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Aspects and Directions of Internal Arc Protection

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Julkaisun nimike
Valokaarisuojauksen näkökohtia ja kehityssuuntia

Tiivistelmä

Valokaarivika keski- tai pienjännitekojeistossa on yksi sähköverkkojen tuhoisimmista vikatyypeistä. Sitä voidaan luonnehtia sähköiseksi räjähdykseksi. Se aiheuttaa ihmisille vakavan palovammariskin ja monia muita vaarallisia vaikutuksia. Valokaari voi aiheuttaa myös erittäin huomattavia taloudellisia menetyksiä laitevaurioina tai sähkönjakelun ja tuotantoprosessien keskeytysten seurauksena. Valokaarivikojen vähentämiseksi ja niiden vaikutusten lieventämiseksi on kehitetty useita menetelmiä. Tässä tutkimuksessa valokaarisuojauksen menetelmistä on esitetty kattava kokonaiskuva laitteiden suunnittelusta valokaaren sammuttamiseen asti. Työssä on myös tutkittu ja esitetty suojauksen kehityssuuntia.

Osa valokaarivioista kehittyy hitaasti. Tutkimuksessa on tarkasteltu kehittyviin vikoihin liittyviä ilmiöitä, testattu niiden havaitsemiseen soveltuvia antureita ja luotu suuntaviivat jatkuvatoimiselle ennakoivalle valokaarisuojaukselle.

Tietoliikenteen merkitys sähköverkoissa kasvaa, kun verkkoja kehitetään älyverkoiksi. Tämä koskee myös valokaarisuojausta, jossa koko suojausjärjestelmältä edellytetään erittäin nopeaa toimintaa. Tutkimuksessa on tarkasteltu IEC 61850 -standardin määrittelemien GOOSE-viestien hyödyntämistä valokaarisuojausjärjestelmässä ja osoitettu kehitetyn järjestelmän avulla kyseisen tekniikan käyttökelpoisuus ja edut.

Valokaarien aiheuttamien vahinkojen lieventämiseksi tutkimus esittää jo olemassa olevien ja tehokkaiksi osoittautuneiden menetelmien standardointia, erityisesti valokaaren optiseen havaitsemiseen perustuvaa suojausta. Valokaaren vaikutusajan minimoimiseksi voimavaroja kannattaa suunnata katkaisijatekniikan kehittämiseen. Kriittisimmissä kohteissa oikosulkulaitteet tarjoavat erittäin tehokkaan suojauksen.

Asiasanat
Valokaari, kojeisto, ennakoiva suojaus, sensorit, IEC 61850.

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Aspects and Directions of Internal Arc Protection

Abstract

An arc fault in medium voltage or low voltage switchgear is one of the most devastating fault types in power systems. Term ‘arc flash explosion’ is a good characterization of the fault type. It causes a serious burn hazard to personnel along with several other safety hazards. An arc fault may also lead to significant economic losses directly, by damaging the equipment and indirectly, through power supply outages and production process interruptions. Several methods have been introduced to prevent arc faults and mitigate their impacts. In this research a comprehensive overview of the methods has been given, starting from the design of equipment until the extinction of the fault arc. Development directions for arc protection have been investigated and suggested.

Part of arc faults develop gradually and it is possible to construct systems for detecting such faults. In this research, mechanism and phenomena related to developing faults have been investigated. Moreover, an online monitoring system enabling preemptive protection has been outlined, and suitable sensors have been tested in a laboratory.

The importance of communication technology in power systems increases along with the progress of smart grids. This also applies to arc protection systems that require extremely short operation time. This research has investigated the feasibility of IEC 61850 based GOOSE messaging in arc protection systems, verified the functionality of a developed implementation and evaluated benefits of the technology.

The dissertation suggests standardization of already existing, effective and proven protection methods, especially protection based on optical detection. In minimizing the arc duration, efforts should be directed towards development of circuit breaker technology. In most critical sites, short-circuit devices can be applied.

Keywords

Arc fault, switchgear, preemptive protection, sensors, IEC 61850.

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I am very grateful to Dr. G. Amjad Hussain and professor Matti Lehtonen for excellent cooperation and encouragement during the research on arc prediction technology at Aalto University. I also express my deep gratitude to IEEE Fellow John A. Kay, Rockwell Automation, for valuable contribution in our articles. Special thanks to all other co-authors.

I want to express my gratefulness to current and former colleagues Anssi Mäki, Katja Sirviö, Jukka Rinta-Luoma and Sampo Voima for encouragement and for the social network at the University of Vaasa. Professor N. Rajkumar deserves special thanks for proofreading.

The Graduate School of the University of Vaasa, Ulla Tuominen Foundation and Vaasan Teknillinen Seura are acknowledged for their financial support, enabling the finalization of the dissertation.

This dissertation is definitely not my life’s work. This is just a thesis. And work is only a slice of my life.

September 2016

Lauri Kumpulainen

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Abbreviations

AC	alternating current
ANSI	American National Standards Institute
CL	current-limiting
CPU	central processing unit
CT	current transformer
DNP3	distributed network protocol
DSP	digital signal processor
DWT	discrete wavelet transform
ETO	emitter turn-off thyristor
F	Fahrenheit
FFT	Fast Fourier Transform
GOOSE	Generic Object Oriented Substation Event
GTO	gate turn-off thyristor
HFCT	high frequency current transformer
HRG	high-resistance grounding
HV	high voltage
I/O	input/output
I0	zero sequence current
ICT	information and communication technology
Idiff	differential current
IEC	International Electrotechnical Commission
IED	intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated-gate bipolar transistor
IGCT	integrated gate-commutated thyristor
IR	infrared
ISSA	International Social Security Association
L	light
LAN	local area network
LON	Local Operating Network
LV	low voltage
MAC	message authentication code
MAC	media access control (MAC address, physical address)
MCT	MOS controlled thyristor
MMS	Manufacturing Message Specification
MOS	metal-oxide-semiconductor
MV	medium voltage
NFPA	National Fire Protection Association
PD	partial discharge
PPE	personal protective equipment
RF	radio frequency

SCADA	supervisory control and data acquisition
SMA	SubMiniature version A
SPA	asynchronous serial protocol
SSCB	solid-state circuit breaker
TCP/IP	Transmission Control Protocol/Internet Protocol
TID	thermal ionization detector
USB	universal serial bus
UV	ultraviolet
VT	voltage transformer
VLAN	virtual LAN, virtual local area network
ZSI	zone-selective interlocking

Publications

The dissertation is based on the following appended publications:

I Kumpulainen, L., Hussain, G.A., Rival, M. (2012). “The Big Picture of Arc-Flash Protection”. Proceedings of IEEE PCIC Europe Conference, Prague, 19–21 June 2012, pp. 1–8

II Kumpulainen, L., Hussain, G.A., Rival, M., Lehtonen, M., Kauhaniemi, K. (2014). “Aspects of Arc-Flash Protection and Prediction”. Electric Power Systems Research 116, pp. 77–86

III Kumpulainen, L., Harju, T., Pursch, H., Wolfram, S. (2011). ”High Speed Protection Concept to Minimize the Impacts of Arc-Flash Incidents in Electrical Systems of Ships”. Proceedings of IEEE Electric Ship Technologies Symposium, Alexandria, VA, April 10–13, 2011. pp. 1–6

IV Kumpulainen, L., Kay, J.A., Aurangzeb, M. (2011). ”Maximal Protection: Lowering Incident Energy and Arc Blast Elements by Minimizing Arcing Time”. Proceedings of 2011 IEEE IAS Petroleum and Chemical Industry Technical Conference, Toronto, September 19–21, 2011, pp. 1–6

V Kay, J.A., Kumpulainen, L. (2013). ”Maximizing Protection by Minimizing Arcing Times in Medium Voltage Systems”. IEEE Transactions on Industry Applications, July/August 2013, Vol. 49, Issue 4, pp. 1920–1927

VI Kumpulainen, L., Hussain, G.A., Lehtonen, M., Kay, J.A., (2013). “Preemptive Arc Fault Detection Techniques in Switchgear and Controlgear”. IEEE Transactions on Industry Applications, July/August 2013, Vol. 49, Issue 4, pp. 1911–1919

VII Hussain, G.A., Kumpulainen, L., Lehtonen, M., Kay, J.A. (2014). “Preemptive Arc Fault Detection Techniques in Switchgear and Controlgear – Part II”. IEEE Transactions on Industry Applications, Vol. 50, Issue 3, 2014, pp. 1649–1658

VIII Kumpulainen, L., Jäntti, A., Rintala, J., Kauhaniemi, K. (2016). ”Benefits and performance of IEC 61850 GOOSE based communication in arc protection”. Submitted to IET Generation, Transmission & Distribution.

1 INTRODUCTION

1.1 Importance of internal arc fault protection

Key requirements for electricity distribution have been adequate reliability, safety to personnel and reasonable costs. Environmental awareness has recently emerged, bringing new challenges. The emphasis of each requirement varies depending on regulation, culture, policy and application. In process industry applications, for instance, very high reliability is a primary target since the interruption costs are very high.

Faults in power systems cause interruptions, equipment damage, and safety hazard to personnel. All of these possible consequences have economic impacts. High power arc faults in metal-clad switchgear are a special fault type, releasing a lot of energy and causing significant damage and safety hazard. Arc faults are often considered as the most severe and devastating fault type in power systems, including a number of detrimental impacts.

Safety related impacts are serious. In the USA, for instance, each year more than 2000 people are admitted to burn centers with severe arc flash burns (NFPA 2015; Gammon et al. 2015b). In the worst cases with direct human interaction, arc faults lead to fatality. In Finland 14 lethal arc fault accidents occurred during 1977-1986 (Kalliomäki 2010).

However, the safety hazard is only one aspect of arc faults. The damage to equipment and extensive power supply and process interruptions often lead to very high costs, in the order of millions of dollars per incident (Wilson et al. 2007). In case of human injuries, the total costs may be even higher due to medical and legal expenses.

Traditional protection approaches, e.g. overcurrent relay protection with operation times typically of several hundreds of milliseconds, are ineffective in arc faults. Dedicated protection with arcing time less than one hundred milliseconds provides far better mitigation of the thermal impact. If maximal protection is needed e.g. in order to limit the pressure impact of an arc fault, there is arc protection technology able to reduce the arcing time to as low as a few ms.

1.2 Objectives of the work

The main objectives of this thesis are the following:

- To create a comprehensive view of present and future technologies for internal arc protection in medium voltage (MV) and low voltage (LV) switchgear. This big picture should cover the whole range from early indication of arc fault incidents to the elimination of the fault arc. The view should also be developed to recognize the most potential areas for research and development, including standardization and requirements, where significant improvements can be achieved.
- To develop technology for early indication of slowly developing internal arc faults. Appropriate sensors and online monitoring of the equipment provide proactive and preemptive protection, totally preventing high-energy arc faults.
- To study whether IEC 61850 GOOSE based technology can be successfully applied in the internal communication of arc protection systems and to evaluate its benefits.

1.3 Outline of the thesis

The dissertation consists of a summary section and the appended original publications. The contents of the summary are divided into 9 chapters as follows.

Chapter 1 introduces the topic, defines the objectives of the research and presents the outline of the thesis.

Chapter 2 discusses the arc flash phenomenon and the causes and consequences of arc faults in metal-clad switchgear.

Chapter 3 gives a review of arc protection related standards and evaluates development needs in standardization and requirements.

Chapter 4 presents first a comprehensive view of current arc protection technologies. Next, a more detailed description of the state-of-the-art technology based on simultaneous detection of light and overcurrent is given. Finally, the chapter introduces arc protection relays and devices utilized in the elimination of the fault arc.

Chapter 5 explains the importance of the speed of fault arc elimination. The existing technology and commercial examples of short-circuit devices are introduced. Development directions of circuit breakers, providing significantly shorter operation time, are discussed.

Chapter 6 investigates preemptive technology, i.e. sensors and systems to detect developing faults in MV and LV switchgear. A number of physical phenomena and sensor technologies are analyzed.

Chapter 7 presents the results of an experimental investigation of sensors and methods that can be used in the detection of slowly developing arc faults. Technologies for detecting partial discharges and thermal ionization are evaluated.

Chapter 8 discusses the feasibility and benefits of IEC 61850 GOOSE based communication in arc protection applications. A new practical implementation is introduced and its performance is verified by laboratory measurements.

Chapter 9 is the final chapter before the appended publications, presenting the conclusions and contributions of the research.

1.4 Scientific contribution

The thesis is more practically than theoretically oriented, yet providing scientific contribution. The main contribution is the creation of a comprehensive view of arc protection and the recognition of the most potential development directions. The scientific contributions can be summarized as follows:

- Development of methods for arc fault prediction in switchgear.
- Development of IEC 61850 GOOSE based solution for the internal communication of arc protection system.
- The recognition of the promising methods in order to speed up fault arc elimination, and generally enhance arc mitigation, including both existing and future solutions.

In addition to scientific contributions, the thesis has identified a more practical area where significant improvements can be achieved: standardization of arc protection.

1.5 Summary of publications

The publication section of this thesis consists of eight publications, five of which are refereed journal articles and three are refereed conference publications. The first publication was published in 2011, and the last included paper was submitted in 2016. The author of this dissertation is the primary author of six of the publications and the secondary author of two publications.

Publication I, “The Big Picture of Arc-Flash Protection”, presents for the first time a comprehensive view of internal arc protection, covering the whole range from arc fault prevention until fast arc elimination. Both passive and active methods are discussed. The author of this dissertation developed the holistic view.

Publication II, “Aspects of Arc-Flash Protection and Prediction”, supplements and deepens the comprehensive view and provides a technological review of internal arc protection, including a short analysis of the feasibility of IEC 61850 GOOSE based communication in arc protection systems. The author of this dissertation was the principal author of the paper.

Publication III, ”High Speed Protection Concept to Minimize the Impacts of Arc-Flash Incidents in Electrical Systems of Ships”, presents advancements in the detection of light, integration of current sensors into low voltage circuit breakers, and arc quenching technology. The author of this dissertation coordinated the research and was the first author of this paper.

Publication IV, ”Maximal Protection: Lowering Incident Energy and Arc Blast Elements by Minimizing Arcing Time”, analyses both the thermal impact and the pressure wave of arc faults. As extremely fast arc elimination is the most efficient way to mitigate the pressure impact, arc elimination technologies are addressed, and the possible risks caused by short-circuit devices are discussed. The author is the developer of the main idea of the paper.

Publication V, ”Maximizing Protection by Minimizing Arcing Times in Medium Voltage Systems”, deepens the analyses presented in Publication IV, especially regarding MV circuit breakers and short-circuit devices. The first author of the publication was John A. Kay, and the author of this dissertation gave a major contribution both to the literature survey and analysis presented in the paper.

Publication VI, “Preemptive Arc Fault Detection Techniques in Switchgear and Controlgear”, investigates preemptive arc fault protection technologies. It discusses several possible sensor technologies and provides preliminary test results of selected sensor types. The author initiated the research, provided the initial literature survey and the goal for the research and developed the main idea of the paper together with G. Amjad Hussain.

Publication VII, “Preemptive Arc Fault Detection Techniques in Switchgear and Controlgear – Part II”, is a continuation paper to publication VI. It reports more detailed laboratory test results of the selected sensors. The author was the developer of the initial concept and contributed to this paper by providing test equipment to the measurements and analysis which were mainly carried out by G. Amjad Hussain in the laboratory of Aalto University.

Publication VIII, ”Benefits and performance of IEC 61850 GOOSE based communication in arc protection”, studies the communication aspects of arc protection systems, especially the feasibility of GOOSE based communication. The author of this dissertation was the first author of the paper and one of the developers of the initial idea. He also provided the theoretical contribution including the literature survey and participated in the laboratory measurements of the developed system. The presented system was implemented by experts with Vamp Oy, Anssi Jäntti and Juha Rintala.

1.6 Other publications by the author with closely related topics

The author has also acted as the primary author or co-author in the following publications on closely related topics. These publications are not included in the dissertation.

Chávez, R., Kumpulainen, L., Sousa, E., Proteccion Selectiva contra el Arco Interno. Proceedings of IEEE PCIC Brazil, Rio de Janeiro, 16–17 September, 2008.

Kumpulainen, L., Arvola, J., Karri, T., State of the Art of Arc Flash Protection Methods. Proceedings of Western Protective Relay Conference, Spokane, WA, October 20–22, 2008.

Kumpulainen, L., Dahl, S., State of the Art of Arc Flash Protection Methods. Proceedings of 2008 Southern African Power System Protection Conference, Johannesburg, 12–14 November, 2008.

Kumpulainen, L., Dahl, S., Ma, J., Mitigation of Arc-Flash Hazards and Reduction of Costs by Selective Arc-Flash Protection. Proceedings of CICED, China International Conference on Electricity Distribution, Guangzhou 10–13 December, 2008.

Kumpulainen, L., Dahl, S., Selective Arc-Flash Protection. Proceedings of CIRED 2009 Conference, Prague, 8–11 June, 2009.

Kay, J.A., Arvola, J., Kumpulainen, L., Protection at the Speed of Light: Arc-Flash Protection Combining Arc Flash Sensing and Arc-Resistant Technologies, Proceedings of IEEE IAS PCIC Technical Conference, Anaheim, September 14–16, 2009.

Kumpulainen, L., Dahl, S., Minimizing hazard to personnel, damage to equipment, and process outages by optical arc-flash protection, Proceedings of 2010 PCIC Europe Conference, Oslo, June 15–17, 2010.

Kumpulainen, L., Dahl, S., Métodos de protecão selectiva contra arcos eléctricos, Eletricidade Moderna, No 441, Dezembro 2010.

Kay, J.A., Arvola, J., Kumpulainen, L., Protecting at the Speed of Light, IEEE Industry Applications Magazine, May/June 2011.

Kumpulainen, L., Pursch, H., Wolfram, S., Harju, T., Advancements in Arc Protection, Proceedings of CIRED 2011 Conference, Frankfurt, June 6–9, 2011.

Kumpulainen, L., Pursch, H., Wolfram, S., Harju, T., Inovações na proteção contra arco em conjuntos de manobra, Elétricidade Moderna, Janeiro 2012.

Kay, J.A., Kumpulainen, L., Maximizing Protection by Minimizing Arcing Times in Medium Voltage Systems, Proceeedings of IEEE IAS 58th Annual Pulp and Paper Industry Conference, Portland, OR, June 17 – 21, 2012.

Kumpulainen, L., Vähämäki, O., Harju, T., Jäntti, A., Enhancement of Arc-Flash Protection by IEC 61850. Proceedings of PAC World 2012 Conference, Budapest, 25–28 June 2012.

Kumpulainen, L., Hussain, G.A., Lehtonen, M., Kay, J.A, Pre-Emptive Arc Fault Detection Techniques in Switchgear and Controlgear. Proceedings of IEEE PCIC 2012, New Orleans, 24–26 September 2012.

Kumpulainen, L., Rintala, J, Chávez, R., Silva Queiroz, A.R, César Senger, E., Advanced Arc-Flash Protection, Proceedings of IEEE PCIC Brasil, 27–29, Rio de Janeiro, August 2012.

Silva Queiroz, A.R, César Senger, E., Fugeiredo de Oliveira, M., Kumpulainen, L., Chávez, R., Reducing Arc-Flash Incident Energy Level in an Offshore Gas

Production Unit Using IED's – A Case Study, Proceedings of IEEE PCIC Brasil 27–29 August , Rio de Janeiro, 2012.

Hussain, G.A., Kumpulainen, L., Lehtonen, M., Hashmi, M., Shafiq, M., Signal processing of PD measurements to predict arcing faults in MV switchgears, Proceedings of IEEE International Conference on Industrial Technology (ICIT), Cape Town, South Africa, 25–28 February, 2013.

Kumpulainen, L., Rintala, J., Chávez, R., Silva Queiroz, A.R., César Senger, E., Métodos avançados de proteção contra arcos elétricos, Elétricidade Moderna, Março 2013.

Hussain, G.A., Kumpulainen, L., Klüss, J.V., Lehtonen, M., Kay, J.A. (2013). "The Smart Solution for the Prediction of Slowly Developing Faults in MV Switchgear". IEEE Transactions on Power Delivery, Vol. 28, Issue 4, August 2013.

Hussain, G.A., Kumpulainen, L., Lehtonen, M., Kay, J.A., Pre-emptive Arc Fault Detection Techniques in Switchgear and Controlgear – Part II, Proceedings of IEEE PCIC 2013, Chicago, September 23–25, 2013.

Jäntti, A., Vähämäki, O., Rintala, J., Kumpulainen, L., Towards IEC 61850 Based Communication in Arc-Flash Protection Systems, Proceedings of PAC World 2014 Conference, Zagreb, Croatia, 23–26 June 2014.

Jäntti, A., Vähämäki, O., Rintala, J., Kumpulainen, L., Kauhaniemi, K., Evaluating the Arc-Flash Protection Benefits of IEC 61850 Communication, White Paper, Schneider Electric, 2015.

Kay, J.A., Hussain, G.A., Lehtonen, M., Kumpulainen. L., New pre-emptive arc fault detection techniques in medium-voltage switchgear and motor controls, 61st IEEE Pulp and Paper Industry Conference (PPIC), 14–18 June, Milwaukee, WI, USA, 2015.

Hussain, G.A., Shafiq, M., Kumpulainen, L., Mahmood, F., Lehtonen, M., Performance evaluation of noise reduction method during on-line monitoring of MV switchgear for PD measurements by non-intrusive sensors, Electrical Power and Energy Systems 64 (2015).

Silva Queiroz, A.R., Senger, E.C., Figueiredo de Oliveira, M., Kumpulainen, L., Chávez, R., Reducing Arc Flash Incident Energy Level in an Offshore Gas Production Unit Using Intelligent Electronic Device – A Case Study, IEEE Transactions on Industry Applications, Vol. 51, Issue 1, January/February 2015.

Kay, J.A., Hussain, G.A., Lehtonen, M., Kumpulainen. L., New pre-emptive arc fault detection techniques in medium-voltage switchgear and motor controls, IEEE Transactions on Industry Applications, Vol. 52, No 1, January/February 2016.

2 INTERNAL ARC FAULTS IN SWITCHGEAR

2.1 Arc fault phenomenon

2.1.1 Definition of internal arc fault

In this thesis, the definition of an internal arc fault given by CIGRÈ Working Group A 3.24 is applied: "An internal arc fault is an unintentional discharge of electrical energy within an enclosure. When the internal arc fault occurs, the available short circuit current will flow through the arc between phases and/or from phase(s) to ground" (CIGRÉ 2014). IEC Standard 62271-200 defines the arc fault current as "three-phase and – where applicable – the single phase-to-earth r.m.s. value of the internal arc fault current for which the switchgear and controlgear is designed to protect persons in the event of an internal arc" (IEC 2011).

In the literature, term "arc flash" is often used. However, the term "arc flash explosion" expresses better the nature of arc faults (Gammon 2015a). In an internal arc fault, a huge amount of electrical energy turns into radiation and thermal energy extremely rapidly. Due to the very bright light and the pressure wave with possible flying particles, arc faults can be characterized as electrical explosions. An internal arc fault often starts as a line-to-ground fault and rapidly escalates into phase-to-phase fault (Dunki-Jacobs 1986).

2.1.2 Series and parallel arc faults

By definition, a phenomenon called "series arc fault" is not a genuine arc fault, since there is no short circuit and the current is not a fault current. However, since the term is used in the literature, and it has importance in slowly developing arc faults, it is necessary to explain it. Series arc faults are typically caused by loose contacts in series to the connected load. Figure 1 illustrates the difference between series arcing and parallel arc fault.

In a series arc fault the fault current is limited by the load current, and the energy of the fault is low (Müller et al. 2010). Series arcing is difficult to detect, and it can develop to a high-power parallel arc fault. In this thesis, series arc faults are only discussed when examining methods of predicting and preventing parallel, high-power arc faults.

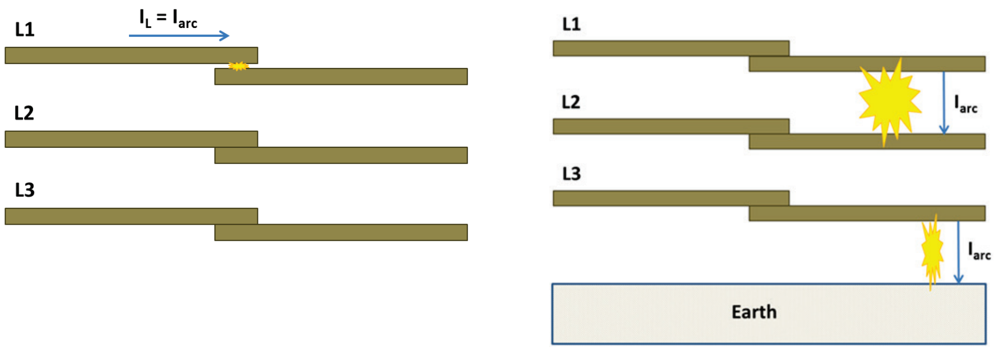

Figure 1. Series arcing and parallel arc fault.

When discussing faults in power systems, an arc fault normally means a high-power parallel arc fault. This thesis is mainly focused on parallel faults in AC systems, high current arcs in gases where the fault arc is formed between two or more conductive parts of a power system. The conductive parts can be two or more phases of the system or the arc can exist between phase and the earth.

2.1.3 Impacts of arc faults

In MV and LV switchgear, air-insulation is very commonly used for several reasons. As an insulating material, air has a self-restoring capacity after a breakdown (Abdel-Salam et al. 2000). Air does not cost anything, and dry air in normal temperature is a poor conductor. However, at high temperatures, more than 2000 K, thermal ionization makes air conductive (Ravindranath & Chander 1977). At sufficiently high temperature, most gas molecules dissociate into atoms. Ionization of atoms and molecules may result from collision of the gas atoms with each other, photoionization resulting from thermal emission, and collisions with high-energy electrons (Abdel-Salam et al. 2000). The ionized air and the ionized material from the electrodes form a conductive plasma channel between the electrodes. The plasma consists mainly of nitrogen and oxygen molecules, atoms and ions of N, O and electrode material, and electrons (Sweeting 2011a). The plasma is very hot, at the terminal points the temperature can be as high as 50,000 K and at points away from the terminal points 20,000 K (Cadick, Capelli-Schellpfeffer & Neitzel 2006).

The hot plasma radiates light. The light is emitted from hot particles, as all hot bodies and particles emit light, and from electrons of the atoms or molecules returning from high energy states to lower states (line radiation). The chemical elements in the plasma can be analyzed from the spectrum of the light since the energy of the emitted photons depends on the difference between the higher and lower energy states, characteristic of the chemical elements.

In a high power arc fault, electrical energy is converted into multiple forms of energy, in the beginning radiation and thermal energy. This occurs with very high power, i.e. a significant amount of energy is released in a very short time period. The arc current is often in the range of tens of kiloamperes. Typically, the power of the arc is high enough to start vaporizing the metal of copper or aluminum busbars.

In order to understand the impacts it is good to understand the energy transfer during an arc fault. Figure 2 has been drawn according to (Anantavanich 2010), and it illustrates the energy transfer in case of internal arcing. The arc has ignited in an enclosure and between two electrodes.

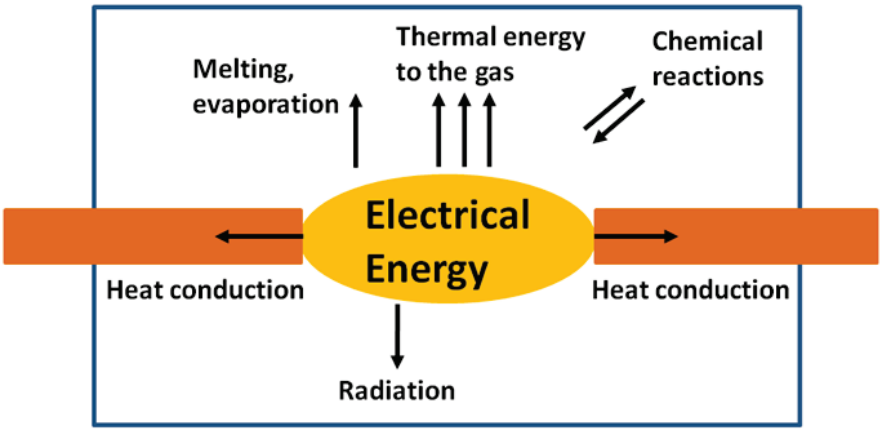

Figure 2. Energy transfer during an arc fault.

In an internal arc fault, part of the electric energy, fed by the power system, heats up the electrodes, and another part is radiated and absorbed by the walls of the enclosure. The surrounding gas is heated up by conduction, convection and radiation absorbed by the gas. Some energy goes to melting and vaporizing the electrodes. The evaporated metal may react chemically with the gas with an endothermic or exothermic reaction. (Anantavanich 2010).

