid is working in island mode [91]. Another classification of energy storage in the microgrid is based on the arrangement of the storage system, which may be aggregated or distributed. The aggregated model has the same principles as the master unit, and the microgrid is supported with a central energy-storage system that, depending on the microgrid arrangement can be connected to the DC bus or may combine with a power electronic interface and connect to the AC bus [92]. This model is very popular for MGs with small scale and low-level generation and demand. On the other hand, in the distributed arrangement, the energy storage system is connected to the renewable energy sources via different and individual power electronic interfaces. In this model, each storage system has responsibility for the control and optimization of the power output of the sources to which it is connected. The intercommunity of the transmission line in the power trade-off between energy storage and MG is a disadvantage of the system [93,94].

One objective of this paper is to adapt the energy storage systems in MG to IEC/ISO 62264 standards, which is discussed as below along with a briefly investigating on the different applications and techniques of storage systems in MG.

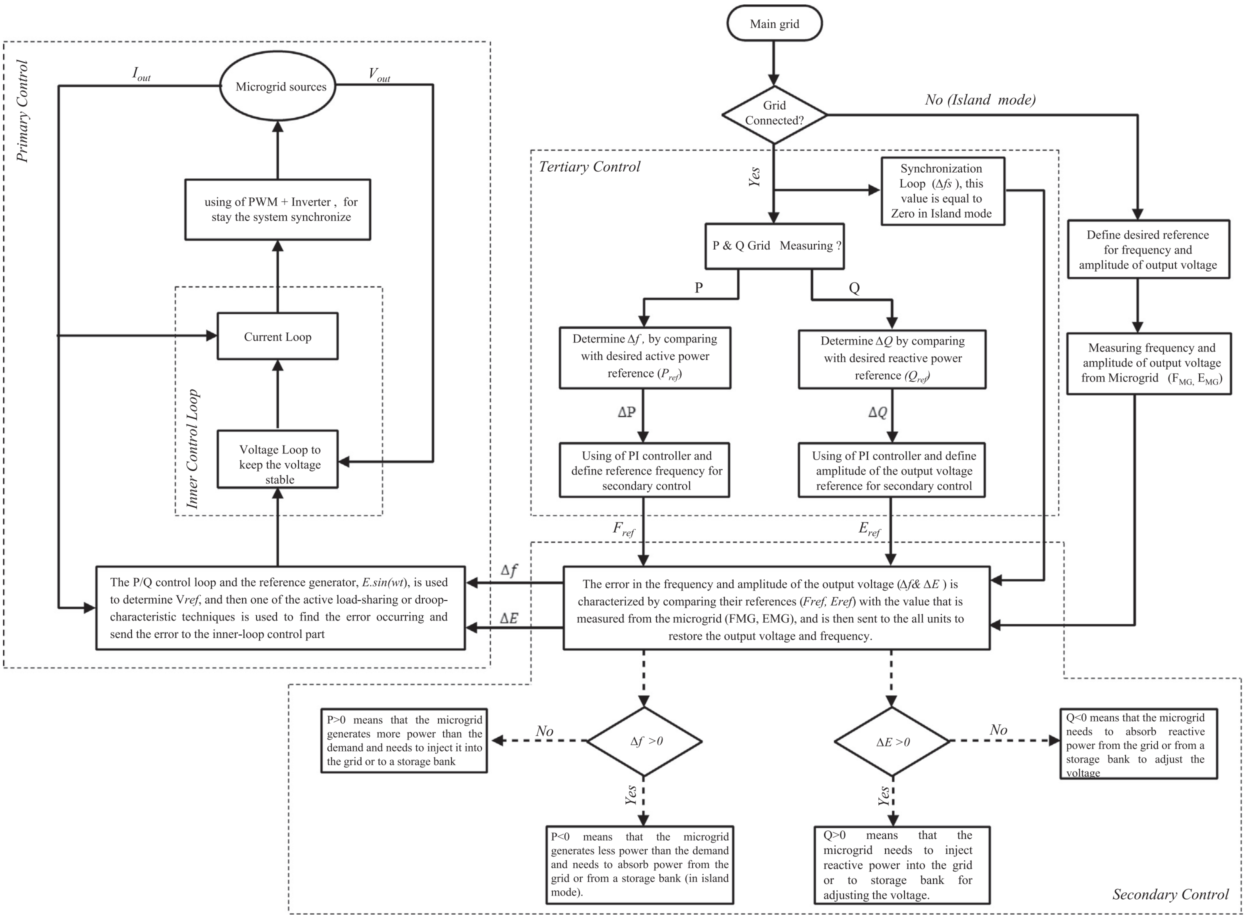

Fig. 4. Hierarchical control of microgrid based on IEC/ISO 62264.

3.1. Application of energy storage in microgrid

An ESS functions like a power-quality regulator in order to yield a specified active or reactive power to customers. The principle of voltage control, which classifies loads by priority and employs load shedding, is not suitable for achieving high power quality impact in a MG. Hence, another benefit of ESSs may be that they result in improved power quality in the MG [95,96]. Moreover, there are different applications that can be provided with energy storage systems, such as black start [97,98], power oscillation damping [99,100], grid inertial response [101], wind power gradient reduction [102], peak shaving [103,104], and load following [105]. Rabiee et al. [106] present a comprehensive review of these applications with wind turbines. Researchers have also recently been endeavoring to come up with various techniques for improving power management and system stabilization of MGs by using ESS. Microgrid storage systems and the power electronic interfaces for linking sources are discussed in [107]. In [108], MG cooperative control methods for island operation are discussed with respect to control over frequency and voltage, as is a control system for decreasing power variation from RESs (such as wind turbines). ESS can also help to stabilize frequency in very large power systems. The influence of electromechanical oscillations on the rapid response of energy storage in a power system is indicated by Mercier et al. [109] and Kim et al. [110].

3.2. Standardization of energy storage system

According to the IEC/ISO 62264 standard, MG hierarchical control configuration falls into the three categories described previously. As the third level is labeled as a connection element in the main grid, and the storage system is based on island mode, storage control does not contain tertiary controls, but rather consists of a secondary and primary level. The secondary level is the centralized control, referred to as the master unit or Microgrid Management System (MMS) [111], and like the control hierarchy, the primary level consists of a local control. Primary control monitors the frequency and determines the surplus or shortage of power. Supervisory control of MS and ESS is the responsibility of the secondary control level [112]. Fig. 5 shows the hierarchical control of energy storage [108]. Owing to its quick response to fluctuations, energy storage is a significant element in MGs, particularly in island mode. Sustaining the MG's frequency and voltage through a storage system takes milliseconds, while the response times of diesel generators, fuel cells, or gas engines is very slow in comparison.

Just like the main responsibility mentioned in the preceding section, power balancing for the regulation of frequency and voltage in a storage element of an island-mode MG is also related to the control level. Nevertheless, due to restrictions in establishing equilibrium between generated and consumed power as a

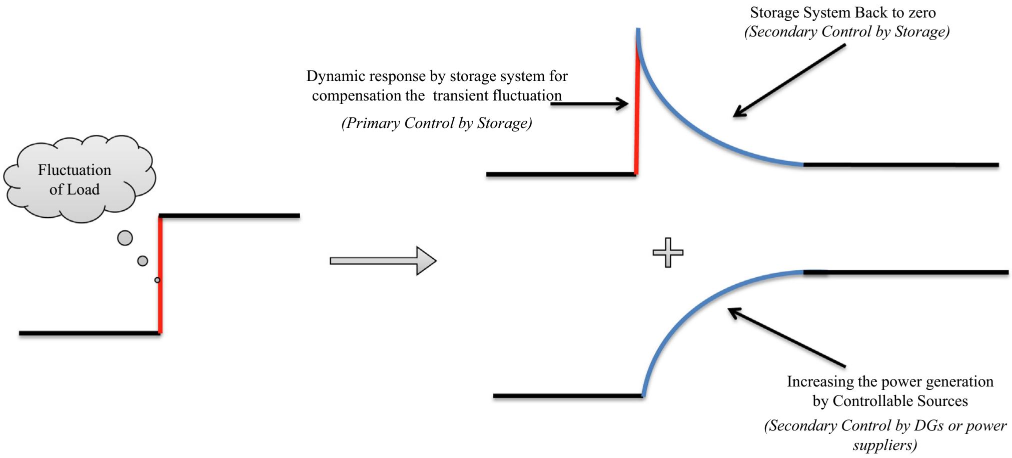

Fig. 5. Hierarchical control responsibility in ESS [108].

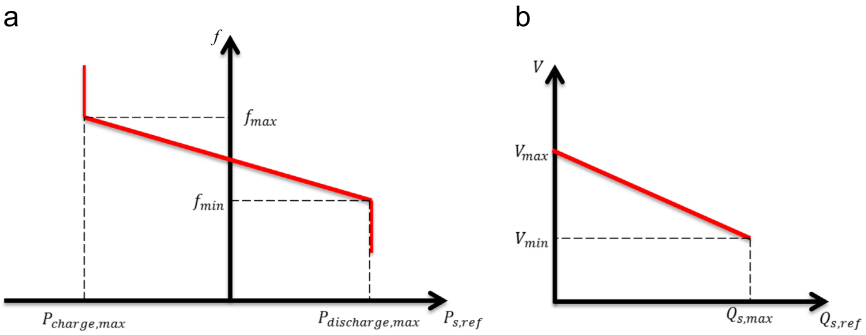

Fig. 6. Frequency and voltage versus active and reactive power.

result of the system capacity on hand, the storage system's output power must be returned to zero as quickly as possible, and this is the duty of the secondary control [108].

3.2.1. *Primary control in energy storage systems*

Controlling the active power in the MG is the responsibility of the storage system, which must monitor it continually. Based on the first level of the IEC/ISO 62264 standard, the network power capability can sense the active power by detecting frequency variations. When the system frequency increases (f is near f_{max}), this means that the power being generated is greater than the demand, and there is a need for surplus energy to be absorbed by the storage system, which is allowed by its current state of charge (SoC) to control the active power. With an increase in demand, the capacity of the system begins to reduce, which may be reasonable if the system frequency is much higher than the minimum frequency (f_{min}). However, when the frequency approaches the minimum frequency (f_{min}) for any reason (such as increasing demand), the storage system must begin to inject power into the system to obtain the most stable condition and improvements in power quality [113]. The characteristic variation is formulated in [114].

In Fig. 6, a storage system control using (a) frequency versus active power and (b) voltage versus reactive power droop characteristics is shown. The performance of reactive power sharing depends on the impedance of the connection line between the storage system and the network.

Hence, controlling the network with reactive power is not the optimal method; it would be better to set the reactive power value to zero in the storage charging process. In this situation, storage charging begins if there is excessive generation capacity, or if there is low demand [113].

3.2.2. *Secondary control in energy storage systems*

The ESS operation may fail if only the ESS is involved in stabilizing the microgrid. Load-sharing of the burden of the ESS and the DG units' output power is a requirement for preventing such an outcome [52]. As illustrated in Fig. 6, the power output set-point of each MS should be calculated and dispatched through the secondary control function, First, based on the IEC/ISO 62264 standards; the responsibility of the secondary control in storage system is monitoring the system fluctuation. Then, after compensating the power variation by primary control in storage and increase the power generation, the secondary control bring the power output of the ESS back to zero. As mentioned in Section 2, it is the local controls that are ultimately responsible for regulating the power output locally in each component, while the secondary control compares the measured power output of the storage system with the reference value in order to obtain the error. The total required power for charge and discharge are obtained with this error (Fig. 4) [108,113].

3.3. *Techniques of energy storage systems*

Storage of energy can be achieved by converting electrical energy into another form, such as chemical or mechanical energy

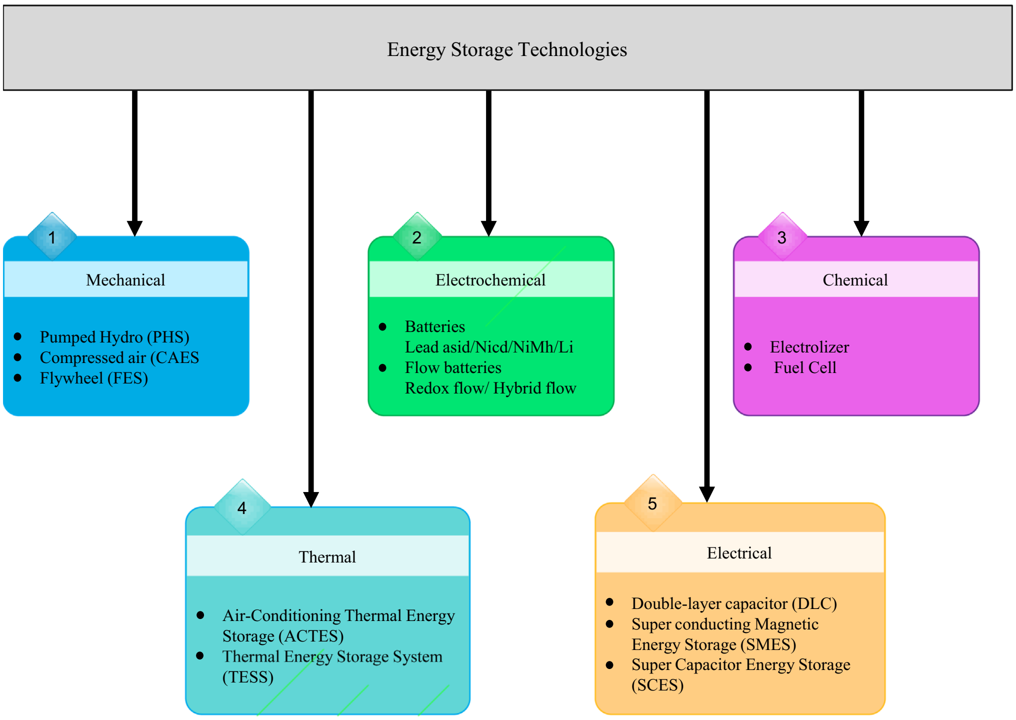

Fig. 7. Different techniques for energy storing.

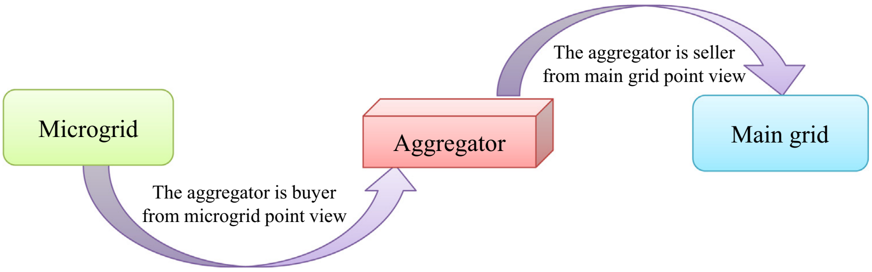

Fig. 8. Role of the aggregator in the market participation.

which a complete classification of ESS types is presented in Fig. 7. In recent years, advanced energy storage technologies have been investigated by researchers, which have presented a comprehensive review by Tan et al. [93] and Akhil et al. [95].

Electrochemical storage technologies (or batteries) are the largest storage group and were investigated by Yang et al. [115] and Divya et al. [116]. Batteries are an advanced technique for storing electrical energy in electrochemical form. They exist in a number of different technologies, including lead-acid [117,118], Nickel-Cadmium (NiCd) [119], Nickel-Metal Hydride (NiMh) [120,121], and Lithium-ion [122]. The lead-acid battery is the most economic option for microgrids, especially for larger systems [116]. The main advantage of this storage technique is that it can be constructed in a wide range of different sizes (from 100 W to several MW), and for this reason it is very popular for microgrid implementation.

Flywheel Energy Storage (FES) is a technique for storing electrical energy in the mechanical energy of a spinning rotor. These are divided into two types: low speed and high speed. Generally, flywheels with speeds of under 10,000 rpm are considered low-speed, and these are much more popular in industry [123–125].

Electric double-layer capacitors can serve as another method of storing electrical energy, in this case between two conductor plates directly and without chemical processing. Such a storage systems can rapidly react to support a MG in a transient condition.

Electrical energy can also be stored in the magnetic field created by the DC flow of a superconducting coil—a storage method called Superconducting Magnetic Energy Storage (SMES). The method is increasing in popularity for MGs, due to the flexibility it offers in exchanging active and reactive power. Moreover, the charging and discharging processes occur rapidly with this technique. For these two reasons, the SMES method is suitable for improving power quality [126].

Pumped-storage hydroelectricity can be used to store excess electrical energy by pumping a large volume of water to an upper level. Under the electricity shortage conditions, water can be converted to electricity using turbine and generator. The infinite technical lifetime of the technique is its main advantage [127]. Compressed air energy storage (CAES) is a method in which electrical energy is used to compress air to a pressure of around 70 bar. The CAES method is very expensive, and is only economic when large volumes of cheap natural storage are available—such as are provided by salt caverns, aquifers, and caverns in hard rock. The compressed air is converted to electrical energy using an expansion turbine and generator [124]. Following Fig. 7, the next storage methods are thermal and chemical techniques. Storage of electrical energy as heat in water tanks is the principle of thermal storage. Under the rubric of chemical methods of electrical storages include fuel cells, electrolysers, and hydrogen tanks [93].

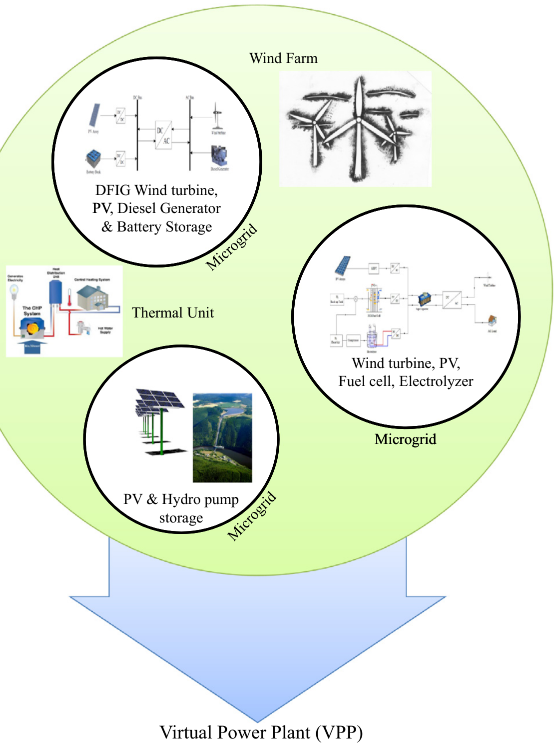

Fig. 9. Concept of VPP.

4. Market participation

Recently, with the appearance of the smart grid and the increasing motivation for the use of MGs, marketing seems a more significant issue than ever. It was stated in the introduction section that the last level of the IEC/ISO 62264 standard concerns the business model and market structure. As mentioned in [128], there are in general three main transactional models, the first of which is known as the pool. This method is based on centralized marketing, in which all power suppliers inject their own production, as well as the price of generation, into the pool, and customers then submit their demand to the same pool in order to make a deal. A significant aspect of all marketing models is the Independent System Operator (ISO), whose main objective is not generation dispatch, but rather matching energy supply to demand in order to ensure reliable system operation. ISO systems in the pool method usually receive bids based on the demand forecasted for the following day. With this strategy, their consumers are supported with the lowest electricity price, and the optimal price for generation is received. There are three types of ISO power pool:

- Tight power: This method′s function usually is based on bounding a control area through metering and interconnection;
- Loose power: Unlike with tight power, there are no control area services in loose power pools. Supporting for consumers is only during emergency conditions;
- Affiliate power pools: The power generation and the energy demand of the consumer cooperate as a single utility by using an aggregator.

A bilateral contract, or direct access, is the second transactional model. This method can be adapted well to MG conditions, because energy buyers and sellers can have electricity marketing directly without a connector system. The third model is a combination of the first two, and is the most complete method as it uses all the features of the pool and the bilateral method together. In this model, customers can select pool power generation first, and on this basis sign a bilateral contract. Moreover, marketing options can be very flexible in the hybrid system, which means there are many different prices based on different services and power quality [128].

4.1. Microgrids in power market competition

The section on storage indicated that a MG can participate in the energy market, like in ancillary service markets. The oligopolistic method, based on a multi-agent system, is the best market structure for MGs [17,129]. The authors of [130] and [131] present a comprehensive review of the implementation of multi-agent systems based on the technical challenges, approaches, and defining concepts, as well as the standards and tools. A market-based, multi-agent system framework for MGs is presented in [132,133]. MG agents are divided into production, consumption, power system, and MGCC agents [17,134]. As mention in Section 3 of this paper, microgrid control and energy management is the main responsibility of the MGCC, which must also coordinate the priority of loads. The MGCC, along with the consumption agent, participate directly in the marketing operation. Moreover, the power system agent is one of the most effective components for determining the buying and selling price for electricity, but does not itself participate in marketing operations. Microgrids buy and sell the shortage or surplus of power to or from a main grid through an aggregator. Therefore, the MG and main grid have different perspectives to the aggregator. For instance, during the selling of power by the MG to main grid, the aggregator is the seller from the point of view of the main grid, and is the buyer from the perspective of the MG (Fig. 8) [135].

Aggregators take care of local distribution systems and greatly reduce the workload burdens on both ISO and the local Distribution Network Operator (DNO), particularly when there are great numbers of retail market participants in the networks. In recent years, many proposals have been provided to change power transactions, of which retail wheeling is one. The main target of the method is to produce a market strategy for reducing the cost of electrical energy. A simple description of it is that electrical suppliers and customers can perform transactions remotely. Moreover, excess power is injected into the utility through the microgrid in open competition [128].

5. Virtual power plant

As mentioned in the introduction, MGs and virtual power plants (VPPs) are two concepts of the LV distribution network that can participate in active network management as a smart grid. The VPP is an energy management system tasked with aggregating the capacity of a number of DGs, ESSs, and dispatchable loads, as is

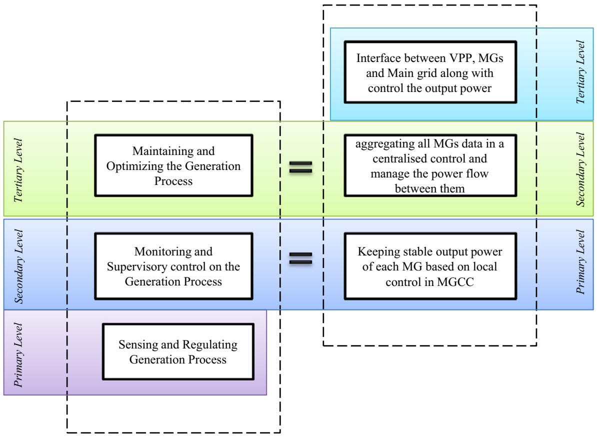

Fig. 10. Microgrid Vs VPP under IEC/ISA 62264 std.

discussed by Pudjianto et al. [19]. Fig. 9 shows the concept of the VPP, which is based on providing centralized control for multiple MGs, DERs, and loads.

VPPs are divided into two different types: commercial and technical. Commercial VPPs have a competitive participation in the electricity market and try to optimize the relation between generation and demand without respect to network limitations. Technical VPPs, on the other hand, try to optimize control and coordination, as well as system operation. To cover the two categories, there are three different approaches that can be used [136]:

- Centralized Controlled Virtual Power Plant (CCVPP)
- Distributed Controlled Virtual Power Plant (DCVPP)
- Fully Distributed Controlled Virtual Power Plant (FDCVPP)

The Smart Grid, Fenix, and Ecogrid projects are the most important European projects using the concept of the VPP and integrated DER [137].

VPPs must always be connected to the main grid and do not have the capacity to work in island mode [138]. Hence, in adapting VPPs to the IEC/ISO 62264 standards, all their control levels are always enabled—unlike in MGs, where the third control level is sometimes disabled. However, there are some different responsibilities in controlling MGs based on the standard level, compared with VPPs. These differences are shown in Fig. 10. The level zero of the standard in VPP is similar to the grid-connection mode of DG units.

The primary control role is the same as the secondary control level in the MG, while the secondary control level tries to optimize the inside of the MG. The tertiary control in VPPs has two levels: the lower level controls the interface between the VPPs and the utility network through the signal sent from the VPPs to the MG, while the upper level handles the control signal from the DNO to the VPPS [138].

6. Future trends and conclusion

Active distribution networks, MGs, and VPPs will become increasingly popular because of the trend toward increasing renewable energy sources. This paper proposed the IEC/ISO 62264 standard for adapting the hierarchical control and energy storage system in MGs and VPPs. To demonstrate the possibility of adapting the standard, a comprehensive review of hierarchical control, storage, and marketing principles, along with the VPP, is presented in this paper. The control strategy of MGs and VPPs is based on the standard of four different levels (*zero to third*).

Power converters in MGs operate on the basis of voltage and frequency in island mode and of active and reactive power in grid-connection mode. Hence, providing accurate reference values for the primary control is the responsibility of secondary and tertiary control levels. Therefore, due to the high accuracy of communication technique, the control method based on communication interfaces in the secondary control and intelligent agents in the tertiary control to optimize references is an extremely interesting area for future research. Adapting VPPs to the IEC/ISO 62264 standard is analogous to a microgrid but shifted a level up. In future research, the short-term scheduling of VPP operations may be a fruitful research area.

In addition, the standardization of the storage system on the basis of the proposed standard, following the loss of network connections in level three, consists of two levels (*primary and secondary*). Since in smart grid infrastructure ESS technology will play a significant role, hybrid-energy storage systems are among the most popular research proposals aimed at achieving the goal of smart storage.

Finally, in the last level of the standard, microgrids have shown the potential to provide ancillary services. An implementable market structure and business models for ancillary services provided by microgrids may also be a very interesting research area for the future.

Acknowledgments

The authors would like to acknowledge the financial support provided by the Finnish Funding Agency for Technology and Innovation, Tekes, to the Smart Grids and Energy Markets (SGEM) research program.

References

[1] KH Sirvio.. Integerating low voltage distribution systems to distribution automation. MSc thesis. Electrical Engineering, University of Vaasa; 2012.
[2] Banos R, et al. Optimization methods applied to renewable and sustainable energy: a review. Renewable Sustainable Energy Rev 2011;15:1753–66.
[3] Lasseter RH. Microgrids and distributed generation. J Energy Eng 2007;133: 144–9.
[4] E.W.E. Association, Pure power–wind energy targets for 2020 and 2030, See also: 〈http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_Full_Report.pdf〉; 2009.
[5] Li H, Chen Z. Overview of different wind generator systems and their comparisons. IET Renew Power Gener 2008;2:123–38.
[6] Herbert GJoselin, et al. A review of wind energy technologies. Renewable Sustainable Energy Rev 2007;11:1117–45.
[7] Chaurey A, Kandpal TC. Assessment and evaluation of PV based decentralized rural electrification: an overview. Renewable Sustainable Energy Rev 2010;14: 2266–78.
[8] Jiayi H, et al. A review on distributed energy resources and MicroGrid. Renewable Sustainable Energy Rev 2008;12:2472–83.
[9] Eltawil M A, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems—a review. Renewable Sustainable Energy Rev 2010;14:112–29.
[10] Z Guoju, et al.. Research on battery supercapacitor hybrid storage and its application in microgrid. In: Power and energy engineering conference (APPEEC), 2010 Asia-Pacific′; 2010. pp. 1–4.
[11] Lopes JP, et al. Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 2006;21:916–24.
[12] Hatziargyriou N, et al. Microgrids. IEEE Power Energ Mag 2007;5:78–94.
[13] Lidula N, Rajapakse A. Microgrids research: a review of experimental microgrids and test systems. Renewable Sustainable Energy Rev 2011;15:186–202.
[14] O Palizban, et al.. Active and reactive power control for a hybrid system with photovoltaic panel, wind turbine, fuel cells, electrolyzer and super capacitor in off-grid mode. In: IEEE international conference on control system, computing and engineering (ICCSCE); 2011. pp. 404–408.
[15] Abu-Sharkh S, et al. Can microgrids make a major contribution to UK energy supply? Renewable Sustainable Energy Rev 2006;10:78–127.
[16] Su S, et al. Self-organized criticality of power system faults and its application in adaptation to extreme climate. Chin Sci Bull 2009;54:1251–9.