A limited part, 10–20 %, of the energy that comes out of the arc is radiation (Stokes & Sweeting 2006). The radiation includes a wide range of wavelengths from ultraviolet until infrared, naturally including visible light. The light of a high power arc flash can be very intense, luminosity values of clearly more than 100,000 lux have been reported (Hughes et al. 2010; Stokes & Sweeting 2006). The intense radiation can cause eye damages, and the thermal radiation also plays a part in the burning impact of the arc. Figure 3 illustrates the characteristic features of arc faults.

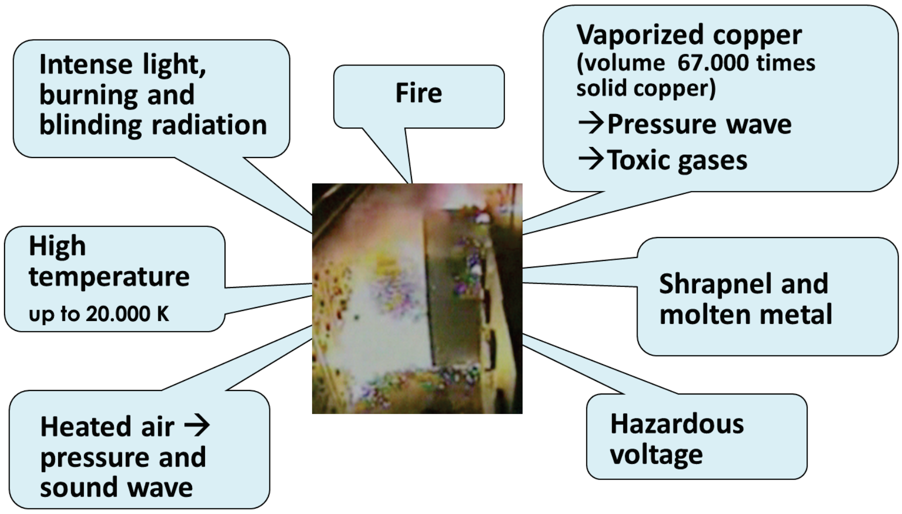

Figure 3. Characteristic features of arc faults.

Most of the arc energy goes to the thermal energy of the plasma cloud (Stokes 2006). The hot plasma and the convection of the hot gases cause a major burn hazard to personnel. The burn hazard is increased by the burning of clothing. Since the fire and possible melting of the clothing have a far longer duration than the arc fault, it can be the most severe burn hazard (Sweeting 2011b). The high temperature also causes chemical reactions and formation of toxic gases from vaporized metal and metal oxides. These can include CuO, CuO_2, Al_2O_3, Fe_3O_4, Fe_2O_3 (Zhang 2012).

One of the most significant impacts of arc faults is the pressure impact. The hot plasma heats up the air inside the switchgear and increases the pressure. A more significant rise in pressure follows the evaporation of the electrodes. Copper, for instance, increases its volume by a factor of 67,000 when turning from solid to gaseous form (Lee 1987), and thus a huge pressure rise is possible. This arc blast can cause several hazardous impacts: it can cause collapse of lungs or other internal damage, ear damage, bone fracture, concussion or traumatic brain injury (Gammon et al. 2015a). Because the blast may include hot droplets of metal, the burn hazard is also increased. Other flying particles, like pieces of insulators, often called shrapnel, add the risk of mechanical injury to personnel. The power of the arc blast is illustrated by the speed of the flying material which can exceed 1120 km/h (Gammon et al. 2015b).

Possible impacts of arc faults on humans include also electrical shock since the body can become a part of the fault circuit. Psychological effects such as depression, job apprehension, and family strife can also be present (St. Pierre 2004).

Serious damage to equipment is also possible. If the arcing time is high the busbars can be totally destroyed, and the arc can burn holes to the switchgear housing. Fire, ignited by the arc fault, can further increase the devastation. The pressure wave can seriously damage the switchgear and even the building where the switchgear is located. There are cases where entire primary substations (HV/MV) have been destroyed. Damage of equipment leads almost always to process outages. The direct costs of the outage of the electricity distribution process are often only a fraction of the indirect costs due to outages in industrial processes e.g. in steel, chemical, oil & gas, or forest industries. The economic impact may include also high medical and legal expenses. Table 1 summarizes the possible consequences of an arc fault.

Table 1. Possible consequences of internal arc faults.

Safety hazards	Arc burns caused by the plasma cloud, hot gases, radiation, ignited clothing and hot flying droplets
	Eye damage caused by intense light
	Ear damage caused by the pressure wave
	Lung collapse or other damage due to the pressure wave
	Bone fracture or concussion caused by the pressure wave
	Wounds and internal damage caused by the shrapnel
	Intoxication caused by toxic gases
	Electrical shock
	Psychological trauma
Damage to equipment	Total evaporation of busbars
	Destruction of switching devices and insulators
	Heat related damage to switchgear enclosure
	Pressure wave related damage to switchgear enclosure
	Damage caused by fire
Indirect consequences	Electricity distribution process outages
	Production process outages
	Medical and legal expenses

Economic analysis is beyond the scope of this thesis. However, although arc faults in switchgear are rather rare events, their consequences are so severe that efficient arc protection is justified. The severe safety hazard related to arc faults also emphasizes the need for dedicated arc protection. There occurred 14 lethal arc fault accidents Finland during 1977–1986. During twice as long a period, 1987–2007, there was only one lethal incident (Kalliomäki 2010). Part of this development can be explained by improved personal protective equipment. However, the widespread implementation of light detection based protection both in new and retrofit installations started in the early 1990s (Karri 2009). It is very likely that the rapid penetration of this technology, even becoming a de facto standard in Finland, was a major factor in the improvement of safety.

2.2 Causes of internal arc faults

Various causes can lead to the failure of insulation and ignition of an internal arc fault. Direct human interaction, like forgotten tools or earthing, the touching of live parts, or other errors while working are common causes, and lead to an immediate safety hazard. Faulty installation, insufficient dimensioning, loose connection and maloperation of a switching device are also clearly caused by human errors but they don't require direct human interaction. Some other causes like vibration, overvoltage, contamination, moisture, vermin and the ageing of insulation could have been avoided by careful planning, construction and operation. IEC Standard 62271-200 provides a list of common locations and causes of internal arc faults, and examples of measures to decrease their probability.

Arc faults can also be divided into two categories: sudden faults and slowly developing faults. Some types of slowly developing faults can be detected by online monitoring techniques before they develop into high-energy faults. Although there are effective reactive arc protection methods, proactive protection, preventing the most serious fault type, would be very desirable. Proactive protection is discussed in chapters 6 and 7.

3 ARC PROTECTION RELATED STANDARDS

3.1 Overview of the standardization

At present there are no internationally recognized standards dedicated to arc protection. In the future, arc protection will most likely have its own international standards. IEC Technical Committee 121 (Switchgear and controlgear and their assemblies for low voltage) is working on the subject, and CIGRÉ (International Council on Large Electric Systems) Working Group B3.37 "Internal arc effects in Medium Voltage switchgear (1–52kV) – mitigation techniques" will prepare a brochure about arc mitigation methods and technologies, including a review of related standards by 2017 (CIGRÈ 2013). In China, both the Chinese national standard and the Chinese Electrical Industrial Standards for Specification of Arc Flash Protection Equipment were expected to be published in 2015 (Zhou et al. 2014).

Currently, the most relevant international standards concerning arc faults are the following:

- IEC 62271-200, High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV (2011).
- IEC TR 61641:2014, Enclosed low-voltage switchgear and controlgear assemblies – Guide for testing under conditions of arcing due to internal fault.
- IEEE Std 1584™-2002, IEEE Guide for Performing Arc-Flash Hazard Calculations
- NFPA 70E®, Standard for Electrical Safety in the Workplace, 2015 Edition, NFPA (National Fire Protection Association)

The IEC standards do not require as detailed arc flash hazard and incident energy study as the North American (IEEE) standards (Vrielink, Picard & Witteman 2011). However, in some countries sophisticated and effective arc protection methods are very common, de facto standards. E.g. in Finland, in practice all new LV switchgears in industrial distribution systems are equipped with optical sensing based arc protection. On MV level, dedicated arc protection is very common in primary substations. When effective methods are widely applied, detailed arc flash incident energy studies are not very relevant.

3.2 IEC standards

IEC 62271-200 (Edition 2.0, 2011) is a MV switchgear standard and it "specifies requirements for prefabricated metal-enclosed switchgear and controlgear for alternating current of rated voltages above 1 kV and up to and including 52 kV for indoor and outdoor installation, and for service frequencies up to and including 60 Hz. Enclosures may include fixed and removable components and may be filled with fluid (liquid or gas) to provide insulation." Arc faults are briefly discussed in the standard.

The standard aims at preventing the occurrence of internal arc faults. It provides a list of locations where faults most likely occur. It also explains causes of failure and possible measures to decrease the probability of faults. When it comes to arc protection, IEC 62271-200 gives examples of supplementary measures that provide protection to persons (IEC 62271-200 2011):

- rapid fault clearance times initiated by detectors sensitive to light, pressure or heat or by a differential busbar protection;
- application of suitable fuses in combination with switching devices to limit the let-through current and fault duration;
- fast elimination of arc by diverting it to metallic short circuit by means of fast-sensing and fast-closing devices;
- remote operation instead of operation in front of the switchgear and controlgear;
- pressure-relief device;
- transfer of a withdrawable part to or from the service position only when the front door is closed

However, information provided by IEC 62271 is limited, e.g. arc limiting devices are, in general, beyond the scope of this standard. This is why the IEC sub-committee SC17C has requested CIGRÉ to carry out a technical review to give recommendations to support an extension of the current standard to cover such a function and to provide assessment of the arc limiting devices. CIGRÉ has founded a working group (WG B3.37) with wider scope (CIGRÉ 2013):

1) Review of methods for arc effect mitigation under internal arc fault conditions of medium voltage switchgear assemblies.
2) Mapping of existing technical solutions related to arc effects mitigation: parameters for detection, means for actuation, power supply issues, etc.
3) Review the status of current standards and existing specifications.
4) Consideration of the benefits and consequences resulting from arc effect mitigation including: limitation of pressure rise in switchgear and switch-

rooms (digital simulations are already used for such purpose), limitation of fire risk and other damages, possible reduction of outage duration, transients on the network, etc.

5) Analysis of the possible methods for verification of performance, assessment and the definition of general requirements for standardized type and routine testing.
6) Guidance for the user on relevant selection parameters: personnel safety, downtime, maintainability, environmental impact, investment costs, life time, immunity to EMI etc. (CIGRÉ 2013)

IEC has also produced other standards, but their relation to internal arc protection is limited:

- IEC TR 61641:2014, "Enclosed low-voltage switchgear and controlgear assemblies – Guide for testing under conditions of arcing due to internal fault" is a guide for testing, not a standard setting requirements.

- IEC 62606:2013, "General requirements for arc fault detection devices" applies only to arc fault detection devices for household and similar uses in a.c. circuits.

- IEC 61482:2009, "Live working – Protective clothing against the thermal hazards of an electric arc", addresses personal protective equipment. The standard is divided into several parts, and it specifies test methods and requirements for materials and garments for protective clothing. (IEC 61482:2009)

3.3 IEEE standards

IEEE Std 1584™-2002, IEEE Guide for Performing Arc-Flash Hazard Calculations, is a safety oriented guide. It provides techniques to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment. Its applications cover an empirically derived model including enclosed equipment and open lines for voltages from 208 V to 15 kV, and a theoretically derived model applicable for any voltage. The standard also provides a good list of arc fault related definitions.

One of the most central definitions is the concept of incident energy: "The amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. Incident energy is measured in joules per centimeter squared (J/cm^2)". The incident energy concept is used for developing strategies to minimize burn injuries.

The guide is based upon testing and analysis of the hazard presented by incident energy. It provides a detailed step-by-step process for arc flash analysis. This analysis ends up with determining the incident energy level and the flash-protection boundary (an approach limit at a distance from live parts that are uninsulated or exposed within which a person could receive a second degree burn) based on incident energy of 5.0 J/cm^2. One should note that the analysis only covers the thermal impact of the arc fault, not e.g. the pressure related impact.

The standard is well known but mostly utilised in North America. Although incident energy levels are seldom calculated in Europe, incident energy calculations are a useful tool when comparing the effectiveness of different arc protection methods. Because the incident energy level depends on four key parameters: the arcing current, the voltage, the working distance and the arcing time, it is relatively easy to see that normally the most practical factors in the mitigation of the thermal impacts of arc faults are the arcing time and the arcing current.

IEEE has also produced a draft standard concerning testing of switchgear: Unapproved Draft Standard PC37.20.7-2001 Cor 1/D3. Draft Guide for Testing Metal-Enclosed Switchgear Rated up to 38kV for Internal Arcing Faults - Corrigendum 1, (IEEE 2009). It is an often cited guide, setting requirements for arc-resistant switchgear.

3.4 NFPA 70E

NFPA 70E, Standard for Electrical Safety in the Workplace® by National Fire Protection Association addresses electrical safety-related work practices, safety-related maintenance requirements, and other administrative controls for the practical safeguarding of employees. It includes links to arc protection, and it provides some commonly used arc fault related definitions, such as

- Arc Flash Boundary: When an arc flash hazard exists, an approach limit at a distance from a prospective arc source within a person could receive a second degree burn if an electrical arc flash were to occur. (A second degree burn is possible by an exposure of unprotected skin to an electric arc flash above the incident energy level of 5 J/cm^2.)

- Arc-Resistant Switchgear: Equipment designed to withstand the effects of an internal arcing fault and that directs the internally released energy away from the employee. NFPA 70E includes an informative annex giving guidance on selection of arc-rated clothing and other PPE (Personal Protective Equipment) when incident energy exposure is determined.

3.5 Discussion on standards

In addition to the standards presented above, there are several national standards related to arc protection, such as AS/NZS 3429:1:2002: Australian/New Zealand Standard™, Low-voltage switchgear and controlgear, Assemblies, Part 1: Type-tested and partially type-tested assemblies. The upcoming Chinese National Standard and the Chinese Electrical Standard for Specification of Arc Flash Protection were expected to be published in 2015 (Zhou et al. 2014).

However, it is obvious that there is lack of comprehensive international standards of arc protection. It is possible that the cooperation between IEC and CIGRÉ, described in 3.2, will lead to new standards. The WG B3.37 aims at delivering its final report in 2017 (CIGRÉ 2013). This could be the first major step towards globally accepted standards and requirements concerning arc fault protection.

Lack of standards and requirements can be seen as a major obstacle to wider implementation of already existing sophisticated and efficient arc protection technologies which are already applied in some countries as de facto standards. What has happened in automotive industry via safety chassis, seat belts, airbags and sensor systems, could analogically happen in electricity distribution: a significantly higher level of safety and reliability can be reached. This also applies to old switchgear since retrofit installation of state-of-the-art arc protection systems is fairly simple.

4 A COMPREHENSIVE VIEW OF ARC PROTECTION

4.1 Elements of the big picture of arc protection

There are a number of means to prevent arc faults and mitigate their impacts. One of the major targets of this thesis is to create a comprehensive view of arc protection, and to find areas for further research and development. One view of the big picture is shown in Figure 4.

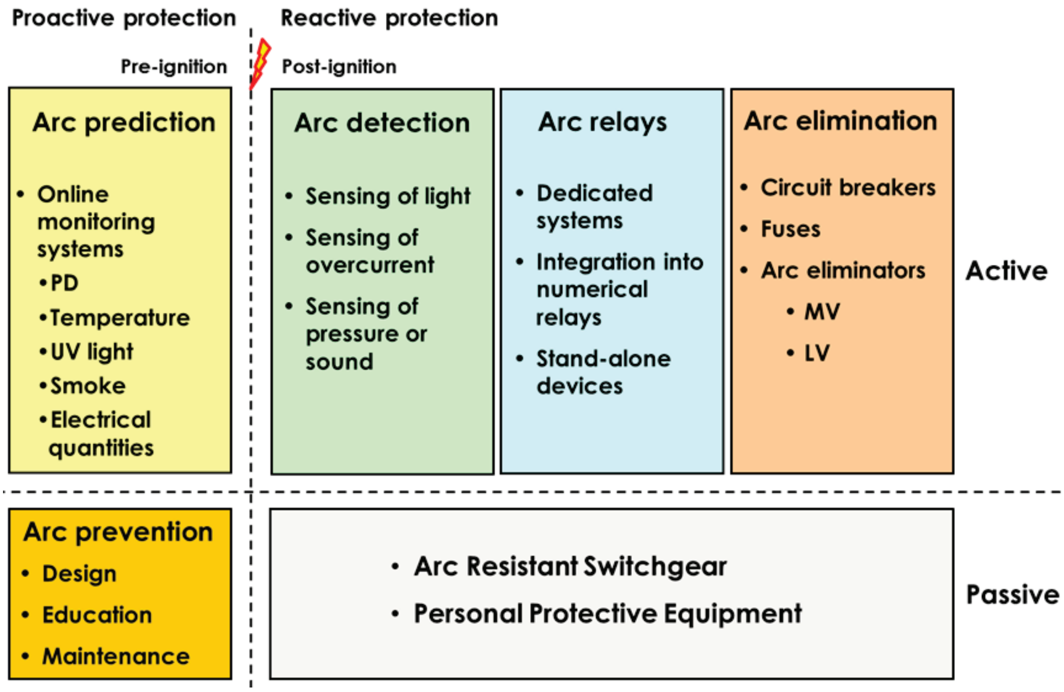

Figure 4. Big picture of arc protection.

In Figure 4, arc protection methods are divided into active and passive methods, and into proactive (operating before arc ignition) and reactive protection. These methods are complementary, not exclusive. Proactive protection, i.e. prevention of arc faults is naturally a primary target. Arc prediction technologies are discussed in chapters 6 and 7. However, since faults cannot be totally eliminated, some type of reactive protection is always needed. At least from technical point of view, specific arc protection methods instead of conventional protection approaches are justified. Economic justification is beyond the scope of this thesis.

State-of-the-art arc protection systems include communication between the components. This has not been presented in Figure 4 which is further explained in the following sections. A separate chapter is dedicated to communication.

4.2 Design, education and maintenance

Design of switchgear is a key issue in arc prevention, and it is supported by IEC and IEEE standardization. In fact IEC 62271-200 states that if switchgear is designed and manufactured satisfying the requirements of the standard, internal arc faults should, in principle, be prevented. However, internal arc faults still occur for a number of reasons.

IEC 62271-200 presents a list of locations where internal arc faults are most likely to occur in metal-enclosed switchgear and controlgear:

- Connection compartments
- Disconnectors, switches, grounding switches
- Bolted connections and contacts
- Instrument transformers
- Circuit breakers

According to experience, another typical location of arc faults is cable termination. By focusing special design attention on the locations listed above, the probability of arc faults can be decreased.

Insulation of buses provides means to reduce the probability of arc faults caused by e.g. falling objects or vermin. Insulation can also prevent single-phase faults from escalating to high-power multi-phase faults (Dunki-Jacobs 1986). Another advantage of an insulated bus is that the insulation may help extinguish the arc (Jones et al. 2000). This observation is not necessarily true in all cases since bus insulation can slow down the movement of the arc. If the arc becomes stationary at an insulation barrier, higher incident energy can be produced (Land 2008; Wilkins, Lang & Allison 2006).

High-resistance grounding (HRG) is another design related technology aiming at reducing the probability of an arc fault. HRG system has a resistance sufficiently high enough connected between the earth and point of connection on the system that there is a minimal current that flows during an earth fault (Sen & Nelson 2007). However, HRG system for arc fault mitigation is only effective in earth faults (Mohla et al. 2012). The benefits and obvious shortcomings of HRG systems in MV systems are well reported in (Kingrey, Painter & Locker 2011) which sees only a limited window of applications of HRG on MV systems.

The human factor is often the direct cause of an arc fault, especially in cases with casualties. Systematic education of personnel, delivering information on the equipment and related safety hazards, is an efficient way to increase safety and reduce the number of accidents.

The same kind of systematic approach also applies to maintenance practices that ensure adequate condition of the equipment and help in identification of possible risks. Preventive maintenance, e.g. visual inspection, thermal imaging, partial discharge (PD) testing, and time-based testing of protection devices are examples of common preventive maintenance actions. Development of on-line monitoring of switchgear is one of the areas of contribution in this thesis, and an example of a more developed maintenance strategy, condition based maintenance.

Special attention should be paid to maintenance of circuit breakers. If a CB fails, the performance of other components of the protection system is insignificant, with the exception of the important breaker failure protection.

4.3 Mechanical arc fault protection methods

Arc containment and a controlled direction of the arc blast and hot gases provide a mechanical barrier between the operator and the arc fault. As long as the doors are closed, arc-resistant switchgear, defined by IEEE Std C37.20.7™ and NFPA 70E, protects personnel from the impacts of the fault. Mechanically reinforced structure also limits damage to the equipment by preventing the expansion of the arc to other compartments. The equipment in the compartment where the arc occurs, however, may suffer heavy damage. Figure 5 presents an example of arc resistant technology, directing the gases away from maintenance personnel through the plenum seen on the top of the switchgear.

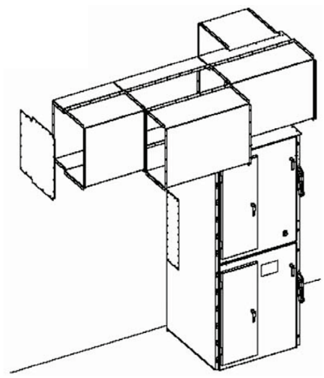

Figure 5. An example of arc resistant technology with an exhaust plenum (Kay, Sullivan & Wactor 2007).

Type testing including high-current arc tests by an accredited laboratory increases the credibility of the design. This applies especially to the mechanical protection provided by the switchgear, since there are several criteria the switchgear has to fulfil before it can be called arc-resistant (Das 2012; IEEE 2009):

- Doors and covers do not open
- Parts that may be a hazard do not fly off
- No holes due to arcing
- None of the cotton indicators ignite
- All the grounding connections remain effective

As Stonebridge (2015) states, it is very important to realise that internal arc fault containment does not provide switching operators or maintenance staff the intended protection if any doors are open or if any covers are not properly closed and fixed in place. However, open doors are not uncommon in the field and in injury scenarios (Jones et al. 2000).

Personal protective equipment (PPE) can also be regarded as mechanical protection from the impacts of arc faults. The concept is very central in North America where incident energy calculations aim at defining the required PPE level. In Europe both incident energy calculations as well as PPE have minor roles. A major limitation of PPE is that it only provides protection to personnel, it does not mitigate damage to the equipment.

International Social Security Association (ISSA) has produced guidelines for the selection of PPE when exposed to the thermal effects on an electric fault arc (ISSA 2011). The well-argued and detailed guidelines are based on IEC 61482 which is not an obligatory standard.

Selection of PPE is always a tradeoff between protection and ergonomic aspects. Reasonable protective clothing is naturally justified but heavy PPE may restrict mobility or vision of the worker and increase the risk of arc fault. Effective active protection methods are normally able to radically limit the incident energy level, making heavy PPE unnecessary. However, as there is always a risk of incorrect settings or maloperation of the equipment and product liability issues, it is easy to understand why manufacturers emphasize the protection of equipment rather than the personnel safety aspect.

4.4 Common principles of mitigating the thermal impact

Conventional overcurrent protection does not provide effective mitigation of the impacts of arc faults. Several other protection approaches have been presented in the literature. The different methods can be evaluated by comparing their incident energy levels, although the primary purpose of the incident energy concept is to provide means for evaluating safe working distances and PPE for employees (IEEE 1584 2002).

Incident energy, as defined in IEEE 1584, depends on four factors: arc fault current, arc duration, system voltage, and the working distance. In most cases the two factors that can be influenced on are the arc fault current and the arc duration. These are discussed in the following sections.

4.5 Fault current limitation

Fault current limitation is less common arc fault mitigation strategy than limitation of the arcing time. However, there are a few well-known means to limit the fault current in arc faults: installation of several smaller power transformers or current-limiting reactors, current-limiting fuses, and fault current limiters.

The fault current can be reduced by choosing several feeding transformers instead of one large unit. The system impedance can also be increased by current limiting reactors. These solutions add costs and losses, and they are rarely applied for arc protection purposes.

A much more common method is to apply current-limiting (CL) fuses which can both limit the current and reduce the arc duration. When the fault current is in the current-limiting range of the fuse, the fuse is able to break the current very rapidly and simultaneously reduce the peak current. This is illustrated in Figure 6.

However, especially in LV systems the arc fault current varies, and due to the voltage drop in the arc, the current can be significantly lower than the bolted fault current (Sweeting 2011a) . This causes uncertainty to the operation time of fuses. When the fault current is low and the current-limiting fuse is not in its current-limiting range, the fuse will not operate as planned. This problem will be discussed more in detail in a later chapter.

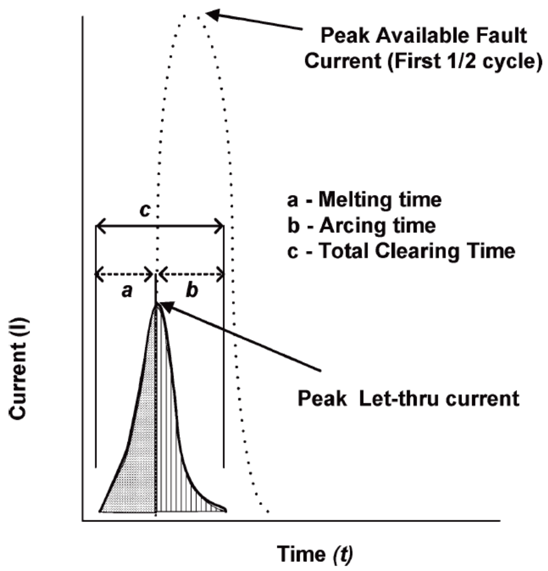

Figure 6. Fuse current let through (Kay 2005; Publication V).

Fast acting fault current limiters are able to limit the fault current very efficiently, and they offer a possibility to significantly reduce released energy in arc faults (Weiland, Schön & Herold 2011). Pyrotechnic fault current limiters are typically employed as bus-tie limiters when the interrupting capability of the circuit breakers of a substation has been exceeded (CIGRÉ 2012). They have not been widely applied in arc protection applications.

Solid-state and superconductive materials based technologies have been applied in fault current limiters. At least in theory these novel technologies are highly efficient but they are still in development stages (CIGRÉ 2012). Development in semiconductor applications provides interesting expectations also in circuit breaker technology.

4.6 Reduction of arc duration

The incident energy is proportional to the arc duration. The reduction of the arcing time is often relatively easy and effective way to mitigate the impact of the arc. Change of operation time settings of overcurrent relays is generally inadequate. In practice, effective arc mitigation can be achieved by combining very fast detection of the arc with protection by protective relays and circuit breakers. In the following, arc mitigation methods based on reduction of arc duration are discussed, emphasizing the most effective methods.

4.6.1 Busbar differential protection

Busbar differential protection schemes, high-impedance and low-impedance, are traditional and effective arc fault mitigation methods in internal faults. The operation time (tripping time) can be lower than one cycle. Busbar differential protection schemes operate when the sum of currents that flow into the bus becomes unequal to the sum of all currents that flow out of the bus (Chowdhury et al. 2009). Neither high-impedance nor low-impedance differential protection is simple. High-impedance protection systems require specific and dedicated current transformers and voltage limiting varistors which adds costs (Gajic 2011; Kay, Arvola & Kumpulainen 2011).

Low-impedance differential protection systems apply digital relays and allow the use of CTs with different ratios (Chowdhury et al. 2009; Gajic 2011). However, the management of the relay settings, maintenance and handling of the maloperation incidents is more complex than in high-impedance schemes (Chowdhury et al. 2009; Kay, Arvola & Kumpulainen 2011). From the arc protection point of view the busbar differential schemes normally do not provide protection against faults in very typical arc fault locations: the cable compartments of the feeders.

4.6.2 Zone-selective interlocking

Zone-selective interlocking (ZSI) is more cost-efficient method to busbar faults than busbar differential protection. ZSI utilizes communication between downstream relays and upstream breaker relay to speed up the busbar protection. If the downstream relay sees the fault and picks up, it sends a blocking signal to the upstream breaker relay. If it does not see the fault, the upstream relay does not receive a blocking signal and trips the main breaker with very short delay required by the downstream relay pickup time and the communication. As IEC 61850 is becoming more widely applied, GOOSE message based communication is replacing wired communication in ZSI applications.

In (D'Mello, Noonan & Aulakh 2013) a significantly faster selective ZSI scheme for LV applications has been presented, enabling instantaneous protection all the time. The scheme is based on peak-to-peak current sensing, current-limiting circuit breakers, and the recognition of the waveform of the downstream fault.

4.6.3 Maintenance switch and instantaneous settings

Maintenance switch is a control switch connected to electronic protective relays, enabling switching from normal settings mode to maintenance settings with instantaneous operation (Luna, Cassidy & Franco 2011). The switch can be activated e.g. when maintenance personnel enter the hazardous area. Maintenance switch provides protection for personnel but does not help in faults occurring outside maintenance time.

4.6.4 Detection of light

The detection of arc can naturally be based on phenomena other than observation of electrical quantities. The electric power of the arc, and the luminous intensity have a strong correlation which allows tracing the evolution of the arc current directly from the luminous signal (Melouki, Lieutier & Lefort 1996). Detection of the light is thus an excellent option for high power fault arc detection. The basic requirements for the detection of light are speed and appropriate sensitivity in the spectral range of fault arcs. As Land (Land & Gammon 2015) states, the key to minimizing arc-flash hazard lies in reducing the duration of the arc fault, and there are a number of new mitigation technologies relying on light detection for fast response times. Thus protection based on detection of light can be considered as a mainstream solution of modern arc protection systems.

Visible light consists of the light spectrum ranging from ca. 380 nm to 780 nm wavelengths. According to previous arc flash tests most of the radiated energy is in the range of 200–600 nm (Wilson et al. 2007). However, some more recent tests indicate that in addition to the range of visible light and ultraviolet (UV) range (below 380 nm), arc faults also emit infrared (IR) radiation. This is in line with the fact that an arc flash event causes a significant thermal impact.

Figure 7 presents emission spectra of arcs in LV arc tests with different busbar materials (Publication III). The figure confirms that the spectrum of the arc is wide, extending from the UV area to the IR area. Peaks in the spectrum reveal the substances involved in the arc. E.g. the peak at ca. 520 nm is caused by copper.

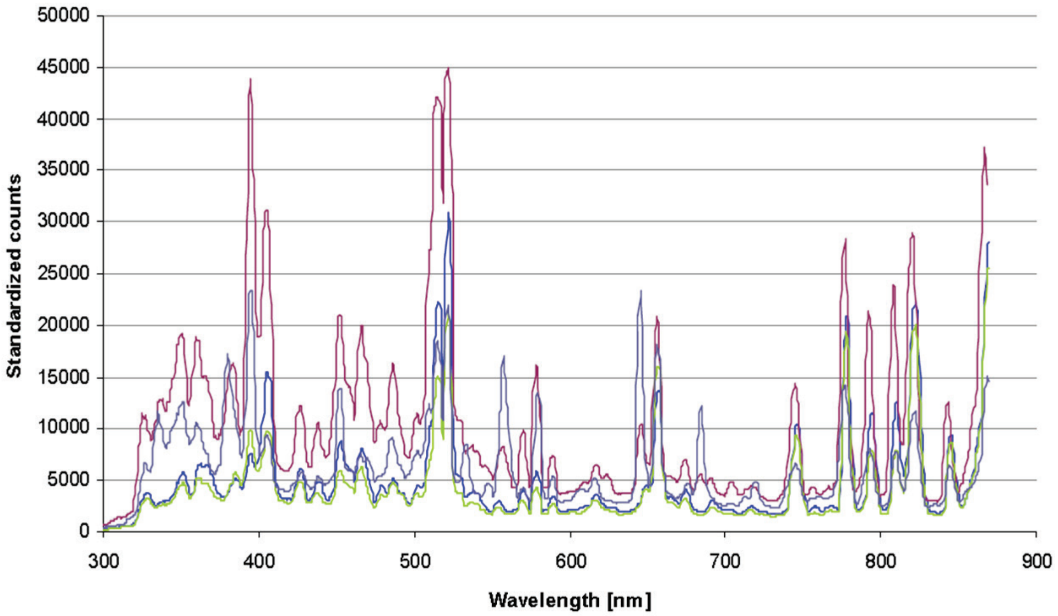

Figure 7. Measured characteristics of arc spectrum on busbars with small distance and different busbar materials. (Publication III)

Generally, sensors with a wide range can be applied in the detection of the light. Figure 8 presents examples of point type sensors and a fibre sensor. The benefit of the point sensor is that it provides more accurate information of the location of the fault which enables more selective protection. On the other hand, a fibre sensor is a cost effective solution. A special type of sensor is the personal sensor that can be attached to the clothing of maintenance personnel, adding safety by ensuring the detection of the possible arc fault.

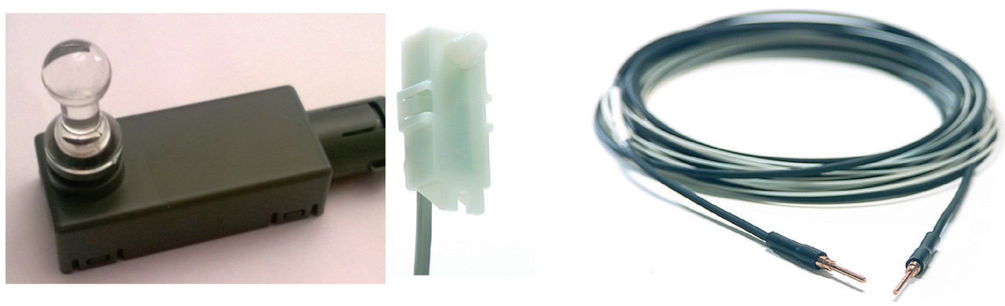

Figure 8. Point sensors and fibre sensor.

The sensitivity of the detection of the light in enclosed switchgear is normally not a problem. The threshold should be high enough to avoid false detection caused by ambient light but low enough to catch arc faults. The required illuminance at floor level in offices is generally 500 lx, varying from 200 lx in archives to 750 lx in premises for technical drawing (EN 12464-1 2002). The intensity of light in high power arc faults is significantly higher. In tests reported by Hughes (Hughes et al. 2010) the light intensity measured 3 meters away from the arc-flash source ranged from 108000 lx to more than 249900 lx (full-scale reading of the applied instrument) while according to Lee (Lee et al. 2015) light intensities more than 1 million lux were recorded for the majority of tests.

Photodiodes can be applied in the detection of light. The detected light is transformed to an electrical current signal. The response can be very fast, time delay as short as 0.03 ms has been reported (Lee et al. 2015). By using sensors with appropriate sensitivity high power fault arcs can be detected within 1 ms (Parikh et al. 2014; Panetta 2013; Land & Gammon 2015; UTU Oy 2016).

Practical experience has shown that approximately 8000–12000 lux sensitivity level of optical sensors gives good results in switchgear installations, causing only low risk of unintentional protection events by ambient light but ensuring reliable and fast detection of fault arcs. Zhou (Zhou et al. 2014) recommends higher, 20–40 klx setting. One of the advantages of light detection is the lack of a requirement to coordinate with downstream devices (Simms & Johnson 2013).

If there is a high risk that ambient light could cause erroneous tripping, narrowband sensors or filters can be applied. Land (Land, Eddins & Klimek 2004) has chosen a narrowband UV filter centered at 325 nm in order to distinguish arc-flash light from ambient visible light. Another application area where a narrowband sensor can be applied is protection in the vicinity of LV air breakers. Some breakers emit light during operation, and this can cause unintentional operation of the arc protection if normal wide range optical sensors are utilized.

Illuminance expressed in lux level is widely applied in sensor sensitivity evaluation. Lux measurement indicates the brightness of the visible light. The photometric quantities have been adjusted to the sensitivity of the human eye. This is why illuminance is not an ideal quantity for evaluating the intensity of the electromagnetic radiation of the arc flash. Measurement of the light intensity as perceived by the human eyes is preferred in (Lee et al. 2015) for eye safety reasons. However, measurement of electromagnetic radiation, irradiance, expressed in Watts per square centimeter (W/cm^2), takes into account the entire electromagnetic radiation without weighting according to the human eye (Fiberoptics Technology 2016). This enables better inclusion of UV and IR parts of the spectrum of the radiation. This could be especially useful in the early detection of developing arcs.

Although there is vast positive experience of the functionality of the existing light sensitive sensors, further research on the electromagnetic radiation of arcs would benefit the standardization of arc detection technologies, including the detection of developing fault arcs.

Taking into account the performance and experience on existing sensors, there is a limited need to further develop the sensing of light. In addition to standardization, system wide self-diagnostics, ensuring the performance of the sensors and the whole system, may be a relevant field of development. One approach has been introduced in (Koksalo 2011) and another type of built-in test is proposed in (Land & Gammon 2015).

4.6.5 Fast detection of overcurrent

Especially in industrial electric systems, high reliability is required. Outages may cause very high outage costs e.g. in process industry when important processes are stopped. The reliability requirement applies naturally to protection systems, i.e. unintentional tripping should be eliminated. This is why many arc protection systems are based on simultaneous detection of more than one phenomenon. The most common combination is the dual-sensing of light and overcurrent. At present, the abnormal current characteristics and the light from the arc are the first easily detectable elements of an arc event (Publication V). Together, these two methods provide an extremely fast and very secure arc detection scheme (Simms & Johnson 2013). Figure 9 presents the principle of the dual sensing criterion, requiring simultaneous detection of both light and overcurrent.

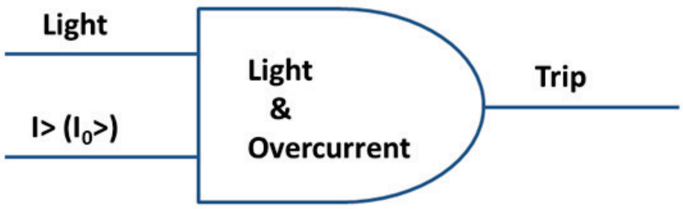

Figure 9. Principle of simultaneous detection of light & overcurrent.

Since most arc faults initiate as single-phase faults (Mohla et al. 2012), it is very important to include the detection of phase-to-earth faults in the arc protection. According to (Shields 1967), arc faults can be destructive even at low current levels. Another reason is that if the arc is detected and eliminated before it escalates into a high-power three-phase fault, the damage will be lower (Dunki-Jacobs 1986). Detection of zero-sequence overcurrent (I_0) is often used in the detection of phase-to-earth arc faults. Detection of zero-sequence voltage is a traditional indicator of phase-to-earth faults, but so far it has not been widely applied in arc fault detection. It may be necessary in some cases where the fault current is very limited (Zhou et al. 2014).

The speed of traditional overcurrent protection is not adequate in arc protection applications. However, the normal current transformers, which are utilized in overcurrent protection purposes, can be utilized in arc protection. Additional CTs are thus not needed. It has been claimed that current measurement slows down arc detection (Parikh et al. 2014), but this is not necessarily true. Standard overcurrent elements are not applied in arc protection applications. Instantaneous detection of overcurrent is enabled by special methods. In (Öhrström, Söder & Breder 2003) an algorithm employing instantaneous sampled current values is described, and 1 ms detection time is demonstrated in three-phase faults. The algorithm was even able to discriminate faults from other power system transients. Another approach (Garzon 2003) takes advantage of the discontinuity of the current waveform (change in di/dt) combined with a relatively low threshold in current magnitude in order to achieve very fast overcurrent detection. In (Wilson et al. 2007) peak-to-peak waveform detectors are utilized in order to eliminate delays associated with conventional root-mean-square (RMS) calculations. Fast detection of overcurrent is also possible by applying an analog comparator, as described in (Jäntti et al. 2014). The comparator enables instantaneous detection of phase or zero-sequence overcurrent. In high power faults, the detection time is in the order of magnitude 1 ms.

The light & overcurrent based protection can be compared with traditional bus differential protection. In addition to the speed and selectivity there are many other benefits. An extensive comparison has been presented in (Zhou et al. 2014), including evaluation of operation principles, speed, stability, selectivity, flexibility, reliability and suitability for retrofitting.

4.6.6 Detection of pressure or sound

Detection of pressure or sound is one option to detect a fault arc. A description of the development and practical applications of a pressure sensor based arc detection, and a short description of the less successful sound based arc detection has been given in (Land, Eddins & Klimek 2004). Thousands of photosensors and pressure sensors were installed in submarines and surface ships. However, after challenges in sensitivity, long-term stability and response time with the pressure sensor, and good results with photosensors, the pressure sensor was dropped from requirements.

In more recent literature Land (Land & Gammon 2015) lists several potential problems related to pressure sensors, but he has patented a sensor overcoming these issues. Parikh (Parikh et al. 2014) suggests arc detection approach utilizing the combination of light and sound detection.

Pressure detectors may have at least a narrow application area replacing optical sensors in switchgear where old air magnetic circuit breakers are used. Since some breakers emit light while operating, light and overcurrent based protection might trip erroneously. If this is a risk, the breaker compartment can be protected by a pressure and overcurrent based application.

4.7 Protection systems based on the detection of light

The detection of light is the fastest arc detection method, applied by a number of manufacturers and by an increasing number of end-users. This is why the following is written from the light-based arc detection point of view, assuming that detection of light is at least one of the operation conditions of the arc protection relay.

4.7.1 Stand-alone devices

In limited applications where no selectivity is required, simple stand-alone devices can be utilized. The operation criteria may be “light only” or a combination of light and overcurrent or pressure. Stand-alone protection can be applied in e.g. wind power and small switchgear applications. Figure 10 presents an example of a switchgear application with “light only” condition. The dashed lines depict the division of the switchgear into several compartments, each one equipped with a light sensor.

The protection system consists of light sensors with associated cabling (grey lines), stand-alone arc protection relay, and the circuit breaker. The protection relay consists of a power module, light sensor input channels, microprocessor, and the I/O module including the trip relay.

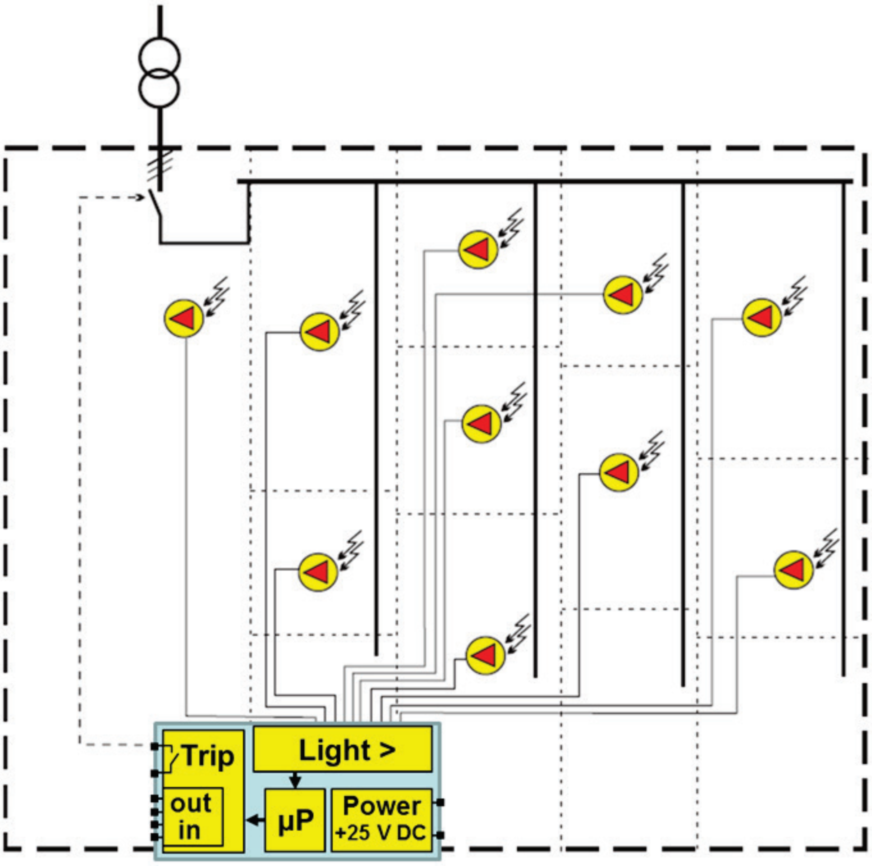

Figure 10. Example of simple protection by a stand-alone device (Publication III).

4.7.2 Arc protection integrated into protection relays

Numerical protection relays can be equipped with an arc protection option, including sensor inputs to light sensors and a high-speed overcurrent protection option. Communication between the relays is needed for selective protection, i.e. tripping of appropriate circuit breakers. Figure 11 presents a scheme of an MV application enabling selective tripping of outgoing feeders, in case an arc fault occurs in outgoing cable compartment.

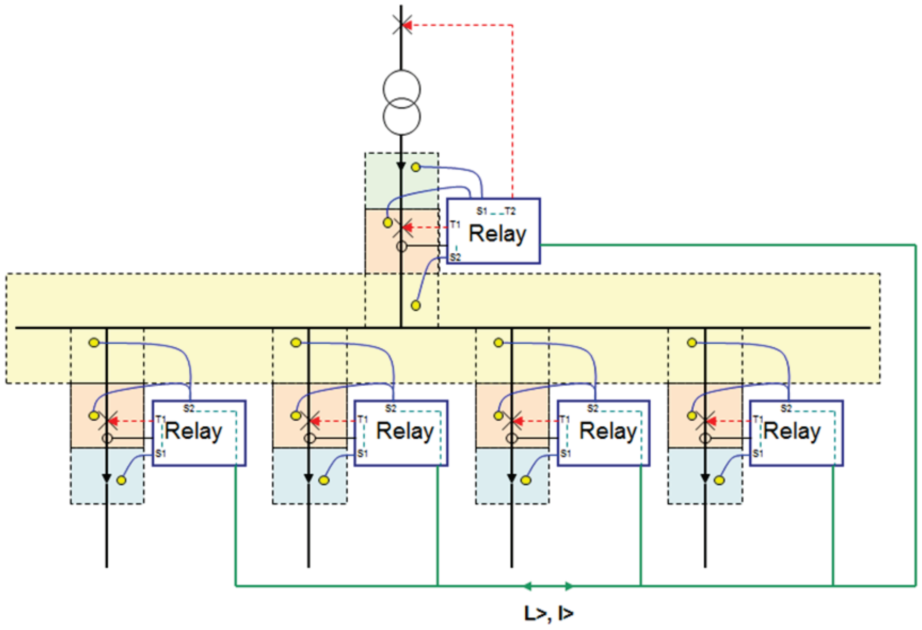

Figure 11. Example of selective protection using common numerical relays equipped with arc protection option.

4.7.3 Dedicated arc protection systems

For complex systems, dedicated arc protection equipment can be applied. While numerical relays are multi-function relays, dedicated arc protection relays are committed to arc protection, and they are the key components of the arc protection system. A typical system consists of sensors, light and current I/O units collecting data from light sensors and current transformers, communication cabling, and a dedicated arc protection relay as the central unit. There may be several central units for final collection of all the data, and tripping the correct circuit breakers if both light and overcurrent are detected.

Figure 12 presents a simplified example of a dedicated arc protection system of MV switchgear. The system is composed of one central unit, one current I/O unit, and four light I/O units. Current is measured by the CTs of the incoming feeders, connected to the central unit and the current I/O unit. Three light I/O units collect information from point type light sensors (two units, VAM 12LD, for outgoing feeders on the left side, and VAM 12L for the incoming feeder on the right), enabling selective protection in case of faults in cable terminations. Fibre type light sensors are connected to one of the light I/O units (VAM 3L). The system is divided into a number of protection zones, and it includes circuit breaker failure protection, tripping the upper voltage level CB in case of CB failure.

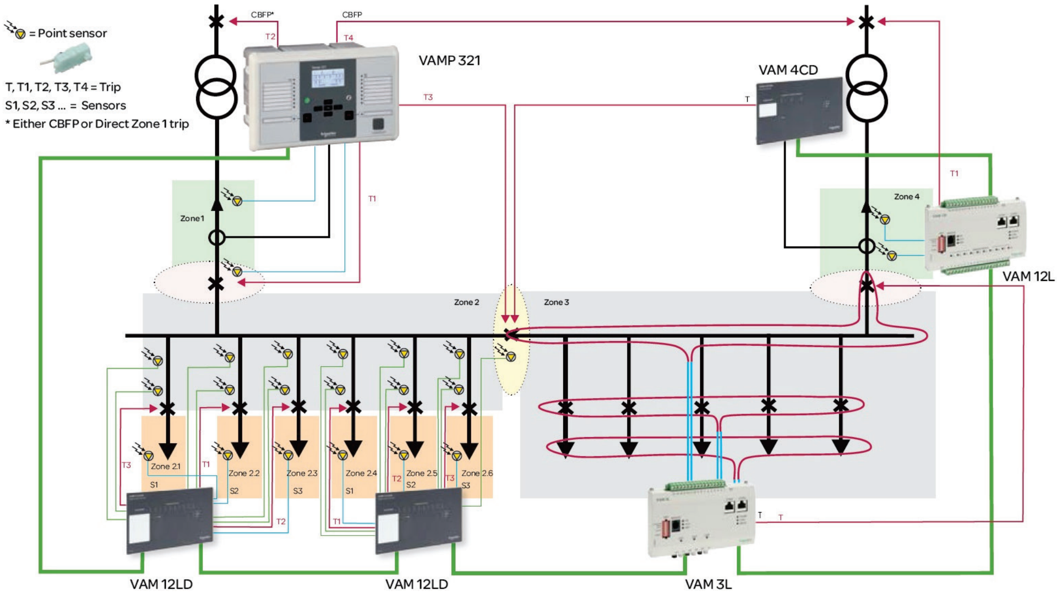

Figure 12. Example of a dedicated arc protection system (Vamp Oy).

4.8 Elimination of the fault arc

4.8.1 Importance of the elimination technology

Minimization of the duration of the arc is usually the most efficient arc mitigation method. In relay based protection (disregarding fuse based approaches), the duration consists of arc detection time, trip time, and arc elimination time. The fault arc can be detected within a couple of milliseconds, and relays are able to send the trip command to the circuit breaker in 1–10 ms depending on the output technology. However, the arc is finally extinguished either by a circuit breaker or by a short-circuit device. The operation time of the CB is often the largest component of the total arcing time. This is illustrated in Figure 13 showing the components of the total arc duration in CB based arc elimination.

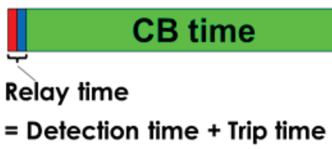

Figure 13. Components of the arcing time when the detection is based on light and overcurrent, and the arc elimination is carried out by a CB.

As Figure 13 illustrates, the operation time of the CB is normally the bottleneck in minimizing the duration of the fault arc and the dissipated energy.

4.8.2 Fuses

The fault arc can be eliminated by a fuse, a circuit breaker or by a short-circuit device. The operation of fuses has already been briefly discussed. The operation time (clearing time) depends on the magnitude of the current, and it can be divided into melt time and arc time. If a high fault current level can be guaranteed ensuring that the arc fault current is in the current-limiting range, current-limiting fuses could provide efficient protection.

However, the fault current level provided by the power system varies. While in arc faults in MV systems the fault current is very close to the bolted fault current (direct short circuit current), in LV systems the fault current can be as low as 20–40 % of the bolted fault current (Sweeting 2011a). Lower fault currents can lead to longer clearing time of protective devices (Lang, Jones & Neal 2011). The highest incident energy can thus be a result of a high or a low arc fault current. This is why incident energy calculations should be carried out with both maximum and minimum fault current, in order to find the worst case. The relationship between the bolted fault current and the arc current is illustrated in (Vrielink, Picard & Witteman 2011), and the impact of fault current variation has been discussed in (Balasubramanian & Graham 2010; Sweeting 2011a; Barkhordar 2010). Land (Land & Gammon 2015) remarks that a small reduction in fault current may substantially delay the opening of the protective device and result in significantly higher heat release.

The drawbacks of fuses are confirmed by standards. The risk of prolonged arcing time and higher energy is clearly illustrated in the figures of IEEE Std 1584™-2002. IEC 62271-200 also states it in a very straightforward way: “In the case of current-limiting fuses, the maximum arc energy may occur at current levels below the maximum interrupting rating.”

4.8.3 Circuit breakers

As stated above, the total operation time of CBs is often the dominant part of arc duration. IEEE 1584 gives general breaker operating times for LV CBs (25–50 ms) and MV CBs (80 ms; 1–35 kV). Manufacturers’ data often present the range of opening time, arc time, and the total interruption time, including the worst case value, e.g. 55–60 or 27–58 ms for MV breakers (ABB 2014; Siemens 2009). In practice the total arcing time is thus often shorter. However, there is another important aspect in real world applications: the maintenance of the circuit breakers. Without routine maintenance and testing, there is a high probability that the interrupting time will not be within the original range or specification defined by the circuit breaker manufacturer (Publication V).

4.8.4 Short-circuit devices

The fastest method of eliminating the fault arc is to utilize a short-circuit device for creating an intentional, controlled short-circuit that brings the voltage down and extinguishes the arc within a few milliseconds. This option is discussed more in detail in the following chapter.

4.9 Summary and areas of development

The sections of the developed big picture of internal arc protection are not exclusive. Best results can be achieved by combinations of different approaches. Many faults can be prevented by appropriate design and maintenance, but reactive protection is still necessary. Similarly, the presented mechanical protection technologies increase the safety of the maintenance personnel while providing limited mitigation of the damage to equipment, if applied as the only protection method.

The development of sensor and online monitoring technologies along with improved signal processing capability enables development of sophisticated methods for early detection of developing faults. Arc fault prediction is thus a very potential direction of the development of internal arc protection.

In reactive protection, methods based on detection of light are prevailing. In order to avoid nuisance tripping, normally another trip condition is applied in combination with light, most commonly overcurrent and zero-sequence overcurrent. Existing methods enable extremely fast arc detection, in the order of 1–2 ms. On the other hand, in most cases the arc is eliminated by CBs with operation time in the order of several tens of ms. The bottleneck in reactive protection is clearly the time needed for arc elimination.

At present, technology is available, enabling drastically more efficient arc elimination: short-circuit devices. However, these devices have not yet achieved a commercial breakthrough. In the long term, it is likely that CB technology will provide significantly better performance. Arc elimination technologies are discussed in more detail in the following chapter.

5 FAST ELIMINATION OF THE FAULT ARC

5.1 The importance of the speed of the elimination

As stated in the previous chapters, the incident energy is proportional to the duration of the arc. In arc protection relay and circuit breaker based protection the circuit breaker time is clearly the dominant part of the total arc duration. Thus developments in circuit breaker operation time will directly lead to more efficient arc protection. This is one of the key directions of technological development from the arc protection point of view.

Benefits and drawbacks of current-limiting fuses have already been discussed in the previous chapter. In the following, three different approaches to minimize the arcing time are presented: fast conventional CBs, power electronics based circuit breakers, and arc eliminators.

5.2 Fast conventional circuit breakers

A new solution to reduce the breaker time has been presented in (Publication III). By integrating current sensors into circuit breakers the time required by the triggering process of the CB can be reduced. This in combination with an efficient interface between the arc detection system and the CB has given promising results in LV arc protection system tests. As short as 10.2 ms clearing time has been achieved, as presented in Figure 14.

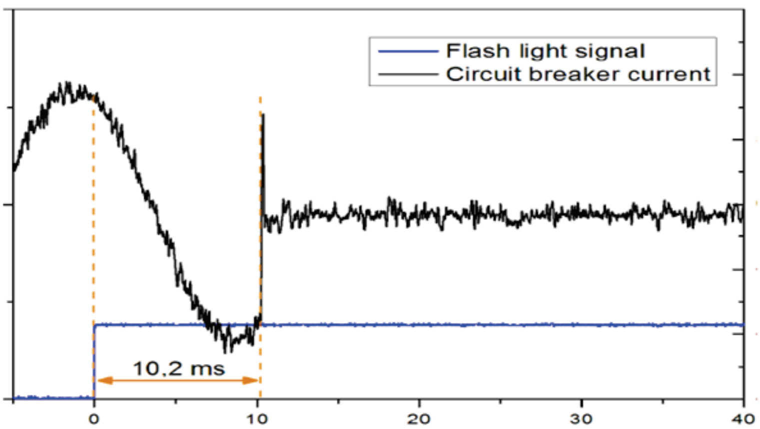

Figure 14. Oscillogram of a CB trip test (Publication III).

5.3 Power semiconductor based circuit breakers

Solid-state circuit breakers (SSCBs) may bring a radical improvement to the arc extinction. In the future, these power electronic devices with operation time less than half cycle can replace traditional mechanical breakers at least in some applications areas. According to (Zhu & Zheng 2013), a 15 kV/600 A SSCB with operation time of as short as 4 ms has been developed.

The system introduced by (Panetta 2013) consists of a fast acting switch, back-to-back connected thyristors, connected in parallel with a resistor. The resistor is needed for the elimination of switching transients, and it also limits the fault current. The system is triggered by a control system equipped with fibre optic sensors. The proposed system was designed and developed for laboratory testing which confirmed that the voltages can be dropped to zero in less than half cycle. Panetta (2013) also brings up gate-turn-off thyristor (GTO) as a more expensive but even faster isolation method. GTOs interrupt the current immediately with a turn-off pulse.

Chen (Chen et al. 2013) lists more technological options to SSCBs. In addition to GTO, insulated gate bipolar transistor (IGBT) and MOS-controlled thyristor (MCT) are mentioned as established development of SSCBs. More choices and hard shutdown capability are provided by later development, integrated gate commutated thyristor (IGCT), MOS turn-off thyristor and emitter turn-off thyristor (ETO) (Chen at al. 2013).