[17] Basu A K. Microgrids: energy management by strategic deployment of DERs—a comprehensive survey. Renewable Sustainable Energy Rev 2011.
[18] Morris G Y. A Framework for the Evaluation of the Cost and Benefits of Microgrids 2012.
[19] Pudjianto D, et al. Virtual power plant and system integration of distributed energy resources. IET Renew Power Gener 2007;1:10–6.
[20] Awerbuch S, Preston AM. The virtual utility: accounting, technology and competitive aspects of the emerging industry. . Kluwer Academic Pub; 1997.
[21] K Dielmann, A van der Velden. Virtual power plants (VPP)—a new perspective for energy generation?. In: Modern techniques and technologies, 2003. MTT 2003. Proceedings of the ninth international scientific and practical conference of students, post-graduates and young scientists; 2003. pp. 18–20.
[22] Farhangi H. The path of the smart grid. IEEE Power Energ Mag 2010;8:18–28.
[23] Zeng Z, et al. Study on small signal stability of microgrids: a review and a new approach,. Renewable Sustainable Energy Rev 2011;15:4818–28.
[24] Obara Sy. Load response characteristics of a fuel cell micro-grid with control of number of units. Int J Hydrogen Energy 2006;31:1819–30.
[25] Uzunoglu M, et al. Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. Renewable Energy 2009;34:509–20.
[26] Kim S-K, et al. Modeling and simulation of a grid-connected PV generation system for electromagnetic transient analysis. Sol Energy 2009;83:664–78.
[27] T Jyung, et al. Improvement of a power quality of microgrid system interconnected to distribution system in emergency condition. In: Transmission & distribution conference & exposition: Asia and Pacific; 2009. pp. 1–4.
[28] XIAO Z, et al. Small-signal stability analysis of microgrid containing multiple micro sources [J]. Autom Electr Power Syst 2009;6:022.
[29] Planas E, et al. General aspects, hierarchical controls and droop methods in microgrids: a review,. Renewable Sustainable Energy Rev 2013;17:147–59.
[30] Ustun TS, et al. Recent developments in microgrids and example cases around the world—a review. Renewable Sustainable Energy Rev 2011;15:4030–41.
[31] Basso TS, DeBlasio R. IEEE 1547 series of standards: interconnection issues. IEEE Trans Power Electron 2004;19:1159–62.
[32] J Niiranen, et al. Experiences from a back-to-back converter fed village microgrid. In: IEEE PES innovative smart grid technologies conference Europe (ISGT Europe); 2010. pp. 1–5.
[33] M Moschakis, et al. Adapting EV-microgrid concepts to European grid standards related to power quality. In: Sixteenth international conference on intelligent system application to power systems (ISAP); 2011. pp. 1–6.
[34] C Brunner, IEC 61850 for power system communication. In: Transmission and distribution conference and exposition, T&D. IEEE/PES; 2008. pp. 1–6.
[35] D Brandl, B Consulting, What is ISA-95? Industrial best practices of manufacturing information technologies with ISA-95 models, ed; 2008.
[36] Guerrero JM, et al. Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization. IEEE Trans Ind Electron 2011;58:158–72.
[37] Carrasco JM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006;53:1002–16.
[38] Bidram A, Davoudi A. Hierarchical structure of microgrids control system. IEEE Trans Smart Grid 2012.
[39] Ahmed O, Bleijs J. Power flow control methods for an ultracapacitor bidirectional converter in DC microgrids—a comparative study. Renewable Sustainable Energy Rev 2013;26:727–38.
[40] Zamora R, Srivastava A K. Controls for microgrids with storage: review, challenges, and research needs. Renewable Sustainable Energy Rev 2010;14:2009–18.
[41] Justo JJ, et al. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renewable Sustainable Energy Rev 2013;24:387–405.
[42] P Piagi, RH Lasseter. Autonomous control of microgrids. In: IEEE power engineering society general meeting; 2006. p. 8.
[43] O Palizban, S Mekhilef, Power optimization and static performance investigation of an island-mode doubly-fed induction generator (DFIG). In: IEEE international conference on control system, computing and engineering (ICCSCE); 2011. pp. 399–403.
[44] O Palizban, S Mekhilef, Modeling and control of photovoltaic panels base perturbation and observation MPPT method. In: IEEE international conference on control system, computing and engineering (ICCSCE); 2011. pp. 393–398.
[45] Ko H-S, et al. Active use of DFIG-based variable-speed wind-turbine for voltage regulation at a remote location. IEEE Trans Power Syst 2007;22:1916–25.
[46] Ledesma P, Usaola J. Doubly fed induction generator model for transient stability analysis. IEEE Trans Energy Convers 2005;20:388–97.
[47] Palizban O. Active and reactive power control for hybrid system with renewable energy sourses. Kualalumpur: Master, Electerical, University of Malaya; 2011.
[48] A Makinen, et al. Influence of DFIG reactive current injection during a voltage dip on the operation of wind turbine circuit breaker. In: IEEE eighth international conference on power electronics and ECCE Asia (ICPE & ECCE); 2011. pp. 88–95.
[49] Blaabjerg F, et al. Overview of control and grid synchronization for distributed power generation systems. IEEE Trans Ind Electron 2006;53:1398–409.
[50] Vasquez J C, et al. Hierarchical control of intelligent microgrids. IEEE Ind Electron Mag 2010;4:23–9.
[51] X Lu, et al. SoC-based dynamic power sharing method with AC-bus voltage restoration for microgrid applications. In: IECON 2012-38th annual conference; 2012. pp. 5677–5682.
[52] J-Y Kim, et al. Coordinated state-of-charge control strategy for microgrid during islanded operation. In: Third IEEE international symposium on power electronics for distributed generation systems (PEDG); 2012. pp. 133–139.
[53] J Guerrero, et al. Advanced control architectures for intelligent microGrids, Part I: Decentralized and hierarchical control, 2013.
[54] P Rodriguez, et al. Control of grid-connected power converters based on a virtual admittance control loop. In: Fifteenth European conference on power electronics and applications (EPE); 2013. pp. 1–10.
[55] Brabandere K De, et al. A voltage and frequency droop control method for parallel inverters. IEEE Trans Power Electron 2007;22:1107–15.
[56] Green T, Prodanović M. Control of inverter-based micro-grids,. Electr Power Syst Res 2007;77:1204–13.
[57] Vandoorn T, et al. Review of primary control strategies for islanded microgrids with power-electronic interfaces. Renewable Sustainable Energy Rev 2013;19:613–28.
[58] Rocabert J, et al. Control of power converters in AC microgrids. IEEE Trans Power Electron 2012;27:4734–49.
[59] K Visscher, S De Haan, Virtual synchronous machines (VSG′s) for frequency stabilisation in future grids with a significant share of decentralized generation. In: Smartgrids for distribution, IET-CIRED. CIRED Seminar; 2008. pp. 1–4.
[60] QC Zhong, G Weiss, Static synchronous generators for distributed generation and renewable energy. In: Power systems conference and exposition, 2009. PSCE′09. IEEE/PES; 2009. pp. 1–6.
[61] Majumder R, Bag G. Parallel operation of converter interfaced multiple microgrids. Int J Electr Power Energy Syst 2014;55:486–96.
[62] Khadem SK, et al. Parallel operation of inverters and active power filters in distributed generation system—a review. Renewable Sustainable Energy Rev 2011;15:5155–68.
[63] Kawabata T, Higashino S. Parallel operation of voltage source inverters. IEEE Trans Ind Appl 1988;24:281–7.
[64] T Wu, et al. The central-limit control and impact of cable resistance in current distribution for parallel-connected DC–DC converters. In: Power electronics specialists conference, PESC′94 Record., 25th Annual IEEE; 1994. pp. 694–702.
[65] Ramos R, et al. Master-slave sliding-mode control design in parallel-connected inverters. AUTOMATIKA: časopis za automatiku, mjerenje, elektroniku, računarstvo i komunikacije 2001;42:37–44.
[66] W-C Lee, et al. A master and slave control strategy for parallel operation of three-phase UPS systems with different ratings. In: Applied power electronics conference and exposition, APEC′04. 19th annual IEEE; 2004. pp. 456–462.
[67] Chen Y-K, et al. ACSS for paralleled multi-inverter systems with DSP-based robust controls. IEEE Trans Aerosp Electron Syst 2003;39:1002–15.
[68] H Shan, et al. Research on a novel digital parallel current sharing control technique of modularized UPS. In: International conference on electrical machines and systems, ICEMS; 2007. pp. 106–109.
[69] Wu T-F, et al. 3C strategy for inverters in parallel operation achieving an equal current distribution. IEEE Trans Ind Electron 2000;47:273–81.
[70] Guerrero JM, et al. Control of distributed uninterruptible power supply systems. IEEE Trans Ind Electron 2008;55:2845–59.
[71] S Chiang, J Chang, Parallel control of the UPS inverters with frequency-dependent droop scheme. In: Power electronics specialists conference, PESC. IEEE 32nd annual; 2001. pp. 957–961.
[72] Barklund E, et al. Energy management in autonomous microgrid using stability-constrained droop control of inverters. IEEE Trans Power Electron 2008;23:2346–52.
[73] Z Jiang, X Yu, Active power—voltage control scheme for islanding operation of inverter–interfaced microgrids. In: Power and energy society general meeting,PES′09. IEEE; 2009. pp. 1–7.
[74] Li Y, Li YW. Power management of inverter interfaced autonomous microgrid based on virtual frequency-voltage frame. IEEE Trans Smart Grid 2011;2:30–40.
[75] Y Li, YW Li, Virtual frequency-voltage frame control of inverter based low voltage microgrid. In: Electrical power and energy conference (EPEC), IEEE; 2009. pp. 1–6.
[76] X Zhang, et al. Reactive power compensation for parallel inverters without control interconnections in microgrid. In: Industrial electronics, IECON 34th annual conference of IEEE; 2008. pp. 922–925.
[77] Guerrero JM, et al. Output impedance design of parallel-connected UPS inverters with wireless load-sharing control. IEEE Trans Ind Electron 2005;52:1126–35.
[78] S Chiang, J Chang, Parallel operation of series-connected PWM voltage regulators without control interconnection. In: Electric power applications, IEE proceedings-; 2001. pp. 141–147.
[79] Laaksonen H, Kauhaniemi K. Stability of microgrid with different configurations after islanding due to fault in the utility grid. Int Rev Electr Eng (IREE) 2008;3.
[80] Guerrero JM, et al. Control strategy for flexible microgrid based on parallel line-interactive UPS systems. IEEE Trans Ind Electron 2009;56:726–36.
[81] H Laaksonen, K Kauhaniemi. Synchronized re-connection of island operated LV microgrid back to utility grid. In: Innovative Smart Grid technologies conference Europe (ISGT Europe), IEEE PES; 2010. pp. 1–8.
[82] O Palizban, K Kauhaniemi. Microgrid control principles in island mode operation. In: PowerTech (POWERTECH), IEEE Grenoble; 2013. pp. 1–6.
[83] A Engler, N Soultanis. Droop control in LV-grids. In: International conference on future power systems; 2005. pp. 6 pp.-6.

[84] IEEE standard for interconnecting distributed resources with electric power systems, IEEE Std. 1574–2003.

[85] M Chandorkar, D Divan. Decentralized operation of distributed UPS systems. In: Proceedings of the international conference on power electronics, drives and energy systems for industrial growth; 1996. pp. 565–571.

[86] Katiraei F, Iravani M. Power management strategies for a microgrid with multiple distributed generation units. IEEE Trans Power Syst, 2006;21:1821–31.

[87] AG Tsikalakis, ND Hatziargyriou. Centralized control for optimizing microgrids operation. Power and energy society general meeting, IEEE; 2011. pp. 1–8.

[88] Chandorkar M C, et al. Control of parallel connected inverters in standalone ac supply systems. IEEE Trans Ind Appl 1993;29:136–43.

[89] Q Shafiee, et al. Distributed secondary control for islanded microgrids —a novel approach,2013.

[90] Han J, et al. Coordinated predictive control of a wind/battery microgrid system 2013.

[91] B Kroposki, et al. Microgrid standards and technologies. In: Power and energy society general meeting-conversion and delivery of electrical energy in the 21st Century, IEEE; 2008. pp. 1–4.

[92] W Li, G Joós. Comparison of energy storage system technologies and configurations in a wind farm. In: Power electronics specialists conference, PESC. IEEE; 2007. pp. 1280–1285.

[93] Tan X, et al. Advances and trends of energy storage technology in microgrid. Int J Electr Power Energy Syst 2013;44:179–91.

[94] Laaksonen H, Kauhaniemi K. New concept for power quality management in microgrid with energy storage based power quality compensator. Int J Distrib Energy Resour (DER J) 2008;4.

[95] Akhil AA, et al. DOE/EPRI 2013 Electricity storage handbook in collaboration with NRECA. In: Albuquerque NM, editor. Sandia National Laboratories; 2013.

[96] J Eyer, G Corey, Energy storage for the electricity grid: benefits and market potential assessment guide, Sandia National Laboratories report, SAND2010-0815, Albuquerque, New Mexico; 2010.

[97] H Laaksonen, K Kauhaniemi, Control principles for blackstart and island operation of microgrid. In: Nordic workshop on power and industrial electronics (NORPIE/), June 9–11, Espoo, Finland; 2008.

[98] JP Lopes, et al. Microgrids black start and islanded operation. In: 15th Power systems computation conference (PSCC), Liege; 2005.

[99] Xu G, et al. Power oscillation damping using wind turbines with energy storage systems. IET Renew Power Gener 2013;7:449–57.

[100] M Beza, M Bongiorno. Power oscillation damping controller by static synchronous compensator with energy storage. In: Energy conversion congress and exposition (ECCE), IEEE; 2011pp. 2977–2984.

[101] M Altin, et al. Methodology for assessment of inertial response from wind power plants. In: Power and energy society general meeting, IEEE; 2012. pp. 1–8.

[102] M Swierczynski, et al. Lifetime investigations of a lithium iron phosphate (LFP) battery system connected to a wind turbine for forecast improvement and output power gradient reduction;2012.

[103] KH Chua, et al. Battery energy storage system for peak shaving and voltage unbalance mitigation.

[104] Levron Y, Shmilovitz D. Power systems' optimal peak-shaving applying secondary storage. Electr Power Syst Res 2012;89:80–4.

[105] Callaway DS. Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy. Energy Convers Manage 2009;50:1389–400.

[106] Rabiee A, et al. A review of energy storage systems in microgrids with wind turbines. Renewable Sustainable Energy Rev 2013;18:316–26.

[107] Thounthong P, et al. Analysis of supercapacitor as second source based on fuel cell power generation. IEEE Trans Energy Convers 2009;24:247–55.

[108] Kim JY, et al. Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation. IEEE Trans Power Electron 2010;25:3037–48.

[109] Mercier P, et al. Optimizing a battery energy storage system for frequency control application in an isolated power system. IEEE Trans Power Syst 2009;24:1469–77.

[110] Kim AR, et al. Operating characteristic analysis of HTS SMES for frequency stabilization of dispersed power generation system. IEEE Trans Appl Supercond 2010;20:1334–8.

[111] JD Kueck, et al. Microgrid energy management system, Oak Ridge, TN: Oak Ridge National Laboratory report ORNL/TM-2002/242; 2003.

[112] A Madureira, et al. Secondary load frequency control for microgrids in islanded operation. In: Proceedings of the international conference on renewable energy and power quality ICREPQ ′05, Spain; 2005.

[113] PC Loh, F Blaabjerg, Autonomous control of distributed storages in microgrids. In: IEEE eighth international conference on power electronics and ECCE Asia (ICPE & ECCE); 2011. pp. 536–542.

[114] J Guerrero, et al. Advanced control architectures for intelligent microgrids, Part II: Power quality, energy storage, and AC/DC microgrids;, 2013.

[115] Yang Z, et al. Electrochemical energy storage for green grid. Chem Rev 2011;111:3577–613.

[116] Divya K, Østergaard J. Battery energy storage technology for power systems—an overview. Electr Power Syst Res 2009;79:511–20.

[117] A Palo Alto, Valve regulated lead acid (VRLA) battery qualification assessment, EPRI ID 1019216, EPRI2009.

[118] PT Moseley, et al. Valve-regulated lead-acid batteries: access online via Elsevier; 2004.

[119] Baker J. New technology and possible advances in energy storage,. Energy Policy 2008;36:4368–73.

[120] J Dunbar, High performance nickel metal hydride batteries. In: WESCON/94.'Idea/Microelectronics′. conference record; 1994. pp. 236–241.

[121] Crompton T P. Battery reference book. Newnes; 2000.

[122] Nair N-KC, Garimella N. Battery energy storage systems: assessment for small-scale renewable energy integration. Energy Build 2010;42:2124–30.

[123] K Veszpremi, I Schmidt, Flywheel energy storage drive for wind turbines. In: Seventh international conference on power electronics and drive systems, PEDS′07; 2007. pp. 916–923.

[124] Klimstra MHJacop. Smart power generation: Avain 2011.

[125] Hyytinen T. Hybrid power generation concept for small grids. Master, Electrical and Energy Engineering, University of Vaasa; 2013.

[126] Molina MG, Mercado PE. Power flow stabilization and control of microgrid with wind generation by superconducting magnetic energy storage. IEEE Trans Power Electron 2011;26:910–22.

[127] P Alto, Results from case studies of pumped-storage plants, EPRI ID 10231422012.

[128] Chowdhury S, et al. Microgrids and active distribution networks: Institution of Engineering and Technology 2009.

[129] A Sinha, et al. Setting of market clearing price (MCP) in microgrid power scenario. In: Power and energy society general meeting-conversion and delivery of electrical energy in the 21st Century, IEEE; 2008, pp. 1–8.

[130] Stephen D, et al. Multi-agent systems for power engineering applications—Part I: Concepts, approaches, and technical challenges. IEEE Trans Power Syst 2007;22:1743–52.

[131] McArthur SD, et al. Multi-agent systems for power engineering applications —Part II: Technologies, standards, and tools for building multi-agent systems. IEEE Trans Power Syst 2007;22:1753–9.

[132] Z Qiu, et al. A market-based MAS framework for microgrids. In: Proceedings of the 17th world congress the international federation of automatic control Seoul, Korea; July, 2008, pp. 6–11.

[133] S Krovvidi, Competitive microgrid electricity market design,Virginia Polytechnic Institute and State University; 2010.

[134] Dimeas AL, Hatziargyriou ND. Operation of a multiagent system for microgrid control. IEEE Trans Power Syst 2005;20:1447–55.

[135] Kim H, Thottan M. A two-stage market model for microgrid power transactions via aggregators. Bell Labs Tech J 2011;16:101–7.

[136] Peik-Herfeh M, et al. Decision making of a virtual power plant under uncertainties for bidding in a day-ahead market using point estimate method. Int J Electr Power Energy Syst 2013;44:88–98.

[137] Nikonowicz ŁB, Milewski J. Virtual power plants-general review: structure, application and optimization. J Power Technol 2012;92:135–49.

[138] BZTL Vandoorn, JDM De Kooning, B Meersman, L Vandevelde. Smart microgrids and virtual power plants in a Hierarchical Control Structure. In: Presented at the second IEEE PES international conference and exhibition; 2011.

Publication IV

Microgrids in active network management – part II: System operation, power quality and protection

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Renewable and Sustainable Energy Reviews 36 (2014) 440-451

Renewable and Sustainable Energy Reviews 36 (2014) 440–451

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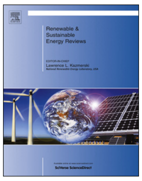

Microgrids in active network management – part II: System operation, power quality and protection

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ARTICLE INFO

Available online 13 May 2014

Keywords:
Black-start operation
Island detection
Microgrid
Power quality
Protection

ABSTRACT

The development of distribution networks for participation in active network management (ANM) and smart grids is introduced using the microgrid concept. In recent years, this issue has been researched and implemented by many experts. The second part of this paper describes those developed operational concepts of microgrids that have an impact on their participation in ANM and in the requirements for achieving targets. Power quality is the most challenging task in microgrids, especially when the system switches from normal parallel operation (grid-connected mode) to island operation. Indeed, following planned or unplanned transitions to island mode, microgrids may develop instability. For this reason, the paper addresses the principles behind island-detection methods, black-start operation, fault management, and protection systems, along with a comprehensive review of power quality. Finally, island detection and the other topics are summarized with a flowchart and tables.

Contents

1. Introduction

Future distribution networks will require completely novel smart grid concepts [1–3]. In this regard, flexible microgrids (MGs) that are capable of intelligently operating in both grid-connected and island modes are required [4–6].

In recent years, several control devices have also been developed to improve the integration of MGs [7–9]. The variations in power generation, interconnection, and electrical interface may constitute barriers to achieving an optimal system for connecting distributed energy resources (DERs) to the grid [10–13].

In the first part of their paper [14], the authors proposed adapting the IEC/ISO 62264 standard to the MG, virtual power plant (VPP), and storage system. The standardization was explained

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http://dx.doi.org/10.1016/j.rser.2014.04.048

Nomenclature

AFD	Active Frequency Drift
AMM	Automate Meter Management
APF	Active Power Filter
APS	Automatic Phase Shift
ARPS	Adaptive Reactive Power Shift
DER	Distributed Energy Resource
DG	Distribution Generation
DMS	Distribution Management System
DL	Dispatchable Load
ESS	Energy Storage System
LC	Local Control
LV	Low voltage
MCB	Miniature Circuit Breaker
MGs	Microgrids
MGCC	Microgrid Control Centre
MMS	Microgrid Management System
NDZs	Non-Detection Zones
NSCI	Negative Sequence Current Injection
PCC	Point of Common Coupling
PF	Positive Feedback
PI	Proportional Integral
P/Q	Active and Reactive Power
RESs	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SFS	Sandia Frequency Shift
SMS	Slip Mode Frequency Shift
SOC	State of Charge
SVS	Sandia Voltage Shift
THD	Total Harmonic Distortion
U/O FP	Under/Over Frequency Protection
U/O VP	Under/Over Voltage Protection
UPS	Uninterruptible Power Supply
UPQC	Unified Power Quality Compensator
UTSP	Unified Three Phase Single Processor
VPF	Voltage Positive Feedback
VU	Voltage Unbalance

on five levels: *level zero* (the generation process), *level one* (the process of sensing and adjusting generation), *level two* (monitoring and supervision), *level three* (maintaining and optimizing), and *level four* (market structure and business model). Based on the investigation in the first part, the tertiary control level is disabled when the MG switches to island mode [15]. Hence, the first objective of the present paper (second part) is the comprehensive investigation of island-detection methods in the MG.

As presented in [16], an MG operates normally in parallel with the utility grid. However, the transition to island operation may occur as a result of a permanent fault in the main grid, or due to an intended disconnection. This is why, in the event that the transition is unsuccessful (for example, due to a fault during transition), a blackout occurs – in which case, the black-start strategy should be used. In Fig. 1, the operational modes of MGs are presented. In this sense, the restoration of service is performed first by disconnecting the distribution generation (DG) units, and thereafter by reconnecting them in a controlled way.

As aforementioned, MGs need to be able to operate intelligently in both grid and island mode [17–19]. Thus, the great challenge is to combine all the various power electronics, communication technologies, interfaces, and energy-storage mechanisms [20,21]. Moreover, stability and voltage regulation are the greatest challenges to the integration of renewable energy into the main network. Hence, power quality for the customer, which is supported through the MG in both operational modes, is very important [22–24].

The protection system is another major challenge to MG operations [25–27]. The protection system for MGs must also function in both grid-connected and island mode [28,29]. As discussed by Justo et al. [30], the principle of protection in conventional grids and in MGs cannot follow the same approach. The responsibility of the protection relay when a fault appears in the main grid is to isolate the DG units and loads, and move to island-mode operation. However, the relay removes the smallest part of the system in which the fault occurs during the island operation.

In order to cover all these issues, the second objective of this paper is a comprehensive literature survey of power quality, fault management, black-start operation, and protection. The investigation provides information on the status of and advances in MG principles from the viewpoints of island and grid-connected modes.

Island operation and detection techniques are dealt with in Section 2. Power quality is presented in Section 3. Microgrid black-start operations, monitoring, and fault management are discussed, along with protection, in Sections 4–6 respectively. Finally, the literature survey concludes in Section 7.

2. Island-mode detection and operation

A microgrid should deliver high-quality power without interruption to customers through the local DG units [31,32]. Their performance in island mode should be based on standards, such as IEEE Std. 1547, UL 1741 (the anti-islanding test configuration) and IEC 61727 [33,34]. However, some countries use different standards for evaluation, such as DIN VDE 0126 in Germany [35] and C22.2 no. 107.1-01 in Canada [36]. The various requirements for the operational limits of voltage and frequency according to the two most important standards for island detection (the IEC and the IEEE) are shown in Table 1. Island-detection methods are generally classified into two main types of techniques: the remote and the local [37,38]. Remote techniques are centralized methods associated with island detection on the utility side. Their high performance and applicability are their advantages, but they are not economical when compared with local techniques [39]. Local techniques involve island detection on the DG side, and can be classified into three different types [40–43]: passive, active, and hybrid methods. Anti-island-detection methods are evaluated through the non-detection zone (NDZ). The NDZ is defined on the basis of an operation failing at the right time on account of loading conditions [44–46]. A broad NDZ is the main disadvantage of local techniques [47], and the largest NDZ area occurs with the passive methods [48]. Thus, the passive methods cannot support high DG penetration. However, the active methods make up for some of the disadvantages, and so some of the methods may support multiple DGs [45,49].

As presented by Mahat et al. [45], hybrid methods are the result of combining both the above detection techniques. In hybrid methods, the active technique is implemented only when islanding is detected by a passive technique. Fig. 2 (which is based on [50]) shows the classification of methods with their advantages and disadvantages.

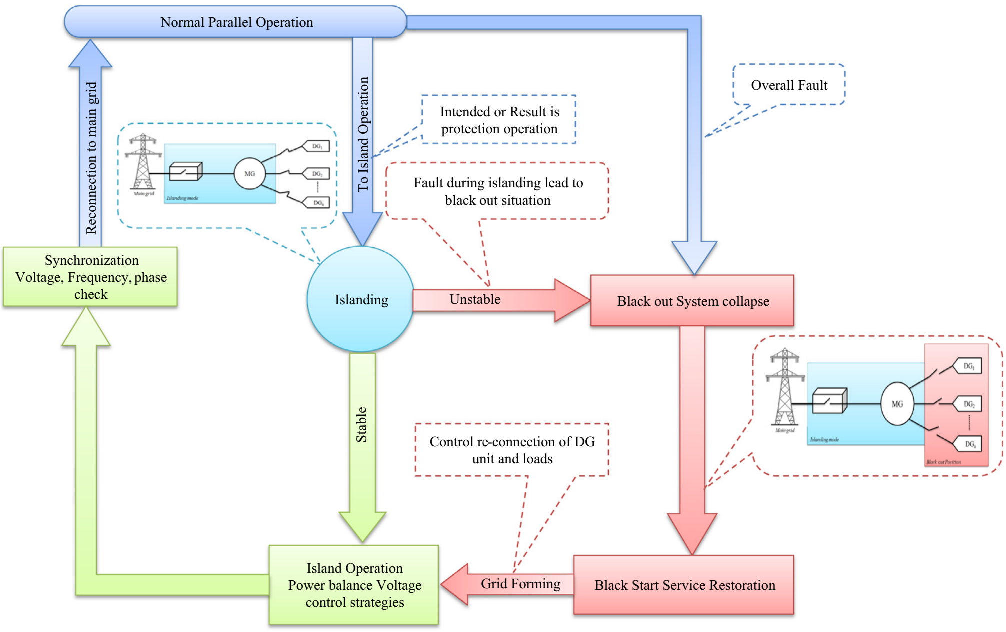

Fig. 1. Operational method of microgrid [16].

Table 1
Frequency & voltage operation limits for IEEE 1547 and IEC 61727. std.

IEEE Std		IEC Std.	
Frequency limitation	**Clearing time (S)**	**Frequency limitation**	**Clearing time (S)**
$f\langle59.3$	0.16	$f\langle59$	0.1
$f\rangle60.5$	0.16	$f\rangle61$	0.1
Voltage limitation (V_{rms})	**Clearing time (S)**	**Voltage limitation (V_{rms})**	**Clearing time (S)**
$V\langle0.5v_n$	0.16	$V\langle0.5v_n$	0.1
$0.5v_n\langle V\langle0.88v_n$	2	$0.5v_n\langle V\langle0.85v_n$	2
$1.1v_n\langle V\langle1.2v_n$	1	$v_n\langle V\langle1.1v_n$	2
$1.2v_n\langle V$	0.16	$1.1v_n\langle V\langle1.35v_n$	0.05

2.1. *Local techniques*

2.1.1. *Passive methods*

In the passive methods, voltage, frequency, and the system's harmonic distortion parameters are continuously monitored. Indeed, these parameters will vary as the mode of MG changes [51,52]. Hence, a suitable setting for maximum and minimum allowed variation improves the ability to distinguish connections [53]. The most common passive methods are discussed by Zeineldin et al. [14]. The methods do not damage the system, and they enable high-speed relay operation. However, these techniques suffer from relatively large NZD [45]. In other words, if the variation in the monitored parameters does not exceed the permitted values (which sometimes come from the standards), then the system does not transfer to island mode [35]. A hybrid method is proposed to solve this problem, and will be discussed later in this paper. Moreover, some important characteristics of the popular techniques are collected in Table 2. These include the monitored parameters, advantages and disadvantages, the NDZ interval, the detection speed, and other details [54–56].

As mentioned, the disadvantage of passive island-detection techniques is the large NDZ. To reduce it, the method can be combined with one of the local active anti-islanding techniques in a hybrid method. A hybrid passive method has been proposed by Jang et al. [57], based on monitoring the voltage unbalance and the total harmonic distortion (THD). This approach enhances the performance of the passive methods, and will be explained in the section about hybrid techniques.

2.1.2. *Active methods*

The second type of anti-island-detection method is based on feedback techniques and on monitoring the response to disturbances deliberately injected into the circuit [58]. Indeed, the active method has the same principle as the control mechanism, and detects the variation of both frequency and voltage at the point of common coupling (PCC) [44,59].

The technique has a smaller NDZ, compared with the passive method; however, it can lead to a degradation in the power quality of the system [53,60–62]. A complete review of these methods is presented by Kunte et al. [59]. An active island-detection strategy

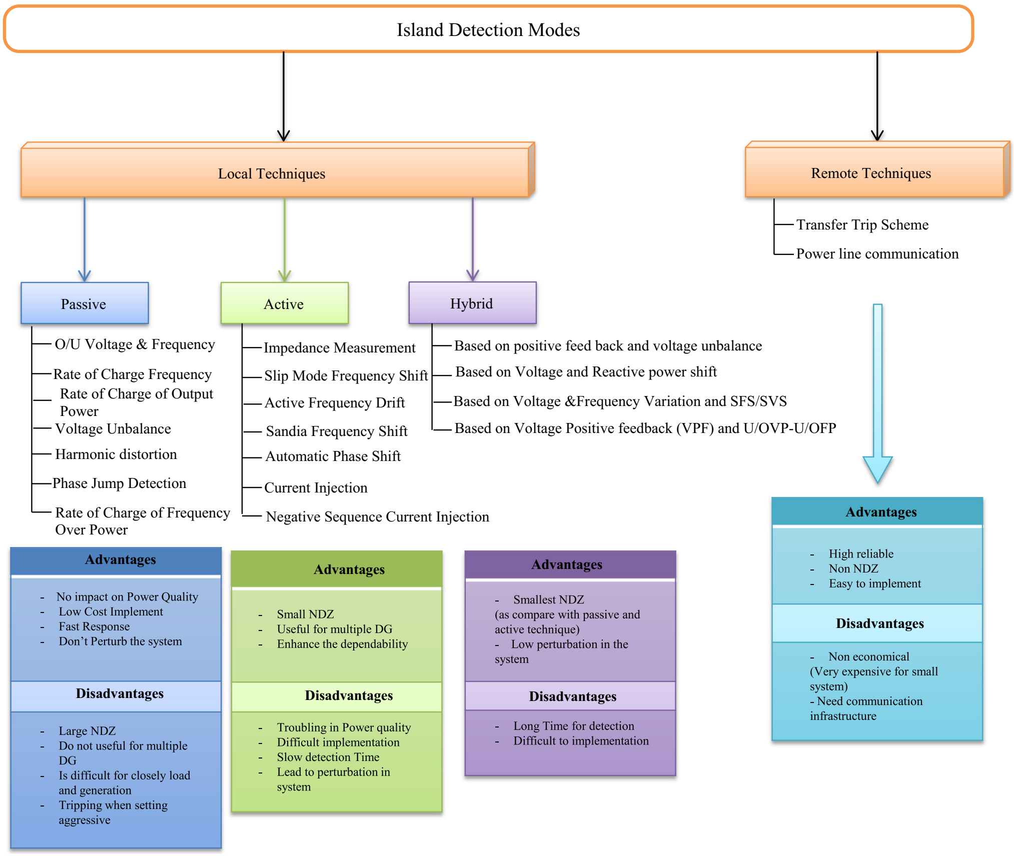

Fig. 2. Classification of island-detection methods [50].

that relies on equipping the DG interface with a *Q*–*f* characteristic is presented in [44]. As with the passive method, some important characteristics of popular techniques, including monitoring parameters, advantages and disadvantages, the NDZ interval, the detection speed, and other details are presented in Table 3 [59,63,64].

2.1.3. *Hybrid methods*

Hybrid techniques of island detection are the result of combining a passive method with an active method [36]. Indeed, the passive technique has operational priority in these island-detection methods, and the active methods operate after passive detection [46]. The main advantage of hybrid methods is that they minimize NDZs, as compared with the other two local techniques. Due to this significant advantage, hybrid techniques are much more effective for island protection. The most common hybrid methods are presented in [36,45,49,65,66], and Table 4 illustrates their advantages and disadvantages, and other important issues regarding this class of techniques.

Moreover, with respect to the definition of passive, active, and hybrid techniques, Fig. 3 shows a complete algorithm for local island-detection methods, developed on the basis of [50]. As can be seen in this figure, the passive and active methods share some common features. Indeed, the differences lie in measuring and monitoring: in passive methods, only measuring occurs, while active methods are based on signal feedback. Hybrid methods combine both passive and active methods in these measuring and monitoring parts.