The disadvantage of the full solid-state circuit breaker is that the on-state losses are huge, and an additional cooling device is needed. This increases costs and reduces reliability. These drawbacks can be mitigated by hybrid technology, including both power electronics and a mechanical circuit breaker, but this in turn increases the opening time. (Vodyakho et al. 2011; Chen et al. 2013)

A more comprehensive review of power electronics in circuit breaker technology has been presented in (Kapoor, Shukla & Demetriades 2012). It confirms that the losses are a problem of SSCBs, but expects that the development of hybrid technology or wide gap semiconductors may soon provide a solution to this problem.

In addition to losses, limited breaking capacity and high costs still limit the implementation of SSCBs in real world applications. Since arc protection applications are very time critical, they are a very prospective field for SSCBs which provide high speed operation.

5.4 Short-circuit devices

In some sensitive application areas, such as marine, mining, oil & gas, process industry or data centres, maximal protection is often justified. This applies to the thermal impact as well as to the pressure impact of the arc fault. Minimization of the thermal impact reduces direct damage but it also lowers the risk of extensive fire, ignited by the arc fault.

The incident energy is proportional to arcing time. This is illustrated in Figure 15 which presents incident energy levels (calculated according to IEEE 1584™-2002) with different arcing times. With conventional overcurrent protection, the arc duration is normally several hundreds of milliseconds. By applying optical arc detection and a normal circuit breaker, the arc duration is in the order of some tens on ms. If the duration of the arc is limited to a few milliseconds, the incident energy and the thermal impact of the arc is minimal.

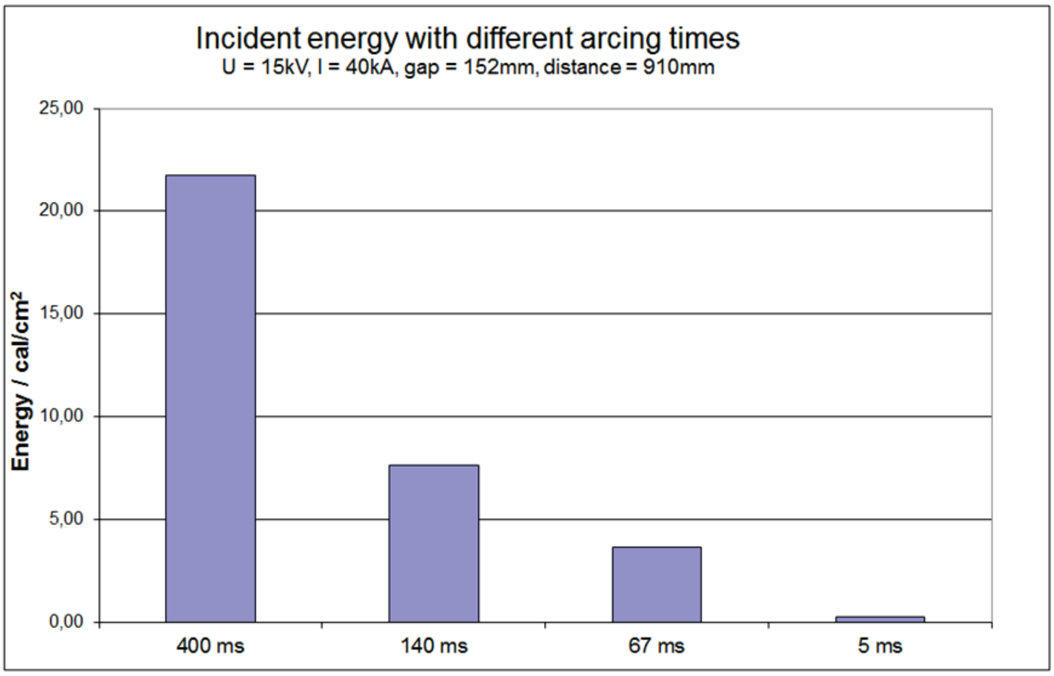

Figure 15. Comparison of incident energy levels with different arcing times (Publication I).

From the pressure impact point of view, the minimization of the arc duration is even more critical. In ship or mine environment, for instance, it is often difficult to direct the hot gases out of the enclosure. Also the safety aspect justifies mitigation of the pressure impact, especially in retrofit installations where the switchgear is not arc resistant. Peak pressure rise inside closed equipment typically occurs within roughly one half-cycle (Gammon et al. 2015a; Bowen et al.

2004). Wahle (Wahle & Summer 2007) shows that with increasing distance from the source, the peaks in the pressure course become less pronounced, because of damping and superposition of pressure waves. When the distance to the source increases, the time between the ignition of the arc and the peak pressure also increases. However, the reduction of the peak pressure requires very fast elimination of the fault arc.

Short-circuit devices provide very efficient technology for arc elimination. This technology is also known as arc eliminator, crowbar switch, high-speed switch or high speed earthing device. It is recognized by the IEC standard 62271-200 as an option to provide the highest possible level of protection to persons in case of an internal arc in MV switchgear. This technology is also well known in LV environment but still not widely applied at any voltage level.

Short-circuit devices have so far been applied in combination with optical arc detection devices which confirms the superiority of light based arc detection. When an arc fault is detected, the arc protection relay sends the trip command both to the short-circuit device and to the appropriate circuit breakers. The short-circuit device creates an intentional, controlled short circuit in the fault circuit at high speed, collapsing the voltage and extinguishing the arc within a few milliseconds. The controlled short circuit can be created by utilizing different technologies; for instance pyrotechnical elements, Thomson coil, micro gas cartridges or spring mechanisms.

The role of the circuit breakers is to carry out the second phase, break the short-circuit current within a few cycles. As a whole, when a short-circuit device is used, the thermal damage caused by the fault is minimal, and the pressure impact is efficiently mitigated.

Concerns related to the impact of the intentional short-circuit have been presented. Questions have arisen whether the dynamic forces caused by the peak current could damage the feeding transformer or a full short circuit could cause damage to motors or generators in the vicinity. These concerns have been discussed in several papers, e.g. in (Divinnie, Stacy & Parsons 2015; Breder 2003; Nailen 2000). A short analysis has been presented in Publications IV and V. The conclusion is that the risk level is acceptable, in fact, often lower than without a short-circuit device, and the benefits from short-circuit devices overweigh the negative consequences of the potentially increased current level.

Combinations of different protection devices could provide very effective total protection. A combination of an arc quenching device with current limiting fuses is a potential solution to overcome the limitations of current limiting fuses. This combination also mitigates the stress to the equipment by reducing the fault clearing time (Kumpulainen, Dahl & Ma 2008). In this combination, the short-circuit device would guarantee the maximum available short-circuit current which then would ensure that the CL fuses operate in their intended operation range, breaking the current within a few ms and even limiting the peak value of the current. In the future, another potential combination could be composed of SSCBs and CL fuses, combining benefits and eliminating disadvantages of both technologies.

5.5 Commercial or patented short-circuit devices

Short-circuit devices for ultra-fast fault arc extinction have been on the market many years. The number of manufacturers is increasing. Although none of the products has yet achieved a real commercial breakthrough, it is possible that arc eliminators will become commonplace in sensitive applications. A list of examples found on the market is presented in Table 2.

Table 2. Examples of commercial short-circuit devices.

Manufacturer	**Product(s)**	**Description**
ABB	UFES™ AX1	UFES™ for MV or LV systems. Switching time less than 1.5 ms and the arc extinguishing time is less than 4 ms (ABB 2016b). Active Arc Eliminator, AX1, less than 5 ms operation time. (Belotti, Manzoni & Geroli 2007; ABB 2016a).
Arcteq	AQ 100	The quenching device creates a three-phase to ground low-impedance parallel path for fault current to flow thus extinguishing the arc fault. The total arcing time is 3 ms. (Arcteq 2016)
Eaton Corporation	ARCON®	For LV systems. The detection can be either light & overcurrent or light only based. As short as 2 ms arcing time has been reported. (Eaton 2016)
General Electric	Arc Vault	Instead of providing a full short-circuit, the device creates a low-impedance path to the current in a specific enclosed volume. Less than 8 ms operation time is reported. (Roscoe, Papallo & Valdez 2011; General Electric 2016)
Schneider Electric	Arc Terminator™	The system consists of optical sensors, a control device with also CT input, and the high speed device with operation time approximately 4–6 (Garzon 2003; Schneider Electric 2010; Divinnie, Stacy & Parsons 2015)

6 PREEMPTIVE ARC FAULT DETECTION

6.1 Objectives of preemptive fault detection and protection

Maintenance of equipment and systems has developed from remedial maintenance towards preventive maintenance. In switchgear applications preventive maintenance is exceptionally justified since the potential hazard and damage caused by arc faults is devastating. Periodic maintenance, e.g. thermal imaging and periodic PD measurements, have traditionally been used. However, development of sensor technologies, protection equipment and ICT now enable continuous (online) monitoring of equipment. Analogically to modern cars, switchgear can be equipped with sensors and systems indicating the initial problem, well before it leads to severe damage.

Arc faults can be divided into two classes: sudden faults and slowly developing faults. Although very fast reactive protection provides relatively good protection, detection of developing faults and prevention of their escalation into high power arc faults would be valuable.

6.2 Mechanisms of slowly developing arc faults

Statistical information on arc faults is limitedly available. There appears to be no solid database containing the analysis of the causes of these failures (Land & Gammon 2015). According to (Land et al. 2003; Land & Gammon 2015), 60–80 % of the examined arcing events in Navy switchboards (LV and <5 kV) had been caused by faulty connections. The European switchgear standard IEC 62271-200 confirms that according to experience, one of the locations in MV switchgear where arc faults are most likely to occur, is the connection compartment. Zheng, Bojovschi & Chen (2012) report that in more than 80 % of the cases of electrical failure of MV switchgears the cause is insulation deterioration, and PD monitoring would alleviate the risk of failure. Moreover, practical experience has shown that in MV systems the degradation of insulation and contamination are common causes of arc faults.

Faulty connections and associated thermal stresses are typical causes for arc faults in LV equipment (Land 2008). The mechanism of how a faulty connection leads to an arc fault is well described in (Brechtken 2001) and (Land et al. 2003).

A bad connection in a contact point leads to higher ohmic resistance and it will heat up excessively when normal load current is conducted through it. Heating leads to expansion, and any presence of moisture or other contamination increases the rate of oxidation. When the current is lower, the connection cools off and contracts. Repeated cycles of heating and cooling loosen the joint which further increases the resistance and the deterioration of the connection continues, leading to higher temperatures. Vibration can increase the speed of the development. When the temperature reaches the melting point, an in-line arc (low power serial arc) is formed. A serial arc often quickly transforms into a high power phase-to-phase parallel arc when the ionized gas causes the short circuit.

In MV systems, electrical stress leading to failure of insulation is typical. According to the definition of IEC 60270 (2000), PDs are "localized electrical discharges that only partially bridge the insulation between conductors and which can or cannot occur adjacent to a conductor. Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally, such discharges appear as pulses having a duration of much less than 1 µs." PDs cause ionization, excitation and recombination processes of the molecules and atoms in the vicinity. As PD is a small electrical avalanche caused by locally disrupted electric fields in dielectric materials, it is a symptom of insulation weakness. It can lead to severe deterioration of the insulating material. It is known as one of the major factors to accelerate the degradation of electrical insulation (Hashmi 2008).

In air-insulated switchgear applications, both internal and surface PDs are possible. Small cracks in the insulation material e.g. of cable terminations, voltage and current transformers or support insulators can cause initiation of PDs. If allowed to continue, PDs erode the insulation, resulting in tracking (surface discharges) or treeing end eventually can cause a complete breakdown of the insulation (Zheng, Bojovschi & Chen 2012). Overvoltages, changes of temperature and vibration accelerate the degradation of the insulation.

Contamination of insulators can lead to surface discharges which then leads to increased local contamination. The ionization of these discharges produces ozone (O_3) and nitrogen oxide (N_2O) which may form nitric acid (HNO_3), deteriorating insulation both chemically and mechanically (Miller 2011). Decay of insulation may lead to PDs and eventually arc faults.

Corona discharge can be described as a discharge, often luminous, caused by an electric field ionizing surrounding air. Corona discharges are less detrimental than PDs. However, the ionization related to corona produces ozone and nitrogen oxides which are detrimental as described above.

6.3 Phenomena and detection methods indicating a developing fault

6.3.1 Classification of the methods

It has proven difficult to reliably detect a developing fault in switchgear, based on normal current and voltage measurements. Other indicators are needed. The detection of PD is a common method. PDs cause many different physical effects that can be detected or measured by various sensors. Heat is another useful indicator of a defect in switchgear. The sensing of heat is important in LV systems where PDs are in practice nonexistent with the exception of off-line diagnostics applying higher voltages.

The detection methods can be classified according to the physical phenomena as illustrated in Figure 16 that has been sketched and modified after (Muhr 2015b).

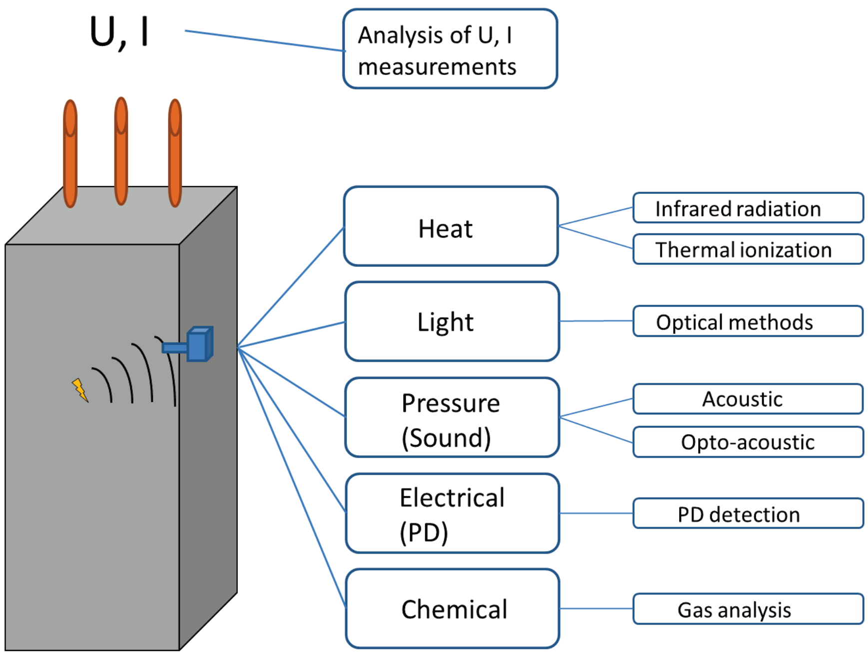

Figure 16. Detection methods for preemptive arc detection.

In addition to detection based on a single phenomenon, multi-criteria methods have been suggested (Sidhu, Sagoo & Sachdev 2000; De Maria & Bartalesi 2012). In the following section, an overview of phenomena and detection methods for the early detection of developing faults in switchgear is given. The most interesting methods and sensors are discussed more in detail in Chapter 7.

6.3.2 Thermal emissions, infrared radiation and thermal ionization

As described above, increased resistance of loose contacts causes production of heat and possibly serial arcing. Also PDs emit heat, since the recombination of ions to form a molecule produces heat. Heat produced by these phenomena lies in the infrared spectrum of electromagnetic radiation. It can be measured by various types of sensors. For arc fault prevention purposes, online monitoring of temperature is more appropriate than time-based inspection. Online infrared technology, including IR sensors, is commercially available. One of the drawbacks of this technology is the large number of required sensors, if all connections or other possible hot spots are going to be monitored.

General thermal monitoring of ambient air does not give good results. Thermal cameras are very suitable for periodic inspection of equipment, but because of high costs they are not a practically feasible solution for online monitoring. Fiber optic temperature monitoring technology is available on the market. It is based on the change of the properties of the light sensing probe when the temperature of the probe changes (Powell 2015).

A feasible solution can be based on thermal ionization. High temperature e.g. due to loose connections and serial arcing causes thermal ionization of materials. Thermal ionization detectors have given very good results in special applications (Land et al. 2003). Common smoke detectors, also based on detection of thermal ionization, have limitedly been applied in switchgear applications.

6.3.3 Chemical emissions

As stated in 6.2, PD activity may cause formation of nitric acid. Nitric acid decomposes insulating materials, and the released gases could be detected by using online analyzers. In air-insulated switchgear the detection of these chemicals is challenging, but in closed gas-insulated switchgear (GIS) the change in the chemical composition of the insulating SF_6 gas can be detected by online analyzers. (Hussain 2015)

Ozone can be detected by an optical ozone sensor based on spectroscopic technique (De Maria & Bartalesi 2012). In this rather complicated approach ozone absorbs some spectral regions of UV light, and a spectrometer can be used for the detection of changes in the ozone concentrations.

6.3.4 Electromagnetic emissions

PD pulses cause surges of current in or on the surface of dielectric material. This acceleration of charged particles produces electromagnetic emission in the RF frequency (3 kHz–300 GHz) region (Xiao et al. 2007). PD detection based on emissions of RF signals has already become a well-known and commercialized technology.

High frequency current transformer (HFCT) has the same operating principle as a normal CT. HFCT can detect PD in the range of several hundred MHz. HFCT sensors are widely used for PD detection, and their application for the location and identification of PD sources is very effective (Álvarez et al. 2015). A number of advantages of HFCT sensors in PD measurements can be listed (Álvarez et al. 2015):

- The sensitivity is rather independent on the shape of the pulses
- Good signal to noise ratio
- High sensitivity
- If two or more sensors are used, location of the source of the PD pulses can be approximated
- The measurements can be recorded for post processing purposes
- High quality HFCT sensors are available and inexpensive.

Along with HFCT technology, coupling capacitors have a long history in PD applications, especially in monitoring of hydrogenerators and motors (Goodeve, Stone & Macomber 1995; Zhu et al. 1999). Capacitive sensors, not requiring capacitors but utilizing stray capacitances between the high-voltage parts, have been introduced (Russwurm 2000).

Rogowski coil works on the inductive principle, i.e. current pulses produced by PDs induce voltage. It is designed with two wire loops connected in electrically opposite directions in order to prevent the effect of external noise and interference. The air cored coil is placed around the conductor, where current pulses produced by PDs in the dielectric are to be measured. (Hussain 2015)

6.3.5 Changes in the electric field

PDs cause changes in the electric field. These can be detected by a rather simple coaxial sensor (D-dot sensor, differential electric field sensor). The construction and operating principle of the D-dot sensor is discussed in the following chapter.

6.3.6 Acoustic emissions

PDs release energy, and a fraction of the energy can produce a mechanical wave and thus a sound which can be detected by acoustic detection methods (Lundgaard 1992a; Lundgaard 1992b). Repetitive PDs can also cause vibrations. According to (Muhr 2015a) the frequencies are in the range of 10 Hz–300 kHz.

A high-frequency microphone can be used in MV air-insulated switchgear to detect acoustic signals from a range of locations (Lundgaard 1992b). In a test reported in (De Maria et al. 2007), both condenser microphone (bandwith 20–1200 Hz) and an omnidirectional optical microphone (10–15000 Hz) were applied. Piezo-electric sensors and opto-acoustic PD measurement, based on deformation of an optical fiber because of a pressure wave, can be applied as well (Muhr 2015a; Muhr & Schwartz 2009). The main advantage of acoustic methods is immunity to electromagnetic interference and the possibility of PD location (Lundgaard 1992b). They are well suited for PD detection systems applying multiple detection techniques.

Piezoelectric sensors rely on the piezoelectric effect created by a PD. They can be tuned to frequencies which are optimal for detecting ultrasonic signals created from PD activity. There are commercially available sensors that can be attached to the casing of the switchgear. (M&B Systems 2015)

6.3.7 Optical emissions

Optical ultraviolet signals are produced by various ionization, excitation, and recombination processes caused by PDs (Muhr & Schwartz 2009). The intensity and wavelength of these signals depend on different factors, such as PD intensity, insulation material, temperature and pressure. According to (De Maria & Bartalesi 2012) the main spectral band of radiation emitted by predischarges lies in the UV region (300–400 nm).

Surface discharges can be detected e.g. by conventional optical fiber with lens, fluorescent optical fiber or by a standard optical probe with photomultiplier detector (Muhr & Schwartz 2009; De Maria et al. 2007). The benefit of optical detection is its immunity to electromagnetic interference.

6.3.8 Changes in the frequency spectrum of the current

Because current is regularly measured and analyzed, it would be very convenient to use normal current measurements for detection of developing faults. In fact, low power series and parallel arcs change the harmonic spectrum of the current (Brechtken 2001; Müller et al. 2010). However, it is very difficult to set a certain threshold level for a specific current component in order to detect a fault developing into an arc fault, but frequency analysis could be one method in a multiple criterion indication system (Müller et al. 2010).

6.3.9 Monitoring of zero-sequence voltage

In MV systems with ungrounded or compensated neutral, changes in zero sequence voltage can give an indication of a developing earth fault. This indication is commonly used by electric utilities in some countries for early detection of high-resistance earth faults. Analysis of zero sequence voltage has also been suggested for the detection of insulation faults in permanent magnet synchronous motors (Urresty et al. 2011). However, for detection of developing faults in switchgear, monitoring of zero-sequence voltage should be used only in combination with other indication methods because it does not give any indication of the location of the fault.

6.3.10 Cable end differential protection algorithm

Cable termination is a typical location of arc faults. The principle of current differential protection may be applied for detection of developing faults in cable terminations (Arvola, Dahl & Virtala 2013). In practice this means comparison of the sum of individual phase current measurements and the measurement of the core balance current transformer. Figure 17 illustrates this principle.

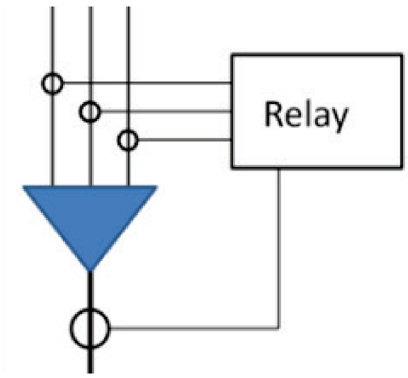

Figure 17. I_{diff} monitoring of cable termination.

6.4 Comparison of sensor technologies

Table 3 presents a short comparison of sensor technologies which can be applied in the detection of developing faults in switchgear. The comparison has been presented in Publication VI and it is partially based on (Land et al. 2003; Russwurm 2000; M&B 2015).

Table 3. Comparison of sensor technologies.

Sensor type	Advantages	Disadvantages
RF Sensor (antenna)	• No connection to the HV equipment is required • Can be used on-line • No coupling device required • Inexpensive, small	• Works only near the PD source • Highly sensitive for a wide range • Sensitive to reflected signals • Direction sensitive
Coupling Capacitor	• Frequency range is 1–500 MHz (wide range) • Very high sensitivity • Can detect surface and internal discharges • Availability	• Requires high insulation level • High price • Each sensor is designed for a certain application
Capacitive Sensor	• No physical connection to the HV • No coupling device • Very inexpensive • Easy to use • Possible portable	• Requires direct line-of-sight • Not very sensitive • Sensitive to noise
High Frequency Current Transformer	• Robust to external noise • No insulation is required if used around the ground wire • Can be used on-line • Ease of use, non-intrusive • Very sensitive	• Usually insulation is required to protect from the high voltages if used on the live wire • Costly
Rogowski coil	• No physical connection • Very high band width • Ease of use, non-intrusive • Very sensitive	• Costly
Piezoelectric Ultrasonic Sensor	• Easy and inexpensive • Can detect surface PDs • Immune to electromagnetic interference • Steel or fiber rods can be used to propagate the emissions from the PD source to the sensor • Very sensitive	• Directional • Sensitive to background sound signal often attenuated • Electrostatic forces may affect the measurements • Time delay
Ultraviolet sensor	• Very inexpensive and sensitive • Easily implemented	• Difficult to calibrate • External light may create problems
Thermal Sensors	• Inexpensive, available, easy to implement • Temperature of individual phases can be compared	• Calibration for different environments • Placement often difficult • Wiring unless wireless sensors • High number of sensors required
Thermal Ionization Detector	• Reliability • Number of sensors required	• Availability
D-dot sensor	• Very compact, cheap • Wideband spectrum • Very sensitive	• Directional • Sensitive to noise

6.5 Conclusions

In many of the slowly developing faults in switchgear it is possible to detect signs of them before they develop into high energy arc faults, and stop the escalation. Mechanisms of developing faults and classification of the physical phenomena on which early warning systems can be based, have been discussed. According to the literature survey, PDs and heat are the most common indicators. Along with the analysis of phenomena, sensor technologies have been investigated, and the comparison of sensor technologies has been presented. The comparison has been utilized in selecting sensors for the experimental investigation, presented in the following chapter.

7 EXPERIMENTAL INVESTIGATION OF SENSORS FOR PREEMPTIVE ARC PROTECTION

7.1 Selection of sensors for online monitoring of switchgear

The aim of the experimental investigation was to evaluate whether some sensor types give useful results for preemptive detection of arc faults. The following criteria were applied for the selection of examined sensors:

- cost-effectiveness, including the number of sensors and input/output devices;
- sensitivity and reliability;
- compactness and ease of use;
- compatibility with the application;
- connectivity of the sensor to protection, monitoring, and the control system (Publication VII).

PDs are characteristic of MV systems. They are naturally less characteristic of LV systems due to the lower voltage stress. From the sensor selection point of view this indicates that PD based detection methods of developing faults are applicable to MV systems while in LV switchgear other sensor technologies, especially thermal indication, can be applied.

A commercial HFCT was selected to act as the reference sensor, since it is one of the most reliable sensors being used in PD measurements in various applications. The outputs of the tested sensor could be validated by comparing them with the output of the HFCT. All the tested sensors were noncommercial, designed for the laboratory. The following sensor types were selected for further examination for MV system:

- D-dot sensor (differential electric field sensor)
- Rogowski coil
- Loop antenna

Figure 18 presents the selected test sensors. For LV system, an ionization detector was developed in the laboratory by using the radioactive material that is contained in the domestically used ionization-type smoke detectors (Publication VII).

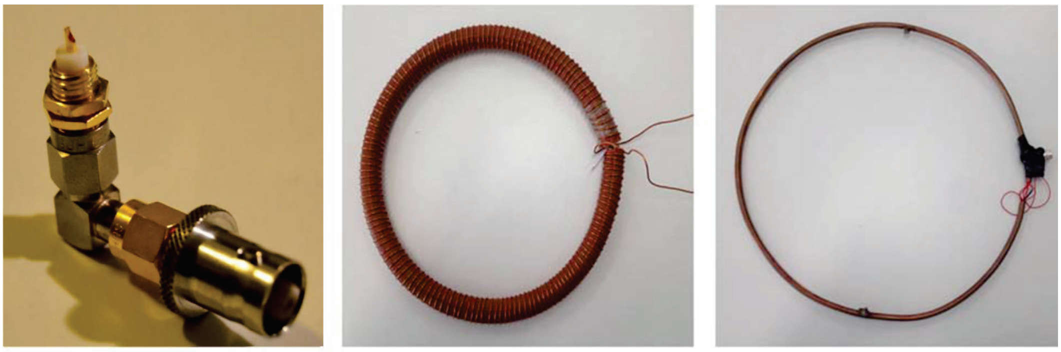

Figure 18. Selected sensors for MV tests.

7.2 D-dot sensor

D-dot sensor is a coaxial sensor made from a standard SubMiniature version A connector (SMA jack). The normal electric field in the energized equipment generates a surface charge density on the center conductor of the sensor. At zero frequency, the center conductor is held at zero potential through the terminating resistance. At higher frequencies (e.g. caused by PDs) with a changing electric field, the current is induced on the center conductor due to the surface charge (Burkhart 1985). The output of a D-dot probe is proportional to the derivative of the electric field with respect to time dE/dt and can be recorded by the oscilloscope as dV/dt (Publication VII).

D-dot sensor is a very inexpensive and robust solution for PD measurement in switchgear. It has a number of benefits: it is small and easy to install; it has a wide bandwidth, 1 Hz–18 GHz; it is rather immune to external discharges if it is installed in a closed grounded metal compartment. However, it may capture some other high frequency signals as well as system frequency signal, but this noise can be identified and eliminated by signal processing (Publication VII).

7.3 Rogowski coil

Rogowski coil can be used both in measurement of AC current in protection relay applications and measurement of high frequency current pulses. Since transients trend to earth to any closest earth path Rogowski coil can also be installed on earth terminals in order to measure transient pulses. In these cases, the required insulation level is lower than in case of installation on the phase conductor.

Rogowski coil is an induction sensor with air core. The winding is constructed of two wire loops connected electrically in opposite directions. The coil is installed around the measured conductor (phase conductor or earth conductor) or it can enclose all three phase conductors when measuring zero-sequence current in a 3-phase system. Voltage is induced in its windings due to changes in the magnetic field around the current carrying conductor. Figure 19 shows the construction of Rogowski coil.