2.2. *Remote techniques*

Following the island-detection classification methods shown in Fig. 2, remote techniques form another detection group. The design of such techniques is based on a communication link between the distributed generator and the main grid [39]. Higher reliability is the main advantage of this method over local techniques [67]. However, the method is uneconomical, as it is expensive to implement. The most popular remote island-detection methods are presented by Xu et al. [23], Mahat et al. [45] and Kunte [59]. The details of these methods, along with their advantages and disadvantages, are summarized in Table 5.

There are many factors that should be considered in selecting the island-detection method. Economic issues, in particular, have always been important [59]. As mentioned, island detection is very significant in MGs because of its strong relation with the MG control and storage system. Hence, remote control is more popular in smart grids and MGs, even when the additional costs are taken into account.

In conclusion, many techniques have been developed for island detection with single DGs. Yet when many DGs are placed in parallel in an MG, the NDZ increase is notable. The solution to this is to use a microgrid control centre (MGCC), thus considering the whole MG as a 'single DG block.' Similar techniques are then implemented at the PCC with the MGCC. Moreover, for both island detection and island operation, a communication and intelligence interface is needed to connect the grid and the island into the MGCC. Indeed, all decisions concerning active or reactive power

Table 2
Passive method island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation/Speed
O/U Voltage/Frequency	– Frequency – amplitude Voltage	Avoid undesired DG tripping	Slow Detection Large NDZ	Large	✓	–	Simple/Slow
ROCOF	Voltage wave form	Highly reliable when there is large mismatch in power	Reliability Fail to operate if DG's capacity matches with its local load	Large	✓	–	Simple/Normal
Change Impedance	Impedance	Small NDZ (Compared to other passive methods)	– No effect if changing be small – Effectiveness decrease the number of connected inverter	Small	✓	–	Simple/Normal
Voltage unbalance	– Voltage magnitude – phase angle – frequency change	Easy Implementation	NDZ effective in small changing	Large	✓	–	Simple/Fast
Harmonic distortion	Total harmonic distortion of grid voltage	Effectiveness does not change where there are multiple inverters, but of course may need to coordination	– The method fail for high values of quality factor – Sensitive to grid perturbation – Threshold is difficult to set	Large	✓	–	Simple/Normal
Phase jump detection	Phase difference between voltage at the PCC and inverter output	Easy Implementation	– Let to nuisance tripping – Threshold is difficult to set	Large	✓	–	Simple/Fast

control, island detection, operation, and storage systems are managed by the MGCC. The decision to switch to island mode, and also to resynchronize after islanding, is thus based on measurements of MGCC on both sides of interconnection mode [68]. As mentioned in the introduction, this study is primarily a technical comparison. However, economic comparisons constitute another important dimension, and are discussed in [39,69].

3. Power quality

As demands on DG units continue to increase [70], power quality, stability, and power balancing are crucial issues for microgrids and smart grids [71]. Moreover, improvements in performance, telecommunications, operations, and regulation – as well as in network planning – are all very significant in designing smart grids [72]. Based on the council of European energy regulators (CEER) [72,73], the coverage of power quality in MGs can be divided into three main parts, as shown in Fig. 4.

Recently, researchers have tried to minimize the most significant issues relating to the quality of electricity in distribution systems, such as harmonic current and unbalancing conditions. Indeed, the evaluation of power quality is based on IEEE 519-1992, IEC 61000-4-30 [74], and EN50160 [75]. In these standards, the THD of the voltage and the individual voltage distortion are limited to 5% and 3%, respectively, in distribution networks below 69 KV [76,77]. Moreover, according to IEEE Standard 1547.2-2008, the voltage fluctuation is limited to ± 5%, as renewable energy sources (RESs) are parallel to low-voltage systems [78].

With electrical storage and distributed generation, power quality could be maintained in much the same way as with uninterruptible power supply (UPS) systems [79].

Moreover, electronic inverters are also used for compensation [80]. Such devices are able to generate reactive power, supplying reactive loads useful in dealing with unbalanced loads and the generation of harmonic currents. Indeed, the main role of an interface converter is to control power injection [81]. Beside the energy storage system in island-operation mode and also inverter, active power filters (APFs) are also effective elements for improving the power quality [82].

As discussed by Savaghebi et al. [83], power-quality problems are of two main types: voltage unbalance and harmonics. As long as a single-phase load is connected to the MG, voltage unbalance can occur in the MG [84]. Indeed, some of the equipments in MGs – such as power converters and induction motors – suffer from voltage unbalance in the system [85]. Using series and shunt APFs is a solution to this problem of unbalanced voltage [86]. In this method, compensation is provided by injecting negative sequence voltage (respectively, current) into the power distribution line for the series (respectively, shunt APF) method [87–89].

Indeed, the main role of the DG inverter in regulating the phase angle and the amplitude of the output voltage is to inject the reactive power or observe it. Thus, another method for optimizing power quality is the control strategy which is presented by He et al. [90]. The use of a two-inverter structure approach for control is described in [91,92], and is similar to a series-parallel APF – one being connected as a shunt and the other in series with the grid [83].

The injection of negative-sequence current by the DG is another method of compensating for voltage unbalance, as discussed in [93]. However, as it uses much of the interface's converter capacity for compensation, the method is not effective under severely unbalanced conditions. It may even have negative effects on the active and reactive power generated by the DG.

Cheng et al. [94] presented another method for compensating for voltage unbalance in MGs. This involves generating a reference

Table 3
Active method island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation /Speed
Impedance measurement	Impedance	– Highly reliable – Dependability	Poor results for multiple inverter connected	Small	✓	_	Simple/Fast
Impedance detection at specific frequency	Harmonic voltage	Easy implementation	nuisance trip problem in multiple inverter case	Small	✓	_	Simple/ Relatively Slow
SMS	Phase of PCC voltage	Effective in multiple inverters	Requires a decrease in the power quality of the DG inverter	Relatively Slow	_	✓	Medium/Slow
AFD	Chopping factor drift between current and Voltage	Strong dependability	appropriate chopping fraction to not reach harmonic limit	Large	_	✓	Complex/ Medium
SFS	Frequency Drift with positive feedback	Most effective method in active technique	Difficult Implementation	Very Small	_	✓	Complex/ Relatively fast
SVS	Voltage amplitude	Easy to implement	In positive feedback operation power quality slightly reduce	Very Small	_	✓	Simple/Fast
APS	Frequency of terminal Voltage	Alleviates the problem for AFD SMS	For non -linear load have large inertia	Just in non-linear load	_	✓	Medium/Fast
Current injection	Disturbance signal through d or q axis controller	Fast response (Compared to other active methods)	Fail for loads having value quality factor more than 3	Very small	_	✓	Complex/Fast
NSCI	Negative sequence voltage	Can be used in both single DG unit and multiple DG unit	No NDZ	None	✓	✓	Complex/Fast

Table 4
Hybrid island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation/ Speed
PF and VU	Three phase voltage continuously	Encompass small changing	Long time for detection	Very small	✓	_	Medium/Slow
Voltage and reactive power	Voltage variation and reactive power shift	Low perturbation	Long time for detection	Very small	✓	_	Medium/Slow
U/O Voltage and Frequency with SFS or SVS	– Voltage amplitude – Frequency Shift	Most effective on hybrid method	Long time for detection	Very small	✓	_	Medium/Slow
VPF and U/OVP-U/OFP	Voltage and frequency	Can be used in multiple DG units	Long time for detection	Very small	_	✓	Medium/Slow

for a negative-sequence conductance based on the negative-sequence reactive power. There is in fact a trade-off between voltage regulation adequacy and the efficiency of unbalance compensation. To cope with this, [83] proposes to directly change the voltage reference in order to compensate for the voltage unbalance in an MG.

As mentioned earlier, THD is another power quality problem that arises due to the tradeoff between current with the main grid and the voltage of the local inverter loads [95]. Hence, a cascaded control structure consisting of an outer-loop current controller and an inner-loop voltage controller has been proposed by Zhong [95]. Indeed, the concurrent determination of the low THD for the grid current and of the voltage of the local load inverter is the goal of the method.

Truly, power quality in MGs can be enhanced with two complementary approaches. These are dedicated APFs and the use of the capability of existing DGs. The general scheme of power quality in MGs – based on the IEC 62264 standard (introduced in the first part of this paper) – is shown in Fig. 5. Indeed, primary power quality includes controlling a DG. Moreover, the responsibility of secondary control is to coordinate the power between the DGs and to support the load with a high-power quality level. The scheme consists of different parts: dedicated units, using DG units as parallel APFs, and back-up support connected to the main grid through a back-to-back converter. In [96] the back-to-back converter was used to test for the presence of power quality problems in grid-connected MGs, and to mitigate them. As mentioned in the Introduction and in Section 2, the target of this paper is a technical evaluation of microgrids. However, economic issues are also important in finding the best methods to improve power quality. The economic evaluation of power quality is discussed by Lin et al. [97] and McGranaghan et al. [98].

4. Black-start operation

Power interruptions can appear in the whole system or in a single part, and can arise from unplanned events in the MG [99]. During island-mode operation, this situation can lead to a blackout [100]. The stability of the system has then been compromised, and all DG units are disconnected from the MG [101–103].

The process of restoring the system is called a black-start [101]. Power management, balancing, and voltage control are the responsibilities of the black-start restoration service, which is embedded in the MGCC. As presented by Lopes et al. [104], black-start operations are divided into two significant categories, as dictated by the availability and sequence of the restoration strategy. The first category is based on bidirectional communication links, the ability to receive the most recent information from microsources (MSs), and the ability to disconnect loads [105].

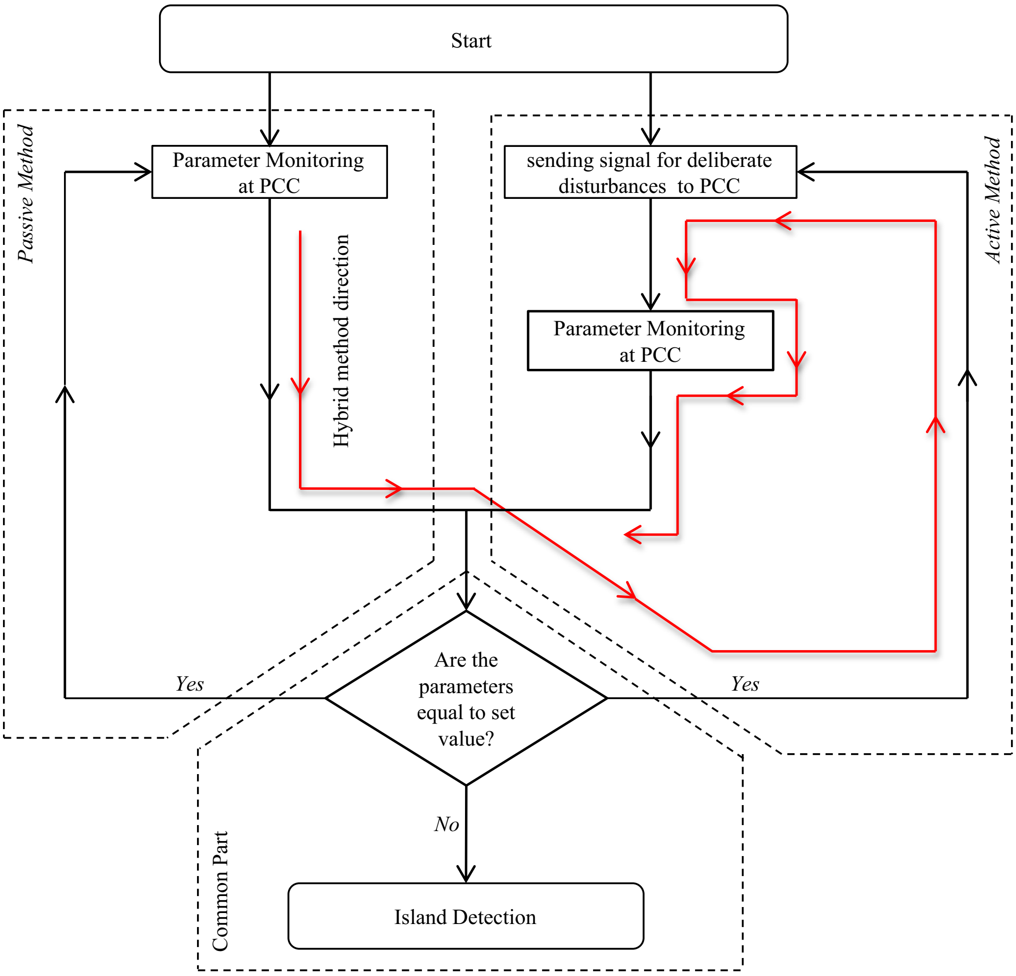

Fig. 3. Algorithm of local island-detection methods.

Table 5
Remote methods island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation /Speed
Transfer trip scheme	Circuit breaker statues by real time voltage	There is no NDZ	Real time monitoring of voltage can be difficult for multiple DG unit	None	✓	_	Simple/Fast
Power line communication	Continuously broadcast single to all DG units	Most effective in multiple DG case	High cost	None	_	✓	Simple/Slow

Next, the most stable sources for generating the initial power are sought. Fig. 6 presents the fundamental principles of black-start operation strategies (in red). Based on the principle, in order to prevent overloading of MSs or large frequency variations during restoration, all the loads should be disconnected as an initial step. Then, in order to avoid large transient currents or changes in power, the grid must be rebuilt in small steps [106].

After that, both controllable and non-controllable loads are connected to the network, in that order, and the loads are slowly increased [104].

The energy storage system has a very significant effect on the maintenance of power balance and on achieving acceptable voltage levels. As presented by Laaksonen et al. [102], the most effective principles for successful black-start operations are as follows: (1) rate the capacity of the storage bank. This can be estimated by considering that it must exceed the largest motor drives and converter-based DG units on the network. However, as a guideline, it should also be between 1.5 and 2 times as large as any directly connected rotating machines. (2) Any directly connected large rotating machines should be attached separately from normal loads. Also, generally speaking, the sequentially connected groups of loads should not exceed the storage available [102]. Further principles of black-start operation are presented by Moreira et al. [107].

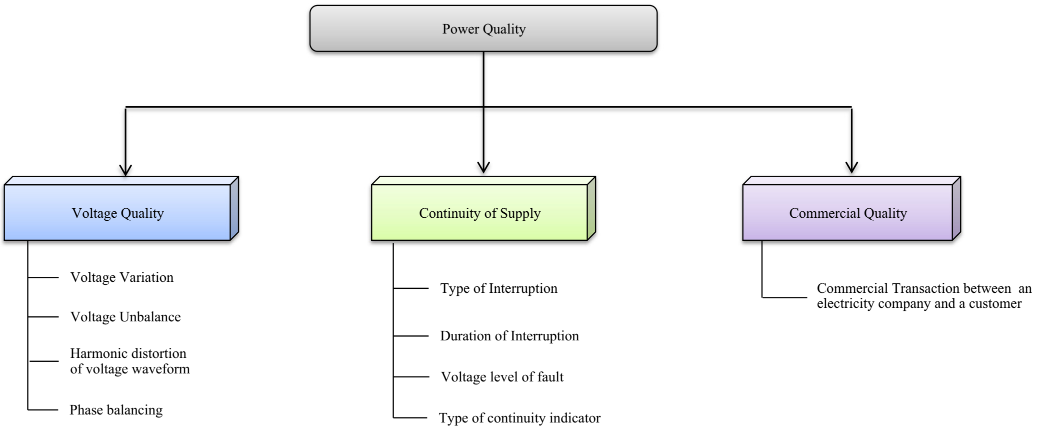

Fig. 4. Power quality coverage issues in microgrid [72].

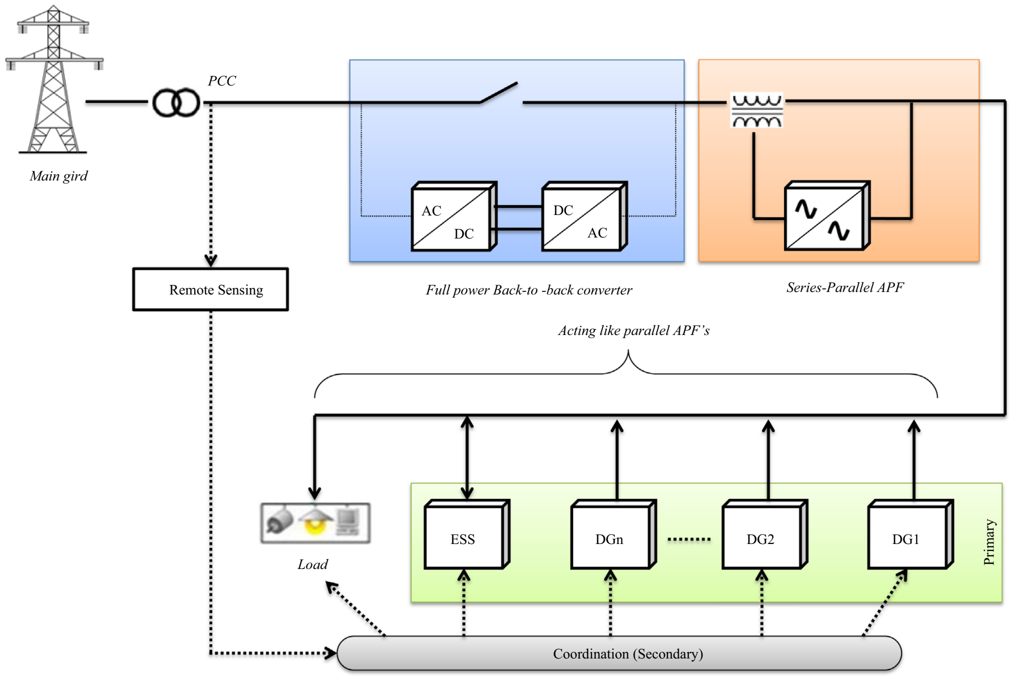

Fig. 5. Power quality scheme.

5. Fault-management principles

As discussed in the introduction, there are two different fault conditions in MGs [108,109]:

- The MG is working in grid-connected mode and a fault appears in the main grid: the MG moves to island mode using one of the methods discussed in Section 2;
- The MG is in island mode and a fault occurs inside the island area. The smallest area containing the fault should be disconnected from the rest of the system. The highest fault current, which can be supplied from the converter-based generators, is the most significant issue in this situation. Generally, these types of generators have design limitations on their converter, which causes the maximum fault current contribution to be no more than twice the rated current of the converter.

As Laaksonen et al. have presented [102], fault management in MG island mode has three parts:

- *Fault detection*: depending on which part of the system the fault occurs in, there are different methods of fault detection in island mode. This will be discussed in Section 6.
- *Fault type*: the detection of the fault type in an islanding MG is based on measurement of the phase voltages.
- *Fault location detection*: by measuring the current through the relay installed in each feeder, it is possible to find the location of fault.

Fault management in MGs is based on the exchange of information through the signals between the MGCC and the protection devices. Since protection in MGs is especially important in island mode, the DG units inside the MG must also have a backup protection setting, in

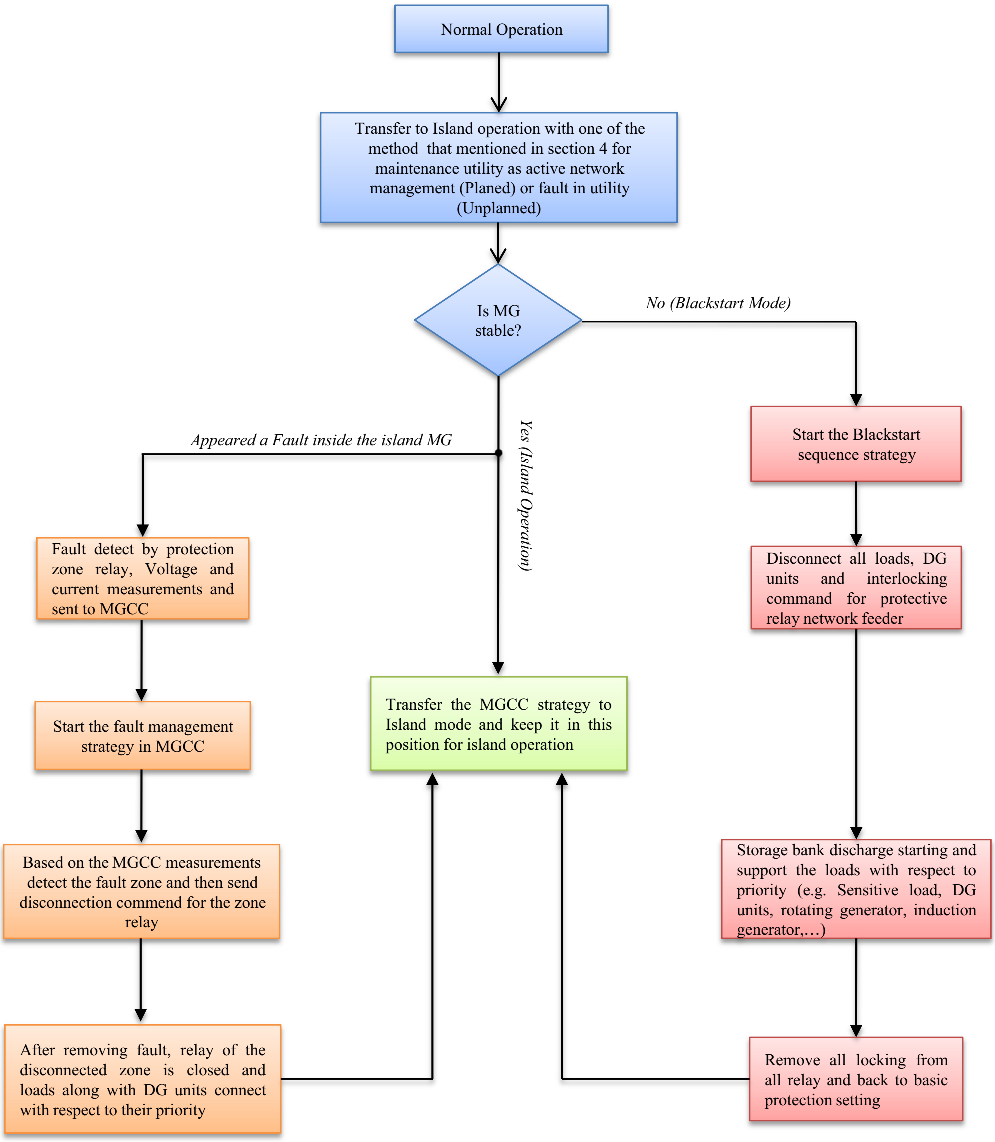

Fig. 6. Principle of black-start operation and fault management strategy. [102] (For interpretation of the references to color in this figure, the reader is referred to the web version of this article)

order to have proper operation in case the communication link with the MGCC is lost. The fault-management strategy during MG islanding is shown in orange in Fig. 6.

6. Protection

The reliability of an MG, in either grid-connected or island mode, depends crucially on the protection system employed [110]. Indeed, the protection device, protection relay, measurement equipment, and grounding are all components of the protection system.

As discussed by Justo [30], safety and fault analysis on one hand and security on the other are two important issues in protection scheme design. Moreover, in investigating these issues, some parameters should be considered. These include sensitivity, selectivity, and the speed of response [111–113].

A number of fundamental structural choices determine the speed requirements and the operational principles of MG protection. The structural choices necessary for fulfilling the speed requirements consist of switch technology, communication technology, and the size of the energy storage bank [114].

As mentioned in Section 5, two specific types of problems occur that, in general, may cause damage. The protection system should attempt to prevent these. The first condition is to maintain MG performance when a fault appears in the main grid [115]. Here, the protection relay must isolate the MG from the fault feeder. Quick switching to island mode must then be achieved through one of the methods mentioned in Section 2.

The second condition is to provide sufficient protection coordination when the system is operating in island mode. This situation removes the smallest part of the system in which the fault occurs [116,117].

The necessary steps and features of the operation of the MG under abnormal conditions arising from faults are described by the Consortium for Electric Reliability Technology Solutions (CERTS) [115]. Under the IEC/ISO 62264 standard, MG protection also has three levels. In the first level, the main structural functions of the fully developed MG include the protection of customers, DG units, and low-voltage feeder. The second level involves protection in the PCC. It should be noted that the third level of the protection also conforms to the grid-connection protection policy.

Researchers have proposed in [114,118] a smart protection system that illustrates suitable protection principles for parallel and island-operated MGs. It also acknowledges the speed requirements for protection. According to these authors, the functions needed for protection in normal and island operation are summarized in the following.

For customers, an overcurrent function is the only protection based on miniature circuit breakers (MCBs) and fuses. The relay is set based on the critical operation mode – in this case, island operation. DG unit protection is based on communication or on local measurement. In the communication method, a transfer signal is received. This could be a trip or a reconnection signal from the microgrid management system (MMS). However, local measuring methods involve voltage, frequency, and synchronization relays. These relays protect the DG unit from any over or under voltage or frequency and assist in synchronizing the unit for connection or reconnection in normal or island operation. Protection of low-voltage feeders can also be based on communications or local measurement in grid-connected mode. The communication policy is the same as for the DG unit. However, the local measuring method uses a directional overcurrent relay, which operates only when a fault appears on the low-voltage feeder. When the MG is connected to the main grid, PCC protection points employ both communication and local measurement. It is the responsibility of the protection system to transfer the disconnection signal from the MV feeder when a fault appears in the main grid. The backup for the transfer signal is the voltage relay applying the local measuring methods when a fault occurs in the main grid. The synchronism check relays used in PCCs are also employed in island-operating mode. Synchronizing the MG reconnection to the main grid according to the voltage phase and frequency difference between the MG and the utility grid is the duty of the relay [118–121].

7. Future trends and conclusion

The growth of renewable energy and its penetration into the main grids has permitted the creation of many new ideas and concepts in network management – including the microgrid. The first part of the paper attempted to propose standards (IEC/ISO 62264) for three different aspects of MG: hierarchical control, storage, and market structure. The second part presented a comprehensive review of the operational issues in MGs that have impacts on their participation in ANM. These issues included island-detection methods, black-start operations, fault-management monitoring and protection, and power quality.

In line with the growth in converter-based DG units and sensitive loads, power quality and power management are crucial for any future MGs. Several methods for power-quality compensation have been proposed in the literature. Indeed, the main performance parameters in power quality are voltage and frequency regulation, along with power sharing.

In the multiple island-detection methods used in MG operations, we noted that the speed and accuracy of detection are the main criteria. Thus, decreasing the operation time while maintaining the protection security is a crucial goal for future research into island-mode detection.

Flexible protection methods are another important issue for the MG. Protection schemes should be able to detect faults and operate in both island- and grid-connection modes. In this paper, several protection devices and measuring types required for different parts of the system have been reviewed. The study of programmable protection devices and high communication capabilities should be taken into account in working on the participation of MGs in ANM.

Acknowledgments

The authors would like to acknowledge the financial support provided by Finnish Funding Agency for Technology and Innovation, Tekes, for the Smart Grids and Energy Markets (SGEM) research program.

References

[1] Farhangi H. The path of the smart grid. Power Energy Mag IEEE 2010;8:18–28.

[2] Siano P. Demand response and smart grids—A survey. Renew Sustain Energy Rev 2014;30:461–78.

[3] Naus J, Spaargaren G, Van vliet BJM, Van der horst HM. Smart grids, information flows and emerging domestic energy practices. Energy Policy 2014;68:436–46.

[4] Kyriakarakos G, et al. Intelligent demand side energy management system for autonomous polygeneration microgrids. Appl Energy 2013;103:39–51.

[5] Firestone, R and Marnay, C. Energy manager design for microgrids; 2005.

[6] Kim J, et al. Mode adaptive droop control with virtual output impedances for an inverter-based flexible AC microgrid. IEEE Trans Power Electron 2011;26:689–701.

[7] Hatziargyriou N, et al. Microgrids. Power Energy Mag IEEE 2007;5:78–94.

[8] Lasseter, R., et al., Integration of distributed energy resources. The CERTS Microgrid Concept, 2002.

[9] Liu, X and Su, B. Microgrids—an integration of renewable energy technologies, in: Proceedings of China international conference on electricity distribution, 2008. CICED 2008. p. 1–7.

[10] Planas E, et al. General aspects, hierarchical controls and droop methods in microgrids: a review. Renew Sustain Energy Rev 2013;17:147–59.

[11] Abu-Sharkh S, et al. Can microgrids make a major contribution to UK energy supply? Renew Sustain Energy Rev 2006;10:78–127.

[12] Carr, JA., et al.A survey of systems to integrate distributed energy resources and energy storage on the utility grid. In: Proceedings of energy 2030 conference. ENERGY 2008. IEEE; 2008. p. 1–7.

[13] Suryanarayanan, S., et al.Achieving the smart grid through customer-driven microgrids supported by energy storage. In: Proceedings of the international conference on industrial technology (ICIT), 2010 IEEE; 2010. p. 884–890.

[14] Palizban O, et al. Microgrids in active network management—Part I: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014. http://dx.doi.org/10.1016/j.rser.2014.01.016.

[15] Palizban, O and Kauhaniemi, K. Microgrid control principles in island mode operation. In Proceedings of the PowerTech (POWERTECH). IEEE Grenoble, 2013, pp. 1–6.

[16] Sirvio KH. Integerating Low Voltage Distribution Systems to Distribution Automation [M.Sc. thesis]. Electrical Engineering, University of Vaasa; 2012.

[17] Colmenar-Santos A, et al. The impact of different grid regulatory scenarios on the development of renewable energy on islands: A comparative study and improvement proposals. Renew Energy 2013;60:302–12.

[18] Prodromidis G, Coutelieris F. A comparative feasibility study of stand-alone and grid connected RES-based systems in several Greek Islands. Renew Energy 2011;36:1957–63.

[19] Bhattacharyya SC. Review of alternative methodologies for analysing off-grid electricity supply. Renew Sustain Energy Rev 2012;16:677–94.

[20] Guerrero JM, et al. Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids. IEEE Trans Indus Electron 2013;60:1263–70.

[21] Hatziargyriou, ND and Meliopoulos, AS.. Distributed energy sources: technical challenges. In proceedings of the power engineering society winter meeting. IEEE; 2002. p. 1017–22.

[22] Kumar KP., et al. A review on power quality in grid connected renewable energy system. CVR Journal of Science and Technology, p. 57.

[23] Xu W, et al. A power line signaling based technique for anti-islanding protection of distributed generators—part i: scheme and analysis. IEEE Trans Power Deliv 2007;22:1758–66.

[24] Blaabjerg F, et al. Overview of control and grid synchronization for distributed power generation systems. Ind Electron IEEE Trans 2006;53: 1398–1409.

[25] Shi, S., et al.. Protection of microgrid 2010.

[26] Nikkhajoei, H and Lasseter, RH.. Microgrid protection. In: Proceedings of the Power Engineering Society General Meeting. IEEE; 2007. p. 1–6.

[27] Zeineldin, H., et al.. Distributed generation micro-grid operation: control and protection. In Proceedings of the power systems conference: advanced metering, protection, control, communication, and distributed resources; PS'06 2006, p. 105–111.

[28] Vilathgamuwa DM, et al. Protection of microgrids during utility voltage sags. Ind Electron IEEE Trans 2006;53:1427–36.

[29] Salomonsson D, et al. Protection of low-voltage DC microgrids. Power Deliv, IEEE Trans 2009;24:1045–53.

[30] Justo JJ, et al. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew Sustain Energy Rev 2013;24:387–405.

[31] Al-Saedi W, et al. Power quality enhancement in autonomous microgrid operation using particle swarm optimization. Int J Electr Power Energy Syst 2012;42:139–49.

[32] Prodanovic M, Green TC. High-quality power generation through distributed control of a power park microgrid. Ind Electron IEEE Trans 2006;53: 1471–82.

[33] Hudson, RM., et al.. Implementation and testing of anti-islanding algorithms for IEEE 929-2000 compliance of single phase photovoltaic inverters. In: Proceedings of the photovoltaic specialists conference, conference record of the twenty-ninth IEEE. 2002. pp. 1414–19.

[34] Basso TS, DeBlasio R. IEEE 1547 series of standards: interconnection issues. Power Electron IEEE Trans 2004;19:1159–62.

[35] Timbus, A., et al.. Islanding detection in smart grids. In: Proceedings of energy conversion congress and exposition (ecce), 2010 ieee, 2010, p. 3631–37.

[36] Doumbia ML, et al. Islanding detection method for a hybrid renewable energy system. Int J Renew Energy Res (IJRER) 2011;1:41–53.

[37] Teoh WY, Tan CW. An overview of islanding detection methods in photovoltaic systems. World Acad Sci Eng Technol 2011;58:674–82.

[38] Khamis A, et al. A review of islanding detection techniques for renewable distributed generation systems. Renew Sustain Energy Rev 2013;28:483–93.

[39] Etxegarai, A., et al.. Analysis of remote islanding detection methods for distributed resources. In: Proceedings of the international conference on renewable energies and power quality. ICREPQ; 2011. p. 13–5.

[40] Llaria A, et al. Survey on microgrids: Unplanned islanding and related inverter control techniques. Renew Energy 2011;36:2052–61.

[41] Hernandez-Gonzalez G, Iravani R. Current injection for active islanding detection of electronically-interfaced distributed resources. Power Deliv IEEE Trans 2006;21:1698–705.

[42] Conti S. Analysis of distribution network protection issues in presence of dispersed generation. Electric Power Syst Res 2009;79:49–56.

[43] Vahedi H, et al. Islanding detection for inverter-based distributed generation using a hybrid sfs and qf method. Int Rev Electrical Eng 2010;5.

[44] ZEINELDIN HH. A Q-f droop curve for facilitating islanding detection of inverter-based distributed generation. IEEE Trans Power Electron 2009;24: 665–73.

[45] Mahat, P., et al.. Review of islanding detection methods for distributed generation. In: Proceedings of the third international conference on electric utility deregulation and restructuring and power technologies, 2008. DRPT 2008;2008. p. 2743–48.

[46] Zeineldin HH, et al. Three-dimensional non-detection zone for assessing anti-islanding detection schemes. Electric Power Compon Syst 2010;38: 621–36.

[47] Narendiran S, et al. Islanding issues of grid-connected PV systems. Int J Eng Technol 2013;5:0975–4024.

[48] Lopes LA, Sun H. Performance assessment of active frequency drifting islanding detection methods. Energy Convers IEEE Trans 2006;21:171–80.

[49] Cardenas A, et al. Islanding detection method for multi-inverter distributed generation. J Electromagn Anal Appl 2009;1:170–80.

[50] Tan WYTCW. An overview of islanding detection methods in photovoltaics. World Acad Sic Eng Technol 2011.

[51] Jang S-I, Kim K-H. An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current. Power Deliv IEEE Trans 2004;19:745–52.

[52] Pigazo A, et al. Wavelet-based islanding detection in grid-connected PV systems. Ind Electron IEEE Trans 2009;56:4445–55.

[53] Vahedi H, et al. A new method for islanding detection of inverter-based distributed generation using DC-link voltage control. Power Deliv IEEE Trans 2011;26:1176–86.

[54] Vieira JCM, et al. Efficient coordination of ROCOF and frequency relays for distributed generation protection by using the application region. Power Deliv IEEE Trans 2006;21:1878–84.

[55] Freitas W, et al. Comparative analysis between ROCOF and vector surge relays for distributed generation applications. Power Deliv IEEE Trans 2005;20:1315–24.

[56] Pai F-S, Huang S-J. A detection algorithm for islanding-prevention of dispersed consumer-owned storage and generating units. Energy Convers IEEE Trans 2001;16:346–51.

[57] Jang SI, Kim KH. An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current. Power Deliv IEEE Trans 2004;19:745–52.

[58] Trujillo C, et al. Analysis of active islanding detection methods for grid-connected microinverters for renewable energy processing. Appl Energy 2010;87:3591–605.

[59] Kunte, RS and Gao, W.. Comparison and review of islanding detection techniques for distributed energy resources. In: Proceedings of the power symposium, 2008. NAPS'08. 40th North American; 2008. p. 1–8.

[60] Massoud A, et al. Harmonic distortion-based island detection technique for inverter-based distributed generation. Renew Power Gener IET 2009;3: 493–507.

[61] Zeineldin, H., et al.. Islanding detection of inverter-based distributed generation In proceedings of generation, transmission and distribution, IEE; 2006. p. 644–52.

[62] Ropp ME, et al. Determining the relative effectiveness of islanding detection methods using phase criteria and nondetection zones. Energy Convers IEEE Trans 2000;15:290–6.

[63] Velasco D, et al. Review of anti-islanding techniques in distributed generators. Renew Sustain Energy Rev 2010;14:1608–14.

[64] Karimi H, et al. Negative-sequence current injection for fast islanding detection of a distributed resource unit. Power Electron IEEE Trans 2008;23: 298–307.

[65] Menon V, Nehrir MH. A hybrid islanding detection technique using voltage unbalance and frequency set point. Power Syst IEEE Trans 2007;22: 442–8.

[66] Yin, J., et al.. A new hybrid anti-islanding algorithm in grid connected three-phase inverter system. In: Proceedings of 37th IEEE power electronics specialists conference (PESC'06); 2006. p. 1–7.

[67] Streutker DR. A remote sensing study of the urban heat island of Houston, Texas. Int J Remote Sens 2002;23:2595–608.

[68] Laaksonen H. Technical Solutions for Low-Voltage Microgrid Concept [Ph.D. dissertation]. University of Vaasa; 2011.

[69] Herman, D.. Investigation of the technical and economic feasibility of micro-grid based power systems. EPRI Interim Report, 1003973, December 2001.

[70] Basu AK, Chowdhury SP, Chowdhury S, Paul S. Microgrids: Energy management by strategic deployment of DERs–A comprehensive survey. Renew Sustain Energy Rev 2011;15(19):4348–56.

[71] Glover JD, et al. Power System Analysis and Design. Cengage Learning; 2011.

[72] Khadem M, Basu M, Conlon MF. UPQC for Power Quality Improvement in DG Integrated Smart Grid Network–A Review. J Emerg Electr Power Syst 2012;13:3.

[73] 5th CEER BENCHMARKING REPORT ON THE QUALITY OF ELECTRICITY SUPPLY, Council of European Energy RegulatorsApril 2012. 2011, Available in ⟨www.energy-regulators.eu⟩.

[74] Vannoy DB, et al. Roadmap for power-quality standards development. Ind Appl IEEE Trans 2007;43:412–21.

[75] Enslin JH, Heskes PJ. Harmonic interaction between a large number of distributed power inverters and the distribution network. Power Electron IEEE Trans 2004;19:1586–93.

[76] A. Martins, et al., Active power filters for harmonic elimination and power quality improvement; 2011.

[77] Lee T-L, Hu S-H. Discrete frequency-tuning active filter to suppress harmonic resonances of closed-loop distribution power systems. Power Electron, IEEE Trans 2011;26:137–48.

[78] Zamora R, Srivastava AK. Controls for microgrids with storage: Review, challenges, and research needs. Renew Sustain Energy Rev 2010;14:2009–18.

[79] Huang S-J, Pai F-S. Design and operation of burn-in test system for three-phase uninterruptible power supplies. Ind Electron IEEE Trans 2002;49: 256–63.

[80] Carrasco JM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. Ind Electron IEEE Trans 2006;53:1002–16.

[81] Vasquez, J.C., et al.. Modeling, analysis, and design of stationary reference frame droop controlled parallel three-phase voltage source inverters. In: Proceedincs of the IEEE Transaction; 2013. p. 272–9.

[82] Khadem, S.K., et al.. A review of parallel operation of active power filters in the distributed generation system. In: Proceedings of the 2011-14th European conference on power electronics and applications. (EPE); 2011. p. 1–10.

[83] Savaghebi, M., et al.., Autonomous voltage unbalance compensation in an islanded droop-controlled microgrid, IEEE Transactions, 2013.

[84] Peas Lopes J, et al. Defining control strategies for microgrids islanded operation. Power Syst IEEE Trans 2006;21:916–24.

[85] Hochgraf C, Lasseter RH. Statcom controls for operation with unbalanced voltages. Power Deliv IEEE Trans 1998;13:538–44.

[86] Wang, G., et al.. A novel control algorithm for cascade shunt active power filter. In Proceedings of the IEEE 35th annual power electronics specialists conference PESC. 2004; p. 771–5.

[87] Savaghebi, M., et al.. Experimental evaluation of voltage unbalance compensation in an islanded microgrid. In: Proceedings of the IEEE international symposium on, industrial electronics (ISIE). 2011; p. 1453–8.

[88] Luo A, et al. Power electronic hybrid system for load balancing compensation and frequency-selective harmonic suppression. Ind Electron IEEE Trans 2012;59:723–32.

[89] Chakraborty S, et al. Distributed intelligent energy management system for a single-phase high-frequency AC microgrid. Ind Electron IEEE Trans 2007;54:97–109.

[90] He J, et al. A flexible harmonic control approach through voltage-controlled DG–grid interfacing converters. Ind Electron IEEE Trans 2012;59:444–55.

[91] Li YW, et al. A grid-interfacing power quality compensator for three-phase three-wire microgrid applications. Power Electron, IEEE Trans 2006;21: 1021–1031.

[92] Li Y, et al. Microgrid power quality enhancement using a three-phase four-wire grid-interfacing compensator. Ind Appl IEEE Trans 2005;41:1707–19.

[93] Hojo, M., et al.. A method of three-phase balancing in microgrid by photovoltaic generation systems. In: Proceedings of the power electronics and motion control conference EPE-PEMC. 2008; p. 2487–91.

[94] Cheng P-T, et al. A cooperative imbalance compensation method for distributed-generation interface converters. Ind Appl IEEE Trans 2009;45: 805–815.

[95] Q.-C. Zhong and T. Hornik. Cascaded current-voltage control to improve the power quality for a grid-connected inverter with a local load, 2013.

[96] Niiranen, J., et al.. Experiences from a back-to-back converter fed village microgrid. In: Proceedings of the innovative smart grid technologies conference Europe (ISGT Europe) IEEE PES. 2010; p. 1–5.

[97] Lin, Z., et al.. Economic evaluation of real-time power quality cost. In: Proceeding of the 45th international universities power engineering conference (UPEC). 2010; p. 1–5.

[98] McGranaghan M, Roettger B. Economic evaluation of power quality. Power Eng Rev IEEE 2002;22:8–12.

[99] Katiraei F, et al. Micro-grid autonomous operation during and subsequent to islanding process. Power Deliv IEEE Trans 2005;20:248–57.

[100] Van der Vleuten E, Lagendijk V. Transnational infrastructure vulnerability: the historical shaping of the 2006 European Blackout. Energy Policy 2010;38:2042–52.

[101] Feltes, J and Grande-Moran, C.. Black start studies for system restoration. In: Proceedings of the power and energy society general meeting-conversion and delivery of electrical energy in the 21st century. 2008; p. 1–8.

[102] Laaksonen, H and Kauhaniemi, K. Control principles for blackstart and island operation of microgrid. In: Proceedings of the nordic workshop on power and industrial electronics (NORPIE/2008). Espoo, Finland: June 9–11, 2008.

[103] Sun, W., et al.. Black start capability assessment in power system restoration. In Proceedings of the power and energy society general meeting, 2011 IEEE; 2011. p. 1–7.

[104] Lopes, JP., et al.. Microgrids black start and islanded operation. In Proceedings of the 15th Power Systems Computation Conference (PSCC); Liege; 2005.

[105] Pogaku N, et al. Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. Power Electron IEEE Trans 2007;22:613–25.

[106] Lidula N, Rajapakse A. Microgrids research: a review of experimental microgrids and test systems. Renew Sustain Energy Rev 2011;15:186–202.

[107] Moreira C, et al. Using low voltage microgrids for service restoration. Power Syst IEEE Trans 2007;22:395–403.

[108] Jiayi H, et al. A review on distributed energy resources and MicroGrid. Renew Sustain Energy Rev 2008;12:2472–83.

[109] Ustun TS, et al. Modeling of a centralized microgrid protection system and distributed energy resources according to IEC 61850-7-420. Power Syst IEEE Trans 2012;27:1560–7.

[110] Nimtaj, B., et al.. A comparison of two numerical relay low impedance restricted earth fault algorithms in power transformer. In: Proceedings of the 8th international conference on electrical engineering/electronics, computer, telecommunications and information technology (ECTI-CON). 2011. p. 792–5.

[111] Peesapati V, et al. Lightning protection of wind turbines–a comparison of measured data with required protection levels. IET Renew Power Gener 2011;5:48–57.

[112] Chowdhury, S., et al.. Islanding protection of distribution systems with distributed generators—A comprehensive survey report. In: Proceedings of the power and energy society general meeting-conversion and delivery of electrical energy in the 21st century IEEE, 2008. p 1–8.

[113] Haron AR, et al. A review on protection schemes and coordination techniques in microgrid system. J Appl Sci 2012;12.

[114] Laaksonen H, Kauhaniemi K. Smart protection concept for LV microgrid. Int Rev Electr Eng (IREE) 2010;5:578–92.

[115] Basak P, et al. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16:5545–56.

[116] Monfared M, Golestan S. Control strategies for single-phase grid integration of small-scale renewable energy sources: a review. Renew Sustain Energy Rev 2012;16:4982–93.

[117] Pouresmaeil E, et al. Multilevel converters control for renewable energy integration to the power grid. Energy 2011;36:950–63.

[118] Laaksonen HJ. Protection principles for future microgrids. Power Electron IEEE Trans 2010;25:2910–8.

[119] Kauhaniemi K, Rintamaeki O. Applying modern communication technology to loss-of-mains protection. J Energy Power Eng 2012;6:429–33.

[120] K. Schwarz and I. Eichbaeumle, IEC 61850, IEC 61400-25 and IEC 61970: Information models and information exchange for electric power systems. In: Proceedings of the Distributech; 2004. p.1-5, .

[121] Quecedo, E., et al.. The use of IEC 61400-25 standard to integrate wind power plants into the control of power system stability. In: proceedings of the european wind energy conference and exhibition; 2007. p. 1–4.

Publication V

Distributed cooperative control of battery energy storage system in AC microgrid applications

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Journal of Energy Storage 3 (2015) 43–51

Journal of Energy Storage 3 (2015) 43–51

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Distributed cooperative control of battery energy storage system in AC microgrid applications

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ARTICLE INFO

Article history:
Received 1 August 2015
Received in revised form 20 August 2015
Accepted 20 August 2015
Available online 26 September 2015

Keywords:
Battery energy storage system
Distributed control
Droop control
SoC balancing

ABSTRACT

The approach to optimal control for distributed battery energy storage systems (BESS) has recently been closely investigated and implemented by numerous experts. The management of the power balance based on the dischargeable energy of each battery is the main issue in this type of BESS control. In this regard, the performance of power sharing between Battery Energy Storage Units (BESUs) with different States of Charge (SoC) can be enhanced. Based on the traditional droop control, the sharing of power between different BESUs is based on power capacities, rather than on energy levels; it thus causes some limitations for the ideal injection and absorption of energy by the energy storage system. In this paper, a decentralized control method for SoC is proposed, based on a modified droop control method in which the SoC of each BESU is balanced during the discharge process. The droop coefficients should be set to be inversely proportional to the SoC of each BESU. Using this control strategy, the storage unit with the highest SoC provides more power to support the load, while the unit with lower SoC provides less power. Thus, the output power of each converter will be proportional to each SoC. The method is validated using simulation results from PSCAD/EMTDC software.

1. Introduction

Renewable energy source (RES) powered generators are the most popular of the energy sources that can be integrated into the main network in the form of Distributed Generators (DG) or Microgrids (MGs) [1–3]. Managing power balance and stability is nonetheless a challenging task, as these factors depend on a number of variables, especially when MGs operate in island mode. To meet this challenge, three major approaches are offered [4]:

- Operating the RES in deloading mode and introducing a limitation on the power supplied by the RES. However, this method is only effective when more power is generated than is demanded, and so cannot be considered during power shortages. Moreover, the method can reduce the efficiency of the energy utility [5].
- Load shedding or power management on the demand side to regulate the loads based on the power generated by the RES. This method needs a rapid response from the demand side and also may cause customer dissatisfaction [6].
- Implementing an energy storage system alongside the RESs and MGs. The system can absorb power when power generation is higher than the demand and can inject the stored power into the system during shortages [7].

The storage of energy can be achieved by converting electrical energy into another form, such as chemical or mechanical energy. In recent years, advanced energy storage technologies have been investigated by researchers who have produced comprehensive reviews, such as Tan et al. [8], Carnegie et al. [9], and Bradbury [10]. Based on these studies, electrochemical storage (battery storage) is the most commonly used technique and covers many applications.

The battery energy storage system (BESS) is a power electronic-based device that can minimize the power variation in the system and increase the integration of RESs through a suitable cooperative control [4]. Such BESSs may be distributed or aggregated in arrangement. The aggregated model operates on similar principles to the master unit [11,12] and the microgrid is supported through a central energy storage system. Depending on the arrangement, this system may be connected to the DC bus [13,14] directly or through a power electronics interface [8]. The model is popular in small-scale MGs that have a low level of generation and demand. In a distributed arrangement, the BESS is connected through different individual power electronic interfaces to each DG. In this method, each storage system has responsibility for the control

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http://dx.doi.org/10.1016/j.est.2015.08.005
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and optimization of the power output of the sources to which it is connected [15].

The control methodologies for the BESUs can be classified as central or decentralized, which cover both of the storage arrangements. Since the storage energy level is different in each BESU, the critical issue in control strategies is to balance the energy. The discussion of centralized control of the power-electronics interfaced DG system with the BESS is well-known and is presented in [16–18]. Recently, different strategies have been proposed for energy storage balance in distributed BESUs [19–24], but these proposed method are based on a centralized control unit and employ a communications system. Thus, operating the system under these control methods involves a high level of risk, as the storage system may go out of control with a malfunction in the central control part or the communication link. In [25], a decentralized strategy that does not need communication between BESUs is described; this considers equalization through an adaptive droop control while the batteries are supplying power to the load. A decentralized strategy for equalizing the SoC during both charging and discharging is proposed in [26] and employs a double-quadrant method. The drawback of this method is that it depends on the initial SoC at each unit, and also requires previous knowledge of the characteristics of the other BESUs. In fuzzy control methodologies, some energy balancing is also proposed based on the fuzzy interface described in [27] for island DC microgrids and adapted to AC microgrids in [28]. In [29], a distributed control strategy is proposed for power electronics-based MGs, based on sharing voltage, frequency, and reactive power. In this method, the control signal for each DG is provided for the lower control level through the measurements of other DGs in each sample frame. In this paper, the control strategy proposed in [29] is adapted, applied, and evaluated for an BESS, considering also the SoC equalization when the batteries are discharging. In a BESU, the dischargeable energy is equivalent to the stored energy. To optimize the operation of the storage unit, control of the SoC is required, but this control should not have any effect on the performance of the BESU control [30]. During the process of charging and discharging, the SoC of each BESU should be balanced and their outputs or inject powers should be based on the SoC of the same BESU. Since the sharing of power between the different BESUs is based on power capacity, rather than on energy levels, some malfunction of the droop control may occur; there are also several general limitations to facilitating power sharing between the units [31–33]. Hence, it is necessary to modify the droop control in order to overcome this limitation. In this paper, a SoC-balancing method based on a modified droop control suitable for adapting control strategies is also employed.

The present paper is organized as follows: the configuration of the BESS is presented in Section 2. Section 3 discusses in detail the coordinating SoC control strategy for the BESS. In Section 4, a simulation study is presented to evaluate the performance of the proposed cooperative control method. Finally, the paper is concluded in Section 5.

2. BESS configuration

The BESS contains several parts with different responsibilities. A configuration involving the battery bank, along with the control block diagram, is shown in Fig. 1. The BESS control block diagram consists of three different parts—namely, as inner control loop, the

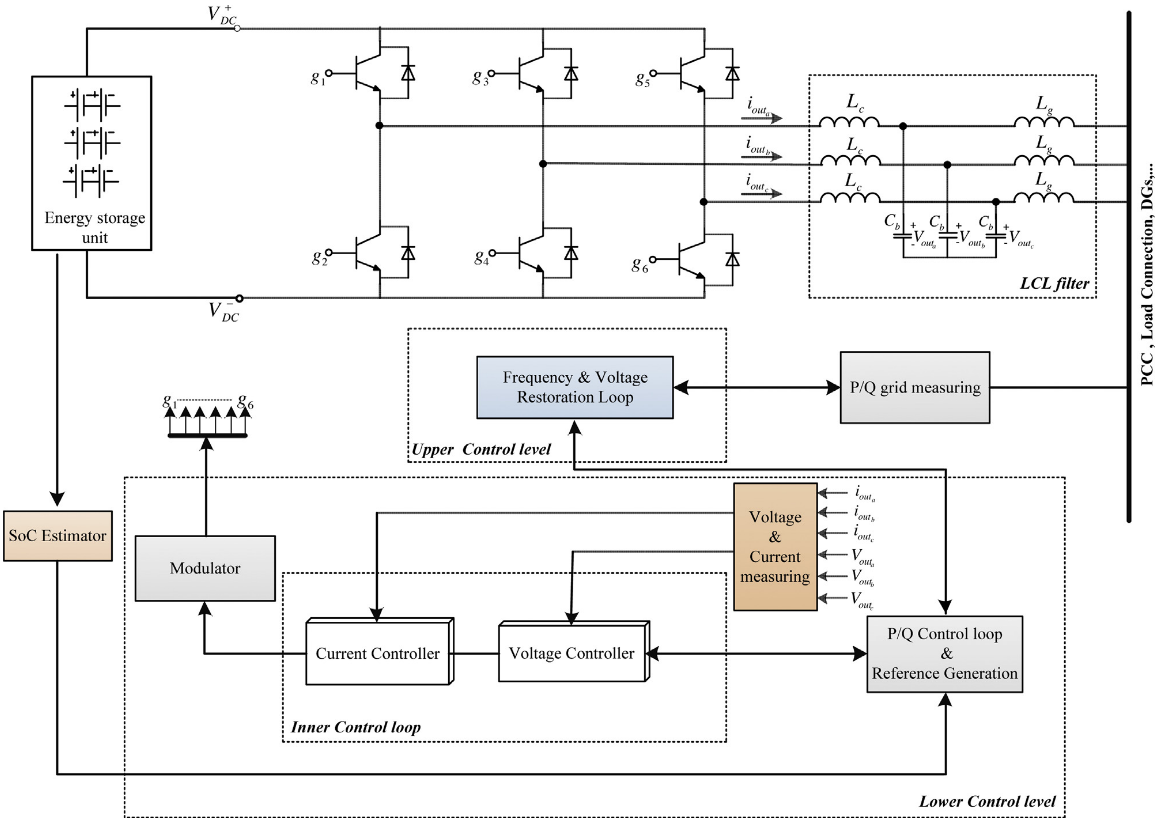

Fig. 1. Configuration of the ESS.

lower control level, and the upper control level. These are explained in detail below:

2.1. Inner control loop

Managing the output power of the BESUs is the main goal of this control level, and is generally accomplished through the inner current and voltage-control loop. The first step is the BESU operating point control, using power electronic devices [34]. In this control part, the desired voltage is determined by comparing the reference and measured values. Then, turn-on and turn-off switching signals are the generated for the six insulated gate bipolar transistors (IGBTs). Reference values for voltage and current controllers are calculated as follows [35,36]:

a. Voltage control loop

$$V^* = \begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = Bc_1 \begin{bmatrix} V_a^{\mathrm{ref}} \\ V_b^{\mathrm{ref}} \\ V_c^{\mathrm{ref}} \end{bmatrix} - Bc_2 \begin{bmatrix} (V_a + V_{ia}) \\ (V_b + V_{ib}) \\ (V_c + V_{ic}) \end{bmatrix}$$

$$i^{\mathrm{ref}} = \begin{bmatrix} i_a^{\mathrm{ref}} \\ i_b^{\mathrm{ref}} \\ i_c^{\mathrm{ref}} \end{bmatrix} = \mathrm{A}V^* + \mathrm{B}V^*$$

$$Bc_1 = Bc_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{A} = \begin{bmatrix} k_{p\nu} & 0 & 0 \\ 0 & k_{pv} & 0 \\ 0 & 0 & k_{pv} \end{bmatrix}, \mathrm{B} = \begin{bmatrix} k_{iv}/\mathrm{S} & 0 & 0 \\ 0 & k_{iv}/\mathrm{S} & 0 \\ 0 & 0 & k_{iv}/\mathrm{S} \end{bmatrix} \tag{1}$$

b. Current control loop

$$i^* = \begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = Bc_1 \begin{bmatrix} i_a^{\mathrm{ref}} \\ i_b^{\mathrm{ref}} \\ i_c^{\mathrm{ref}} \end{bmatrix} - Bc_2 \begin{bmatrix} i_a^l \\ i_b^l \\ i_c^l \end{bmatrix}$$

$$V^{\mathrm{ref}} = \begin{bmatrix} V_a^{\mathrm{ref}} \\ V_b^{\mathrm{ref}} \\ V_c^{\mathrm{ref}} \end{bmatrix} = \mathrm{C}i^* + \mathrm{D}i^*$$

$$C = \begin{bmatrix} k_{pi} & 0 & 0 \\ 0 & k_{pi} & 0 \\ 0 & 0 & k_{pi} \end{bmatrix} \mathrm{D} = \begin{bmatrix} k_{ii}/s & 0 & 0 \\ 0 & k_{ii}/s & 0 \\ 0 & 0 & k_{ii}/s \end{bmatrix} \tag{2}$$

In these equations i^{ref} and V^{ref} are the reference values of the current and voltage, respectively. $V_{a,b,c}$ is the output voltage of the BESU and $V_{i_{a,b,c}}$ is the output voltage of the virtual impedance block. Moreover, the difference between the total amount of these voltage output and reference values is represented by $V_{a,b,c}^*$. The output current measurement is designated by $i_{a,b,c}^l$ and the result of the comparison of this amount with the reference value of current is represented by $i_{a,b,c}^*$. The proportional, as well as the integrational, gains of the PI controller for the current and voltage control loop, respectively, are written as $k_{pi}, k_{ii}, k_{pv}, k_{iv}$.

2.2. Lower control loop

In the BESS configuration, the power control loop consists of a power calculator and a droop control part. To obtain the fundamental components of output active (P) and reactive power (Q) for the droop control, a low-pass filter with cutting frequency (ω_s) is used [35,36].

$$P = \frac{\omega_s}{S + \omega_s} p, \; Q = \frac{\omega_s}{S + \omega_s} q \tag{3}$$

In the control level, the reference voltage and frequency values are created using virtual impedance and a droop control strategy. The responsibility of the droop control is to regulate the amplitude of the voltage and frequency. As shown in Fig. 2 [27], the BESS inverter can be modeled as a controllable AC voltage source ($V\angle\theta$) connected to the microgrid through output impedance ($Z_L\angle\delta$) [36]. In both high and medium voltage systems, the impedance is almost inductive ($Z_L\angle\delta \approx jX$), so the resistive part can be negligible without creating any inaccuracy. However, due to the coupling of active and reactive power when inductance is not present, the implementation of this method can create a particular problem for low voltage systems [37]. Hence, unlike with HV and MV systems, the line impedance with low voltage is more resistive. Since monitoring the frequency is easier, it being constant throughout the network and having a more stable value than the voltage, and also in order to fix the output impedance of the inverter, a suitable virtual impedance (Z_v) is added to the voltage reference, making the output highly inductive.

The frequency and voltage of the droop control for the systems can thus be determined as follows [37,38]:

$$f = f^{\mathrm{ref}} - T_{p(s)} \times (P - P^{\mathrm{ref}}) \tag{4}$$

$$V = V^{\mathrm{ref}} - T_{Q(s)} \times (Q - Q^{\mathrm{ref}}) \tag{5}$$

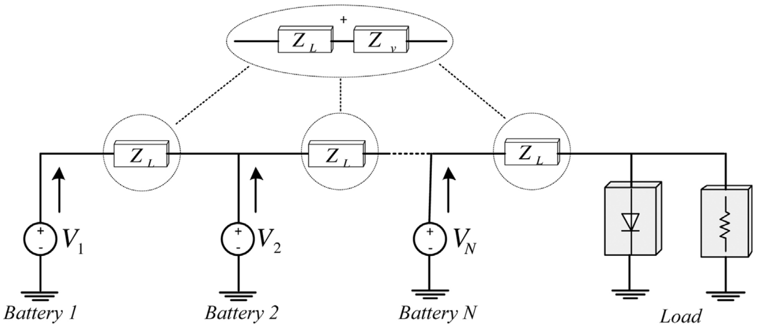

Fig. 2. Equivalent circuit of parallel BESS.

$$T_{p(s)}=\frac{\overbrace{f^{ref}-f^{\min}}^{\Delta f}}{\underbrace{P^{ref}-P^{\max}}_{\Delta P}}\langle 0 \quad , \quad T_{Q(s)}=\frac{\overbrace{V^{ref}-V^{\min}}^{\Delta V}}{\underbrace{Q^{ref}-Q^{\max}}_{\Delta Q}}\langle 0 \tag{6}$$

where P^{ref},f^{ref}, V^{ref}, and Q^{ref} are the reference values of the active power, frequency, voltage and reactive power of the system, respectively. In this formula, the droop coefficients $(T_{P(s)}, T_{Q(s)})$ represent the coordination between adjusting the voltage and the output power of inverter, as discussed later in Section 3.

2.3. Upper control level

The upper control level monitors and reacts to the system in order to keep deviations in the grid frequency and voltage within the permissible range—that is, to ±0.2 Hz in UCTE (Continental Europe) and to ±0.1 Hz in Nordel (North of Europe). It maintains voltage magnitude to −6% to +10 % [38]. Such deviations are regulated toward zero each time there is a load change or when any variation appears in MG power generation.