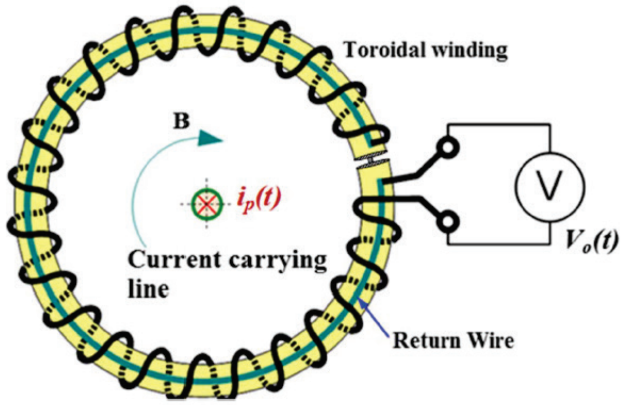

Figure 19. Construction of Rogowski coil (Publication VII).

7.4 Loop antenna

Discharge transients produce electromagnetic emissions which can be detected by radio frequency antennas. The operation is based on Faraday's law of induction, and the output is proportional to the changing magnetic field. Loop antenna is simple and cheap (Rozi & Khayam 2014). It is not as small as D-dot sensor, and it is not as easy to install in the switchgear. In order to get useful measurement, signal processing of the captured signal is necessary to eliminate high frequency noise.

7.5 Thermal ionization detector

As described in earlier chapters, a loose connection is a very common cause of slowly developing arc faults especially in LV systems. Since heat plays a significant role in the mechanism leading to a fault, thermal monitoring provides a way to predict faults. Overheated insulation can also be detected. Direct measurement of the temperature is challenging. However, the ionization of the materials, i.e. the airborne particles, can be detected by a thermal ionization detector (TID) (Land et al. 2001; Land et al. 2003).

The operation of the detector is based on an ionization chamber, applied in common ionization based smoke detectors. A radioactive isotope provides ionization inside the chamber, and the applied DC voltage across the chamber produces flow of the ions, a very small current. The current charges the collector in the chamber, and in normal conditions the collector reaches a constant potential (balance potential). When external ions (from the source of the heat) enter the chamber, they disturb the flow of the current, and the potential of the collector falls which can be detected. This indicates ionization. An electronic amplifier is involved to amplify the measured signal. The detector can even be calibrated to respond to temperatures 200–300 °C which is significantly lower than the melting point of copper. (Land et al. 2001)

The principle of TID is presented in Figure 20. TID technology has been successfully applied in special applications. However, this low-cost technology may have potential to much wider application and commercialization.

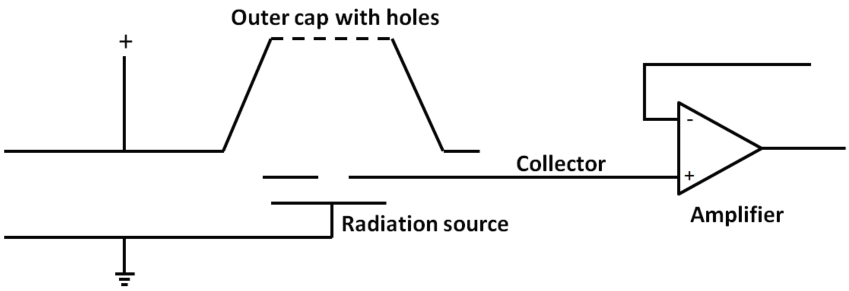

Figure 20. Principle of thermal ionization detector; after (Land et al. 2001).

7.6 Measurements in the laboratory

7.6.1 Measurement setups

In order to get useful results from the practical point of view, MV switchgear was acquired for the measurements in the laboratory. The measurements were carried out using three different setups. Setup 1 was implemented for thermal monitoring. Setup 2 was utilized for the PD measurement of the insulators (PD in voids and the surface discharge) inside the switchgear. Setup 3 was implemented for low power arcing across a very small (0.2 mm) arc gap (Publication VII).

7.6.2 Thermal monitoring, ionization sensor

The thermal ionization sensor was developed in Aalto University's laboratory. Parts from domestically used ionization type smoke detectors were utilized, and the principle described in (Land et al. 2001) was applied. A hot spot was created in a metallic enclosure by using a copper tube and a soldering iron with temperature control. The sensor was installed at the ceiling of the enclosure whereas the hot spot was placed at the base. Two calibrated thermocouples were installed in the enclosure, one next to the hot spot and the other next to the TID. The setup is presented in Figure 21 (Publication VII).

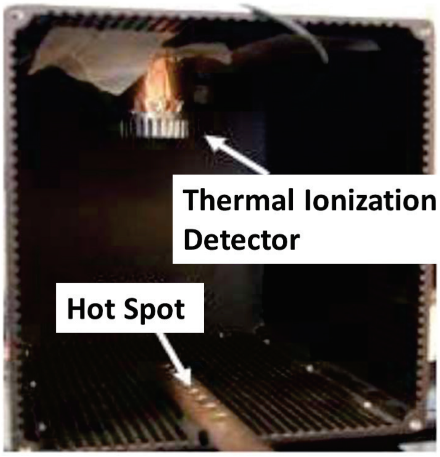

Figure 21. Thermal ionization detection (Publication VII).

The temperature of the hot spot was varied and its impact on the output of the sensor and the thermocouples was measured. Due to the diffusion in the surrounding air, the temperature of the hot spot and the temperature at the sensor were totally different. However, the output of the sensor followed rather accurately the behaviour of the thermocouple that was installed next to the hot spot. This is presented in Figure 22. This confirms that the TID sensor is very sensitive to the thermal ionization effects. The test also indicates that TID sensors can be installed at the ceiling inside an LV switchgear enclosure to monitor a section of the switchgear.

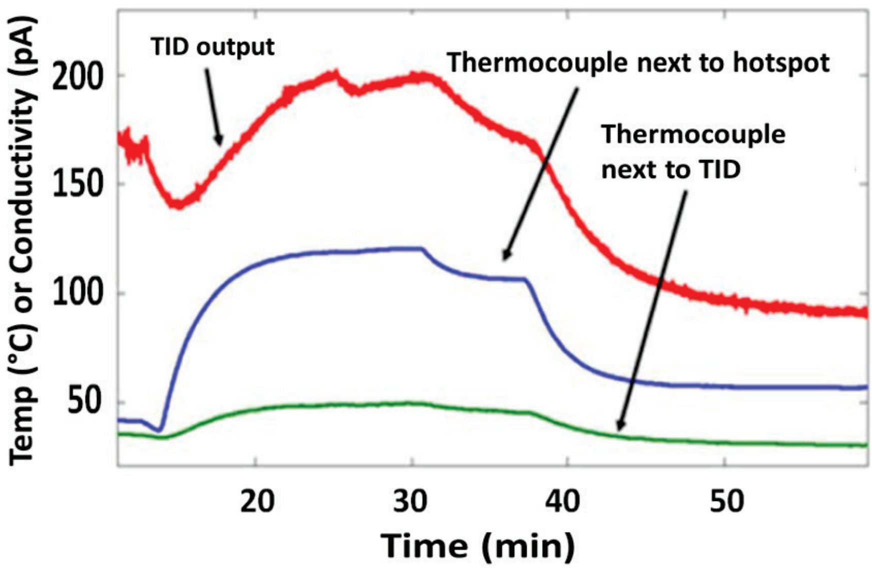

Figure 22. Temperatures measured by the thermocouples and the output of the TID sensor.

7.6.3 Partial discharge measurements

Four types of sensors were applied in PD measurements: Rogowski coil, D-dot sensor, loop antenna, and HFCT as a reference sensor. The measurements were carried out inside a switchgear panel. The circuit breaker was put in the closed position, and the outgoing side of one phase was open circuited while the other two phases were grounded. Only the open ended phase was energized and used to study various PD conditions. PD sources were connected to the open end of the phase. The switchgear was placed on a wooden base and its enclosure was grounded through a single point. The PD sources were energized through an LV regulating transformer and a 0.23/100 kV transformer. The voltage was gradually increased to a level where PD activity could be identified. Figure 23 presents the circuit diagram of the setup, and Figure 24 the positions of the sensors. (Publication VII)

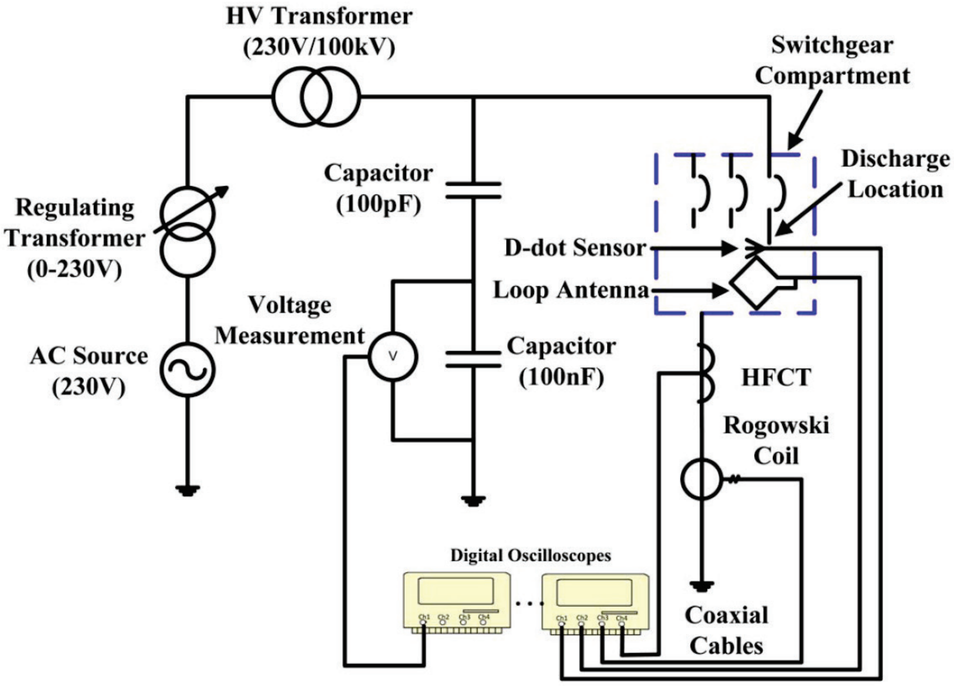

Figure 23. Circuit diagram of the PD measurement setup (Publication VII).

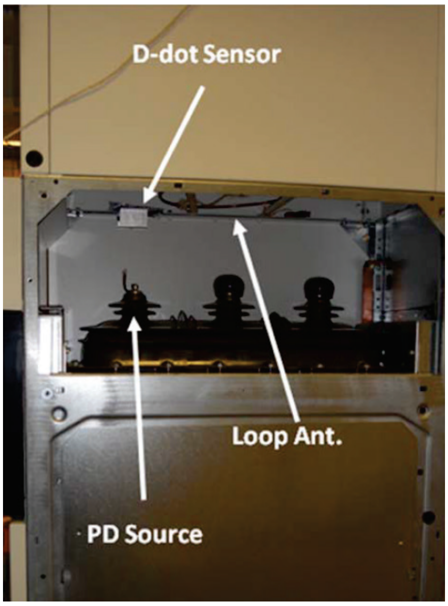

Figure 24. Positions of the sensors (Publication VII).

The D-dot sensor was fixed inside the upper part of the switchgear compartment at a distance of 13 cm from the discharge location. The loop antenna was placed in the same area at a distance of 16 cm from the discharge point, whereas the HFCT and the Rogowski coil were installed around the ground connection of the switchgear.

The sensors were connected to the digital oscilloscopes through a 50 Ω coaxial cable to a 50 Ω channel input of the oscilloscope. Data were captured at a sampling frequency of 20 GHz using a 16-bit digital oscilloscope. The discharges were produced by two sources:

1. PD in the void in an epoxy insulator;
2. Surface discharge at the insulator surface.

7.6.4 Low power arcing measurements

The behavior of the arcing across loose contacts is similar to the low-energy arcs across a small arc gap. Both of them cause RF electromagnetic emissions. In order to study the response of various sensors under the low energy arcing (sparks) across loose contacts, a very small arc gap (rod–sphere) of 0.2 mm was implemented. This setup was constructed on the floor of the laboratory. The system was energized by an LV regulating transformer and a 0.23/100 kV transformer. Since the gap was very small, already very low voltage (< 1 kV) caused a spark in the gap. The sensors, HFCT, Rogowski coil, D-Dot sensor and loop antenna were connected to digital oscilloscopes. Data were captured at a sampling frequency of 20 GHz using a 16 bit digital oscilloscope. Figure 25 presents the measurement setup. (Publication VII)

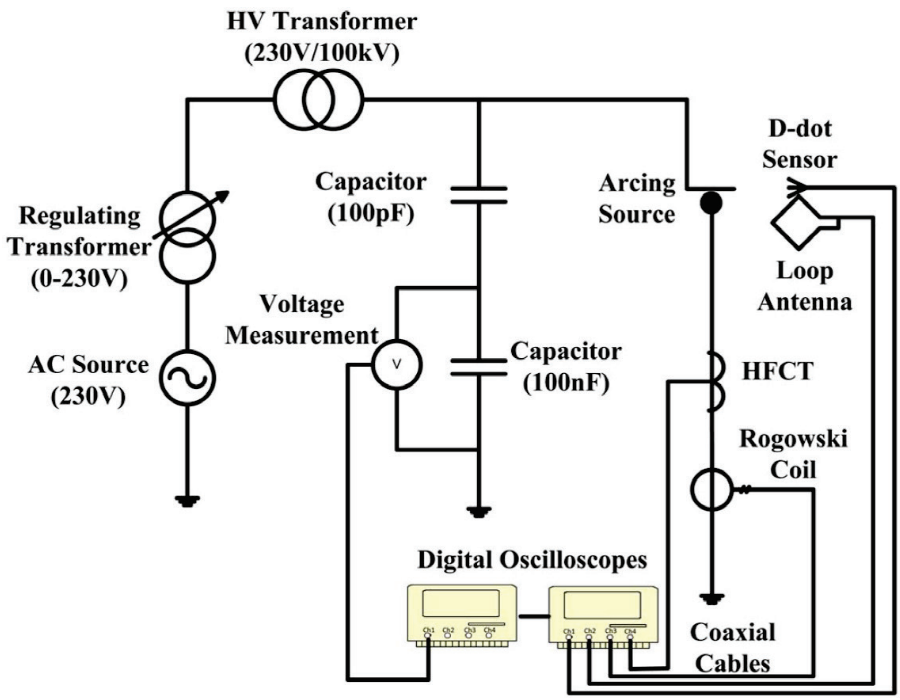

Figure 25. Setup of the low power arcing test. (Publication VII)

7.6.5 Analysis of the measured results

Online PD measurements are often affected by several electromagnetic disturbance sources (Hashmi 2008). Even measurements in laboratory conditions include noise that should be eliminated in order to extract the PD related signal. The same applies to the RF signal measurements of the emissions from low power arcing. In switchgear, signals may reflect from the metallic walls and get distorted which makes the identification of the original PD signal more difficult. A number of signal processing techniques have been introduced for the de-noising of measured signals. Analysis of them is beyond the scope of this thesis. However, in the research reported in (Publication VI), Discrete Wavelet Transform (DWT) gave very good results.

De-noised signals captured by all the sensor types in the test case of “voids in an insulator” are presented in Figure 26. Although the amplitudes of the signals differ from each other and especially from the reference sensor HFCT, the results strongly indicate that all the investigated sensor types are able to indicate the occurrence of PD. Results from other two test cases support this conclusion.

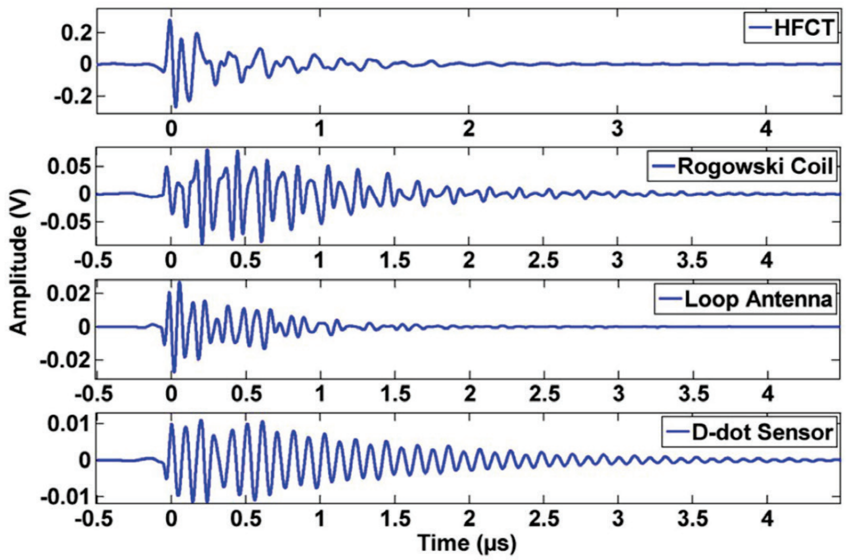

Figure 26. The measured signals of the sensors, case “PD in voids in an insulator”. (Publication VII)

In addition to time-domain analysis of the signals, frequency-domain comparison was carried out, confirming the consistency of the measured sensors. Moreover, the ratios of the peak-to-peak values on the measured signals and cumulative energies were calculated, confirming that all the examined sensors can give satisfactory results for the online monitoring of switchgear. (Publication VII; Hussain 2015)

7.7 Outline of the connection to upper level systems

Online monitoring systems provide continuous information on the state of the monitored object or system. The information is presented to the user or transferred to the automation system in an appropriate way, often after significant processing and filtering. In MV and LV switchgear applications, based on the required signal processing capacity, it seems justified to have a separate processing unit which collects the information from the sensors. Only the filtered information would be sent to upper level systems. The filtered information to be sent could be an analog signal, indicating e.g. the level of PD activity. More likely the information could be digital information, indicating alarming level of PD activity or temperature. In some sensitive applications, the monitoring system could initiate a trip signal as well.

Since arc protection relays already have to communicate with the upper level systems, it seems natural to send the alarm signal of a developing arc fault through this existing communications channel. It would also be relatively simple to build multi-criteria monitoring functions in protection relays, taking into account the information from the different types of sensors.

Figure 27 shows a possible implementation in a typical MV distribution system. In this figure, only the D-dot sensor has been implemented. However, the thermal sensors can also be combined in the same system. The data acquisition and signal processing unit acquires data at a certain data rate and performs the signal processing of the data before sending to the upper level systems via the protection relay. Figure 27 also illustrates the importance of the internal communication in online monitoring systems. Communication is needed between the various components and units of the system, as well as between the substation and the control room. The communication need is discussed more in detail in the next chapter.

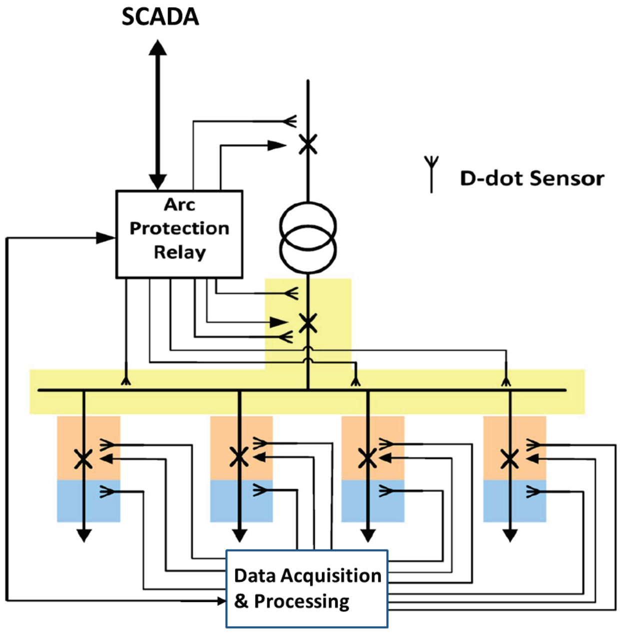

Figure 27. Possible configuration of D-dot sensor based PD monitoring system in MV switchgear.

7.8 Conclusions of the experimental investigations and evaluation of the practical feasibility

The primary goal of this part of the research was to contribute to the development of online monitoring systems for switchgear, preventing slowly developing arc faults before they escalate into high energy faults. Primarily for MV switchgear, four types of electromagnetic sensors, including a HFCT as a reference sensor, were tested in a laboratory in order to examine their performance and to evaluate the need for further development. For thermal detection in LV systems, a self-made thermal ionization detector was tested using thermocouples as reference.

Electromagnetic emissions, which resemble the impacts of defects in MV insulation, were created, and the output signals of the sensors were recorded. Because the recorded signals include a lot of noise, a denoising method had to be applied in order to extract the useful information from the measured data. Widely applied DWT was chosen for this purpose. The denoising method has briefly been described in Publication VII. A more thorough analysis can be found in (Hussain 2015).

The measured signals were analyzed through different ways. The time-domain and frequency-domain analysis of the measurements indicate that all the sensors captured the same fault. Comparisons of the size, cost, ease of use and sensitivity, of different sensors indicate that the D-dot sensor is the most potential sensor for the discharge (PD or low power arcing) monitoring in air-insulated MV switchgear. However, at present there is minimal experience on applying D-dot sensors in detection of PDs while Rogowski coil is a better-known alternative.

The output of the thermal ionization detector was compared with the thermocouples installed at different locations in the enclosure. Results indicate that the TID installed at the ceiling of the enclosure follows the temperature of the hot spot almost as well as the thermocouple installed next to the hotspot. This brings significant benefits to the installation of the sensor, especially in retrofit installations.

When evaluating the practical feasibility of the sensors, further development is still needed. For thermal monitoring and the detection of loose contacts in LV switchgear, thermal ionization based detection can be utilized. Further tests have been carried out with the TID, producing very promising results. However, there are a number of remarks related to the tested thermal ionization sensor. (Hussain 2015).

D-dot sensor and Rogowski coil are potential sensors for detecting PDs in MV switchgear. They require high sampling rate and signal processing beyond the capacity of present numerical protection relays. At present, it is justified to have a have a separate processing unit, collecting information from the sensors, and sending the processed (de-noised) data to either local protection devices or to upper level control systems (Hussain 2015). In practice this means a separate add-on system to the protection system. In the future, increased processing speed and dedicated digital signal processors (DSP) probably enable the integration of PD monitoring as well as thermal monitoring into protection relays.

8 TOWARDS IEC 61850 GOOSE BASED COMMUNICATION IN ARC PROTECTION SYSTEMS

8.1 Application of IEC 61850 standard in arc protection systems

The IEC 61850 is a set of standards, intended to provide interoperability between all devices in power utility automation systems (IEC 61850 2013). This chapter evaluates the feasibility and benefits of IEC 61850 in arc protection. IEC Technical committee 57, "Power systems management and associated information exchange", published the first version of Technical Report IEC 61850-1, "Communication networks and systems in substations – Part 1: Introduction and overview", in 2003. The report has become a widely applied international standard of communication in substations. Since 2003, a number of extensions to the standard have been published, extending the scope out of substations, e.g. including integration of distributed energy sources. The second edition of the technical report IEC 61850-5, "Communication networks and systems for power utility automation – Part 5: Communication requirements for functions and device models", was published in 2013. In spite of becoming the leading standard, IEC 61850 standard has not totally replaced other communication approaches or protocols, such as Modbus, Profibus, DNP3, LON and SPA.

As a standard solution IEC 61850 provides an interesting option for the internal communication of arc protection systems, instead of proprietary communication approaches. At present, Ethernet based communication, and in particular IEC 61850 based technology, is not commonly applied in arc protection systems. The already previously explained ZSI is a common application closely related to arc protection. IEC 61850 and GOOSE have successfully been utilized in ZSI applications. However, ZSI is slower than light & overcurrent based arc protection (Cabrera, Chiu & Nair 2012).

In (Rocha et al. 2011), GOOSE messages are limited to relay-to-relay communication in light & overcurrent based arc protection system. GOOSE messaging can also be applied for the communication between other components of the arc protection system: sensors, input/output units, relays, and circuit breakers. The essential question is whether GOOSE based approaches provide the required speed and reliability.

8.2 Communication needs in arc protection

Figure 28 illustrates the basic communication needs of an arc protection system utilizing a dedicated arc protection relay. Communication is needed in the connection of light and current sensors to the system (A, B), in the internal communication between I/O units and the relay (C), in the connection to the circuit breaker (D) and in the communication to the upper level systems (E), for control and supervision.

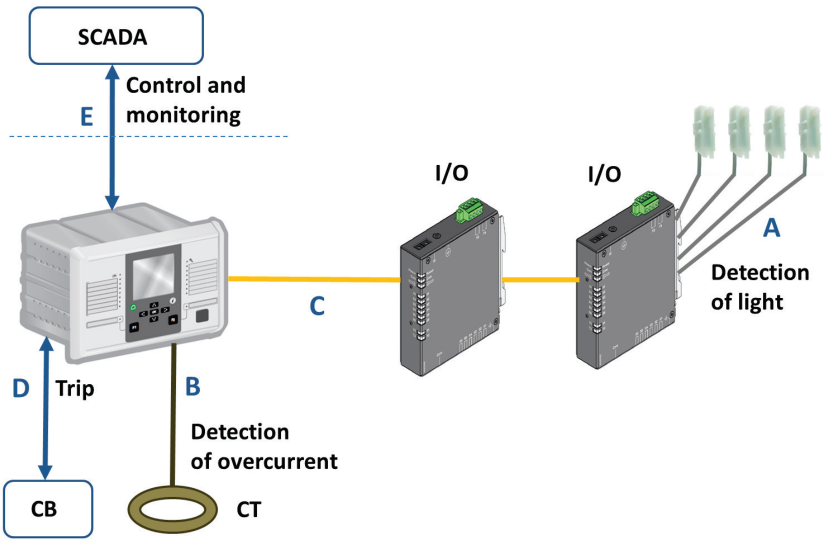

Figure 28. Basic communication needs in arc protection.

An application closer to the real world has been illustrated in Figure 12 on page 35. The system includes a non-standard communication solution. In this system architecture, the central unit is always required, and it has a central role in maintaining the communication, performing system self-supervision, and communicating to upper level systems. All units are linked to the central unit of the system by modular communication cables. The command to the circuit breaker is sent via CB wiring.

The communication system of the system illustrated in Figure 12 utilizes different wires of the communication cable for two different purposes. The first, faster pathway is reserved for the primary purpose, i.e. for delivering the information on sensor activation which in then converted to the trip signal to appropriate circuit breakers. To achieve high performance, minimal amounts of data are transferred in this communication pathway. The second pathway is slower, and it is used e.g. during the installation and configuration of the system. The modular cable has still another function: it supplies power from the central unit to the I/O units.

8.3 Communication speed requirements

The external communication does not require high speed communication while the internal communication of an arc protection system is very time critical. The trip time of state-of-the-art systems is only a few milliseconds, even as low as 1-2 ms. In the system described above, very fast communication was achieved by minimizing the number or size of the transferred data blocks. The performance of the existing systems also sets high expectations for systems utilizing IEC 61850 based communication.

IEC 61850 definition of transfer time is presented in Figure 29. The overall transfer time is the time between function f_1 in physical device PD1 and another function f_2 in PD2. The transfer time includes the time needed for processing (coding/decoding) at both sender and receiver ends, and the network transfer time. (IEC 61850-5 2013)

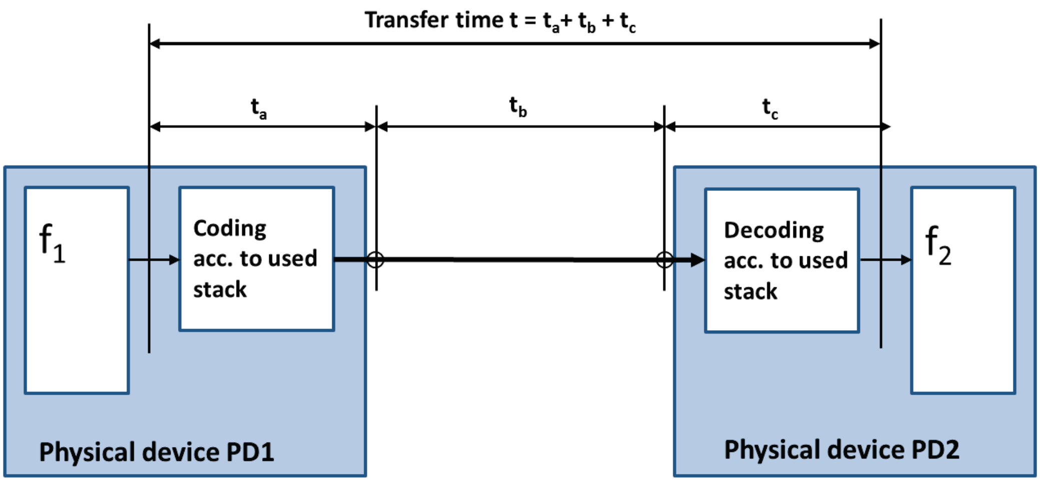

Figure 29. Definition of overall transfer time (IEC 61850-5 2010).