Based on the method proposed in [29], on this control level, at regular sample intervals, the frequency and voltage are measured. The average and measurement errors of these values are sent to the lower control level, which acts to restore the voltage and frequency. Moreover, because of variations in the voltage at different points, the reactive power also must be measured for each generating unit with the decentralized control method and, along with the frequency and voltage, is shared with the other units. The variation in each reactive power and the restoration compensator are deduced from (7) in the decentralized control [29].

$$\begin{bmatrix}\Delta V_{\text{BESU}_k}\\ \Delta f_{\text{BESU}_k}\\ \Delta Q_{\text{BESU}_k}\end{bmatrix} = E\begin{bmatrix}\Delta V^*_{\text{BESU}}\\ \Delta f^*_{\text{BESU}}\\ \Delta Q^*_{\text{BESU}}\end{bmatrix}$$

$$\begin{bmatrix}\Delta V^*_{\text{BESU}}\\ \Delta f^*_{\text{BESU}}\\ \Delta Q^*_{\text{BESU}}\end{bmatrix} = \text{F}\begin{bmatrix}(V^{\text{ref}}_{\text{BESU}} - \overline{V}_{\text{BESU}_k})\\ (f^{\text{ref}}_{\text{BESU}} - \overline{f}_{\text{BESU}_k})\\ (\overline{Q}_{\text{BESU}_k} - Q_{\text{BESU}_k})\end{bmatrix}$$

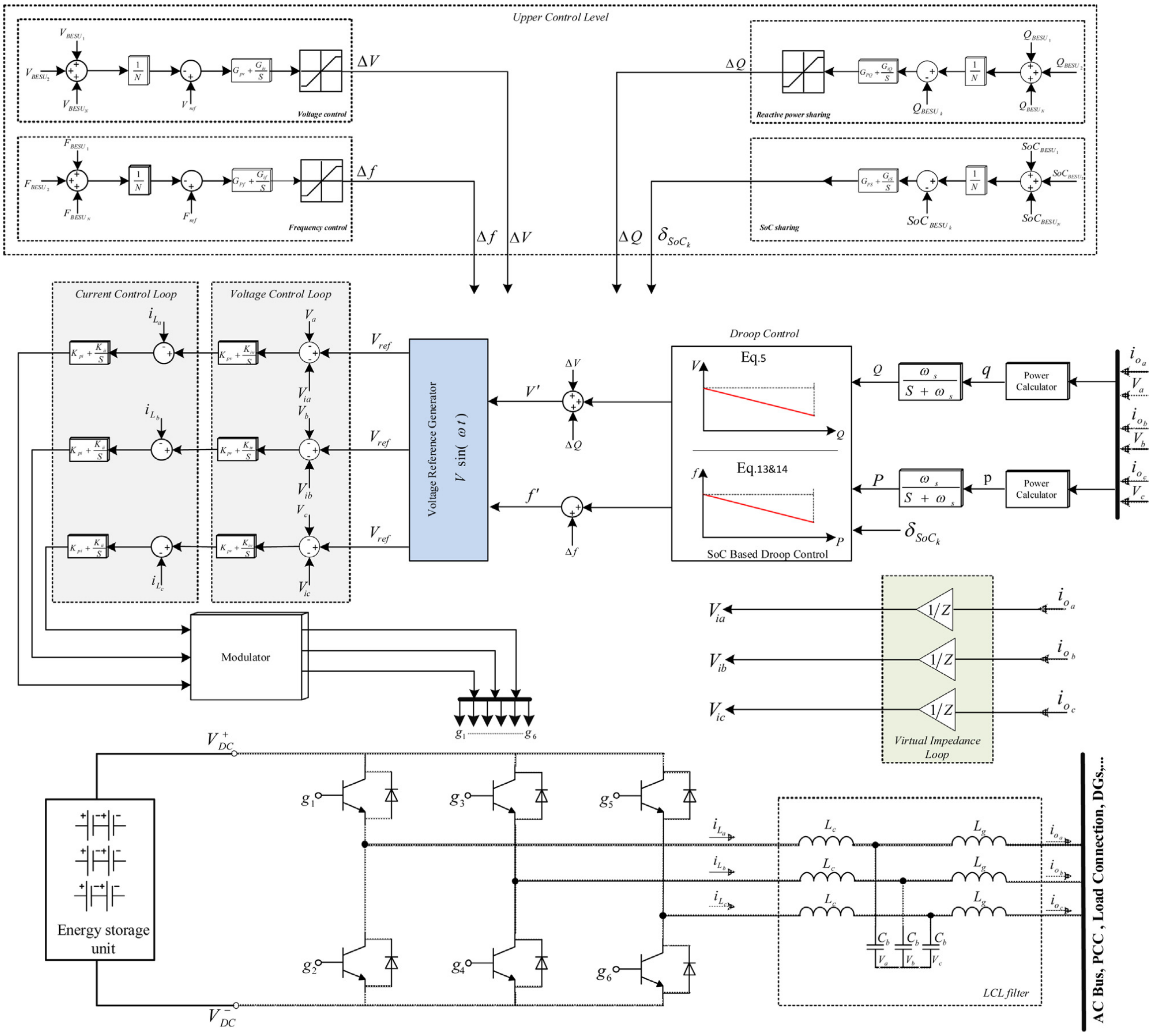

Fig. 3. Distributed control block diagram for BESU.

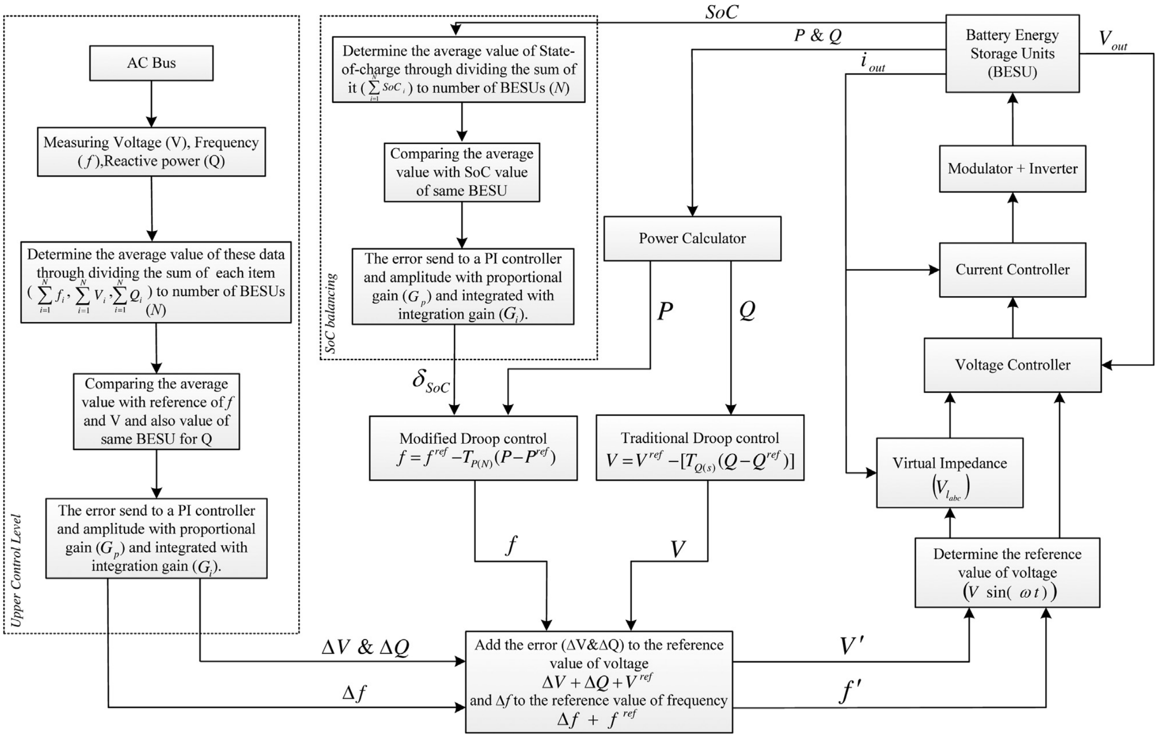

Fig. 4. Flowchart of the proposed distributed control for BESU.

$$\overline{V}_{\mathrm{BESU}_k} = \frac{1}{N}[V_{\mathrm{BESU}_1} + V_{\mathrm{BESU}_2} + \ldots + V_{\mathrm{BESU}_N}]$$

$$\bar{f}_{\mathrm{BESU}_k} = \frac{1}{N}[f_{\mathrm{BESU}_1} + f_{\mathrm{BESU}_2} + \ldots + f_{\mathrm{BESU}_N}]$$

$$\overline{Q}_{\mathrm{BESU}_k} = \frac{1}{N}[Q_{\mathrm{BESU}_1} + Q_{\mathrm{BESU}_2} + \ldots + Q_{\mathrm{BESU}_N}]$$

$$E = \begin{bmatrix} G_{pv} & G_{iv}/s & 0 & 0 & 0 & 0 \\ 0 & 0 & G_{pf} & G_{if}/s & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{PQ} & G_{iQ}/s \end{bmatrix}$$

$$F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

In these equations, $\Delta V_{\mathrm{BESU}_k}$, $\Delta f_{\mathrm{BESU}_k}$, and $\Delta Q_{\mathrm{BESU}_k}$ are the restoration values of the voltage, frequency, and reactive power, respectively. The $\overline{V}_{\mathrm{BESU}_k}$, $\bar{f}_{\mathrm{BESU}_k}$, and $\overline{Q}_{\mathrm{BESU}_k}$ are the average voltage, frequency, and reactive power of BESU_k at each sample time. G_P and G_i are the control parameters of the upper control PI compensator for voltage (v), frequency (f), and reactive power (Q).

One additional significant issue to be considered is that the SoC of batteries may be different. For this reason, in seeking to obtain optimal control, the SoC needs to be balanced at each BESU. A SoC-balancing method based on droop control is thus added to the upper control level (see Section 3).

3. Coordinated SoC control strategy for BESS

In the battery energy storage technique, the operational voltage and current levels are generated through a series or parallel connection of cells [39]. The quantity of electrical charge in the cell from the fully charged state to the discharged state is called the capacity of the battery. Moreover, the SoC is the ratio between the remaining capacity and the full charge; this equals 100% for full charge and 0% for full discharge. As demonstrated in (8), the variation in SoC (ΔSoC) is based on time and its relation to capacity (C_i) [27].

$$\Delta \mathrm{SoC} = \frac{idt}{C_i}$$

$$\mathrm{SoC} = \mathrm{SoC}_{t=0} - \int \frac{idt}{C_i} \tag{8}$$

Generally, the power capacity, rather than the energy level, is used to allocate the required power between the different BESUs, which leads to some problems in the system control. With the power sharing method, the batteries with lower energy levels will inject the same power to the system with BESUs that have higher energy levels, so the lowest units will run out of energy first and will no longer contribute to maintaining the frequency. On the other hand, during the charging process, the absorbing energy is the same for batteries with the lowest and highest energy levels, so when an BESU becomes full, it cannot absorb much generated power, even when the combined power capacities of the unit are higher than the total power demand, and the RES potential will be wasted.

Because of this issue, the traditional droop control has several general limitations to facilitating power sharing between the BESUs and needs to be modified so that the power generated through the BESU is inversely proportional to the energy level. This means that, in the modified droop control, the power is proportionally shared between BESUs, based on the available energy, so that the unit with

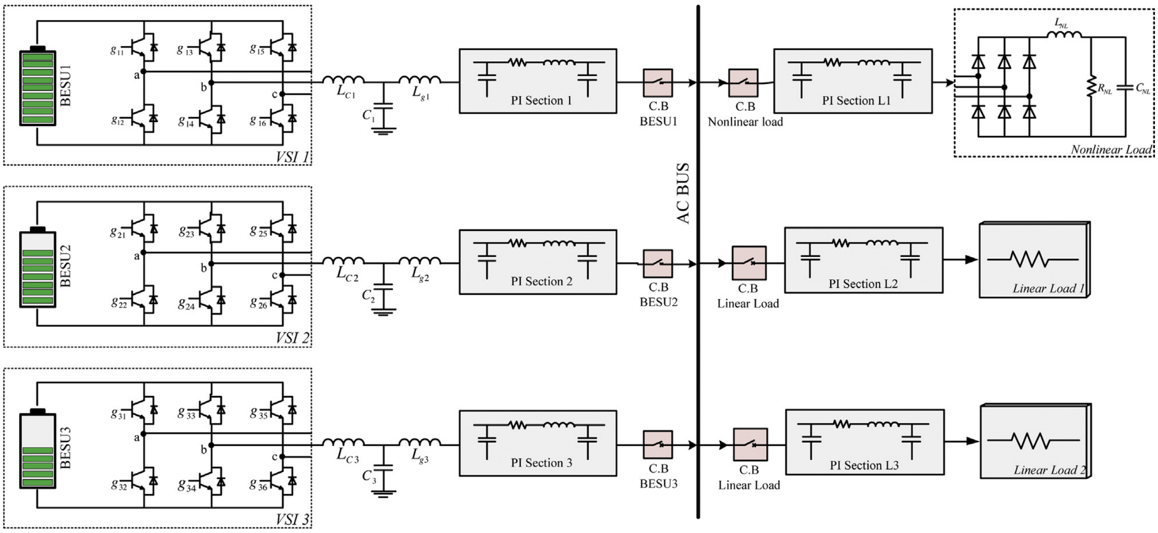

Fig. 5. Configuration of the studied system.

the lowest energy level provides the least power, cooperating instead with the unit with the highest energy level in order to support the load and system. To regulate the power sharing, the droop coefficient needs to be adjusted based on the energy level. In this regards, Lu et al. [25], and Morstyn et al. [36] modified the traditional droop control by multiplying $(1/\alpha)$ with the droop coefficient for DC and AC microgrids. However, in these methods, a battery energy-level limitation is needed to prevent the coefficient going to infinity $(\alpha = \max(E - E_{\min}/E_{\max} - E_{\min}, 0.01))$. Additionally, this limitation increases the risk of BESU control such that a malfunction in the limitation may give rise to a significant problem in controlling the storage system. To overcome the problem, a method for modifying the traditional droop control is here proposed. As mentioned earlier, the optimal continuous operation of a BESS requires accurate SoC control. Since the SoC control should not disturb the BESS control performance, an advanced control structure on the upper control level should be studied when monitoring the SoC of the BESU [30]. In the first step of this strategy, it is necessary to measure the average value of the SoC in all the BESUs ($\mathrm{So\overline{C}_{BESU}}$). To determine the average value of the state of charge, the SoC of each BESU ($\mathrm{SoC}_{\mathrm{BESU}_k}$) $\{K = 1, 2, \ldots, N\}$ must be measured at each sample time and sent to the other units to calculate the total amount of the available state of charge ($\mathrm{SoC_{Total}}$):

$$\mathrm{SoC_{Total}} = \mathrm{SoC}_{\mathrm{BESU}_1} + \mathrm{SoC}_{\mathrm{BESU}_2} + \ldots. + \mathrm{SoC}_{\mathrm{BESU}_N} \tag{9}$$

It is then necessary to divide the sum of all state-of-charge values by the number of battery energy storage units (N).

$$\mathrm{So\overline{C}_{BESU}} = \frac{\mathrm{SoC_{Total}}}{N} \tag{10}$$

Based on (10), the same reference value will be used in each unit and for obtaining the deviation of each BESU (ϑ_k); the average value of SoC is then compared with the SoC value of the same BESU ($\mathrm{SoC}_{\mathrm{BESU}_k}$):

$$\vartheta_k = \mathrm{So\overline{C}_{BESU}} - \mathrm{SoC}_{\mathrm{BESU}_k} \tag{11}$$

Table 1
Simulation parameters.

Type	Item	Symbol	Values & units	Type	Item	Symbol	Values & Units
Upper level control	Amplitude voltage proportional term	G_{PV}	0.2×10^3	Electrical system setup	Filter inductance	L_c	$L_g/2$
	Amplitude voltage integral term	G_{iV}	0.1×10^{-2}		Output impedance	L_g	600
	Frequency proportional term	G_{Pf}	0.1×10^{-2}		Filter capacitance	C_b	100 μf
	Frequency integral term	G_{if}	0.2×10^3		Linear load (1)	R_{LL_1}	200 Ω
	Reactive power proportional term	G_{PQ}	0.1×10^3		Linear load (2)	R_{LL_2}	100 Ω
	Reactive power integral term	G_{iQ}	0.2×10^{-3}		Nonlinear load resistance	R_{NL}	200 Ω
	SoC proportional term	G_{PS}	0.2×10^3		Nonlinear load inductance	L_{NL}	0.084
	SoC integral term	G_{iS}	3		Nonlinear load capacitance	C_{NL}	235 μf
Inner control loop	Voltage proportional term	K_{PV}	0.35		Reference value of frequency	f_{ref}	50
	Voltage integral term	K_{iV}	0.4×10^3		Reference value of voltage	V_{ref}	200
	Current proportional term	K_{Pi}	0.35		LPF Cutting frequency	ω_s	31.42 rad/s
	Current integral term	K_{ii}	0.2×10^3		Number of units	N	3

Transmission line value of the system

From	To	Length (m)	Parameters					
			R_0	X_{L_0}	X_{C_0}	R_+	$X_{\mathrm{L}+}$	$X_{\mathrm{C}+}$
ESU_1	AC bus	100	0.656×10^{-3}	0.3268×10^{-3}	6.643	0.164×10^{-3}	0.0817×10^{-3}	3.571
ESU_2		150	0.456×10^{-3}	0.1268×10^{-3}	6.643	0.143×10^{-3}	0.0417×10^{-3}	3.571
ESU_3		200	0.32×10^{-3}	0.09×10^{-3}	6.643	0.112×10^{-3}	0.00517×10^{-3}	3.571
LL_1, LL_2		50	0.256×10^{-3}	0.1515×10^{-3}	6.643	0.0955×10^{-3}	0.0325×10^{-3}	3.571
NL		50	1.0052×10^{-3}	0.03729×10^{-3}	6.643	0.423×10^{-3}	0.00417×10^{-3}	3.571

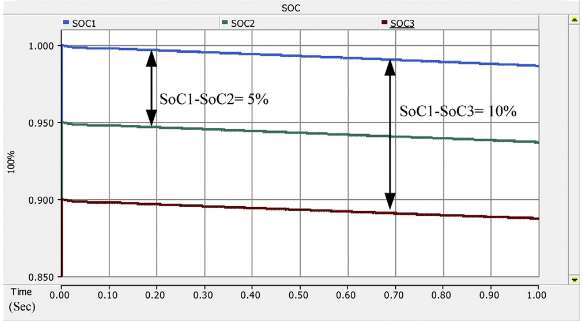

Fig. 6. Difference between SoC value at starting time.

A simple PI controller that is sufficiently fast to avoid full charge or discharge is added in order to determine the suitable value of the SoC. Indeed, the deviation of the SoC is amplified by the gain G_{PS} and integrated with the gain G_{iS}. The control signal in every sample period (δ_{SoC_k}) is shown in (12).

$$\delta_{\mathrm{SoC}_k} = G_{Ps}\vartheta_k + G_{is}\int \vartheta_k dt \qquad (12)$$

To set the droop coefficients based on the energy level of each BESU, the output signal of the PI controllers is added to the traditional droop coefficient which is presented in (4) and the new droop coefficient value ($T_{P(N_k)}$) is defined as:

$$T_{P(N_k)} = T_{P(S)} + \delta_{\mathrm{SoC}_k} \qquad (13)$$

Hence, by combining the traditional droop control (4) and (13), the modified droop control shown in (14) is obtained.

$$f_k = f^{\mathrm{ref}} - T_{P(N_k)} \times (P_k - P^{\mathrm{ref}}) \qquad (14)$$

To equalize the energy storage discharge, we should consider the BESU with the lowest SoC discharge to be slower than all the others, in order to ensure a stored energy balance. The frequency is equal in each sample period and place and the variation is also within the acceptable range.

$$f_1 \approx f_2 \approx .... \approx f_N \qquad (15)$$

So, combining (15) with (14), it obtains:

$$P_1 T_{P(N_1)} = P_2 T_{P(N_2)} = ... = P_N T_{P(N_N)} \qquad (16)$$

Based on (13) and (14), and in order to achieve equalization, the droop coefficients at each BESU should be inversely proportional to the output power. In other words, for a set of BESUs with different SoC levels arranged as

$$\mathrm{SoC}_{\mathrm{BESU}_1} \rangle \mathrm{SoC}_{\mathrm{BESU}_2} \rangle .... \rangle \mathrm{SoC}_{\mathrm{BESU}_N} \qquad (17)$$

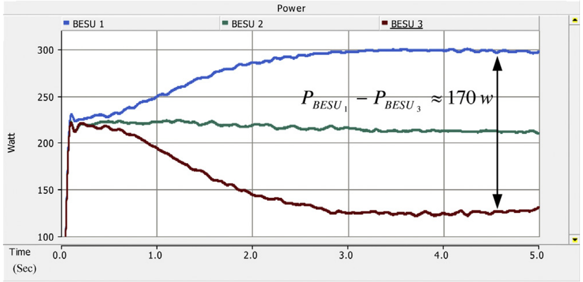

Fig. 7. Power sharing without SoC control.

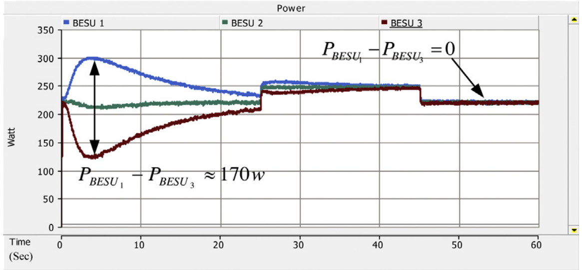

Fig. 8. Power sharing waveforms.

Based on (12) and (13), the control signal and droop coefficients of each BESU can be defined as

$$\delta_{\mathrm{SoC}_{\mathrm{BESU}_1}} \langle \delta_{\mathrm{SoC}_{\mathrm{BESU}_2}} \langle .... \langle \delta_{\mathrm{SoC}_{\mathrm{BESU}_N}} \qquad (18)$$

$$T_{P(N_1)} \langle T_{P(N_2)} \langle .... \langle T_{P(N_N)} \qquad (19)$$

This means that the droop coefficient of the battery with the highest SoC is adjusted to the lowest value of all the others. Likewise, the BESU with the lowest SoC has the highest droop coefficient. It can be concluded from (16) and (19) that if $\mathrm{SoC}_i > \mathrm{SoC}_j \{i, j = 1, 2, ..., N\}$, then $|P_i| > |P_j|$. A control diagram of the proposed method, as well as of all upper and lower control levels, is shown in Fig. 3. Moreover, a flowchart of the distributed control strategy based on the proposed method to give the modified *P/f* droop control is presented in Fig. 4.

4. Simulation study

A PSCAD/EMTDC simulation model of the BESU was developed in order to test and evaluate the distributed cooperative control of BESS based on the new modified droop control method. The simulation system consists of three battery bank units connected to the AC bus through a power electronics interface. As shown in Fig. 5, the AC bus supports two linear and one nonlinear load in a balanced three-phase system. Two resistors (R_{L1}, R_{L2}) are used as the linear load, with one of them connected to the system from the beginning and the other one attached between $t = 25$ s and $t = 45$ s. The nonlinear load includes a diode rectifier loaded by a capacitor (C_{NL}) and a resistor load (R_{NL}), which also connected to the system from starting time.

To advance the simulation, the different distances between the loads and the storage unit are considered, so that the each load is 50 m away from the AC bus and the distances to storage units are 200 m, 150 m, and 100 m for BESU_1 to BEUS_3, respectively; to model the distances and distribution lines, nominal pi-section models are

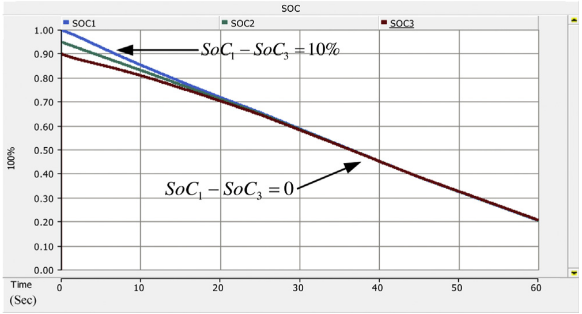

Fig. 9. SoC waveforms.

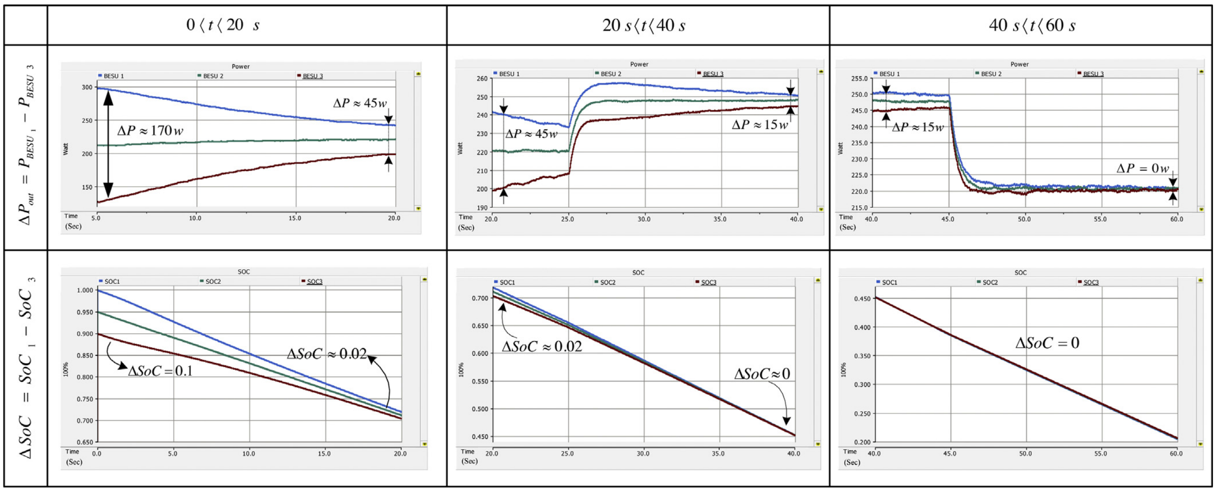

Fig. 10. SoC and power sharing waveforms in three different interval times.

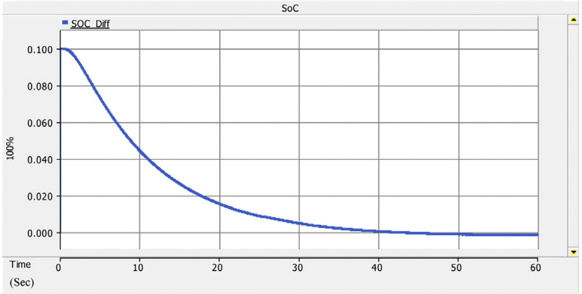

Fig. 11. Difference between highest and lowest of SoC.

used. Table 1 summarizes the main parameters of the system, which are identical for all three BESUs, as well as the parameters of the distribution lines. As shown in Fig. 6, the initial value of the SoC was adjusted by 5% so that Battery 1 is full of charge (100%) when the SoC of Batteries 2 and 3 are at 95% and 90%, respectively. To further evaluate the proposed method, and also demonstrate its effect on the system, in the first 5 s ($0 \leq t \leq 5$s), the upper control level is off and the system operates based on the individual information of each BESU. During this time, the proposed power sharing technique is also off and, as shown in Fig. 7, the output power of each BESU is constant during this period. At $t = 5$ s, the controlling method is started and, as illustrated in Figs. 8 and 9, BESUs with different charge levels close to each other equalize step by step by sharing power based on their SoC levels, such that Battery 1 provides more power than Battery 3, which has 10% lower SoC. Hence, the SoC value, and thus the output power, of each BESU approach that of the others.

The system operated for 60 min and, to evaluate the power sharing based on the SoC modified droop control, three different interval times were analyzed. The equalization of the power and SoC based on the three different interval times is shown in Fig. 10.

The speed of convergence of SoC and power sharing decreases with each step on account of the decreasing error value between them. After $t = 25$ s, the speed of the SoC droop is faster than before because of the increasing load power (injecting more power); after $t = 45$ s,it has returned to normal. In the energy level, the highest difference is between SoC1 and SoC3, where it has changed from 10% to 0%, as shown in Fig. 11. Additionally, the highest difference in output powers is between the P_{BESU1} and P_{BESU3}; as illustrated in Fig. 12, the value also changes from almost 175 W to zero. Finally, as shown in Fig. 13, despite the power variation in the system, the power delivered to the AC bus and loads is constant.

5. Conclusion

The main issue in controlling the distributed energy storage system during the charging and discharging processes is to balance the SoC of each BESU while also regulating the output or inject power based on the SoC of the same BESU. In this regard, this paper proposes a modified droop control methodology for power sharing in a decentralized control methodology which is adapted, applied, and evaluated for energy storage systems during the discharge

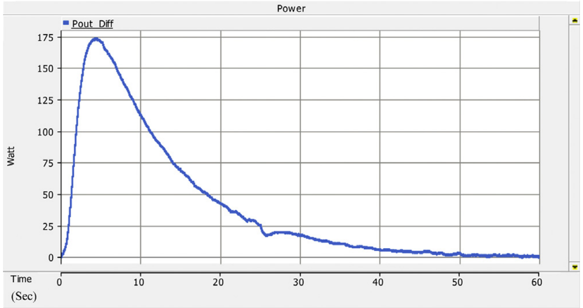

Fig. 12. Difference between highest and lowest of power.

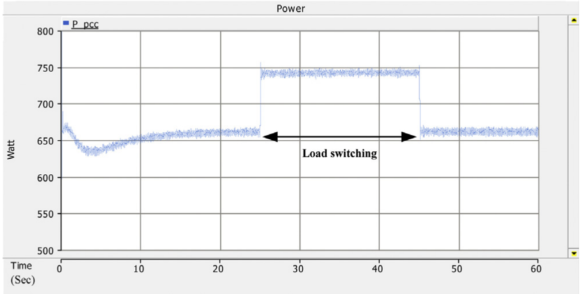

Fig. 13. Power delivered to the AC bus and loads.

process. To achieve ideal power sharing, dynamic SoC balancing is used; in this method, the power can be shared between the different BESUs, taking their SoCs into account. Based on this technique, the BESU with lowest SoC delivers less power, while the unit with highest SoC injects most power to the system. Thus, the output powers related to each BESU are approached together and also the differences between the SoC rates are reduced, step by step. Future research should investigate connecting the system to a microgrid with centralized or decentralized control methods and studying the system during the charging process.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Finnish Funding Agency for Technology and Innovation, Tekes, to the EV system and grid integration (ECV-echarge-UVA) project (Grant No. 40029/14).

References

[1] Priyanka Paliwal, N.P. Patidar, R.K. Nema, Planning of grid integrated distributed generators: a review of technology, objectives and techniques, Renew. Sustain. Energy Rev. 40 (2014) 557–570.

[2] R. Viral, D. Khatod, Optimal planning of distributed generation systems in distribution system: a review, Renew. Sustain. Energy Rev. 16 (2012) 5146–5165.

[3] J.P. Lopes, et al., Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities, Electr. Power Syst. Res. 77 (2007) 1189–1203.

[4] Y. Xu, Wei Zhang, G. Hug, S. Kar, Zhicheng Li, Cooperative control of distributed energy storage systems in a microgrid, IEEE Trans. Smart Grid vol. 6 (2015) 238–248.

[5] Y. Xu, W. Zhang, W. Liu, X. Wang, F. Ferrese, C. Zang, H. Yu, Distributed subgradient-based coordination of multiple renewable generators in a microgrid, IEEE Trans. Power Syst. vol. 29 (2014) 23–33.

[6] S.A.N. Pourmousavi, M. Hashem, Real-time central demand response for primary frequency regulation in microgrids, IEEE Trans. Smart Grid 3 (2012) 1988–1996.

[7] Jen-Hao Teng, Shang-Wen Luan, Dong-Jing Lee, Yong-Qing Huang, Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable PV generation systems, IEEE Trans, Power Syst. vol. 28 (2013) 1425–1433.

[8] X. Tan, Qingmin Li, H. Wang, Advances and trends of energy storage technology in microgrid, International Journal of Electrical Power &, Int. J. Electric. Power Energy Syst. vol. 44 (2013) 179–191.

[9] R. Carnegie, Douglas Gotham, David Nderitu, V. Paul Preckel, Utility Scale Energy Storage Systems (Benefits, Applications, and Technologies), State Utility Forecasting Group, 2013, 2015.

[10] K. Bradbury, Energy Storage Technology Review, Duke University, pp, 20101–34.

[11] H. Laaksonen, K. Kauhaniemi, Synchronized re-connection of island operated LV microgrid back to utility grid, IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe) (2010) 1–8.

[12] H. Laaksonen, et al., Microgrid Voltage Level Management and Role as Part of Smart Grid Voltage Control, IEEE PowerTech, Trondheim, 20111–8.

[13] C. Wang, Modeling and Control of Hybrid Wind/photovoltaic/fuel Cell Distributed Generation Systems, Doctoral Thesis in MONTANA State University, 2006.

[14] C. Wang, M.H. Nehrir, Power management of a stand-alone wind/photovoltaic/fuel cell energy system, IEEE Trans. Energy Convers. 23 (2008) 957–967.

[15] W. Li, G. Joos, Comparison of energy storage system technologies and configurations in a wind farm, Power Electronics Specialists Conference, Orlando, FL, 2007, pp. 1280–1285.

[16] P. Thounthong, et al., Analysis of supercapacitor as second source based on fuel cell power generation, IEEE Trans. Energy Convers. 24 (2009) 247–255.

[17] J.Y. Kim, J.-H. Jeon, S.-K. Kim, C. Cho, Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation, IEEE Trans. Power Electron. vol. 25 (2010) 3037–3048.

[18] Y. Li, et al., Design, analysis, and real-time testing of a controller for multibus microgrid system, IEEE Trans. Power Electron. 19 (2004) 1195–1204.

[19] Y. Zhang, H. Jie Jia, L. Guo, Energy management strategy of islanded microgrid based on power flow control, IEEE PES, Innov. Smart Grid Technol. (ISGT) (2012) 1–8.

[20] T. Dragicevic, J.M. Guerrero, J.C. Vasquez, D. Skrlec, Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability, IEEE Trans. Power Electron. vol. 29 (2014) 695–706.

[21] X. Lu, et al., SoC-based droop method for distributed energy storage in DC microgrid applications, IEEE International Symposium on Industrial Electronics (ISIE) (2012) 1640–1645.

[22] H. Kakigano, Y. Miura, T. Ise, Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique, IEEE Trans. Power Electron. vol. 28 (2013) 2246–2258.

[23] C. Li, T. Dragicevic, N.L. Diaz, J.C. Vasquez, J.M. Guerrero, Voltage scheduling droop control for State-of-Charge balance of distributed energy storage in DC microgrids, IEEE International Energy Conference (ENERGYCON) (2014) 1310–1314.

[24] C. Li, T. Dragicevic, M. Garcia Plaza, F. Andrade, J.C. Vasquez, J.M. Guerrero, Multiagent based distributed control for state-of-charge balance of distributed energy storage in DC microgrids, 40th Annual Conference of the IEEE Industrial Electronics Society, IECON (2014) 2180–2184.

[25] X. Lu, Kai Sun, J.M. Guerrero, J.C. Vasquez, Lipei Huang, State-of-charge balance using adaptive droop control for distributed energy storage systems in DC microgrid applications, IEEE Trans. Ind. Electron. vol. 61 (2014) 2804–2815.

[26] X. Lu, K. Sun, J.M. Guerrero, J.C. Vasquez, L. Huang, Double-quadrant state-of-charge-based droop control method for distributed energy storage systems in autonomous dc microgrids, IEEE Trans. Smart Grid vol. 6 (2015) 147–157.

[27] N.L. Diaz, T. Dragicevic, J.C. Vasquez, J.M. Guerrero, Intelligent distributed generation and storage units for dc microgrids—a new concept on cooperative control without communications beyond droop control, IEEE Trans. Smart Grid vol. 5 (2014) 2476–2485.

[28] A. Nelson Leonardo Diaz, D. Wu, T. Dragicevic, J.C. Quintero, V. Guerrero, M. Josep, Fuzzy droop control loops adjustment for stored energy balance in distributed energy storage system, Proc. IEEE, ECCE-Asia (2015) .

[29] Q. Shafiee, J.M. Guerrero, J.C. Vasquez, Distributed secondary control for islanded microgrids—a novel approach, IEEE Trans. Power Electron. vol. 29 (2014) 1018–1031.

[30] J.-Y. Kim, S.-K. Kim, J.-H. Jeon, Coordinated state-of-charge control strategy for microgrid during islanded operation, 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) (2012) 133–139.

[31] J. Guerrero, P. Loh, M. Chandorkar, T. Lee, Advanced control architectures for intelligent microgrids, Part I: decentralized and hierarchical control, IEEE Trans. Ind. Electron. vol. 60 (2013) .

[32] J.M. Guerrero, C.L. Poh, L. Tzung-Lin, C. Mukul, Advanced control architectures for intelligent microgrids—part II: power quality, energy storage and AC/DC microgrids, IEEE Trans. Ind. Electron. vol. 60 (2013) 1263–1270.

[33] J.M. Guerrero, et al., Droop control method with virtual output impedance for parallel operation of uninterruptible power supply systems in a microgrid, Twenty Second Annual IEEE Applied Power Electronics Conference (2007) 1126–1132.

[34] A. Bidram, A. Davoudi, Hierarchical structure of microgrids control system, IEEE Trans. Smart Grid 3 (2012) 1963–1976.

[35] N. Pogako, et al., Modeling, analysis and testing of autonomous operation of an inverter-based microgrid, IEEE Trans. Power Electron. vol. 22 (2007) 613–625.

[36] T. Morstyn, B. Hredzak, V.G. Agelidis, Distributed cooperative control of microgrid storage, IEEE Trans. Power Syst. (2014) 1–10.

[37] O. Palizban, K. Kauhaniemi, Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode, Renew. Sustain. Energy Rev. 44 (2015) 797–813.

[38] J.M. Guerrero, J.C. Vasquez, J. Matas, L.G. de Vicuña, M. Castilla, Hierarchical control of droop-controlled AC and DC microgridsña general approach toward standardization, IEEE Trans. Ind. Electron. vol. 58 (2011) 158–172.

[39] B. Dunn, Kamath Haresh, Tarascon Jean-Marie, Electrical energy storage for the grid: a battery of choices, Science vol. 334 (2011) 928–935.

Correction on equation seven:

$$
\begin{bmatrix} \Delta V_{BESU_k} \\ \Delta f_{BESU_k} \\ \Delta Q_{BESU_k} \end{bmatrix} = E \begin{bmatrix} \Delta V^{*}_{BESU} \\ \Delta f^{*}_{BESU} \\ \Delta Q^{*}_{BESU} \end{bmatrix} \qquad \begin{bmatrix} \Delta V^{*}_{BESU} \\ \Delta f^{*}_{BESU} \\ \Delta Q^{*}_{BESU} \end{bmatrix} = F \begin{bmatrix} (V^{ref}_{BESU} - \overline{V}_{BESU_k}) \\ (f^{ref}_{BESU} - \bar{f}_{BESU_k}) \\ (\overline{Q}_{BESU_k} - Q_{BESU_k}) \end{bmatrix}
$$

$$
\overline{V}_{BESU_k} = \frac{1}{N}\left[V_{BESU_1} + V_{BESU_2} + \ldots + V_{BESU_N}\right] \qquad \bar{f}_{BESU_k} = \frac{1}{N}\left[f_{BESU_1} + f_{BESU_2} + \ldots + f_{BESU_N}\right] \tag{7}
$$

$$
\overline{Q}_{BESU_k} = \frac{1}{N}\left[Q_{BESU_1} + Q_{BESU_2} + \ldots + Q_{BESU_N}\right]
$$

$$
E = \begin{bmatrix} G_{pv} + G_{iv}/s & 0 & 0 \\ 0 & G_{pf} + G_{if}/s & 0 \\ 0 & 0 & G_{PQ} + G_{iQ}/s \end{bmatrix} \qquad F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

Publication VI

Decentralized Secondary Control of Energy Storage Systems in Autonomous Microgrids

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Submitted to

IET Generation, Transmission & Distribution (2016)

Decentralized Secondary Control of Energy Storage Systems in Autonomous Microgrids

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Abstract: the hierarchical control of microgrids that consist of distributed generators and energy storage systems is a necessary element for the optimal control of future grids. This paper investigates the hierarchical control of such systems based on the decentralized control methodology. Since the energy level of each storage unit is different, the main challenge in controlling distributed storage systems is equalizing the energy level during the charge and discharge periods. Some limitations on balancing exist in traditional droop control because the demanded or absorbed power share is based on the power capacity, rather than on the energy level. Hence, in this paper, a modified droop control is employed to avoid this disadvantage and to share the power with respect to the energy level of each storage unit. By employing the proposed method in distributed energy storage, the battery with the highest State of Charge (SoC) supports the load by injecting more power than the battery with the lowest SoC. This works inversely in charge mode and more power is absorbed by the battery with the lowest SoC, and the battery with the highest SoC absorbs the least power. The method is validated by simulated results from PSCAD/EMTDC software.

1. Nomenclature

f_{BESU}^{ref}	Reference value of frequency in BESU
$\bar{f}_{BESU_k}$	The average *frequency* of BESU$_k$
Δf_{BESU_k}	Restoration values of the frequency
Δf_{BESU}^{*}	The difference between reference and frequency
$i_{a,b,c}^{l}$	The output current measurement
$i_{a,b,c}^{*}$	The difference between reference and output current
$i_{a,b,c}^{ref}$	Reference value of current in *a,b,c*
Q_{BESU}^{ref}	Reference value of reactive power in BESU
$\overline{Q}_{BESU_k}$	The average *reactive power* of BESU$_k$
ΔQ_{BESU}^{*}	The difference between average and output reactive power
ΔQ_{BESU_k}	Restoration values of the reactive power
$V_{a,b,c}$	The output voltage of the BESU
$V_{i_{a,b,c}}$	The output voltage of the virtual impedance block
$V_{a,b,c}^{*}$	The difference between reference and output voltage
$V_{a,b,c}^{ref}$	Reference value of voltage in *a,b,c*
V_{BESU}^{ref}	Reference value of voltage in BESU
$\overline{V}_{BESU_k}$	The average *voltage* of BESU$_k$
ΔV_{BESU_k}	Restoration values of the voltage
ΔV_{BESU}^{*}	The difference between reference and output voltage
$G_{p(v/f/Q)}$	Proportional gain for (*voltage/frequency/reactive power*) in secondary control
$G_{i(v/f/Q)}$	Integration gain for (*voltage/frequency/reactive power*) in secondary control
$k_{p(v/i)}$	Proportional gain for (*voltage/current*) in primary control
$k_{i(v/i)}$	Integration gain for (*voltage/current*) in primary control

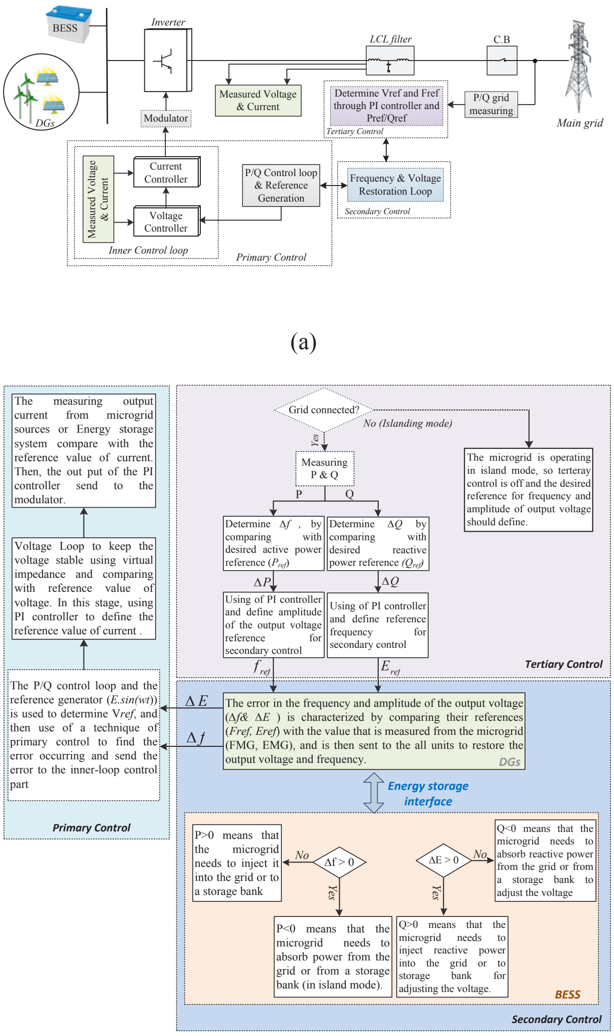
2. Introduction

Distributed Generators (DGs) and Microgrids (MGs) are forms of Renewable Energy Sources (RESs) that can be integrated into the main network. MGs consist of the methodical organization of such DG systems [1-4]—an organization that leads to increases in system capacity and achieves high power quality [5]. The control of such a system is critical, and implementing a hierarchical control system is necessary to achieve optimum performance. In [6], a comprehensive analysis of the hierarchical control of MGs is presented. Based on the scheme of MGs, hierarchical control can be described as having four levels, responsible for processing (*inner control loops, or zero level*), sensing and adjusting (*primary level*), monitoring and supervising (*secondary level*), and maintenance and optimization (*tertiary level*). Generally, the hierarchical control level is obliged to provide control over the power generation from the DG units. Since, these units either have some instability in power production or slow controllability to variation inside the MG [7], an Energy Storage System (ESS) is required to cover the fluctuation during island mode. In recent years, advanced energy storage technologies have been investigated by researchers such as *X. Tan et al.* [8], *R. Carnegie et al*. [9], *K. Bradbury* [10] and also a matrix of available technologies and applications is proposed by the authors of the current paper in [11]. These studies indicate that electrochemical storage (i.e., battery storage) is the most commonly used technique to cover applications involving frequent charging and discharging processes. The energy storage system within an MG is an auxiliary resource and usually does not participate control actions when MG is connected to the main network. Hence, the third control level is not used in the storage control technique and the hierarchical control of Battery Energy Storage System (BESS) consists of three levels: the inner control loop, the primary level, and the secondary level [12].

There are many different technical possibilities for each of the control levels of a MG. *Vandoorn et al.* [13] presents a complete review of primary techniques, which are based on local measurements only. Comprehensive research into hierarchical control and secondary control level is presented by *Guerrero et al.* in [14]. Based on their investigation, secondary control levels can be classified into two types: *centralized* and *decentralized* , and the challenges of the control level, and their solutions, are presented in [15]. These two types have almost the same duty, though there are some differences between them. Indeed, power management in the centralized methods is done through the MG Central Controller (MGCC) part, while in the decentralized control type, it has been removed and the secondary control is located beside each primary control. The major disadvantage of centralized methods is the dependency of the system on the MGCC and the control will face critical problems due to any malfunction in the control center. Recently, in order to deal with this problem, different methodologies based on decentralized control method have been proposed [16-19], although performance and efficiency have been improved by planning decentralize control methods. Some challenges nonetheless remain when implementing the control strategy. One of the major challenges in the employing of a fully decentralized control system is the impossibility of controlling the system during transient variations and some of other management functions [19]. One way to deal with these challenges and to approach high-level control is to install a distributed energy storage system beside each DG. Based on this structure, the arrangement includes a set of DGs and Battery Energy Storage Units (BESUs) that are controlled through distributed secondary control strategies. Since the storage energy level is different in each BESU, the critical issue in control strategies is to balance the energy. Hence, in this paper a novel energy balancing scheme for BESUs is proposed by using a decentralized control approach. Recently, different approaches have been used for balancing energy storage in distributed BESUs [20-25]. However these proposed strategies operate with centralized control methods. As mentioned, operating the system under these control methods involves a high level of risk. A decentralized strategy for BESUs is presented by *X. Lu et al.* [26], which this employs an adaptive droop control. However, the energy equalization is being only considered when the batteries are supplying power (discharge mode). In [27] the method is extended and a double-quadrant technique is presented to equalize the energy with a decentralized method for both the charging and discharging process. Nevertheless, the methods consider only DC MG and also a drawback of this method is the dependence on the initial energy in each unit and the previous knowledge of the characteristic of other BESUs. In fuzzy control methodologies, some energy balancing is also proposed on the basis of the fuzzy interface, described in [28] for island DC microgrids and adapted to AC microgrids in [29]. A decentralized control method for MGs based on power electronics is proposed by *Shafiee et al*. [18]. In this technique, the voltage, frequency, and reactive power of the DGs in each sample frame is measured and shared with others, thus allowing a control signal for each DG to be provided. In [30], the control strategy is adapted, applied, and evaluated for a BESS, and energy equalization is considered when the batteries are discharging. In this regards and to develop the previous research, the method is further developed through investigating the charge mode of BESU with decentralized control for both DGs and BESSs in this paper.

Since the energy level of each BESU is different, there are some limitations when using the traditional droop control method; in which, the power demanded or absorbed by different BESUs is based on power capacity, rather than on energy levels [31-33]. Hence, a modification in the droop control method to improve the performance of distributed energy storage system control is required. An improved droop coefficient is also proposed for DC and AC MGs by *X. Lu et al.* [27] and *Morstyn et al.* [34], respectively. The principle of equalization in these methods is to multiply the droop coefficient by ($1/\alpha$), where α indicates the level of energy in each storage unit. The value of α falls between 0.01 (discharged) and 1 (charged) so as to prevent the droop coefficient from going to infinity. The risks of these control methods are high on account of problems that arise from this limitations and lead to significant problems in the control of the BESS, such as overcharging and over discharging. To overcome these problems, a SoC-balancing method based on a modified droop control suitable for adapting control strategies is also developed for the charging and discharging periods proposed in this paper.

The present paper is organized as follows: The configuration of the MG and BESS, with a comprehensive analysis of hierarchical control, is presented in Section 3. Section 4 discusses in detail the development of the equalization of energy and distributed control strategies for the BESS. In Section 5, a simulation study is presented to evaluate the performance of the proposed cooperative control method. Finally, the paper is concluded in Section 6.



(a)

(b)

Fig.1Power electronic based sources (a) configuration, (b) principle of hierarchical control

3. DG and BESS Configuration

The DGs and BESSs are power electronic control-based devices that contain several parts with different responsibilities. In Figure 1 (a), a configuration of the power electronic base sources that can involve a DG or a battery bank is demonstrated. Generally, power generation units, as well as BESSs, connect to the system through inverters. The inverters are not used only for converting the power from DC input to AC output: they also implement advanced capabilities, such as active and reactive power control and the regulation of output voltage. The power management and control operate through different control blocks in different levels. In this regard, the details of the hierarchical control and the responsibility of each control block are presented in a flowchart in Figure 1(b). Moreover, the most relevant levels of the hierarchical control to the research are explained in detail below:

3.1 Inner Control Loop

The main aim of this control level is to manage the output power from sources; this is generally accomplished through inner current and voltage control loop. In this control part, the desired voltage should first be determined to generate the turn-on and turn-off switching signals for the six insulated gate bipolar transistors (IGBTs).

To provide signal control, the measured values are compared with the reference values. Moreover, to determine the reference value for voltage and frequency, a proper voltage and current-control loop is required. *D. Dong* [35] and *C. Tarasantisuk et al.* [36] present a complete modeling and control design methodology for converters and discuss the current and voltage-control loops. The reference values for voltage and current controllers are calculated as follows [34, 37]:

$$V^* = \begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = Bc_1 \begin{bmatrix} V_a^{ref} \\ V_b^{ref} \\ V_c^{ref} \end{bmatrix} - Bc_2 \begin{bmatrix} (V_a + V_{ia}) \\ (V_b + V_{ib}) \\ (V_c + V_{ic}) \end{bmatrix}, \quad i^{ref} = \begin{bmatrix} i_a^{ref} \\ i_b^{ref} \\ i_c^{ref} \end{bmatrix} = AV^* + BV^*$$

$$, \quad Bc_1 = Bc_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A = \begin{bmatrix} k_{pv} & 0 & 0 \\ 0 & k_{pv} & 0 \\ 0 & 0 & k_{pv} \end{bmatrix}, \qquad (1)$$

$$B = \begin{bmatrix} k_{iv}/s & 0 & 0 \\ 0 & k_{iv}/s & 0 \\ 0 & 0 & k_{iv}/s \end{bmatrix}$$

$$i^* = \begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = Bc_1 \begin{bmatrix} i_a^{ref} \\ i_b^{ref} \\ i_c^{ref} \end{bmatrix} - Bc_2 \begin{bmatrix} i_a^l \\ i_b^l \\ i_c^l \end{bmatrix}, \quad V^{ref} = \begin{bmatrix} V_a^{ref} \\ V_b^{ref} \\ V_c^{ref} \end{bmatrix} = Ci^* + Di^* \quad , \qquad (2)$$

$$C = \begin{bmatrix} k_{pi} & 0 & 0 \\ 0 & k_{pi} & 0 \\ 0 & 0 & k_{pi} \end{bmatrix}, \quad D = \begin{bmatrix} k_{ii}/s & 0 & 0 \\ 0 & k_{ii}/s & 0 \\ 0 & 0 & k_{ii}/s \end{bmatrix}$$

3.2 Primary control

The main aim of this control level is to regulate the reference values for the frequency and amplitude of the voltage in order to feed the inner current and voltage control loops. To give the fastest possible response (on the order of milliseconds) to any variation in sources or demand is the responsibility of the primary control level. The power converters for the DG unit are classified into two general categories: grid-forming and grid-following [38, 39]. Different strategies for the grid-forming method are presented by *T.L. Vandoorn et al.* [13], while grid-following techniques are discussed by *F. Blaabjerg et al.* [40].

Grid-forming and grid-following power converters operate on a voltage and current basis, respectively. Hence, it is possible for a power converter in the grid-forming (voltage-based) type to control the MG individually. However, power converters in grid-following (current-based) types can manage the system correctly only in grid-connected mode. Since the objective of this paper is to propose a modified droop control, the principle of this control method—which is a type of grid-forming method—is explained as follows:

a) Droop control

Inertia is the most significant difference between a converter-based MG and a conventional power generator for controlling the system. The lack of inertia in MGs means that the active and reactive power strategy is based on line characteristics [41]. A complete and extensive review of technical investigation into the control strategy is provided by *Guerrero et al.* [31] and *Bidram et al.* [42]. Since the line impedance is more inductive at both high and medium voltage networks, a *(P/f, Q/V)* droop control is employed for those systems, and thus a local voltage set-point value is used to adjust the operational voltage. However, in low voltage distribution systems the lines are basically resistive, Thus, the method creates a problem for the systems, so that, the active and reactive power in the DGs and BESSs will be coupled. [31]. In this paper, for the control block diagram, a low-pass filter with a cutting frequency (ω_s) is first used to obtain the fundamental components of the output active (P) and reactive power (Q) for the droop control [34, 37].

$$P = \frac{\omega_s}{S+\omega_s} p \qquad Q = \frac{\omega_s}{S+\omega_s} q \tag{3}$$

Then, to fix the output impedance of the inverter and also to have a more stable value to provide a control signal with easier control processing, a virtual impedance loop is added to the voltage reference to make the output highly inductive. Therefore, the frequency and voltage of the droop control is determined as follows:

$$f = f^{ref} - T_{p(s)}.(P - P^{ref}) \tag{4}$$

$$V = V^{ref} - T_{Q(s)}.(Q - Q^{ref}) \tag{5}$$

$$T_{p(s)} = \frac{\overbrace{f^{ref} - f^{\min}}^{\Delta f}}{\underbrace{P^{ref} - P^{\max}}_{\Delta P}} \langle 0 \quad , \quad T_{Q(s)} = \frac{\overbrace{V^{ref} - V^{\min}}^{\Delta V}}{\underbrace{Q^{ref} - Q^{\max}}_{\Delta Q}} \langle 0 \tag{6}$$

3.3 Secondary Control

Secondary control is used in MGs and BESSs to realize secure output through the links established between different DG units and ESSs. Compared to the primary control level, the secondary control has a slower dynamic response to variations [42]. The responsibility of this control level is to supervise and monitor the system, in order to keep deviations in the grid frequency and voltage within the permissible range. The allowable range of variation is ± 0.2 Hz in UCTE (Continental Europe) and to ± 0.1 Hz in Nordel (North of Europe) and the voltage magnitude keep within -6% to +10 % [14, 34]. Such deviations are regulated toward zero by the BESS each time there is a load change or when any variation appears in the MG power generation.

In the control method proposed in [18], the frequency and voltage are measured at regular sample intervals. The error value, which is the result of comparing the measured and average values, is sent to the primary control level, which acts to restore the voltage and frequency. Moreover, because of variations in the voltage at different points, the reactive power also must be measured for each generating unit with the decentralized control method and, along with the frequency and voltage, is shared with the other units. The variations in each reactive power and the restoration compensator are deduced from Equations (7), (8), and (9) in the decentralized control method.

$$\begin{aligned} \Delta V_{BESU_k} &= G_{pv}(V_{BESU}^{ref} - \bar{V}_{BESU_k}) + G_{iv}\int (V_{BESU}^{ref} - \bar{V}_{BESU_k})dt \\ \bar{V}_{BESU_k} &= \frac{\sum_{i=1}^{N} V_{BESU_i}}{N} \end{aligned} \tag{7}$$

$$\begin{aligned} \Delta f_{BESU_k} &= G_{pf}(f_{BESU}^{ref} - \bar{f}_{BESU_k}) + G_{if}\int (f_{BESU}^{ref} - \bar{f}_{BESU_k})dt \\ \bar{f}_{BESU_k} &= \frac{\sum_{i=1}^{N} f_{BESU_i}}{N} \end{aligned} \tag{8}$$

$$\begin{aligned} \Delta Q_{BESU_k} &= G_{PQ}(\bar{Q}_{BESU_k} - Q_{BESU_K}) + G_{iQ}\int (\bar{Q}_{BESU_k} - Q_{BESU_k})dt \\ \bar{Q}_{BESU_k} &= \frac{\sum_{i=1}^{N} Q_{BESU_i}}{N} \end{aligned} \tag{9}$$

The purpose of the third control level is to manage the power flow by adjusting the voltage and frequency when the MGs are connected to the main grid. As this paper investigates the use of DGs with BESSs when the MG operates in island mode, this control level is presented only briefly in Fig. 1(b) and is discussed with greater depth in [6, 14].

As mentioned earlier, there are several limitations on the use of the traditional droop control because it shares power based on power capacity. Hence, this paper proposes a modified droop control method to share power based on the energy level of each BESU, as explained with more details in the following section.

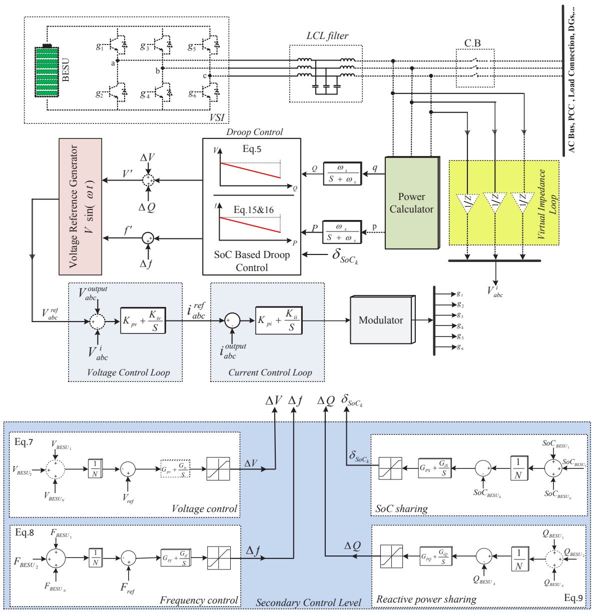


Fig.2 The distributed proposed control method for one BESU

4. State-of-charge-based droop control method

The equalization of power and the balancing of the energy in the BESSs must occur when the system is either in the charging or discharging mode. Based on the primary level of hierarchical control, the power capability of the system can sense the active power by detecting frequency variations.

The frequency of the system increases when the power generated through the DGs is more than the power demands (f is near f_{max}), so the surplus energy must be absorbed by the BESS (*charge mode*). However, the frequency will decrease and approach the minimum value (f_{min}) when the demand increases, so in this situation the BESS injects the stored energy into the system to improve the system stability (*discharge mode*) [32, 43]. The power matching in the system can be demonstrated as follows:

$$P_{req} = -(P_{Gen} - P_{demand}) \tag{10}$$

where the amount of power that needs to be absorbed and injected by the BESU (P_{req}) is equal to the difference between the total power generated by the DGs (P_{Gen}) and the total power of the demand side (P_{demand}). It should be noted here that the output power of the BESU is positive when discharging and negative when charging.[27]

Generally, power capacity rather than energy level is used to distribute the required power between the BESUs. This type of power sharing can lead to some issues in the control system, where the storage units with lower energy level run out of energy earlier than the other units and the frequency is lost during discharge. Moreover, the storage units with the highest energy level become full and drawing energy will not be possible even if P_{req} is negative and the power demand is lower that the generated power, which would lead to renewable power potential being wasted during the unavailability of the charging process.

To deal with this significant difficulty, it is necessary to modify the droop control. In the new droop control method, the power absorbed by the BESU should be inversely proportional to the energy level. For this reason, the power shared between the storage units is based on the available energy level, so that the unit with highest energy level injects more power to the system when it operates as a supplier and absorbs the lowest power during the charging process.

To achieve to this optimum control system, the droop coefficient needs to be modified so that it is regulated on the basis of the SoC (energy level). Since the control system and modifications should not affect the performance of the BESS, an advanced control structure for the storage system and also for combining DGs on the secondary level is required. In Fig. 2, a control diagram of the proposed method is shown. In the first step of this strategy, the SoC of each BESU (SoC_{BESU_k}) $\{K = 1,2,...,N\}$ must be measured at each sample time and sent to the other units to calculate the total available state of charge (SoC_{Total}):

$$SoC_{Total} = SoC_{BESU_1} + SoC_{BESU_2} + ... + SoC_{BESU_N} \tag{11}$$

Then, to determine the average value of the state of charge ($So\overline{C}_{BESU}$), the sum of all the state-of-charge values is divided by the number of battery energy storage units (N).

$$So\overline{C}_{BESU} = \frac{SoC_{Total}}{N} \tag{12}$$

Based on (12), the same reference value will be used in each unit and to obtain the deviation of each BESU (ϑ_k); the average value of SoC is then compared with the SoC value of the same BESU (SoC_{BESU_k}):

$$\vartheta_k = So\overline{C}_{BESU} - SoC_{BESU_k} \tag{13}$$

A necessary requirement for a control system is stability. To ensure this requirement, a PI controller is considered in this control method [44]. The objective of the PI controller is to determine the controller parameters in the transfer function so that the system behaves stably [45]. In this regard, the deviation of the SoC is amplified by the gain G_{PS} and integrated with the gain G_{iS}, and the control signal in each sample period (δ_{SoC_k}) is obtained as follows:

$$\delta_{SoC_k} = G_{Ps}\vartheta_k + G_{is}\int \vartheta_k dt \tag{14}$$

Likewise, the BESU with the lowest SoC should have the highest droop coefficient. However, the inverse proportionality cannot be used for the charging period, and the droop coefficient should be set to be proportional when the batteries absorb energy. Hence, due to the requirement for SoC balancing, the new droop coefficient value ($T_{P(N_k)}$) is defined on the basis of droop coefficient for discharging and charging mode in (15).