According to (Sevov, Zhao & Voloh 2013) modern IEC 61850 implementations can transfer messages between relays with delays of about 2–4 ms. IEC 61850-5 defines transfer time classes for control and protection. These are presented in Table 4. The standard allows as high as 3 ms transfer time for trips. From arc protection point of view this requirement is not very strict. At least in the most demanding applications where the pressure wave is mitigated by a short-circuit device, every millisecond counts.

Table 4. Classes for transfer times (IEC 61850-5 2013).

Transfer time class	Transfer time [ms]	Application examples: Transfer of
TT0	>1000	Files, events, log contents
TT1	1000	Events, alarms
TT2	500	Operator commands
TT3	100	Slow automatic interactions
TT4	20	Fast automatic interactions
TT5	10	Releases, status changes
TT6	3	Trips, blockings

In 61850 based solutions, there are issues affecting the performance, such as processing speed, communication traffic and cyber security. In order to avoid delays caused by network traffic, virtual local area networks (VLAN) are used to separate the priority and non-priority traffic in the network (Ingram et al. 2013; Sevov, Zhao & Voloh 2013; Dixon et al. 2014). Another means to enable very fast GOOSE communication is to utilize high speed fibre media for networking the devices (Kumpulainen et al. 2012; Mazur, Kay & Kreiter 2013). In previous studies it has been stated that the speed of GOOSE based communication can be as good as in direct serial communication (Dixon et al. 2014).

8.4 Cyber security aspects of GOOSE based communication

Cyber security has become an important or even a must-have part of protective relays. Utilities and power users must protect their processes from hackers (Ransom 2014; Hohlbaum, Schwyter & Alvarez 2011). Cyber security is a rapidly changing field which is quite new to the power and automation industries (Alvarez 2014; Hong, Liu & Govindarasu 2014). Hoyos, Dehus & Brown (2012) lists a number of weaknesses of GOOSE and shows how they can be exploited in cyber attacks. Practical experience has shown that although IEC 61850 is a standardized protocol, multi-vendor environments are often problematic. The same applies to the installing of IEDs from different manufacturers within the same cyber security system (Sarralde & Yarza 2014).

One of the main challenges in applying GOOSE in arc protection is how to retain the speed while providing adequate cyber security. Security can be increased by authentication and encryption of the GOOSE messages. However, in arc protection applications the operation time is exceptionally critical and it is difficult to implement security for GOOSE messages without degrading the performance because encryption and other security measures tend to increase communication delays (Hohlbaum, Schwyter & Alvarez 2011; Hong, Liu & Govindarasu 2014; Hoyos, Dehus & Brown 2012). (Kim & Kim 2014) and (Cleveland 2012) see encryption unacceptable in time critical applications and state that authentication is the only security measure included as a requirement. Message Authentication Code (MAC) is one option to provide security. In practice this means digital signing or sealing the message. However, this increases the length of the message and requires more processing which increases transfer time. According to (Sarralde & Yarza 2014), even just simple authentication based on MAC for the critical messages must be analyzed in each situation to determine whether the increased delay is acceptable.

VLAN provides logical separation by creating a separate virtual network segment (Strydom & Mulholland 2015). Two advantages of VLANs are the separation of the traffic between the segments and security. When using port based VLANs a specific port or a group of ports is assigned to belong to a VLAN while in tag based VLANs a VLAN identifier (tag) is sent as part of the message (Wester, Adamiak & Vico 2011). It is possible to apply VLAN tagging so that each GOOSE message becomes a virtual cable with the message contents virtually wired only to the other IEDs that need the data (Tibbals & Dolezilek 2011). VLAN messages also include a priority flag which prioritizes data flows through network switches (Wester, Adamiak & Vico 2011). When GOOSE messages are equipped with both ID tags (authentication) and priority tags, Ethernet switches are able to authenticate, redirect and prioritize the messages.

Physical isolation of the communication network is an effective means to improve cyber security. Systems can be divided into multiple security zones and the use of removable media can be limited in the station computers (Hohlbaum, Schwyter & Alvarez 2011). Also it should be noted that due to the nature of GOOSE messages they are not routable and thus on default will not pass gateways or firewalls.

8.5 System architecture of a new, GOOSE based solution

The key idea of the developed implementation is to respond to the challenging performance and cyber security requirements by physical isolation, i.e. by having a dedicated LAN cable for the arc protection system, isolated from the substation LAN (IEC 61850 station bus). This solution provides two crucial benefits. The background traffic in the substation LAN has no impact on the performance of the arc protection system, and physical isolation is a strong means against cyber attacks.

If the connection to upper level systems is vital, a connecting device, the Arc Terminal, can be used. The Arc Terminal has two independent processors which provides physical separation. One processor is used for vertical communication and the other for horizontal communication (for I/O units). The processors do not share any memory directly, while they have two independent network stacks and two physically different Ethernet connectors for the different networks.

As a whole, the new system has the same four basic components as the previously described system: sensors, I/O units for collecting information from the sensors, central units (Arc Terminal), and cables. However, in this system architecture the central unit is no longer required for maintaining the system. The new I/O units enable the use of a distributed architecture. The communication and system self-supervision are decentralized. This is one of the main benefits of this architecture, which also makes the system more robust.

The optional Arc Terminal has a role somewhat similar to that of the central unit of the previous system. It can be used as a user-interface to the arc protection system, as well as an information collection, logging, and communication device. The Arc Terminal can also be used as a gateway for transmitting information to upper level information systems, e.g. SCADA. However, it must be emphasized that the Arc Terminal provides physical isolation of the networks which is very good from both performance and cyber security points of view. In case of a simple standalone system where there is no need to communicate information vertically, the Arc Terminal can be replaced with a simple local monitoring and configuration display.

The key component of the new system is the I/O unit, utilising Microchip PIC32MX microcontroller hardware. Figure 30 illustrates the basic principle of the new system architecture based on new I/O units and a dedicated LAN cable. Figure 30.a shows the system in a completely independent configuration, and Figure 30.b shows the system with the Arc Terminal and SCADA connection included. The latter example utilizes two physically separated LANs.

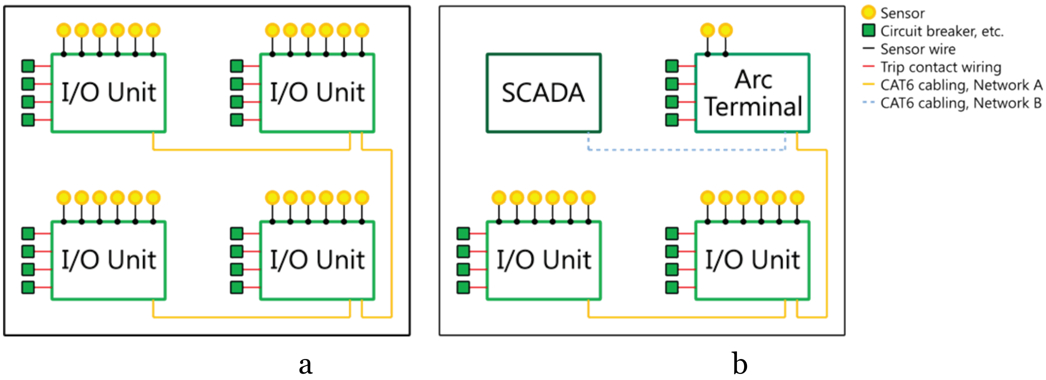

Figure 30. Illustration of the new system architecture.

The inputs of the new I/O units can be light sensors or current sensors. The outputs can be electromagnetic relays or semiconductor outputs to deliver trip signals to CBs. A selective arc protection system can be implemented by dividing the protection into zones, called groups. A single group consists of a fixed set of sensors and CBs which are tripped when the arc is detected in the group in question. A single group could contain just a single light sensor or dozens of light sensors and several current sensors. Theoretically, each sensor could be configured to send its information to multiple groups and CBs could be controlled by signals from different groups.

IEC 61850 GOOSE communication operates over Ethernet and the system uses standard Ethernet cables with RJ-45 connectors. Each I/O unit has a built-in Ethernet switch and two Ethernet connectors which can be used to daisy chain the I/O units. As the communication is Ethernet based, all the topologies supported by Ethernet are also supported by the system. GOOSE messaging is used for the group and sensor activation information and another set of messages is used for other data transfer such as transferring settings.

A major advantage of the new architecture is that extensive arc protection systems can be built. Each of the devices in the new system has a built-in Ethernet switch, which is acting as a repeater. Cable lengths up to 100 m are supported for each link and thus the range can easily be extended to at least several hundreds of meters. However, each additional hop causes a small delay to the end-to-end message transfer times and these accumulate among the device chain. Also transferring the auxiliary power over the modular cable poses its own limitations to the cable lengths.

8.6 Performance of the communication of the GOOSE based system

8.6.1 Setup of the tests

A series of laboratory tests was conducted in order to evaluate the performance of the described communication system. Since the focus was on the performance of the communication, "light only" detection principle was applied, i.e. trip purely from light sensor activation without measuring current. The presence of overcurrent information would have slightly increased the traffic in the communication channel. However, increased traffic was included in some of the test cases by causing multiple simultaneous light sensor detection events.

The performance was evaluated by measuring the time from the detection of light to the moment when the trip signal output was activated on the receiving I/O unit and sent to the appropriate circuit breakers. A strongly simplified illustration of the test setup is presented in Figure 31.

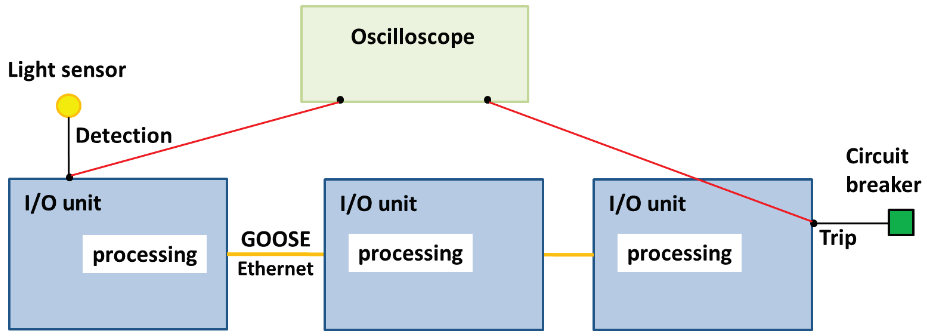

Figure 31. Simplified illustration of the test setup.

The tests were conducted with multiple configurations. This enabled the evaluation of the performance of GOOSE messaging through several I/O units, including cases where additional traffic was intentionally introduced in order to stress the communication channel.

The test setups consisted of a number of optical sensors, 6 light detection I/O units (the main components of the tests), one monitoring unit, and communication cables. This setup simulated a real life MV substation configuration, illustrated in Figure 32. The light was produced by either a dedicated flashtube-type camera flash or by an LED flash. The measured signals were the detection of light at the input connector of an I/O unit and the trip signal to the circuit breaker, measured at the semiconductor output of another

I/O unit. The signals were measured at the connectors of the I/O units by an oscilloscope, and the time between these signals was recorded.

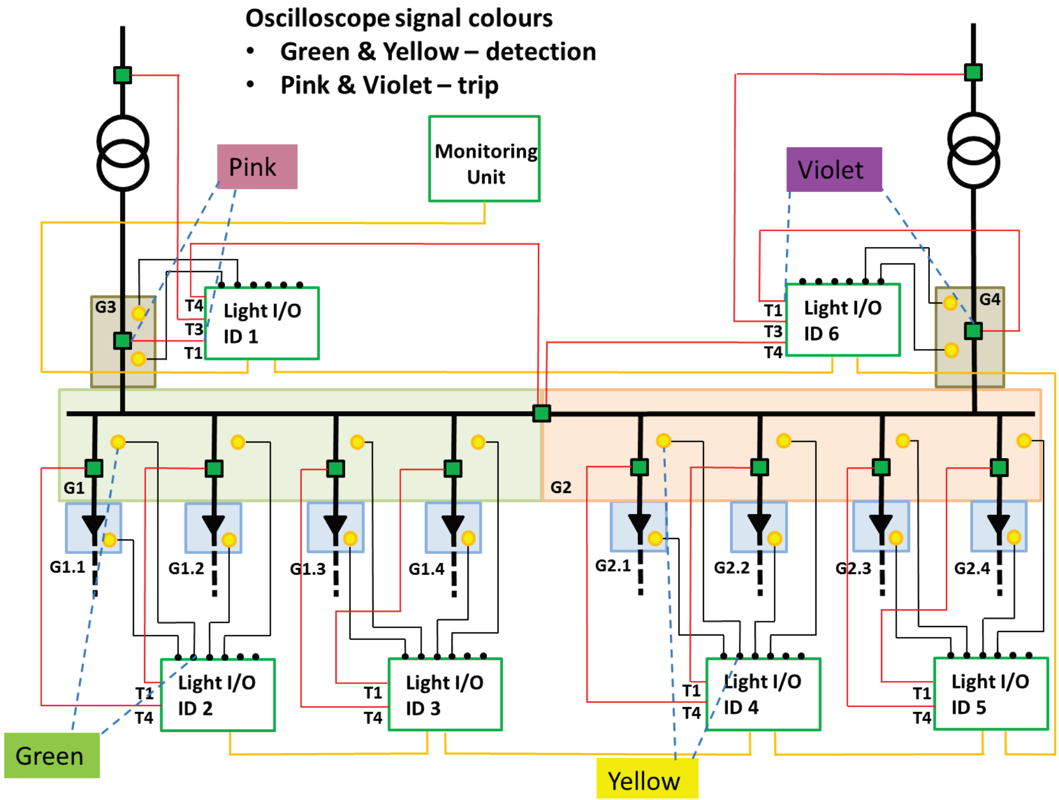

Figure 32. Measurement setup, simulating MV substation (Publication VIII).

8.6.2 Results of the communication tests

Each test setup was measured 10 times, and the mean, minimum and maximum values were recorded or calculated. The most relevant setups were the following:

A. Remote trip (detection in I/O unit ID 2, trip from unit ID 1), communication through four other I/O units, no other traffic in the communication channel. Light source: LED flash.
B. Remote trip, some traffic in the communication channel, caused by the activation of another light detection input at exactly the same time (I/O unit ID 4). Light source: flashtube-type camera flash.
C. Remote trip, a lot of traffic (activation of 8 sensors, i.e. a simulated “bus fault” situation) in the communication channel. Light source: flashtube-type camera flash.

Examples of the oscilloscope recordings of the measurements have been presented in Publication VIII. Table 5 provides a summary of the numerical results, i.e. delays from detection of light to the trip signal, of the different test cases. The I/O units are equipped with very fast semiconductor outputs instead of mechanical relay outputs.

Table 5. Summary of the results of the test setups A, B and C.

Case	Mean / µs	Min / µs	Max / µs
Case A	319	278	357
Case B	528	359	625
Case C	563	373	657

8.6.3 Analysis of the communication test results

The test results indicate that the new GOOSE based communication system is very fast. The mean operation time in all the examined cases was less than 0.6 ms. The worst measured value was recorded when there was a considerable amount of traffic in the communication channel. Even in this case the measured value was less than 0.7 ms. The tests strongly indicate that the presented approach in applying GOOSE communication for the internal communication of arc protection systems provides adequate communication speed.

8.7 Evaluation of the developed GOOSE based solution

Practical implementations of arc fault protection systems consist of multiple components, requiring peer-to-peer communication. This study has investigated the applicability and benefits of IEC 61850 based communication, including discussion on cyber security aspects. The developed GOOSE communication based system provides many benefits, including the following:

- The communication is based on an established standard.
- GOOSE messages can be prioritized and supervised.
- The developed system includes extensive self-supervision.
- Physically extensive protection systems are possible, since the new I/O units operate as Ethernet switches.
- The central unit is not necessary; in its place an optional gateway/terminal unit can be used.
- High number of protection groups (zones) enables selective protection.
- As generally in IEC 61850 applications, the simplified wiring reduces costs.

The GOOSE based approach also includes potential drawbacks. The most obvious challenges, when comparing the existing, proprietary non-standard communication solution with the GOOSE based system, are performance and cyber security. Due to the high performance requirements set by arc protection applications, physically separated LAN for the arc protection system should be used. When a dedicated LAN is used, background traffic in the station bus does not have an impact on the performance of the communication in the arc protection system. Physical isolation also considerably mitigates cyber security concerns, eliminating direct GOOSE based attacks.

The performance of the developed system has been verified by laboratory testing. The tests indicate that the performance is very good. Even in the worst case a communication delay of less than 1 ms was achieved.

9 CONCLUSIONS AND CONTRIBUTIONS OF THE THESIS

In this doctoral dissertation, aspects and development directions of internal arc protection have been investigated. A comprehensive view of arc protection technologies has been developed. The view extends from the prevention of arc faults to the rapid elimination of fault arcs. One of the main contributions is the identification of the areas where significant improvement can be achieved by further research and development: faster arc elimination, preemptive arc protection and communication.

Methods for arc fault prediction in switchgear have been developed. Feasible sensors for the detection of slowly developing faults have been identified. In MV systems, D-dot sensor and Rogowski coil can be utilized in the recognition of partial discharges. In LV systems, online thermal monitoring can be applied. Thermal ionization detector is able to monitor the temperature of the compartments of the switchgear. Functionality of these sensors has been verified by laboratory tests. Moreover, the connection of the sensors to upper level information systems has been outlined.

Communication plays an important role in modern protection systems. In substation automation, IEC 61850 is the leading and expanding communication standard. In this thesis, an application utilizing 61850 GOOSE based communication for the internal communication of an arc protection system has been developed, and its performance has been verified. The developed solution has several benefits:

- The communication is based on an established standard.
- GOOSE messages can be prioritized and supervised.
- The developed system includes extensive self-supervision.
- Physically extensive protection systems are possible, since the new I/O units operate as Ethernet switches.
- The central unit is not necessary; in its place an optional gateway/terminal unit can be used.
- High number of protection groups (zones) enables selective protection.
- As generally in IEC 61850 applications, the simplified wiring reduces costs.

Analysis of the most promising methods of mitigating arc faults by minimizing the arcing time has been given, including both existing and future solutions. The major bottleneck is the duration of the arc elimination. State-of-the-art arc protection systems can detect an arc fault and send the trip signal within 1–2 ms. However, the arcing time in common applications is normally tens of milliseconds, depending on the operation time of the circuit breaker. This level of arcing time provides reasonably effective mitigation of the thermal impacts of the arc fault, but effective mitigation of the pressure impact requires elimination of the arc within a few milliseconds.

Very rapid fault arc extinction is possible by utilizing short-circuit devices, available currently from several manufacturers. This technology can be considered justified in sensitive environments, such as data centers, ships, mines and oil & gas industries. Hybrid applications, composed of short-circuit devices and current-limiting fuses or power semiconductor based circuit breakers and CL fuses could be an interesting option to reduce the arcing time and the duration of the short circuit. In the long term, high power solid-state circuit breakers will most likely provide a major improvement in arc protection.

In addition to scientific contributions, a more practical area where significant impact can be achieved, has been identified: standardization of arc protection. Lack of standards and requirements can be seen as a major obstacle to implementation of already existing efficient arc protection technologies. What has happened in automotive industry via safety chassis, seat belts, airbags and sensor systems, can analogically happen in switchgear industry: significantly higher level of safety and reliability can be reached. A comparison between the development of safety in automotive industry and the opportunities for switchgear safety and reliability is presented in Table 6.

Table 6. Improvements of safety and reliability in the automotive industry and opportunities in switchgear technology.

Cars	**Switchgear**
Safety chassis	Arc-resistant switchgear
Seat belt	Arc protection based on detection of light
Airbag	Short-circuit device; In the future power semiconductor based very fast circuit breakers
Vehicle bus (internal communication)	Standard-based communication of the protection system, e.g. IEC 61850
Systems and sensors monitoring the condition of the vehicle and the environment	Preemptive arc protection system based on online monitoring, self-diagnostics and appropriate sensors

One of the main targets of this dissertation was to recognize development directions of arc protection. Basing on the analysis made, future work is especially needed in the following areas:

- Development and implementation of proactive and preemptive technologies, sensors and online monitoring systems.

- Implementation of standards-based communication solutions in arc protection systems.

- Utilization of existing ultra-fast arc elimination technology, short-circuit devices, and development of faster circuit breakers, in order to reduce the arcing time.

- International standardization of existing, efficient and proven technologies.

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THE BIG PICTURE OF ARC-FLASH MITIGATION

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Abstract - This paper provides a big picture of arc-flash mitigation. From pre-arc issues, both preventive measures as well as various arc fault prediction technologies are discussed. Arc fault prediction is explained as identifying a developing arc fault by analyzing pre-arc conditions, in practice by on-line monitoring. Because preventive or predictive measures can not totally eliminate the risk of arc faults, arc fault mitigation is justified. Two mitigation approaches, current-limiting and time-limiting, are discussed, and the risks related to current limitation are illustrated. Performance of light and overcurrent detection based mitigation is presented, and aspects of arc elimination by either circuit breaker or by an arc eliminator are discussed.

Index Terms — Arc faults, Preventive maintenance, On-line monitoring, Incident energy, Arc detection, Arc elimination.

I. INTRODUCTION

Although high power arc faults are rare incidents, their consequences are often catastrophic. Along with hazard to personnel, equipment damage and long system interruptions are common, causing substantial economic losses.

A number of options are available to limit risks related to arc faults. Some of the approaches emphasize arc prevention while others focus on technologies for arc mitigation. This paper gives both the big picture of the whole field and more detailed analysis of a few controversial technologies. The emphasized areas are arc prediction by on-line monitoring technologies, current-limiting vs. time-limiting arc mitigation options, and arc eliminators.

II. THE BIG PICTURE

This paper gives one holistic picture of arc-flash protection, from arc prevention to rapid arc elimination, emphasizing a few technologies. Figure 1 illustrates the big picture of this approach. The big picture can be divided into active and passive technologies, and proactive and reactive protection. Proactive protection can be defined as activities before the arc ignites, and reactive protection is based on fast detection of the arc.

By good design and maintenance, the risk of arcing faults can be reduced but not totally eliminated. Developments in sensor technologies and communication have enabled on-line monitoring systems that can be used for arc prediction. These systems can indicate some of the slowly developing faults.

However, there are faults that cannot be prevented or predicted. Therefore, reactive arc-flash protection, operating after arc ignition, is often considered justified.

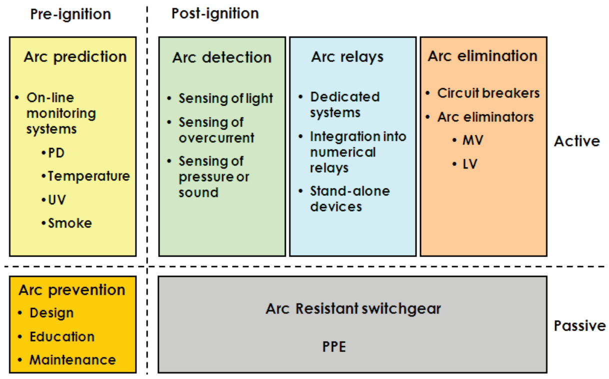

Fig. 1. The big picture of arc mitigation

III. ARC-FLASH PREVENTION

A. Education

Either direct or indirect human action is a very common cause of arc faults. Education of workers and designers, safety culture and rules regarding operation in environment with possible arc-flash hazard should be commonplace. This is justified not only by personnel safety reasons. In addition to direct damage and process interruption related costs, high medical or legal costs may be possible due to arc-flash accidents.

B. Design

Prevention of internal arcs in switchgear starts naturally in design. Requirements have been set in IEC and IEEE standards, such as [1], [2], [3], and [4]. The IEC standard [1] also lists examples of measures to decrease the probability of internal faults. Some additional design options are evaluated below.

C. High Resistance Earthing

High-resistance earthing (grounding) can be seen as arc-flash preventive technology, because it drastically reduces the dissipated energy, and likely prevents a sustained arcing fault in LV systems. This is why proponents of this technology have proposed that it should become a standard of the industry. [5]

However, high-resistance grounding is only effective in ground faults and requires that the first ground fault can be cleared before the second ground fault causes phase-to-phase fault [6]. Although majority of arcing faults start as phase-to-ground faults, other protection means are necessary when HRG is applied. Additionally, high-resistance neutral grounding seems to have very limited window of application on MV systems for several reasons as explained in [7].

Kumpulainen, L., Hussain, G.A., Rival, M. (2012). “The Big Picture of Arc-Flash Protection”. Proceedings of IEEE PCIC Europe Conference, Prague, 19–21 June 2012, pp. 1–8. Copyright © 2012, PCIC Europe. Reprinted with permission.

D. Insulated vs. Bare Buses

Insulated bus appears to be superior to bare bus, but there are different opinions. First, it is obvious that insulation provides means to reduce the probability of arcing faults caused e.g. by falling objects or by vermin. Another advantage is that insulation prevents single-phase from escalating to high power multi-phase faults [8].

The third possible advantage is that the arc may travel to insulated area and become self-extinguishing [9]. This is, however, controversial. In tests reported in [10], the arc moved slowly and burned through the insulation, causing more damage. The insulation does not necessarily extinguish the arc.

It has also been noticed in switchgear tests that the movement of the arc, which is fast with bare bus, stops at the starting point of the insulation. Somewhat stable arc at the insulating barrier point causes melting and vaporization of metal, leading to more significant damage compared to moving arc. Figure 2 illustrates the impact of a stationary arc in the point where bus insulation starts. Although the duration of the arc in this test was only some tens of milliseconds, the arc melted some of the busbar metal.

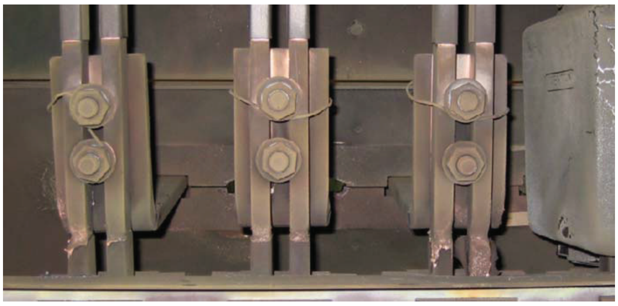

Fig. 2. Partial melting of LV busbar after short-time stationary arcing at the insulation barrier (U=726V, I_k=77kA, t_{arc}=65ms)

This observation is in line with the one made in [10]: if plasma is allowed to concentrate, the rate of damage will accelerate. Also according to low voltage testing reported in [11], an insulating barrier prevents arc motion, and produces higher arcing currents, higher incident energy. The barrier effect was increased at the higher test voltages.

E. Maintenance

Probability of arcing faults can be lowered by appropriate preventive maintenance of equipment. Preventive maintenance is effective in e.g. ageing, corrosion, pollution or vibration related faults. Instead of traditional time-based maintenance, condition-based is the current trend. Condition monitoring of equipment, often by on-line measurements and communication to upper level information systems, is a very interesting option to prevent arcing faults.

IV. ARC-FLASH PREDICTION TECHNOLOGIES

A. Arc-flash Prediction

Loose connections and degradation of insulation are common causes of arc faults. In these cases, it may be possible to analyze pre-arc conditions in order to find early signs of arc faults. This can be called arc fault prediction.

B. Arc Fault Indicating Phenomena [12]

1) Electromagnetic emissions (MV): Load current in loose connection can cause micro sparks and ionization of the air. Surface discharges and corona also can cause ionization. Random partial discharges may occur in insulations.

2) Acoustic (ultrasonic) emissions (MV): Partial discharges also cause mechanical vibrations to electrical equipment. An acoustic signal is emitted as a result of such vibration.

3) Optical emissions (MV): Optical ultraviolet (UV) signals are produced as a result of various ionization, excitation and recombination processes during partial discharges. Every material emits light of different wavelengths as a result of these phenomena. Intensity and wavelength of these optical signals largely depend on different factors such as insulation material, temperature, PD intensity and pressure.

4) High frequency current components (mostly MV, also LV): PD is basically a surge of electrons and hence a current pulse. These current pulses are superimposed on the normal load current. These pulses have very small rise time and high frequency. Normal current measuring devices such as CTs are not sensitive enough to record such high frequency pulses, but sensitive equipment can measure such current components.

5) Harmonic Current Components (MV and LV): Because current is practically always measured and analyzed for protection purposes, it would be very convenient to use normal phase current measurements for finding developing faults.

6) Thermal Emissions (IR emission and thermal ionization): In LV systems the heating phenomena are mainly caused by resistance of loose contacts, series arcing across loose contacts or terminations, ionization, excitation of atoms, and recombination of ions to form a molecule due to partial discharges.

In case of medium voltage switchgear heat is produced due to serial arcing and corona in addition to increased contact resistance. Heat produced due to these phenomena lie in the range of infrared spectrum of electromagnetic radiation.

7) Chemical Emissions (MV and LV): During the process of ionization a neutral item or molecule loses or gains electrons thereby acquiring a net charge. These ions combine with the ions of other atoms to produce a molecule which is called by product of PD. Most common by products of PD in the air insulated switchgears are ozone and nitrogen oxide. When they react with the moisture and water molecules, they form nitric acid [13]. Nitric acid is very dangerous for most of the dielectrics and insulators. It plays major role in the decomposition of the chemical structure of the insulating material.

C. Sensing of Pre-arc Conditions

Many sensor technologies can be applied for detecting the above mentioned pre-arc phenomena. In the following, a short summary and evaluation of the technologies is presented.

1) RF antenna: For on-line monitoring purposes PD detection in the higher frequency range (HF/VHF/UHF), antenna type sensors are widely used. Since there are many practical constraints for sensor installation, practical antenna design can differ depending on the application.

2) Coupling capacitor: Coupling capacitors are used to transfer PD energy from PD source to the measurement setup. Sometimes they are used as proximity sensors for current or voltage measurement. The main disadvantage is that the capacitors have to be designed in order to withstand 50/60 Hz rated voltages levels of the equipment, and they should be manufactured to have low inductance in order to have good high-frequency response. [14], [15], [16]

3) High frequency CT: The working principle of HFCT is the same as normal 50/60Hz current transformer. The magnetic field around a wire (e.g. ground connection or live wire) caused by the HF current induces a voltage in the winding of the HFCT. HFCT sensor is one of the most popular inductive sensors in condition monitoring technologies for all kind of applications on power system equipment due to its portable, cost effective, non-intruding characteristic and the independency of the frequency of the measured signal [17].

4) Rogowski coil: Figure 3 illustrates the operation principle of Rogowski coil. The air cored sensor is placed around the conductor, where current pulses caused by PD are to be measured. The changing current induces voltage in the coil. [18]

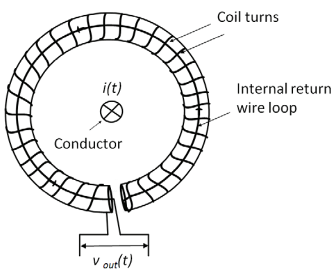

Fig. 3. Operation principle of Rogowski coil

5) Piezoelectric ultrasonic sensor: Piezoelectric sensors are directional sensors that can detect PD in air insulated switchgear. Internal discharges in insulation do produce ultrasound signals, but these will generally not be picked up when using an ultrasonic probe. The attenuation in the insulation, and poor coupling of the air/solid interfaces mean that acoustic signals which originate inside the insulation, are generally not accessible via ultrasonic methods. [19], [20]

6) Ultraviolet sensor: Ultraviolet sensors are sensitive to the ultraviolet light. PD phenomenon or arcing in the switchgear always emits light in this wavelength region.

7) Thermal sensors: High temperature is resulted from the PD and also because of increased resistance caused at the joints or terminations. There is a wide variety of thermal sensors. Some sensors work on the principle of resistance change of the material, whereas others work on electron emission due to heat. Such sensors are less sensitive. If these sensors are kept in contact with the insulation, they may melt themselves due to excessive heat produced by arcing. If they are kept at a larger distance, they may not sense the temperature accurately rather sense the room temperature only [21].

Measurement of all three contacts in the main busbar section by using only one sensor is not possible because orientation is too difficult [22]. It is hardly justified to install sensors in every possible fault location.

There are some sensors which can measure infrared radiations emitted due to heat. Conventionally, infrared thermal sensors and thermographs were widely used to locate the hot spot created due to loose contacts and partial discharge. Such IR thermal cameras are very expensive and not practical to implement for online condition monitoring.

There are infrared sensors available in the market, which are very small in size, accurate, and easy to install in the switchgear permanently for the online monitoring purpose. They are able to give voltage as an output signal [16].

Some manufacturers have implemented thermal ionization detectors which detect the presence of certain ions in the switchgear [21].

D. On-line Monitoring Systems

Traditionally, preventive maintenance has been carried out by using time-based inspection and portable devices, detecting e.g. partial discharges or thermal phenomena. However, technological development has enabled on-line monitoring systems.

On-line monitoring requires more than sensors and meter. In most cases, the sensors produce data that has to be processed. There has to be communication between the sensors and the local processing unit, and communication to the control room where the alarms are finally shown. So far these systems have not been widely implemented. Developments both in sensor technology, as well as progress of communication are paving the way for future condition based maintenance, including means to arc-flash prevention.

V. REACTIVE PROTECTION: CURRENT OR TIME BASED APPROACH

A. Why Reactive Protection is Needed

Preventive or predictive measures are not totally able to eliminate the risk of arc faults. Causes like direct human interaction or equipment malfunction may still lead to serious faults. This is the reason that reactive protection, i.e. reacting to phenomena detected after arc ignition, along with proactive measures, i.e. action based on pre-arc conditions, is in most cases justified.

B. Arc-flash Incident Energy

Incident energy is a concept defined in [23]. Its primary purpose is to provide means for evaluating needed safe working distances and personal protective equipment (PPE) for employees. However, incident energy calculations can also be used when estimating damage to equipment, and especially when different protection approaches are compared.

Incident energy of an arc-flash incident depends on voltage, distance, current and arcing time [23]. In practice, the key factors are arcing current and arcing time. Some protection approaches emphasize limitation of current while most solutions pursue short arcing time.

C. Arcing Current

Fault arc is a highly random phenomenon. During arcing e.g. the length of the arc varies and the arc resistance is not constant. However, this is not the only uncertainty related to estimation of arcing current. The magnitude of arcing current is often derived from bolted fault current, but the bolted fault current is not a constant either. Both the maximum and minimum values are needed for arc-flash studies [23]. The highest incident energy can be caused by the highest or lowest bolted and arcing fault current. This is because lower arcing fault current often leads to longer trip time [23], [24] [25].

According to [26] the initial symmetrical short-circuit current is calculated:

(1) $I_k'' = \frac{cU_n}{\sqrt{3}Z_k}$

where

c = voltage factor
Un = nominal system voltage (line-to-line)
Zk = short-circuit impedance

Figure 4 presents the system diagram and equivalent circuit diagram related to equation (1). It illustrates the importance of the impedance of the feeding network (consisting of R_{Qt} and X_{Qt}).

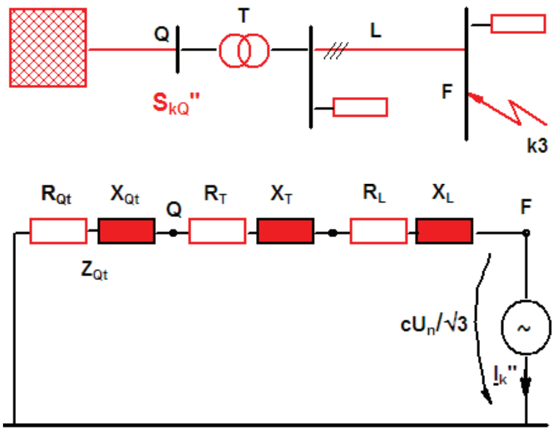

Fig. 4. System diagram and equivalent circuit diagram for calculating short-circuit current according to [26].

The impact of available fault current variations on arc-flash calculations has been studied in [24], [27] and [28]. The available fault current data from the utility is not always available. In calculations the utility network is assumed to be infinite bus, but this leads to incorrect estimation of minimum fault current. The source impedance can vary because of e.g. changes of network connection or connected generators. Often the connection of renewable energy sources leads to lower short-circuit power. While conventional synchronous generators are able to provide 5-10 times their nominal current, photovoltaic systems, based on power electronics, provide fault currents only close to their nominal current [24]. For example, in Denmark the high share of wind power has led to reduction of short-circuit power [29].

The available short-circuit power has major influence on short circuit current on MV level but minor impact on LV (<1000 V) level, because the impedance of MV/LV transformer is dominant.

D. Risks Related to Current-Limiting Approach

Limitation of arcing current leads to reduction of incident energy, provided that the arcing time will not be significantly affected. However, in spite of being widely reported, the fact that lower current can cause higher incident energy is probably not adequately understood.

For high-voltage, arcs the arcing current is practically the same as the bolted fault current, and it can be calculated according to e.g. IEC standard 60909 [30]. Especially, for applications under 1000 V, the arc fault current is lower than the bolted fault current [23]. According to [30], the current can typically fall to between 20-40 % of the prospective current, and [31] confirms that the arcing fault current can be as low as 33% of the calculated bolted fault current at any particular location per [32].

The fact that arcing current can be significantly lower than the prospected current sets challenges to protection. The protection must be able to detect the fault, and what is especially important in arcing fault incidents, it must be able to operate fast.

The impact of the reduction of arcing current should not be analyzed without examining the impact on operation time of the protection and thus arcing time and released energy. When inverse time overcurrent protection is applied the faults with high fault currents will be cleared much quicker than the low current faults. According to [28], the largest arc energy with the normal time graded protection is normally produced by the minimum arcing fault current. In the tests reported in [25] 361 out of 869 locations had incident energy calculations determined at the low range of the estimated current.

The behavior of current-limiting fuses depends on the current level. When the current is in the current-limiting range, CL fuses are very effective in reducing the incident energy level, the pressure wave and even the mechanical stress caused by the high fault current. When high current can be taken for granted, CL fuses are an excellent solution. However, CL fuses provide current-limiting action only in case of very high fault currents [33], [34]. The maximum arc energy may thus occur at current levels below the maximum interrupting rating [1]. This is also clearly illustrated in the test result figures of [23] regarding CL fuses.

Differences in arcing current magnitude can also be caused by various electrode configurations. In test reported by [25], significantly lower currents than predicted in [23] were measured. Because of higher clearing times of overcurrent protection, incident energy calculations greater than three times the standard [23] calculations were reached.

What is as alarming as higher incident energy levels caused by lower current is that according to [33], [10] and [35] the protection may not properly respond to these lower fault current values. Especially, arcing earth fault current may be difficult to detect.

In conclusion, current-limiting approach to mitigate the impact of arcing faults includes many uncertainties and risks related especially to the impact on arcing time.

E. Incident Energy Limiting by Reducing Arcing Time

Incident energy is directly proportional to arcing time. This is illustrated in Figure 5. Reduction of arcing time has become the dominant approach in arc-flash mitigation. Various technologies have been presented in e.g. [36].

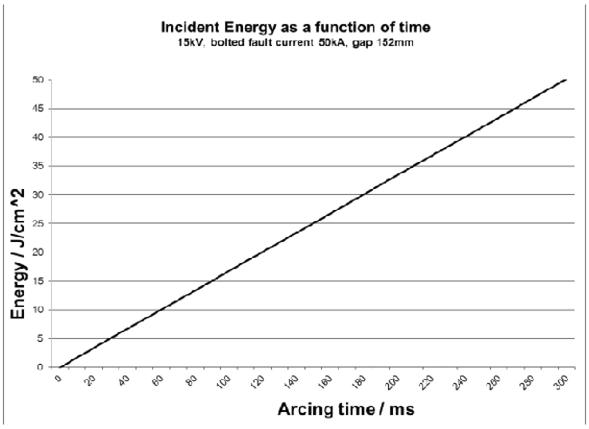

Fig. 5. Incident energy as a function of time.

Compared to traditional overcurrent protection, protection time in busbar faults can be improved by zone-selective interlocking. Traditional busbar differential protection provides better performance with ca. 1 cycle operation time. However, busbar differential is not effective if the fault occurs in cable compartment, typically in cable terminations, and in some countries busbar differential is considered as obsolete technology. A maintenance switch, activating instantaneous tripping when carrying out maintenance work, provides very fast tripping, but it is only intended for personnel protection.

F. Light and Overcurrent Based Protection

The rising technology to reduce arcing time is based on simultaneous detection of light and overcurrent. Together, these two conditions provide an extremely fast and very secure arc flash detection scheme [37]. One of the advantages of light detection is the lack of a requirement to coordinate with downstream devices and the ability to operate extremely fast (½ cycle or less) [37]. Still another benefit is that retrofit installation is fairly easy and widely applied. Because existing current transformers can be utilized, only light sensitive sensors, I/O units collecting the sensor data, and central unit of the arc-flash protection system have to be installed.

Although this technology has been applied for a long time, and there are thousands of installations, only recently it has gained wider acceptance by a number of manufacturers and end customers. In some countries light and overcurrent based protection is de facto standard solution. In some other technological cultures, arc-flash incident energy calculations are applied, and dual-sensing principle is recognized as an efficient option to lower incident energy levels.

State-of-the art arc-flash protection relays provide as fast as 1ms trip time, several protection zones for selective tripping, and versatile communication options. When applying this technology, the arcing time depends on practically solely on the operation time of the primary device responsible for arc elimination, i.e. normally the circuit breaker or in some cases the arc eliminator.

Figure 6 presents a comparison of incident energy levels of a MV system case, illustrating the impact of arcing time. Arcing time 67ms of the example corresponds in practice a system with light and overcurrent based protection tripping circuit breaker, and the 5ms case illustrates the efficiency of protection system enhancement by an arc eliminator.

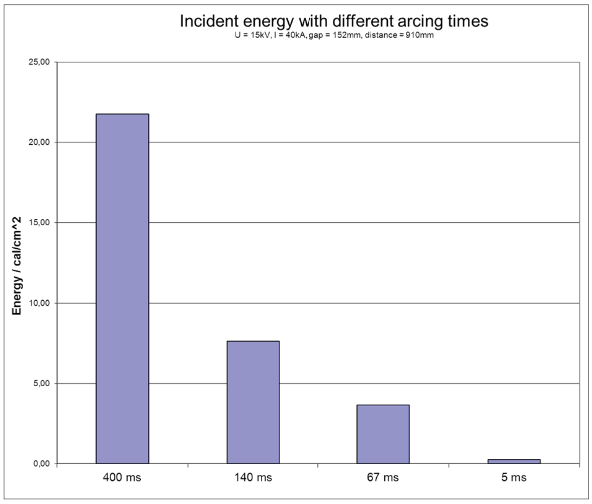

Fig. 6. Comparison of incident energy levels with different arcing times

Figure 7 presents a complete arc-flash protection scheme of an MV switchgear. Selective protection can be achieved, so that for example, in cable termination faults, only the breaker of the outgoing feeder will trip.

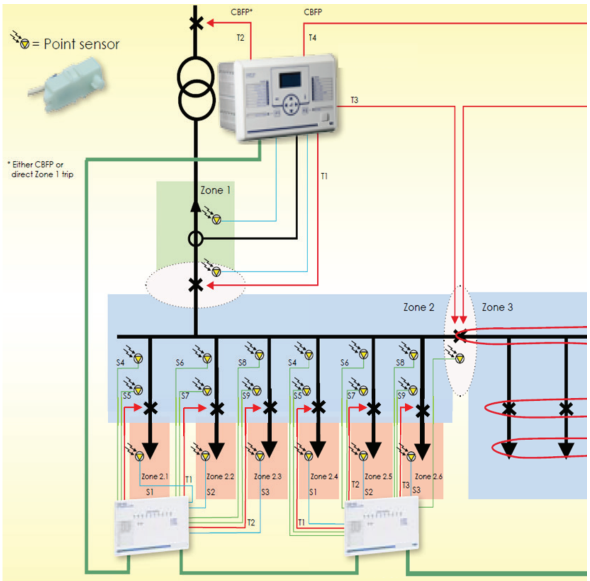

Fig. 7. Example of selective arc-flash protection scheme of MV switchgear

Operation of light and overcurrent based arc-flash protection systems can be tested by using a current injection device (current condition) and powerful light source, e.g. external camera flash (light condition). Although most manufacturers provide systems with full self-supervision, maintenance testing with a few years interval is recommended.

VI. ARC-FLASH ELIMINATION

A. Elimination Technologies

There are three basic technologies for arc elimination: fuses, circuit breakers, and arc eliminators. Current-limiting fuses have been discussed above. The following focuses on CB and arc eliminator technology.

B. Circuit Breakers

For light and overcurrent based protection, the relay trip time is typically less than half cycle. When semiconductor output is used instead of relay output, as short as 1ms trip time is possible. Because operation time of CB's are some tens of milliseconds, it is clear that the arcing time depends practically only on CB time.

There are two good questions concerning CB's:

- What is the actual operation time, i.e. should a few cycles be added to the value given by the manufacturer?
- What if the CB fails?

According to [32] CB operation time is the maximum time, and many breakers actually trip faster than do their publicized curves. This is perfectly in line with experience gained in switchgear arc fault testing. Conservative value for total arcing time is thus the sum of relay time and CB time, the latter being the by far dominant part. This aspect should be taken into consideration when selecting CB's.

CB is the component that finally breaks the current. Thus is it most important to ensure that the CB's are in working order, whatever the arc-flash mitigation strategy is. Because no device can be 100% reliable, circuit breaker failure protection (CBFP), tripping the upstream breaker, should be applied.

C. Arc Eliminators

Arc eliminator is a device that eliminates arc extremely fast by creating an intentional parallel short circuit. The technology is also called crowbar technology, arc quenching or high speed earthing. So far arc eliminators have not been widely applied, although the technology is listed as an option to provide highest possible level of protection already in an IEC standard [1]. One of the most interesting application areas is retrofit installation in switchgear that is not arc resistant. A very significant improvement of both safety related and equipment damage related hazards could be achieved, because arc eliminator also mitigates the pressure impact along with the mitigation of the thermal impact.

The operation principle of an arc eliminator is simple: when an arc flash fault is detected, the device will create an intentional high speed short circuit in the system so that the voltage collapses and the arc is extinguished. Various manufacturers have different technologies in the methods related to the creation of the short circuit, e.g. pyrotechnical pressure element, Thomson coil, micro gas cartridges, or a spring mechanism assisted by an electromagnetic repulsion system.

Arc eliminators are used along with light and overcurrent based arc-flash detection. The arc detection system is able to trip the eliminator within 1-2ms, and the high speed primary circuit device operates within a few milliseconds. Fast communication between the arc-flash protection relay and the short-circuit device is necessary. A typical arcing time is less than 5ms. Along with tripping the short-circuit device, the arc-flash relay sends a tripping command to the normal circuit breaker, and the circuit breaker eliminates the short-circuit current within a few cycles.

Because the arcing time is minimal, hazard and damage caused by arc fault are almost nonexistent. Figure 8 shows an example of a clean LV compartment after an arc fault test with an arc eliminator. Of course, a power system interruption is caused when an arc eliminator operates. Otherwise, it might be difficult to justify investments both in arc prediction and arc elimination technologies.

Fig. 8. Clean compartment after an arc fault test with an arc eliminator

Short-circuit devices have been opposed to be applied because of the concern on the high current they cause. The concern seems to be exaggerated. Like stated above, in MV systems the arcing current is almost equal to bolted fault current. Thus, the creation of intentional, symmetrical short-circuit does not significantly increase the current. In LV systems, there are options to reduce the level of the current by for instance, using a combination of an arc quencher and CL fuses or by small additional resistance in the circuit that will lower the stress caused to power system components.

When estimating the risks caused by the high current, two additional issues should be kept in mind. Transformer failures caused by short-circuit events are relatively rare events, and according to IEEE and IEC standards, transformers shall be designed to withstand the electromagnetic forces and the thermal stresses produced during the flow of a short-circuit current [38].

Additionally, because it is also very difficult to find any evidence or experience of real cases where arc eliminators had caused damage to equipment, the risk level related to high current caused by arc eliminators can be estimated acceptable.

VII. CONCLUSIONS

This paper has outlined a big picture of arc-flash mitigation. Developments in sensors and on-line monitoring techniques enable prediction of developing arc faults. Several arc fault indicating phenomena and sensors technologies have been examined.

Because many faults cannot be foreseen, reactive protection is often considered as a necessity, as electronic stability control systems or intelligent warning and braking systems hardly will replace safety belts and airbags. The risks related to current limiting arc-flash mitigation approach have been presented. The efficiency of new implementations of light and overcurrent based protection concept has been shown.

However, the estimation of the risk level and justification of prevention or protection system is a business decision. If can be predicted that the development of safety requirements in switchgear along with economic evaluations are going to lead into increasing application of dedicated, fast arc-flash protection systems. In some countries light and current based protection is already a de facto standard.

Arc eliminators give maximal protection, leading to minimal damage. Concern on the impacts of the high current due to short-circuit devices has been discussed, and the risk level is estimated acceptable.

VIII. ACKNOWLEDGEMENTS

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Review

Aspects of arc-flash protection and prediction

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ABSTRACT

This paper provides a technological review of arc-flash protection of air insulated switchgear. It covers the whole range starting from switchgear design aspects until ultra-fast arc elimination. Special attention is paid to proactive technologies enabling preemptive detection of slowly developing faults. Various arc faults indicating phenomena are examined, and several sensor technologies for online monitoring are evaluated. Because preventive or predictive measures cannot totally eliminate the risk of arc faults, reactive protection by fast operating protection is justified. Two major reactive protection approaches are discussed: the current-limiting approach and the arcing time based approach. The benefits of protection based on simultaneous detection of light and overcurrent are explained. Finally the paper discusses arc elimination technologies and evaluates the concerns related to short-circuit devices.

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Contents

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1. Introduction

Internal high power arc fault in switchgear is a reasonably rare incident, but can have very serious consequences unless the arc is rapidly extinguished. An arc fault causes hazardous impacts: thermal impact, pressure wave, flying particles, electrical and toxic impact. In addition to the hazard to personnel, substantial economic losses due to equipment damage and long system interruptions are common consequences.

There are a number of options to limit the risks related to arc faults. Some of the approaches emphasize arc prevention while others focus on technologies for arc mitigation. This paper gives an extensive overview of the whole field. Emerging technologies in arc fault prevention and very fast reacting protection systems are discussed more in detail.

2. A holistic view of existing arc-flash protection technology

Various approaches aiming at prevention or mitigation of arc flash incidents have been presented. There are significant differences in the methodology, based on traditions and cultural difference. Standardization is only partially a reason for different practices. For example in Europe, in spite of the influence of IEC standards, there is no universal practice to deal with arc flash issues.

Arc-flash protection methods can be categorized into many ways. Examples of categorization are division into passive and active methods, and division into proactive and reactive methods. Passive methods do not have any active component. Active methods include measurements and either reactive response (after arc-flash has been detected) or proactive response (pre-arc action when indication of a developing fault has been detected).

Approaches aiming at prevention of arc-flash, like design of switchgear, education of personnel, and maintenance practices, can be categorized into pre-ignition methods and passive methods. Fig. 1 presents the categorization and a holistic view of arc-flash protection.

In the following sections, the elements of the holistic view are examined in more detail. Special attention is paid to emerging technologies of arc prediction, i.e. online monitoring in order to detect developing fault before they escalate into high power arc faults.

However, there are faults which cannot be predicted by online monitoring, e.g. faults caused by direct human interaction or by animals, or faults caused by incorrect operation of switching devices. Therefore, reactive arc-flash protection, operating after arc ignition, is often considered justified. Along with online monitoring technologies, efficient arc mitigation technologies are reported in detail.

3. Arc-flash prevention

3.1. Education

Either direct or indirect human action is a common cause of arc faults. Education of workers, safety culture and rules regarding operation in an environment with possible arc-flash hazard should be commonplace. Incident energy calculations and arc labeling of switchgear are a good example of safety culture.

Education of personnel is justified for safety and economic reasons. Arcing faults cause direct damage costs and costs due to process interruption, and when humans are involved, high medical or legal costs are possible.

3.2. Design

Prevention of internal arcs in switchgear starts naturally in design. Requirements have been set in IEC and IEEE standards [1–4]. The IEC standard [1] presents a list of locations where internal arc faults are most likely to occur in metal-enclosed switchgear and controlgear:

- Connection compartments
- Disconnectors, switches, grounding switches
- Bolted connections and contacts
- Instrument transformers
- Circuit breakers

The standard also lists possible causes of internal arc faults and examples of measures to decrease the probability of faults. These measures include both technical solutions and personnel related recommendations. Some additional design options are evaluated below.

3.3. High resistance grounding

High resistance grounding, limiting phase-to-ground fault currents, can be seen as an arc-flash preventive technique. It reduces drastically the dissipated energy, and sustained arcing faults in low voltage (LV) systems. This is why proponents of this system have proposed that it should become a standard of the industry [5].

However, high-resistance grounding is only effective in ground faults and requires that the first ground fault can be cleared before the second ground fault causes phase-to-phase fault [6]. Although majority of arc faults start as phase-to-ground faults, other protection means are necessary when high resistance grounding is applied. Additionally, high-resistance neutral grounding seems to have very limited window of application on medium voltage (MV) systems for several reasons explained in [7].

3.4. Insulated vs. bare busbar

Insulated bus appears to be superior to bare bus, but there are different opinions. First, it is obvious that insulation provides means to reduce the probability of arc faults caused e.g. by falling objects or by vermin. Another advantage is that insulation prevents single-phase faults from escalating to high power multi-phase faults [8].

The third possible advantage is that the arc may travel to insulated area and become self-extinguishing [9]. This is, however, controversial. In tests and real arc faults reported in [10], the arc

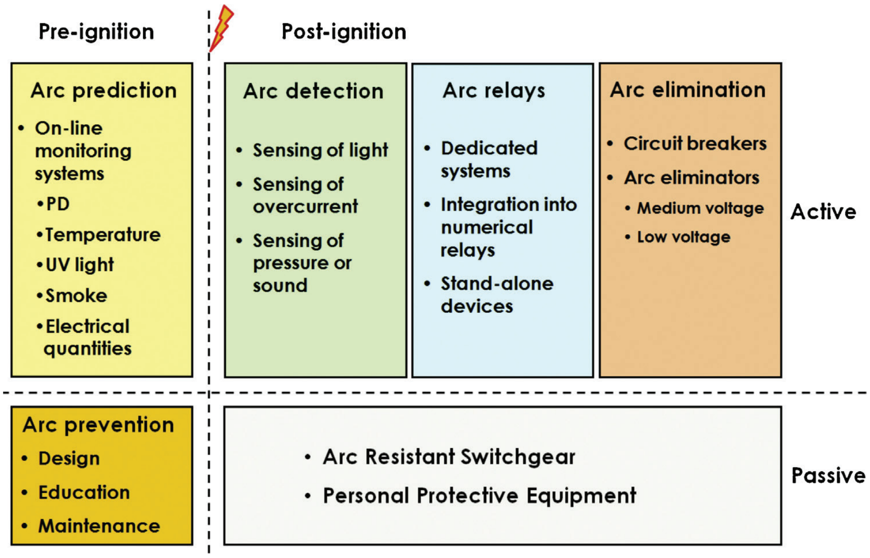

Fig. 1. The categorization and the holistic view of arc-flash protection.

moved slowly and burned through the insulation, causing more damage. The insulation does not necessarily extinguish the arc.

It has also been noticed in partially insulated switchgear tests that the movement of the arc, which is fast with bare bus, stops at the starting point of the insulation. Somewhat stable arc at the insulating barrier point causes melting and vaporization of metal, leading to more significant damage compared to moving arc.

Fig. 2 illustrates the impact of a stationary arc in the point where bus insulation starts. The figure presents LV busbars after an arc-flash test with fast protection. It must be noted that in this case the buses are only partially insulated. The insulation does not cover the joint area. Although the duration of the arc in this test was only some tens of milliseconds, the arc melted some of the busbar metal at the insulating barrier point.

This observation is in line with the one made in [10]: if plasma is allowed to concentrate, the rate of damage will accelerate. Also according to low voltage testing reported in [11], an insulating barrier prevents arc motion, and produces higher arcing currents and higher incident energy. The barrier effect was increased at the higher test voltages.

3.5. Maintenance

The probability of arc faults can be lowered by appropriate preventive maintenance of equipment. Visual inspection, thermal imaging, partial discharge testing, and time-based testing of protection devices are examples of preventive maintenance actions. Preventive maintenance is effective against aging, corrosion, pollution or vibration related faults. Condition monitoring of equipment, often by on-line measurements and communication to upper level information systems, is a very interesting option to prevent arc faults.

4. Proactive protection: arc-flash prediction technologies

4.1. Arc-flash prediction

Loose connections and degradation of insulation are common causes of arc faults. These fault types develop gradually, and it may be possible to analyze pre-arc conditions and find early signs of developing faults. This can be called arc fault prediction. Existing technologies enable on-line monitoring of electrical apparatus. A combination of different monitored physical phenomena adds reliability to detection of developing faults [12].

In the following, first an overview is given of potential arc fault prediction methods which are based on common current and voltage measurements, then other phenomena and sensor technologies are discussed.

4.2. Detection of developing faults by analysis of phase currents

Since current is practically always measured and analyzed anyway for protection purposes, it would be very convenient to use normal phase current measurements to find developing faults. Low current arcs, preceding actual high current and high power arcs in low voltage systems (e.g. in loose connections), have been studied.

In [13], the harmonic spectrum of the phase currents in a low voltage system was analyzed. The focus was on 3rd, 5th and 7th harmonic. The paper concludes that it is generally possible to design an operable preventive protection.

Low voltage systems and harmonics were also discussed in [14]. The paper examines the characteristics of low current arc faults which can precede high power arc faults. A detailed harmonic analysis is presented for higher frequencies and the frequencies in between the harmonics. In lower harmonics area the third harmonics could be an indicator of lower power arc faults. In higher frequency area up to 2 kHz, the broadband signal of the arc can be a strong indicator. In the range of 2–5 kHz, the re-ignition of the parallel arc causes slight elevation in the current spectrum. However, because some loads generate harmonics and increased higher frequency components, this detection method cannot be the only recognition criterion of developing arc faults.