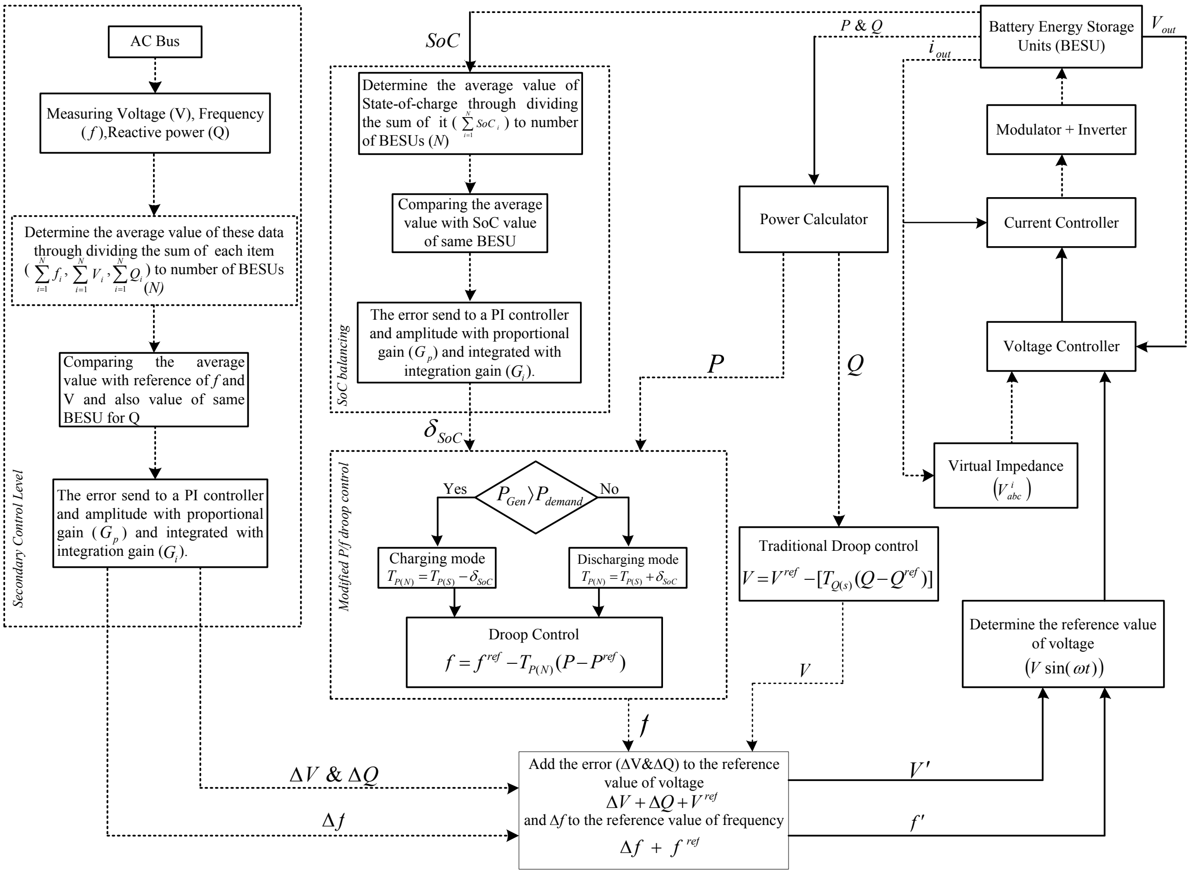


Fig.3 The flowchart of the distributed control strategy

$$T_{P(N_k)} = \begin{cases} T_{P(S)} + \delta_{SoC_k} \xrightarrow{\qquad} \text{Discharging mode} \\ T_{P(S)} - \delta_{SoC_k} \xrightarrow{\qquad} \text{Charging mode} \end{cases} \tag{15}$$

Hence, by combining the traditional droop control (4) with (15), the modified droop control shown in (16) is obtained.

$$f_k = f^{ref} - T_{P(N_k)}.(P_k - P^{ref}) \tag{16}$$

In this equation, the frequency is equal in each sample period and location, and the variation is also within the acceptable range.

$$f_1 \approx f_2 \approx .... \approx f_N \tag{17}$$

So, combining (16) with (17) gives:

$$P_1 T_{P(N_1)} = P_2 T_{P(N_2)} = ... = P_N T_{P(N_N)} \tag{18}$$

Based on (15) and (16), and in order to achieve equalization, the droop coefficients at each BESU are configured to be inversely proportional and proportional respectively, to the output power during discharging and charging time. For instance, for set of BESUs with different SoC levels arranged as:

$$SoC_{BESU_1} > SoC_{BESU_2} > ... > SoC_{BESU_N} \tag{19}$$

On the basis of (11-14) the control signal is defined as (20) and based on (15) the droop coefficients of each BESU are obtained as (21) in discharge process and (22) for the charge period:

$$\delta_{SoC_1} < \delta_{SoC_2} < ... < \delta_{SoC_N} \tag{20}$$

$$T_{P(N_1)} < T_{P(N_2)} < ... < T_{P(N_N)} \tag{21}$$

$$T_{P(N_1)} > T_{P(N_2)} > ... > T_{P(N_N)} \tag{22}$$

Taking into account (20–22) and (18), during the charging period, the BESU with the highest SoC absorbs the least amount of energy, while most of the energy is injected into the storage unit with lowest SoC level (if $SoC_i < SoC_j$ {i,j=1,2,…,N}, then $|P_j| < |P_i|$). On the other hand, during the discharge, the droop coefficient of the battery with the highest SoC is adjusted to the lowest value of all the others. Likewise, the BESU with the lowest SoC has the highest droop coefficient (if $SoC_i < SoC_j$ {i,j=1,2,…,N}, then $P_i<P_j$).

Figure 3 presents a flowchart of the distributed control strategy based on the proposed method, applying the modified *P/f* droop control. As shown in the flowchart, through comparing the power generation and the power demand, it defines whether the battery is in charging or discharging mode. Then, utilizing the proposed method for secondary control and employing the modified droop control in primary level, the power demand (absorbed or injected) is shared among BESUs based on the available energy of each unit. Since the droop coefficient is adjusted proportionally and inversely proportionally for the charging and discharging period, respectively, by the addition and subtraction of an error to the droop coefficient, sharing the absorbed and injected power between BESU requires no limiter, as was necessary in the previous techniques.

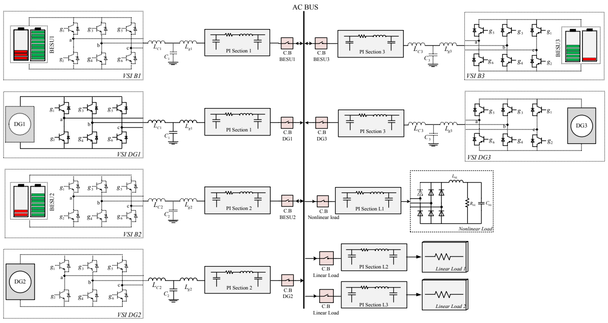


Fig.4 A configuration of the studied system

5. Simulation Study

To evaluate the proposed distributed cooperative control of BESS and the decentralized control of DGs based on the modified droop control method, PSCAD/EMTDC software is used in this paper. The configuration of the studied system is shown in Figure 4; it consists of three BESUs and DGs connected to an AC bus through a power electronics interface. During the time that these storage units operate as a power supplier (discharge mode), the initial value of the SoC is adjusted with 5% steps, so that *Battery 1* is full of charge (100%) when the SoCs of *Batteries 2* and *3* are at 95% and 90%, respectively. To charge these batteries, a DG is located beside each BESU and the initial value of the SoC is also adjusted with 5% steps for the charging case. This means that the SoC of the *battery 1* is at 20% while *batteries 2 and 3* have SoC values of 15% and 10%, respectively.

To advance the simulation, the various distances between the storage units and the DG are considered: the distances between the storage units and DGs and the AC bus are *200 m*, *150 m*, and *100 m* for $BESU_1$ to $BESU_3$ and DG_1 to DG_3, respectively. To model the distances and distribution lines, a nominal pi-section model is used. The AC bus supplies two linear loads and one nonlinear load in a balanced three-phase system. Two resistors (R_{L1}, R_{L2}) are used as the linear load; both are connected to the system from the start. The nonlinear load includes a diode rectifier loaded by a capacitor (C_{NL}) and a resistor load (R_{NL}), also connected to the system from starting time. The entire load is located *50 m* away from the AC bus. The main parameters for modeling the system are identical for all three BESUs and DGs; these, together with the parameters of all the distribution lines, are available in Table 1.

The equalization of the energy levels of each BESU for both discharging and charging periods is illustrated in Figure. 5(a, b). As shown in this figure, BESUs with different energy levels approach each other step by step. However, during both periods, due to the decreasing error values between the SoC and power sharing, the speed of convergence decreases with each time step.

In this modeling, to support the inverters of the DGs on the DC side (power generation), a single phased DC voltage source model is used and the inverters in BESUs are based on lithium-ion batteries. The capacity of these inverters is defined based on the maximum power demanded from the linear and nonlinear loads (≈1.5 kW). During the discharge period, generally, each storage unit should support 33.3% of the total load (≈500W). However, because of differing storage capacities in each storage unit, the storage units support the load demanded by taking into account the stored energy level in each storage unit. As shown in Figure 6.a, the battery with the highest SoC (*Battery 1*) provides more power than the one with the lowest energy level (*Battery 3*). Since the stored energy in $BESU_1$ is %10 greater than that in $BESU_3$, so the power generated through the first storage unit is almost 580 W, whereas unit number three supports the system by generating almost 420 W (10% less than $BESU_1$). At the end of the simulation time, the power generated by the storage units is the same and the difference between the generated powers is nearly zero. As mentioned, the BESUs charge by using DGs beside each storage unit and, for power generating, use more than 85% of the capacity of the inverters (1.3–1.5 kW). During the charging period, after supporting the power demanded by the loads, the rest of the power generation must be absorb by BESUs (approximately 3 kW).

In the charging process, the absorbed power is shared between the storage units based on the level of discharge. This means that $BESU_1$, with most stored energy, absorbs the lowest power, while $BESU_3$ with the lowest energy level absorbs the maximum amount of generated power. As shown in Figure 6.b, the first storage unit with 20% energy level absorbs around 950 W, which is the almost 30% of the total absorbed power and the lowest rate, compared to the other units. In $BESU_3$, the initial stored energy is around 10% (the lowest), so the highest rate of generated power (≈1150 W) has been absorbed by this unit. As in the discharging method, the difference between the shared powers decreases step to step. As demonstrated by the result (Fig. 6.b), the energy absorption is equal (≈1 kW) for all storage units and the difference between them is nearly zero at the end of the investigation time.

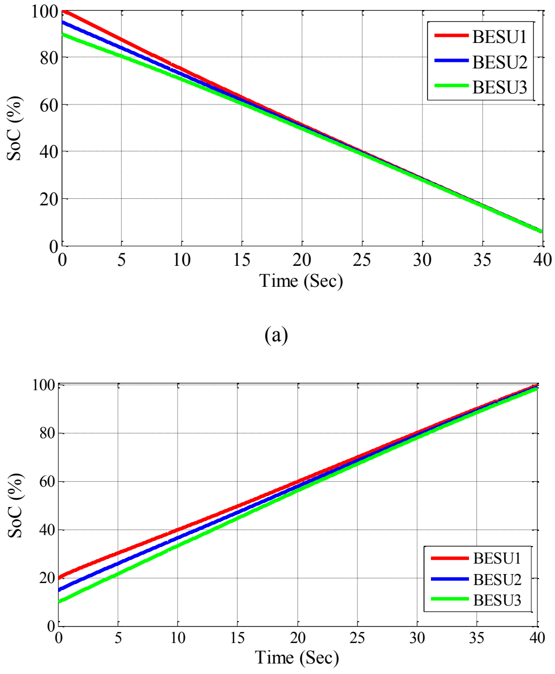
The total duration of the simulated period is *40 seconds* and, to evaluate the power sharing based on the SoC modified droop control, two different time intervals are analyzed. The equalization of the power and SoC based on the time intervals is shown in Figure 7 (for discharging mode) and Figure 8 (charging mode). The initial difference in energy level between the storage units with the highest differences ($BESU_1$ and $BESU_2$), is 10%, and at $t = 20\ s$, the difference decreases to almost 2%. The difference continues to reduce step by step in the second time interval, reaching almost zero at $t = 40$ s.

This equalization is also illustrated in the absorbed and injected power, with the difference in injected power being almost *175 W* during the discharge mode and *200 W* in the charging process; at the end of the first time interval, the difference is *40 W* for discharge and *100 W* for charging period. The difference values drops below *10 W* and *40 W* at the $t = 40\ s$ for charge and discharge mode respectively. Moreover, it should be noted here that the fluctuation in power is higher during the charging process than during discharging because of the variation in output power of the DGs.

6. Conclusion

Controlling the microgrid and managing power in the system through energy storage is a crucial topic, and a hierarchical control system is needed to obtain a high performance implementation in a modern system. To approach high-level control, this paper has proposed a distributed energy storage system installed beside each DG and controlled through a decentralized secondary control method. Since the energy level of each storage unit is different, the main challenge in distributed control strategy is balancing the energy. A droop control method with the ability to share power based on the SoC of each battery is proposed. In this strategy, the droop coefficient is set to be inversely proportional during the discharging period and proportional during the charging period. Thus, the storage unit with the *highest/lowest* energy level provides *more/less* power to support the load when the storage unit operates as a power supplier, and absorbs *less/more* power when the power generated exceeds the demand.

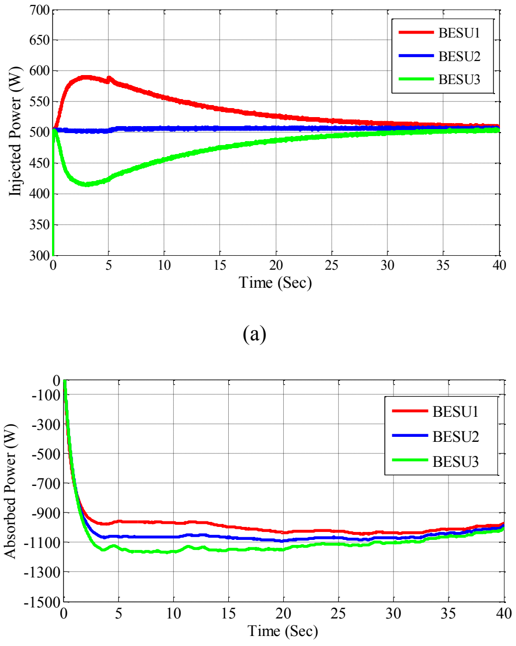
Since the proposed MG is supported by DGs and BESSs combining the decentralized control method, increasing the efficiency of the secondary control is a benefit of the proposed method. Indeed, because the dependency on the central control systems is decreased in the proposed method, the overall reliability in the system is potentially greater than in previous works and the number of unplanned interruptions of the system decreases. Moreover, the other benefit of this system is the increase in the life time of the BESS by balancing the energy level among the different storage units and sharing power based on the available energy of each storage unit. The analysis of these issues and the investigation of the performance of the proposed system in different applications of the energy storage system are interesting topics for future work.



(a)

(b)

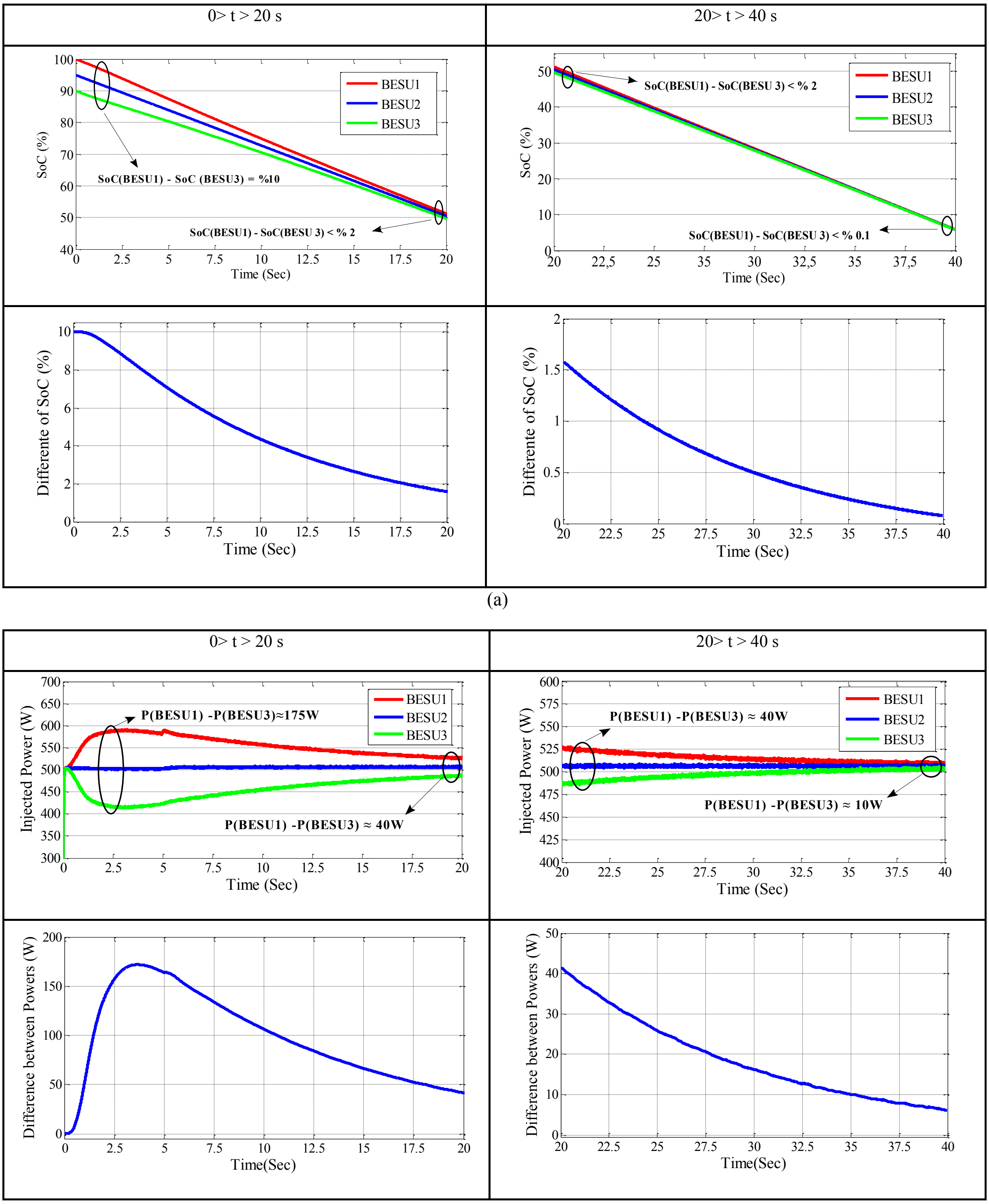
Fig.5 the energy levels of BESUs (a) discharge (b) charge period



(a)

(b)

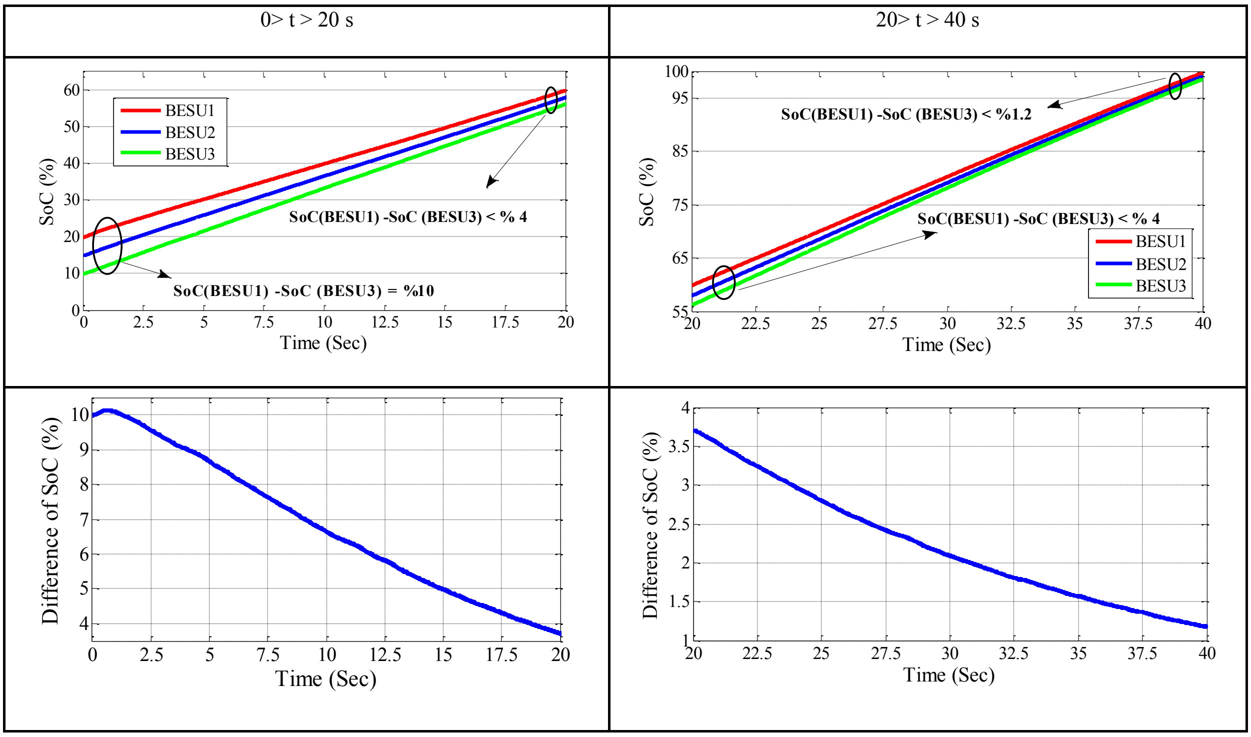
Fig.6 Input / Output power of BESUs (a) discharge (b) charge period



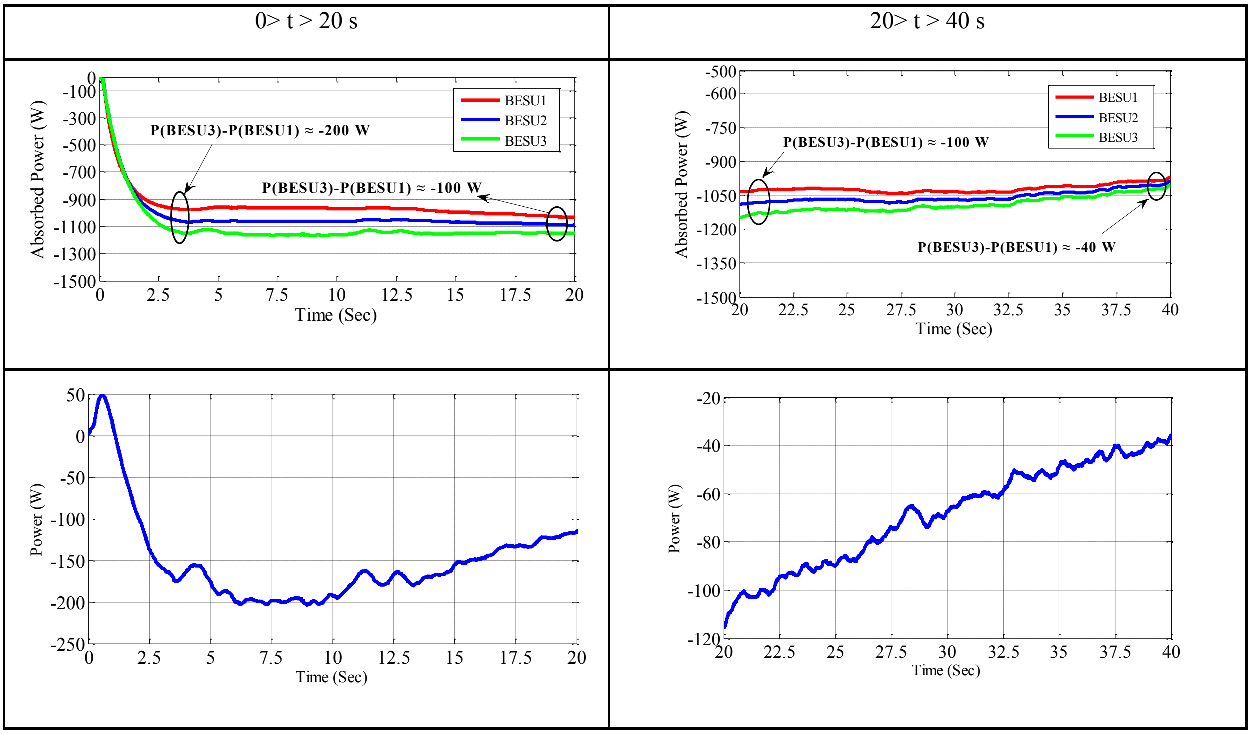
(a)

(b)

Fig.7: The equalization of the SoC (a) and power (b) in discharging mode



(a)



(b)

Fig.8: The equalization of the SoC (a) and power (b) in charging mode

Table.1 Simulation parameters

type	Item	Symbol	Values & Units	type	Item	Symbol	Values & Units
Secondary control level	Amplitude voltage proportional term	G_{PV}	0.2×10^3	Electrical System Setup	Filter inductance	L_c	$L_g/2$
	Amplitude voltage Integral term	G_{iV}	0.1×10^{-2}		Output impedance	L_g	600 mH
	Frequency proportional term	G_{Pf}	0.1×10^{-2}		Filter capacitance	C_b	$100\mu f$
	Frequency Integral term	G_{if}	0.2×10^3		Linear load (1)	R_{LL_1}	200Ω
	Reactive power proportional term	G_{PQ}	0.1×10^3		Linear load (2)	R_{LL_2}	100Ω
	Reactive power Integral term	G_{iQ}	0.2×10^{-3}		Nonlinear load resistance	R_{NL}	200Ω
	SoC proportional term	G_{PS}	0.2×10^3		Nonlinear load inductance	L_{NL}	0.084 mH
	SoC Integral term	G_{iS}	3		Nonlinear load capacitance	C_{NL}	$235\mu f$
Inner Control loop	Voltage proportional term	K_{PV}	0.35		Reference value of frequency	f_{ref}	50 Hz
	Voltage Integral term	K_{iV}	0.4×10^3		Reference value of voltage	V_{ref}	400 V
	Current proportional term	K_{Pi}	0.35		LPF Cutting frequency	ω_s	$31.42 rad/s$
	Current Integral term	K_{ii}	0.2×10^3		Number of battery units	N	3

Distribution lines								
From	To	Length (m)	Parameters					
			R_0	X_{L_0}	X_{C_0}	R_+	X_{L+}	X_{C+}
DG₁ & BESU1	AC Bus	100	0.656×10^{-3}	0.3268×10^{-3}	6.643	0.164×10^{-3}	0.0817×10^{-3}	3.571
DG₂ & BESU₂		150	0.456×10^{-3}	0.1268×10^{-3}	6.643	0.143×10^{-3}	0.0417×10^{-3}	3.571
DG₃ & BESU₃		200	0.32×10^{-3}	0.09×10^{-3}	6.643	0.112×10^{-3}	0.00517×10^{-3}	3.571
LL₁ , LL₂		50	0.256×10^{-3}	0.1515×10^{-3}	6.643	0.0955×10^{-3}	0.0325×10^{-3}	3.571
NL		50	1.0052×10^{-3}	0.03729×10^{-3}	6.643	0.423×10^{-3}	0.00417×10^{-3}	3.571

References

[1] M. Barnes.,J. Kondoh.,H. Asano.,*et al.*: "Real-world microgrids-an overview", in IEEE International Conference on System of Systems Engineering (SoSE), April 2007, pp. 1-8.

[2] W. Gu.,Z. Wu.,R. Bo., *et al.*: "Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review", International Journal of Electrical Power & Energy Systems, 2014, vol. 54, pp. 26-37.

[3] T. Logenthiran.,D. Srinivasan.,D. Wong.:"Multi-agent coordination for DER in MicroGrid", in IEEE International Conference on Sustainable Energy Technologies, (ICSET), 2008, pp. 77-82.

[4] T. Ackermann.,G. Andersson., L. Söder.:"Distributed generation: a definition", Electric Power Systems Research, 2001, vol. 57, pp. 195-204.

[5] Y.W. Li.,C.N. Kao.:"An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid", IEEE Transactions on Power Electronics,2009, vol. 24, pp. 2977-2988.

[6] O. Palizban.,K. Kauhaniemi.:"Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode",Renewable and Sustainable Energy Reviews, 2015, vol. 44, pp. 797-813.

[7] J.A. Lopes.,C.L. Moreira., A.G. Madureira.:"Defining control strategies for microgrids islanded operation", IEEE Transactions on Power Systems, 2006, vol. 21, pp. 916-924.

[8] X. Tan., Q. Li.,H. Wang.:"Advances and trends of energy storage technology in microgrid", International Journal of

Electrical Power & Energy Systems, 2013, vol. 44, pp. 179-191.

[9] R. Carnegie.,D. Gotham.,D. Nderitu.,P.V. Preckel.:"Utility Scale Energy Storage Systems (benefits, applications, and technologies)", State Utility Forecasting Group,2013.

[10] K. Bradbury.:"Energy storage technology review", Duke University, 2010, pp. 1-34.

[11] O. Palizban, K. Kauhaniemi.:"Energy storage systems in modern grids—Matrix of technologies and applications" Journal of Energy Storage,in press, 2016, DOI:10.1016/j.est.2016.02.001.

[12] O. Palizban.,K. Kauhaniemi., J.M. Guerrero.:"Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation", Renewable and Sustainable Energy Reviews, 2014, vol. 36, pp. 428-439.

[13] T.L. Vandoorn.,J.D.M De Kooning.,B. Meersman.,L. Vandevelde.:"Review of primary control strategies for islanded microgrids with power-electronic interfaces", Renewable and Sustainable Energy Reviews, 2013, vol. 19, pp. 613-628.

[14] J.M. Guerrero.,J.C. Vasquez.,J. Matas., *et al.*:"Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization", IEEE Transactions on Industrial Electronics,2011, vol. 58, pp. 158-172.

[15] O. Palizban.,K. Kauhaniemi.:"Secondary control in AC microgrids challenges and solutions", in International Conference on Smart Cities and Green ICT Systems (SMARTGREENS),May 2015, pp. 1-6.

[16] A. Bidram.,A. Davoudi.,F.L. Lewis.,J.M. Guerrero.:"Distributed cooperative secondary control of microgrids using feedback linearization", IEEE Transactions on Power Systems, 2013, vol. 28, pp. 3462-3470.

[17] A. Bidram.,A. Davoudi.,F.L. Lewis., Z. Qu.:"Secondary control of microgrids based on distributed cooperative control of multi-agent systems", IET Generation, Transmission & Distribution, 2013, vol. 7, pp. 822-831.

[18] Q. Shafiee.,J.M. Guerrero.,J.C. Vasquez.:"Distributed secondary control for islanded microgrids—A novel approach", IEEE Transactions on Power Electronics, 2014, vol. 29, pp. 1018-1031.

[19] Q. Shafiee.,J.C. Vasquez,J.M. Guerrero.:"Distributed secondary control for islanded MicroGrids-A networked control systems approach," in 38th Annual Conference on IEEE Industrial Electronics Society (IECON), 2012, pp. 5637-5642.

[20] Y. Zhang.,H.J. Jie.,L. Guo.:"Energy management strategy of islanded microgrid based on power flow control", in IEEE PES Innovative Smart Grid Technologies (ISGT), 2012, pp. 1-8.

[21] T. Dragicevic.,J.M. Guerrero.,J.C Vasquez.,D. Skrlec.:"Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability", IEEE Transactions on Power Electronics, 2014, vol. 29, pp. 695-706.

[22] X. Lu.,K. Sun.,J.M. Guerrero., *et al.*:"SoC-based droop method for distributed energy storage in DC microgrid applications", in IEEE International Symposium on Industrial Electronics (ISIE), 2012, pp. 1640-1645.

[23] H. Kakigano.,Y. Miura., T. Ise.:"Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique," IEEE Transactions on Power Electronics, 2013, vol. 28, pp. 2246-2258.

[24] C. Li.,T. Dragicevic.,N.L. Diaz., J.C. Vasquez.,J.M. Guerrero.:"Voltage scheduling droop control for State-of-Charge balance of distributed energy storage in DC microgrids", in IEEE International Energy Conference (ENERGYCON), 2014, pp. 1310-1314.

[25] C. Li.,T. Dragicevic.,M. Garcia Plaza., *et al.:*"Multiagent based distributed control for state-of-charge balance of distributed energy storage in DC microgrids", in 40th IEEE Annual Conference of the Industrial Electronics Society, IECON ,2014, pp. 2180-2184.

[26] X. Lu.,K. Sun.,J.M. Guerrero.,J.C. Vasquez.,L. Huang.:"State-of-charge balance using adaptive droop control for distributed energy storage systems in DC microgrid applications", IEEE Transactions on Industrial Electronics, 2014 , vol. 61, pp. 2804-2815.

[27] X. Lu.,K. Sun.,J.M. Guerrero.,J.C. Vasquez.,L. Huang.:"Double-Quadrant State-of-Charge-Based Droop Control Method for Distributed Energy Storage Systems in Autonomous DC Microgrids", IEEE Transactions on Smart Grid, 2015, vol. 6, pp. 147-157.

[28] N.L. Diaz.,T. Dragicevic.,J.C. Vasquez.,J.M. Guerrero.:"Intelligent distributed generation and storage units for dc microgrids—A new concept on cooperative control without communications beyond droop control", IEEE Transactions on Smart Grid, 2014, vol. 5, pp. 2476-2485.

[29] N.L. Diaz.,D. Wu.,T. Dragicevic.,J.C. Vasquez.,J.M. Guerrero."Fuzzy Droop Control Loops Adjustment for Stored Energy Balance in Distributed Energy Storage System," 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), 2015, pp 728-735.

[30] O. Palizban.,K. Kauhaniemi.:"Distributed cooperative control of battery energy storage system in AC microgrid applications", Journal of Energy Storage, 2015, vol. 3, pp. 43-51.

[31] J.M. Guerrero.,M. Chandorkar.,T.L. Lee.,P.H. Loh.:"Advanced Control Architectures for Intelligent MicroGrids, Part I: Decentralized and Hierarchical Control", IEEE Transactions on Industrial Electronics, 2013, vol. 60, pp.1254-1262.

[32] J.M. Guerrero.,P.H. Loh.,T.L. Lee., M. Chandorkar.:"Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids," IEEE Transactions on Industrial Electronics, 2013, vol. 60, pp. 1263-1270.

[33] J. M. Guerrero.,N. Berbel.,J. Matas., *et al.*:"Droop control method with virtual output impedance for parallel operation of uninterruptible power supply systems in a microgrid," in Twenty Second Annual IEEE Applied Power Electronics Conference, APEC , 2007, pp. 1126-1132.

[34] T. Morstyn.,B. Hredzak.,V.G Agelidis.:"Distributed Cooperative Control of Microgrid Storage", IEEE Transactions on power systems, 2015, vol.30,5,pp. 2780-2789.

[35] D. Dong, "Modeling and control design of a bidirectional PWM converter for single-phase energy systems", M.Sc. Thesis, Virginia Polytechnic Institute and State University, 2009.

[36] C. Tarasantisuk,V. Chunkag.,P. Thounthong.:"Control of Parallel-connected AC to DC Converter with Droop Technique for DC Microgrid Application", Energy Procedia, 2013, vol. 34, pp. 351-361.

[37] N.Pogako.,M. Prodanovic., T.C. Green.:"Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," IEEE Transaction on power electronic, 2007, vol. 22, pp. 613-625.

[38] J. Rocabert,A. Luna.,F. Blaabjerg.,P. Rodriguez.:"Control of power converters in AC microgrids", IEEE Transactions on Power Electronics, 2012, vol. 27, pp. 4734-4749.

[39] P. Rodriguez,I. Candela.,C. Citro.,J. Rocabert.,A. Luna.:"Control of grid-connected power converters based on a virtual admittance control loop", in 15th European Conference on Power Electronics and Applications (EPE), 2013, pp. 1-10.

[40] F. Blaabjerg,R. Teodorescu.,M. Liserre.,A.V. Timbus.:"Overview of control and grid synchronization for distributed power generation systems", IEEE Transactions on Industrial Electronics, 2006,vol. 53, pp. 1398-1409.

[41] T. Vandoorn,J.M. Guerrero.,J.M. De Kooning.,J.C. Vasquez.,L. Vandevelde.:" Microgrids: Hierarchical Control and an Overview of the Control and Reserve Management Strategies" IEEE Industrial Electronics Magazine, 2013,vol.7,4,pp.42-55.

[42] A. Bidram.,A. Davoudi.:"Hierarchical structure of microgrids control system" IEEE Transactions on Smart Grid, 2012, vol. 3, pp. 1963-1976.

[43] P. C. Loh.,F. Blaabjerg.:"Autonomous control of distributed storages in microgrids" in IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE & ECCE), 2011, pp. 536-542.

[44] K. J. Åström,T. Hägglund.:"The future of PID control" Control engineering practice, 2001, vol. 9, pp. 1163-1175.

[45] G. Liu,S. Daley.:"Optimal-tuning PID control for industrial systems" Control engineering practice, 2001, vol. 9, pp. 1185-1194.

Publication VII

Evaluation of the Hierarchical Control of Distributed Energy Storage Systems in Islanded Microgrids Based on Std IEC/ISO 62264

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IEEE-PES General meeting conference 2016

Evaluation of the Hierarchical Control of Distributed Energy Storage Systems in Islanded Microgrids Based on Std IEC/ISO 62264

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***Abstract*— In this paper, a decentralized control methodology based on hierarchical control levels is investigated. In recent years, efforts have been made to develop standards for Microgrids (MGs), and the decentralized control method evaluated here is based on the IEC/ISO 62264 standard. Since the main challenge to decentralized control in Battery Energy Storage Systems (BESSs) is the different levels of stored energy, a modified droop control is used here to share the power between the different storage units, based on the energy level of each unit. The power coefficients of the droop control are set inversely proportionally and directly proportionally, respectively, to the state of charge (SoC) of each battery unit during discharging and charging mode. To evaluate this decentralized method based on the IEC/ISO 62264 standard, PSCAD/EMTDC software is used.**

***Index Terms*—** Decentralize control, Droop control, Hierarchical control, IES/ISO62264 Standard, Microgrid.

I. INTRODUCTION

Recently, with the growing use of renewable energy, Distributed Generation (DG) and consequently Microgrids have become more interesting system for implementation and research. Since the power produced by these sources is not stable and their response to variation within the MG is slow, an Energy Storage System (ESS) must be used to cover the fluctuation. The critical point in such a system is to control the MG and ESS by managing the power between these two different systems. To achieve the optimum operating performance for the system, a hierarchical control needs to be implemented. A comprehensive investigation of MGs is presented in [1], on the basis of which hierarchical control can be described as having four and three levels, respectively, for MGs and ESSs. The control levels are responsible for processing (*inner control loop*), sensing and adjusting (*primary level*), monitoring and supervising (*secondary level*), and maintaining and optimizing (*tertiary level*). However, energy storage is a local resource that generally contributes to the MG in island operating mode. The third control level thus does not operate and hierarchical control of ESSs consists of three levels: the inner, primary, and secondary control loops. Each control level can be implemented using a number of different technologies; *Vandoorn et al.* [2] and *Guerrero et al.* [3] present a complete investigation into the primary and secondary control level, respectively. Secondary control levels can be classified as *centralized* or *decentralized*, and the challenges of the control level, and their solutions, are presented in [4]. The major challenges when employing a fully decentralized control system are the impossibility of controlling the system during transient variations and some other management functions. To solve these challenges and reach high level control, a distributed cooperative strategy for ESS and MG is proposed and evaluated by the authors in [5].

At the same time, over the last several years, researchers have been also working on obtaining standards for designing the most suitable overall MG. As shown in Fig. 1, a brief statistical study using the *web of science and IEEE xplore* search engine showed an increasing trend for research into hierarchical control in MGs and standardization in this area over the last ten years. There are no precise standards to have been developed for adapting MGs, but some Distributed Energy Resource (DER) standards can be used. In [6] a summary of the European and American standards applicable to MGs is presented. To approach this open research question, the authors of the paper proposed applying the international standard IEC/ISO 62264 to MGs and ESSs [7], taking account of the hierarchical control of these systems. The IEC/ISO 62264 standard consists of five different levels: *level zero* (the generation process), *level one* (the process of sensing and adjusting generation), *level two* (monitoring and supervising), *level three* (maintaining and optimizing), and *level four* (market structure and business model).

The objective of this paper is to evaluate and adapt the proposed distributed control strategy for MGs [5] based on the IEC/ISO 62264 standard. A short introduction to the standard is given in Section 2. In section 3, definition of the hierarchical control level and the methodology of the distributed control system are presented. The control method is adapted and evaluated on the basis of the IEC/ISO 62264 standard in Section 4. A simulation study is presented in Section 5 to evaluate the performance of the distributed control method. Finally, the paper is concluded in Section 6.

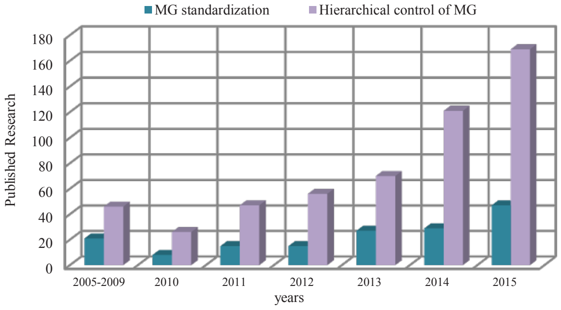

Fig.1 Statistics about hierarchical control and standardization of MG

II. IEC/ISO 62264 STANDARD

As mentioned, the variation in power generation and interconnection, as well as the electrical interfaces between different sources, energy storage systems, and the main grid may be barriers to achieving a common standard for connecting DERs to the grid [6]. To address these issues, the IEC/ISO 62264 international standard is intended to be applied to MGs, which are considered here from a hierarchical control viewpoint. The objective of IEC/ISO 62264 is to offer consistent terminology for supplier and manufacturer communications, and thus to serve as a foundation for clarifying applications and information. IEC/ISO 62264 is represented on five levels [8]: *Level zero* indicates the process of manufacturing or production and discusses the fundamental information and management.

Level one specifies sensing, sensors, and actuators to monitor and regulate generation. In this level, direct control for providing stable output from units and the measurement of deviations in the response to each immediate variation in the system are discussed. Moreover, the collection of data and the transmission of the information to the upper control level are further objectives of this level.

Level two indicates the control activity for monitoring and supervising the process in order to keep it stable and under control. In this level, the information received from level one is analyzed to determine the limits of the system. Moreover, in this level, the position of the system is determined and, on the basis of this position, the control strategy aims to optimize the operation of the system.

Level three creates a connection between two different part of the control system, taking into account the demand and detecting energy limitations.

Level four concerns the market structure and business model of the system. In this level of the standard, the exchange of production between the generator and consumer, capital and how to exploit it, and consumer service are considered. Based on this standard, control of the system is in hierarchical form and all commands are executed by imposing them from a higher level.

III. DECENTRALIZED CONTROL OF MGS & BESS

The DGs and Battery Energy Storage Systems (BESUs) are power electronic control-based devices that contain several parts with different responsibilities. The hierarchical control approach is necessary in such a system in order to achieve an optimum control strategy. The definitions and responsibilities of each control level of the power electronic base sources are as follows [9, 10]:

The *inner control loop* manages the output power of the sources as a target of the control level; this is accomplished by the inner current and voltage control loop. The *primary control* feeds the inner current and voltage control loop by adjusting the reference value of the frequency and voltage. The *secondary control* ensures a secure output from sources by supervising and monitoring the system for regulating the deviation of both voltage and frequency. The *Tertiary control* manages the power flow by adjusting the voltage and frequency when the MGs are connected to the main grid.

Since the objective of this paper is to adapt the IEC/ISO62642 standard to the decentralized control method for MG (DGs and BESSs), the distributed control strategy used in this paper is presented as follows [5]:As proposed in [11], in distributed control methods for DGs, the error rate for the frequency and voltage is determined by comparing the measurements at regular intervals with the average value. The error rate is then sent to the primary control level to restore the voltage and frequency. The restoration compensator is determined as below:

$$\Delta V_{ESU_k} = G_{pv}(V_{ESU}^{ref} - \overline{V}_{ESU_k}) + G_{iv}\int (V_{ESU}^{ref} - \overline{V}_{ESU_k})dt$$
$$\overline{V}_{ESU_k} = \frac{\sum_{i=1}^{N} V_{ESU_i}}{N} \tag{1}$$

$$\Delta f_{ESU_k} = G_{pf}(f_{ESU}^{ref} - \bar{f}_{ESU_k}) + G_{if}\int (f_{ESU}^{ref} - \bar{f}_{ESU_k})dt$$
$$\bar{f}_{ESU_k} = \frac{\sum_{i=1}^{N} f_{ESU_i}}{N} \tag{2}$$

Since the voltage value is different in each part of the system, the reactive power of each sample point must be measured and considered in order to obtain the reference value for the primary control. The control signal for the reactive power is calculated as:

$$\Delta Q_{ESU_k} = G_{PQ}(\overline{Q}_{ESU_k} - Q_{ESU_K}) + G_{iQ}\int (\overline{Q}_{ESU_k} - Q_{ESU_k})dt$$
$$\overline{Q}_{ESU_k} = \frac{\sum_{i=1}^{N} Q_{ESU_i}}{N} \tag{3}$$

In these equations, ΔV_{ESU_k} , Δf_{ESU_k} and ΔQ_{ESU_k} are the restoration values of the voltage, frequency, and reactive power, respectively, while, $\overline{V}_{ESU_k}$, $\bar{f}_{ESU_k}$ and $\overline{Q}_{ESU_k}$ are the average voltage, frequency, and reactive power of ESU_k at each sample time. G_p and G_i are the control parameters of the upper control PI compensator for voltage (v), frequency (*f*), and reactive power (Q).

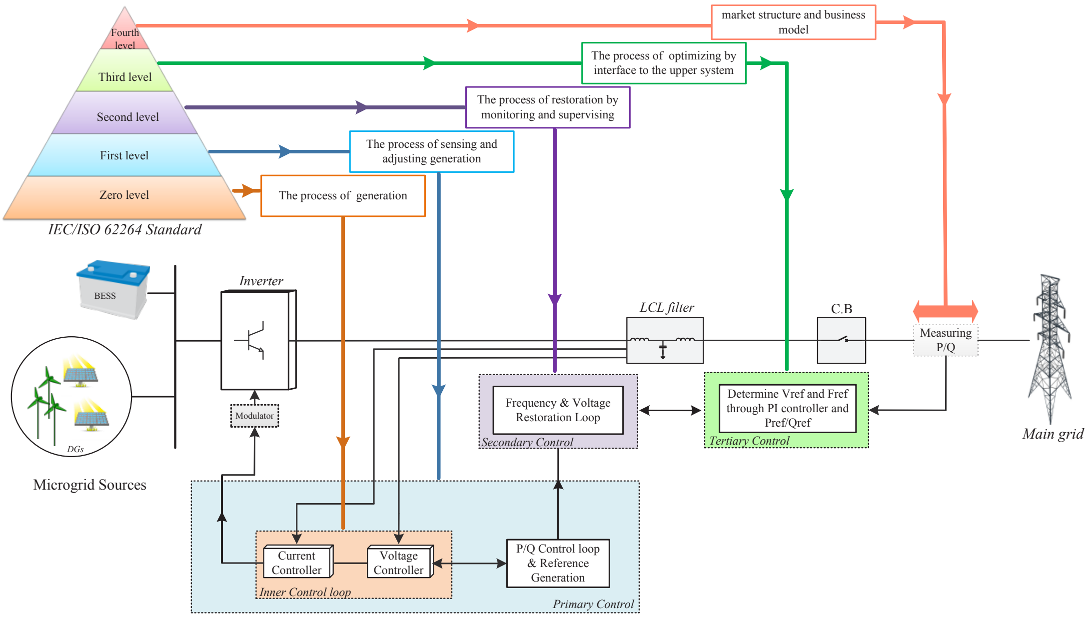

Fig.3 : Microgrid sources (DGs and BESS) Vs. IEC/ISO62264 Standard

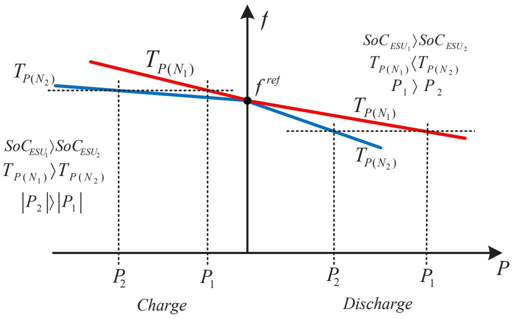

Fig.2 modified droop control

In a BESS, the energy level of each unit is different, and there is also variation from step to step. Hence, to adapt the decentralized method to the system, an accurate reference value based on the available energy of the system in each sample intervals is required.

The reference value for the energy level and the control signal for SoC in this decentralized control strategy are defined as [5]:

$$\delta_{SoC_{ESU_k}} = G_{PS}(\overline{SoC}_{ESU_k} - SoC_{ESU_k}) + G_{is}\int(\overline{SoC}_{ESU_k} - SoC_{ESU_k})dt$$

$$\overline{SoC}_{ESU_k} = \frac{\sum_{i=1}^{N} SoC_{ESU_i}}{N} \qquad (4)$$

where $\delta_{SoC_{ESU_k}}$ and $\overline{SoC}_{ESU_k}$ are the control signal and the reference value for SoC, respectively. Moreover, the number of storage units is shown with *N*. Generally, in traditional droop control, the power from the storage unit is shared based on the power capacity of each unit. The strategy lead to some problems in the ESS control where the storage units that have lower energy levels will run out of energy earlier than the others in discharge mode, while BESUs with higher levels of energy become full and are no longer able to absorb energy during charging.

To overcome this problem, a modified droop control has been presented by the author in [5], on the basis of which power sharing between the BESSs takes account of the energy level of each unit. In this method, the droop coefficient is inversely proportional to the energy level during discharge and directly proportional during charging. The new droop coefficient $(T_{P(N_k)})$ and the modified droop control is obtained as follows:

$$T_{P(N_k)} = \begin{cases} T_{P(S)} + \delta_{SoC_k} \longrightarrow \textit{Discharging mode} \\ T_{P(S)} - \delta_{SoC_k} \longrightarrow \textit{Charging mode} \end{cases} \qquad (5)$$

$$f_k = f^{ref} - T_{P(N_k)}.(P_k - P^{ref}) \qquad (6)$$

Fig. 2 shows the curve of the state-of-charge-based droop control. Power injection during discharge and the absorption of energy during charging is based on the energy level of each storage unit.

IV. DECENTRALIZED CONTROL VS. IEC/ISO62264

Based on the definition of the different levels in the IEC/ISO 62264 standard and of decentralized control in DGs and BESSs, these two issues conform to each other here.

Level zero of the IEC/ISO 62264 standard considered the fundamental information on production units; the responsibility of DGs and BESSs in this level is to implement the *inner control loop* through voltage and current control loops so as to keep the power output at given reference value.

The *first level of the IEC/ISO 62264 standard* detects any variation in the system and acts to cover it immediately by measuring the difference and transferring it to the upper control level. In DGs and BESSs, determining accurate reference values for voltage and frequency so as to maintain optimum control of the power converter is the responsibility of the *primary control level*. Since the *second level of the IEC/ISO 62264 standard* monitors and supervises the system to keep it stable and under control, the *second control level* in DG and BESS hierarchical control can be covered by the standard level.

Monitoring and supervising the variations in power, voltage, and frequency—as well as determining the reference value for the primary control based on the variation—are the responsibility of the control level. The duties of the third level of the IEC/ISO 62264 standard are to create a program to manage the coverage area and produce the optimized strategy to support the subsystem, and the objectives of the tertiary control level in DGs and BESSs is power management and the reinstatement of secondary control. Moreover, optimizing the set-point operation of the system from both technical and economic points of view is the other objective of the final level of control in the MG, with the *fourth level of the IEC/ISO 62264 standard* discussing the market structure and the business mode of system. The adaptation of decentralized control and the proposed standard are illustrated in Fig. 3.

Although the structure of control is same for both DGs and BESSs, there are some differences in responsibility of hierarchical control between them. The responsibility of the hierarchical control of MGs is to provide stable power for connecting to the main grid or supporting the linear and nonlinear loads. Hierarchical control is defined based on the type of the connection for the MG. However, as mentioned in the introduction, storage control does not contain tertiary controls but consists only of an inner control loop, primary, and secondary control levels. The responsibility of the hierarchical control of a BESS, in addition to providing stable power, is managing the energy level of the energy storage system and avoiding the problems overcharging or over discharging. The following section evaluates the decentralize control strategy, as discussed in Section 3, for the charging and discharging period when there is a difference in energy levels.

V. SIMULATION RESULTS

PSCAD/EMTDC is used to simulate the distributed cooperative control of BESSs and DGs based on the IEC/ISO 62264 standards. The system include three battery storage units which are adjusted by 5% difference in their energy level for both charging and discharging mode, so that $SoC_{ESU_1} \rangle SoC_{ESU_2} \rangle SoC_{ESU_3}$. Moreover, to achieve an advanced simulation, each DG and BESS is in a different location with different distances between them (*200 m*, *150 m*, and *100 m* to the AC bus for BESU$_1$ to BESU$_3$ and DG$_1$ to DG$_3$, respectively). Two resistors (R_{L1}, R_{L2}), acting as the linear load and a nonlinear load, represented with a diode rectifier loaded by a capacitor (C_{NL}) and a resistor load (R_{NL}) are to connected to the AC bus. The entire load is located *50 m* away from the AC bus. The configuration of the system is shown in Fig. 4 and Table 1 summarizes its main parameters, which are identical for all three BESUs and DGs.

As mentioned, the hierarchical control of BESSs based on the IEC/ISO 62264 standard, besides providing stable power, is also responsible for injecting power during power shortages (discharging mode) and absorbing energy to charge storage units (charging mode). Equalization of the energy levels for each battery storage unit for discharging and charging are shown in Fig. 5. The power is shared in such a way that the unit with the greatest SoC (Battery 1) provides more power than the unit with the least SoC (Battery 3), when storage unit operate as a power supplier. The situation is inverted when power is absorbed through these storage units. Fig. 6 shows the absorbed and injected power of each unit in the process of discharging and charging. In power sharing, the difference between the powers is reduced gradually, based on the closing energy level of each unit. The speed of convergence decreases with each step taking on account of the decreasing error values between the power shared and the SoC. The low fluctuations in injected and absorbed power in the storage unit are a result of the hierarchical control level of the MG, which is evaluated on the basis of the IEC/ISO 62264 standard here. The variation in the power absorbed is higher than that of the injecting power because of the variation in the power generated by the DGs.

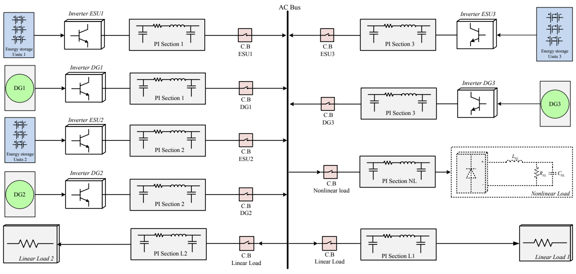

Fig.4 The system study for simulation

Table I Simulation parameters

type	Item	Symbol	Values
Secondary level control	Amplitude voltage proportional term	G_{PV}	0.2×10^3
	Amplitude voltage Integral term	G_{iV}	0.1×10^{-2}
	Frequency proportional term	G_{Pf}	0.1×10^{-2}
	Frequency Integral term	G_{if}	0.2×10^3
	Reactive power proportional term	G_{PQ}	0.1×10^3
	Reactive power Integral term	G_{iQ}	0.2×10^{-3}
	SoC proportional term	G_{PS}	0.2×10^3
	SoC Integral term	G_{iS}	3
Load	Linear load	R_{LL}	200Ω
	Nonlinear load resistance	R_{NL}	200Ω
	Nonlinear load inductance	L_{NL}	0.084 mH
	Nonlinear load capacitance	C_{NL}	235μf

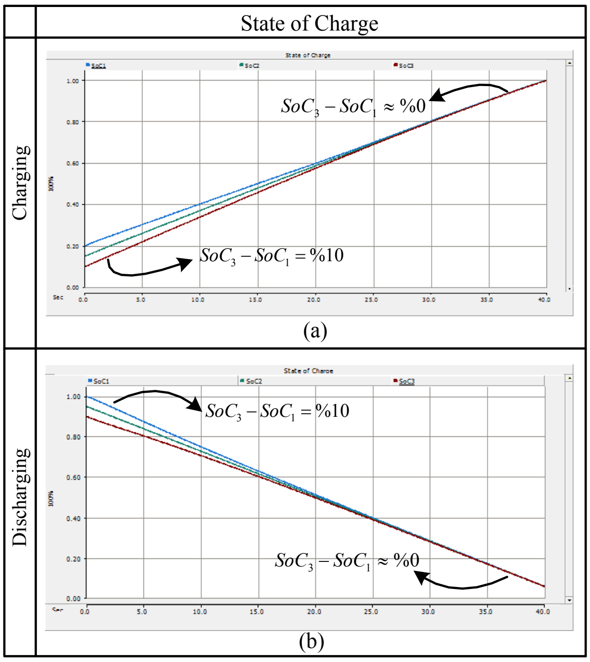

Fig.5: Converge of SoC (a) charging mode (b) discharging mode

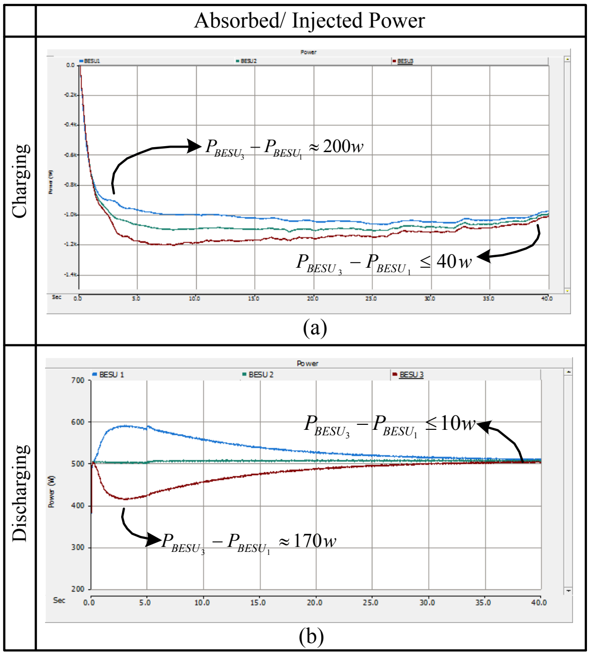

Fig.6: power sharing (a) charging mode (b) discharging mode

VI. CONCLUSION

In this paper, a decentralized control method for microgrids has been described in conformity to the IEC/ISO62264 standard. To deal with the challenge represented by the difference in energy levels between the storage units, a modified droop control with the ability to share the power between the different units based on their energy levels in the decentralized control is employed. The benefit of decentralized control of MGs is the improvement in the efficiency of the distributed cooperative control of DGs and ESSs, as well as the increase in the power reliability of the system.

The hierarchical control of MGs with decentralized control is evaluated based on the IEC/ISO62264 standard. The standardization involves the target of each control level and does not depend on details such as the type of control. Hence, the standardization can be extended to other control types of microgrid. The investigation of decentralized control in different ESS applications remains an open research question for future work.

VII. REFERENCES

[1] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system,", *IEEE Transactions on Smart Grid,* vol. 3, pp. 1963-1976, 2012.

[2] T. Vandoorn, J.D.M. De Kooning, B. Meersman, *et al.* "Review of primary control strategies for islanded microgrids with power-electronic interfaces," *Renewable and Sustainable Energy Reviews,* vol. 19, pp. 613-628, 2013.

[3] J.M.Guerrero, J.C.Vasquez, J.Matas, *et al.* "Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization" *IEEE Transactions on Industrial Electronics,,* vol. 58, pp. 158-172, 2011.

[4] O. Palizban and K. Kauhaniemi "Secondary control in AC microgrids challenges and solutions" in *International Conference on Smart Cities and Green ICT Systems (SMARTGREENS),* 2015, pp. 1-6.

[5] O. Palizban and K. Kauhaniemi "Distributed cooperative control of battery energy storage system in AC microgrid applications" *Journal of Energy Storage,* vol. 3, pp. 43-51, 2015.

[6] E.Planas, A.G.de-Muro, J.Andreu, *et al.* "General aspects, hierarchical controls and droop methods in microgrids: A review" *Renewable and Sustainable Energy Reviews,* vol. 17, pp. 147-159, 2013.

[7] O. Palizban, K. Kauhaniemi,J.M. Guerrero, "Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation" *Renewable and Sustainable Energy Reviews,* vol. 36, pp. 428-439, 2014.

[8] "IEC 62264-1: Enterprise-Control System Integration, Part 1: Models and Terminology," *Bureau of Indian Standards (BIS),* vol. Industrial Process Measurement and Control (ETD 18), 2003.

[9] O. Palizban and K. Kauhaniemi, "Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode" *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 797-813, 2015.

[10] F. Blaabjerg, R. Teodorescu, M. Liserre, *et al.*"Overview of control and grid synchronization for distributed power generation systems",*IEEE Transactions on Industrial Electronics,* vol. 53, pp. 1398-1409, 2006.

[11] Q.Shafiee, J.M.Guerrero, J.C.Vasquez "Distributed secondary control for islanded microgrids—A novel approach", *IEEE Transactions on Power Electronics,* vol. 29, pp. 1018-1031, 2014.