4.3. Detection based on zero sequence voltage or current differential

In MV systems with ungrounded or compensated neutral, changes in zero sequence voltage can give an indication of a developing ground fault. This indication is commonly used by electric utilities in some countries for early detection of high-resistance ground faults. However, for detection of developing

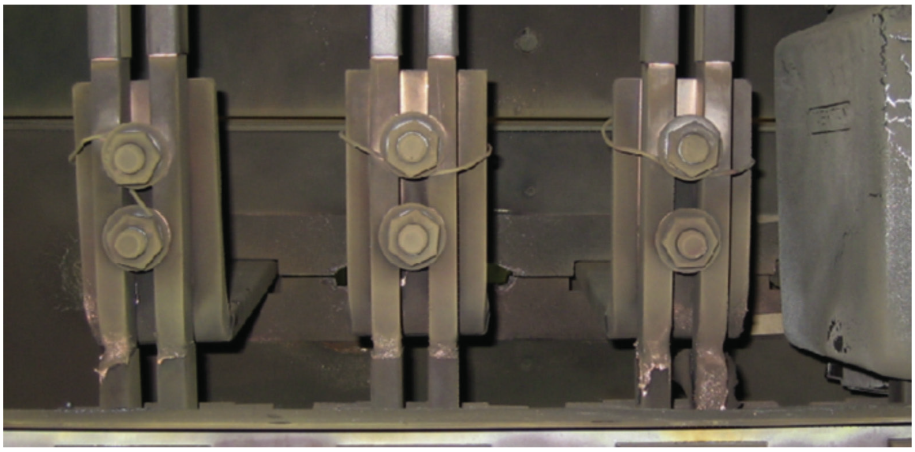

Fig. 2. Partial melting of LV busbar after short-time stationary arcing at the insulation barrier. (U = 726 V, I_k = 77 kA, t_{arc} = 65 ms.)

faults in switchgear, monitoring of zero-sequence voltage should be used in combination with other indication methods because it does not reveal the location of the fault.

Cable termination is a typical location of arc faults. Principle of current differential protection may be applied for detection of developing faults in cable terminations [15]. In practice this means comparison of the sum of individual phase current measurements and the measurement of the core balance current transformer. Fig. 3 illustrates this principle.

4.4. Other phenomena indicating developing arc fault

In addition to commonly measured electrical quantities, there are various physical quantities that can potentially indicate an arc development. The utilization of these phenomena often requires sensor installations in the switchgear. Potential physical phenomena have been listed and shortly described below, along with their detection methods. Detailed evaluation of them has been reported in [16,17].

(1) *Electromagnetic emissions*: Load current in loose connection can cause micro sparks and ionization of the air. Partial discharges (PD) and corona also cause ionization. Ref. [18] gives an extensive review of PD measurement techniques in gas-insulated switchgear while this paper focuses on air insulated switchgear.

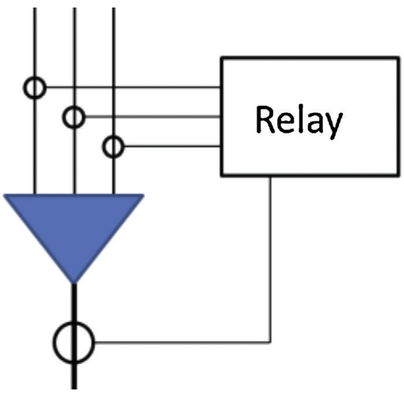

Fig. 3. I_{diff} monitoring of cable termination.

(2) *Acoustic (ultrasonic) emissions*: PDs also cause mechanical vibrations in electrical equipment. An acoustic signal in ultrasonic range of spectrum is emitted as a result of such vibration.
(3) *Optical emissions*: Optical ultraviolet (UV) signals are produced as a result of various ionization, excitation and recombination processes during PDs. Every material emits light of different wavelengths as a result of these phenomena.
(4) *High frequency current components*: PD is basically a surge of electrons and hence a current pulse. These current pulses are superimposed on the normal load current. These pulses have very small rise time and high frequency.
(5) *Thermal emissions (infrared emission and thermal ionization)*: The heating phenomena are mainly caused by increased resistance of loose contacts, series arcing across bad contacts or terminations. Ionization, excitation of atoms, and recombination of ions due to PDs also cause thermal emissions. Heat produced due to these phenomena lie in the range of infrared spectrum of electromagnetic radiation.
(6) *Chemical emissions*: During the process of ionization a neutral item or molecule loses or gains electrons thereby acquiring a net charge. These ions combine with the ions of other atoms to produce a molecule which is called by-product of PD. Most common by-products of PD's in the air insulated switchgears are ozone and nitrogen oxide. When they react with the moisture and water molecules, they form nitric acid [19]. Nitric acid is corrosive in nature and may cause severe damage to the contacts as well as dielectrics and insulators. It plays a major role in the decomposition of the chemical structure of the insulating material.

4.5. Sensor technologies

Many sensor technologies can be applied for detecting the above mentioned pre-arc phenomena. A short summary and evaluation of the technologies is presented in the following.

(1) *RF antenna*: Antenna type sensors are widely used for PD detection in the higher frequency range (HF/VHF/UHF).
(2) *Coupling capacitor*: Coupling capacitors are used to transfer partial discharge energy from electrical network to the measurement setup. Sometimes they are used as proximity sensors for current or voltage measurement. The main disadvantage is that the capacitors have to be designed in order to withstand 50/60 Hz rated voltage level of the equipment, and should be

manufactured to have low inductance in order to have good high-frequency response [20,21].

(3) *High frequency current transformer (HFCT)*: The working principle of HFCT is the same as normal 50/60 Hz current transformer. Partial discharges induce a current proportional to the current of the discharge. HFCT sensor is one of the most popular inductive sensors in condition monitoring technologies for most kind of applications in power systems due to its portability, cost effectiveness, and non-intruding characteristics [22].

(4) *Rogowski coil*: The air cored sensor is placed around the conductor, where current pulses caused by partial discharge are to be measured. The changing current induces voltage in the coil. Rogowski coils can be designed for the desired frequency. They are immune to external interferences [23].

(5) *Piezoelectric ultrasonic sensor*: Piezoelectric sensors are directional sensors that can detect PD in air insulated switchgear. Internal discharges in insulation do produce ultrasound signals, but the signal may get attenuated through the insulation and through air. Thus piezoelectric sensors are not optimal for internal PD detection due to lower sensitivity and directionality [24,25].

(6) *Ultraviolet sensor*: Ultraviolet sensors are sensitive to ultraviolet light, emitted by PDs in insulation material or arcing across loose contacts. Mal-operation is possible due to the availability of other light sources, if this technique is implemented alone.

(7) *Thermal sensors*: There is a wide variety of thermal sensors. Some sensors work on the principle of resistance change of the material, whereas others work on electron emission due to heat. Such sensors are less sensitive. If these sensors are kept in contact with the insulation, they may melt themselves due to excessive heat produced by arcing. If they are kept at a larger distance, they may not sense the temperature of the hot spot accurately, but rather sense the temperature of the surrounding air only [26].

There are some sensors which can measure infrared radiations emitted due to heat. Conventionally, infrared thermal sensors and thermographs were widely used to locate the hot spot created due to loose contacts and partial discharges. Such IR thermal cameras are very expensive and not practical to implement for online condition monitoring. In the market there are infrared sensors which are very small in size, accurate, and easy to install in the switchgear permanently for the online monitoring purpose [21]. Some manufacturers have implemented thermal ionization detectors which detect the presence of certain ions produced by thermal effects in the switchgear [26].

Table 1 presents a summary of the phenomena, sensor types, and applicable switchgear type.

Table 1
Summary of sensor technologies.

Phenomenon	Sensors	Switchgear type
Electromagnetic emissions	RF antenna	MV
Acoustic (ultrasonic) emissions	Piezoelectric probe	MV
Ultraviolet emissions	Optical sensors	MV
High frequency PD pulses	HFCT, RC, CC	MV
Thermal emissions	Thermocouples, IR sensors, TID	MV, LV
Chemical emissions	Analyzers	MV, LV
Fast variation in electric field	Differential electric field sensor	MV

5. Reactive protection

5.1. Why reactive protection is needed

Preventive or predictive measures are not able to eliminate the risk of all arc faults. Causes like direct human interaction or equipment malfunction may still lead to serious faults. This is the reason why reactive protection, i.e. reacting to phenomena detected after arc ignition, is always justified. However, traditional overcurrent protection is fairly inefficient in arc-flash faults because it is too slow and leads to long arcing time and high released energy.

5.2. Arc-flash incident energy

Incident energy is a concept defined in [27]. Its primary purpose is to provide means for evaluating needed safe working distances and personal protective equipment (PPE) for employees. However, incident energy calculations can also be used when estimating potential damage to equipment, and especially when different protection approaches are compared.

Incident energy of an arc-flash incident depends on voltage, distance, current and arcing time [27]. In practice, the key factors are arcing current and arcing time. Some protection approaches emphasize limitation of current while most solutions aim at short arcing time.

5.3. Arcing current

Fault arc is a highly random phenomenon. During arcing the length of the arc varies and the arc resistance is not constant. However, this is not the only uncertainty related to the estimation of arcing current. The magnitude of arcing current is often derived from bolted fault current, but the bolted fault current is not a constant either. Both the maximum and minimum values are needed for arc-flash studies [27]. The highest incident energy can be caused by the highest or lowest bolted and arcing fault current. This is because lower arcing fault current often leads to longer trip time [27–29].

According to [30] the initial symmetrical short-circuit current is calculated:

$$I''_k = \frac{cU_n}{\sqrt{3}Z_k} \quad (1)$$

where c = voltage factor (0.95, 1.00, 1.05 or 1.10); U_n = nominal system voltage (line-to-line); Z_k = short-circuit impedance

Fig. 4 presents the system diagram and the equivalent circuit diagram related to Eq. (1). It illustrates the importance of the impedance of the feeding network (consisting of R_{Qt} and $\underline{X}_{Qt}$).

The impact of available fault current variations on arc-flash calculations has been studied in [28,31,32]. The available fault current data from the utility is not always available. In calculations the utility network is assumed to be infinite bus, but this leads to incorrect estimation of minimum fault current. The source impedance can vary because of changes of network connection or connected generators. Often the connection of renewable energy sources leads to lower short-circuit power. While conventional synchronous generators are able to provide 5–10 times their nominal current, photovoltaic systems, based on power electronics, provide fault currents only close to their nominal current [28]. For example, in Denmark the high share of wind power has led to reduction of short-circuit power [33].

The available short-circuit power from the utility has major influence on short circuit current on MV level but minor impact on LV (<1000 V) level because of the high impedance of MV/LV transformers. The impedances of the MV/LV transformer and the LV conductors are very dominating in the circuit. Often infinite source

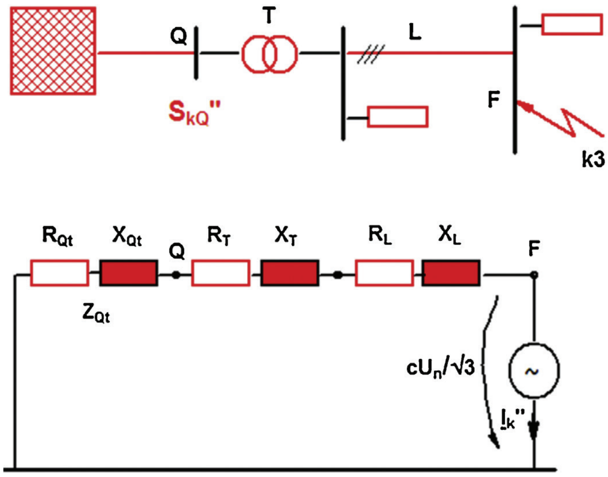

Fig. 4. System diagram and equivalent circuit diagram for calculating short-circuit current according to [26].

impedance on the transformer primary has been applied in short-circuit current calculations, but this does not guarantee the most conservative incident energy calculations [31].

5.4. Current-limiting approach in arc-flash protection

Limitation of arcing current leads to reduction of incident energy, provided that the arcing time is not significantly affected. However, in spite of being widely reported, the fact that lower current can cause higher incident energy is probably not adequately understood.

The fault arc always has some impedance, and the arcing current is lower than in a fault without fault impedance (bolted fault). For high-voltage arcs, the impedance of the arc is very low, and the arcing current is practically the same as the bolted fault current, and it can be calculated according to e.g. IEC standard 60909 [34]. Especially for applications under 1000 V, the impedance of the arc is often significant, and the arc fault current is lower than the bolted fault current [27]. According to [35], the arc fault current can typically fall between 20% and 40% of the prospective or bolted fault current, and [34] confirms that the arc fault current can be as low as 33% of the calculated bolted fault current at any particular location per [36].

The fact that arcing current can be significantly lower than the prospected current sets challenges to protection. The protection must be able to detect the fault, and what is especially important in arc fault incidents, is that it must be able to operate very fast.

The impact of the reduction of arcing current should not be analyzed without examining the impact on operation time of the protection, the arcing time and the released energy. When inverse time overcurrent protection is applied the faults with high fault currents will be cleared much quicker than the low current faults. According to [32], the largest arc energy with the normal time graded protection is normally produced by the minimum arcing fault current. In the tests reported in [29] 361 out of 869 locations had incident energy calculations determined at the low range of the estimated current. The behavior of current-limiting (CL) fuses depends on the current level. When the current is in the current-limiting range, CL fuses are very effective in reducing the incident energy level, the pressure wave and even the mechanical stress caused by the high fault current. When high current can be taken for granted, CL fuses are an excellent solution. However, current limiting fuses provide current-limiting action only in case of very high fault currents [37,38]. When used in combination with switching devices the maximum arc energy may occur at current levels below the maximum interrupting rating [1]. The risk of higher

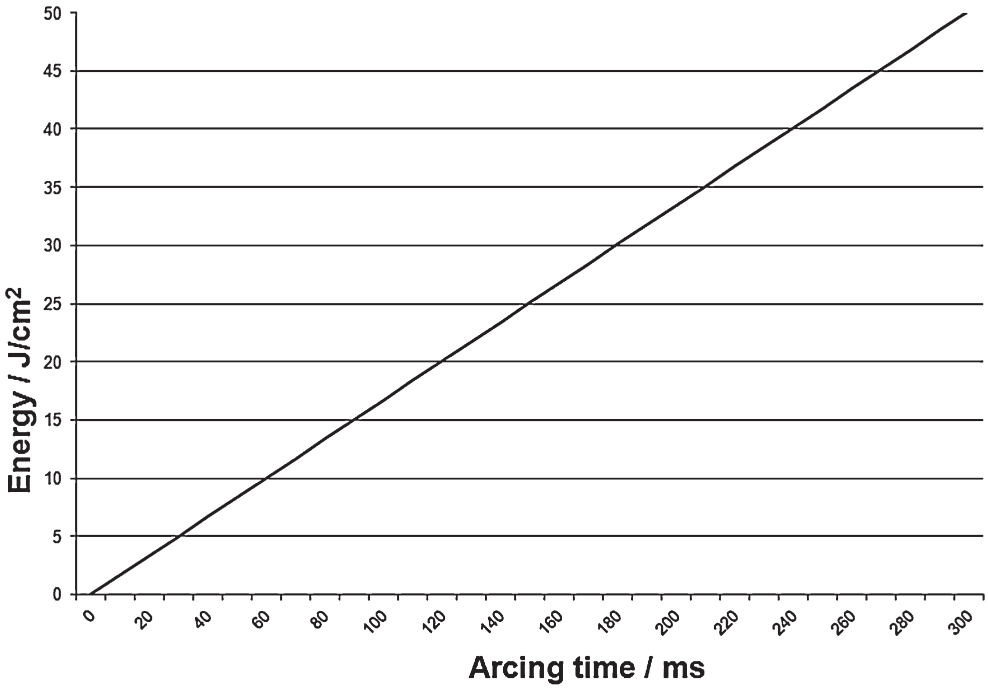

Fig. 5. Incident energy as a function of time (according to [24]; U = 15 kV, I_k = 50 kA, gap 152 mm, working distance 910 mm).

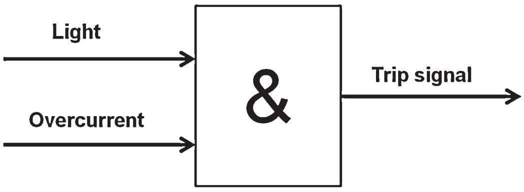

Fig. 6. The basic principle of light and overcurrent based arc-flash protection.

incident energy level because of lower current is also clearly illustrated in the test result figures of [27] regarding CL fuses.

Differences in arcing current magnitude can also be caused by various electrode configurations. In tests reported in [29], significantly lower arc currents than predicted by the equations in [27] were measured. Because of higher clearing times of overcurrent protection, incident energy calculations can be greater than three times the standard calculations [29].

Another significant risk caused by low fault current is that the protection may not properly respond or even trip at all [37,39]. Calculation of minimum fault current is essential.

In conclusion, current-limiting approach to mitigate the impact of arc faults includes many uncertainties and risks related to the arcing time and incident energy.

5.5. *Limitation of incident energy by reducing arcing time*

Incident energy is directly proportional to the arcing time. This is illustrated in Fig. 5. Reduction of arcing time has become the dominant approach in arc-flash mitigation. Various technologies have been presented in [40].

Compared to traditional overcurrent protection, protection time in busbar faults can be improved by zone-selective interlocking. Traditional busbar differential protection provides better performance with approximate 1 cycle operation time. However, busbar differential is not effective if the fault occurs in cable compartment, typically in cable terminations. In some countries busbar differential protection is considered as obsolete technology for arc-flash protection.

A maintenance switch, activating instantaneous tripping when maintenance work is carried out, provides very fast tripping, but it is primarily intended for personnel protection only.

5.6. *Light and overcurrent based protection*

The rising technology to reduce arcing time is based on simultaneous detection of light and overcurrent. Together, these two conditions provide an extremely fast and very secure arc flash detection scheme [41]. Along with detection of phase overcurrent, zero-sequence overcurrent detection can be applied for phase-to-ground faults. Fig. 6 illustrates the basic operation principle of light and overcurrent based protection.

The light of the fault arc is detected by sensors sensitive to light. Both point type of sensors and loop type of fiber sensors are commonly applied. Point sensors monitor a restricted area, e.g. cable termination compartment, and they are able to indicate the fault location rather accurately enabling selective protection. Fiber optic sensors typically monitor larger areas, such as the whole busbar area or several circuit breaker compartments [42].

The sensitivity level of the sensor is not a critical issue because the light intensity caused by an arc fault is normally very high compared to ambient light intensity, and because of the overcurrent condition. Practice has shown that the only situation where special attention has to be paid to the detection of light is the protection of the circuit breaker compartment of LV systems, if the CB emits

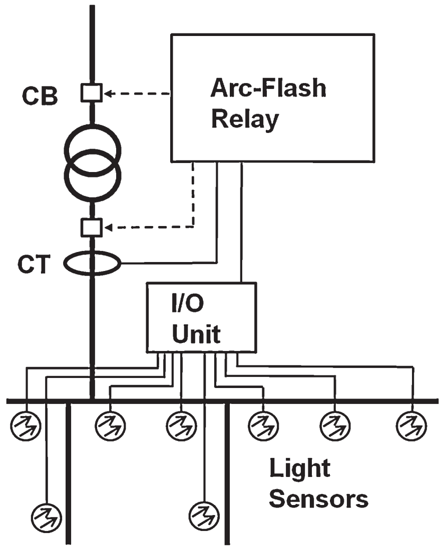

Fig. 7. An example of a light and overcurrent detection based arc-flash protection system.

light. Fig. 7 presents a scheme of a simple arc-flash protection system including current measurement, light sensors and the I/O unit for sensors, and the arc-flash relay.

One of the advantages of light detection is the lack of a requirement to coordinate with downstream devices and the ability to operate extremely fast (½ cycle or less) [41]. Another benefit is that retrofit installation is fairly easy when point type of sensors are applied.

Existing current transformers can be utilized in detection of overcurrent. Like the light from the fault arc, the overcurrent can be detected within 1 ms. Thus, the arc detection time using light and current based detection is approximately 1 ms.

Light and overcurrent based protection can be integrated into common numerical protection relays or it can be applied by using dedicated arc-flash protection relays. State-of-the art arc-flash relays provide very short trip time, several protection zones for selective tripping, and versatile communication options. When applying this technology, almost all the arcing time consists of the operation time of the primary device responsible for arc elimination, i.e. normally the circuit breaker or in some cases the arc eliminator. Arc eliminator is explained in Section 6.

Fig. 8 presents a comparison of incident energy levels of a MV system case, illustrating the impact of arcing time. Arcing time 67 ms of the example corresponds in practice to a system with light and overcurrent based protection tripping circuit breaker, and the 5 ms case illustrates the efficiency of protection system enhancement by an arc eliminator.

When applying current and light base arc-flash protection, selective protection can be achieved, especially with optical point sensors indicating the fault location. This means that e.g. in cable termination faults, only the breaker of the outgoing feeder will trip while the rest of the systems remains energized.

6. Fault arc elimination

6.1. *Elimination technologies*

There are three basic technologies for arc elimination: fuses, circuit breakers, and arc eliminators. CL fuses have been discussed

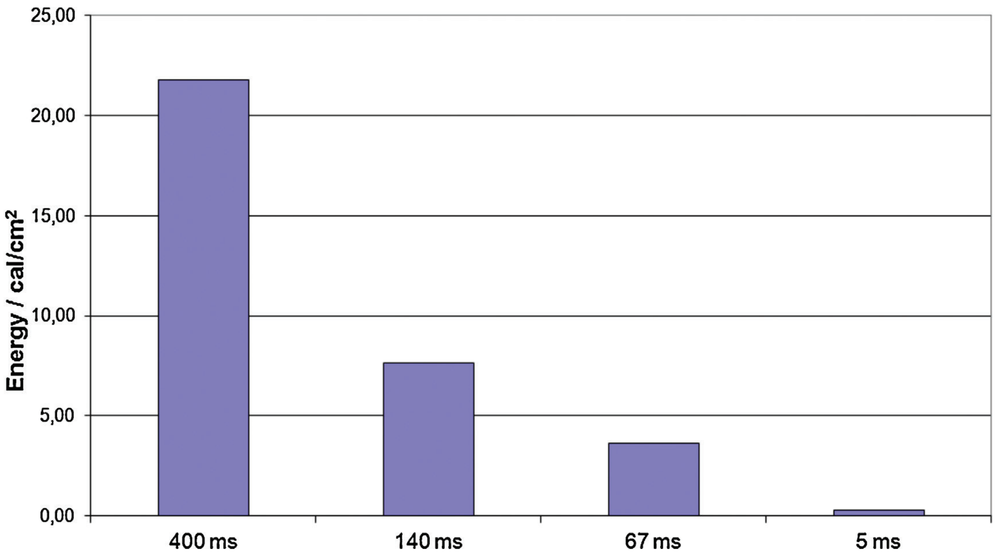

Fig. 8. Comparison of incident energy levels with different arcing times (according to [24]; U = 15 kV, I_k = 40 kA, gap = 152 mm, distance = 910 mm).

above. The focus of the following subsections is on CB and arc eliminator technology.

6.2. Circuit breakers

For light and overcurrent based protection, the relay trip time is typically less than half cycle. When semiconductor output (IGBT, Insulated Gate Bipolar Transistor output) is used instead of mechanical output relay, trip time can be as short as 1 ms. Since operation times of circuit breakers are some tens of milliseconds, it is clear that the arcing time depends practically on CB operation time only.

Good questions have been raised concerning CB's:

- What is the actual operation time, i.e. should a few cycles be added to the value given by the manufacturer?
- What if the CB fails?

According to [35], CB operation time is the maximum time, and many breakers actually trip faster than what is in the datasheets. This is perfectly in line with experience gained in switchgear arc fault testing. Conservative value for total arcing time is thus the sum of relay time and CB time, the latter being the dominant part. This aspect should be taken into consideration when selecting CB's.

CB is the component that finally breaks the current. Thus it is most important to ensure that the CB's are in working order. Since no device can be 100% reliable, circuit breaker failure protection (CBFP), tripping the upstream breaker, should be applied.

6.3. Arc eliminators

An arc eliminator is a device which eliminates an arc extremely fast by creating an intentional parallel short circuit. The technology is also called crowbar technology, arc quenching or high speed grounding. So far arc eliminators have not been widely applied, although the technology is listed as an option to provide highest possible level of protection in IEC standard [1]. One of the most interesting application areas is retrofit installation in switchgear which is not arc resistant. A very significant improvement of both personnel safety and mitigation of equipment damage can be achieved. In addition to minimization of incident energy, arc eliminator also mitigates the pressure impact. The effectiveness of arc eliminator technology against the pressure wave has been illustrated in [43,44].

The operation principle is simple: when an arc fault is detected, the device will create an intentional high speed short circuit in the system so that the voltage collapses and the arc is extinguished. Various manufacturers have different technologies in the methods related to the creation of the short circuit, e.g. pyrotechnical pressure element, Thomson coil, micro gas cartridges, or a spring mechanism assisted by an electromagnetic repulsion system.

Arc eliminators are used in combination with light and overcurrent based arc-flash detection. The arc detection system is able to trip the eliminator within 1–2 ms, and the high speed primary circuit device operates within a few milliseconds. Fast communication between the arc-flash protection relay and the short-circuit device is necessary. A typical arcing time is less than 5 ms. The arc-flash relay also sends a tripping command to the circuit breaker, and the CB eliminates the short-circuit current within a few cycles. Since the arcing time is minimal, hazard and damage caused by arc fault are almost nonexistent. Of course, a power system interruption is caused when an arc eliminator operates.

Short-circuit devices have been opposed because of the concern on the high current they cause. Of course high current can be detrimental to transformers, but the concern seems to be exaggerated. In MV systems the arcing current is almost equal to bolted fault current. Thus, the creation of an intentional, symmetrical short-circuit does not significantly increase the current. In LV systems, there are options to reduce the level of the current. A combination of an arc quencher and CL fuses can be used, or a small but current tolerant resistor can be added to the circuit in order to lower the stress to power system components.

When estimating the risks caused by the high current, two additional issues should be kept in mind. Transformer failures caused by short-circuit events are relatively rare, and according to IEEE and IEC standards, transformers shall be designed to withstand the electromagnetic forces and the thermal stresses produced during the flow of a short-circuit current [45].

Additionally, since it is very difficult to find any evidence or experience of real cases where arc eliminators had caused damage to equipment, the risk level related to high current caused by arc eliminators can be estimated acceptable [46].

7. IEC 61850 based communication in arc-flash protection systems

In arc-flash protection systems, the speed and reliability requirements for communication are very high, because every millisecond increases the released energy and leads to larger damage. Exchange of information is essential not only between the relays but also between the sensors detecting the arc and the relays, and between the relays and the circuit breakers. One example of a successful approach is minimization of the transmitted information and the use of high-speed serial protocol. Even selective protection is possible, when the transmitted bit includes the information on the activated sensor and thus the protection zone [47]. Communication delays are very low, enabling less than 2 ms total detection and trip time.

Ethernet based communication, in particular IEC 61850 [48] based technology, is widely applied in protection systems but in arc-flash protection systems it is so far rather rarely deployed. However, when carefully applied, adequate performance and reliability can be achieved along with the benefits this technology provides.

Generic Object Oriented Substation Event (GOOSE) messages over Ethernet are a standardized method for communication in protection applications. Zone-selective interlocking (ZSI, reverse interlocking) is a common application related to arc-flash protection where IEC 61850 and GOOSE have successfully been utilized [49]. GOOSE messaging reduces coordination time and simplifies relay protection coordination [50]. However, ZSI is slower than light and overcurrent based arc-flash protection [51].

In [52], GOOSE messages are limited to relay-to-relay communications in light and overcurrent based arc-flash protection system. GOOSE messaging can also be applied in the communication between other components of the arc-flash protection system: sensors, input/output units, relays, and circuit breakers.

In order to increase reliability and to avoid delays caused by network traffic, virtual local area networks (VLAN) for separated traffic can be established [50,53]. Another means to enable very fast communication is to utilize high speed fiber media for connection to devices [47,54]. It has been shown that the speed of GOOSE based communication is as good as in direct serial communication [53].

There are several important benefits of applying IEC 61850 standard based GOOSE messaging for arc-flash protection. It allows standard Ethernet components and longer distance between the components when fiber optic interface is applied. The standard based solution also is easier to monitor than manufacturer specific solution, and it enables multi-vendor systems. One of the major benefits is simplified and reduced wiring which also reduces costs [51].

8. Conclusions

This paper has given a holistic view of arc-flash mitigation technologies discussing both passive and active methods. Special attention has been paid to proactive on-line monitoring techniques that enable detection of slowly developing faults. So far these methods have not been widely applied. Since these techniques are not effective in all faults, reactive protection is justified.

Incident energy levels can be reduced significantly by reactive protection techniques having extremely short operation times or by limiting the fault current. Time-limiting approach has been preferred to current-limiting approach because the latter includes many uncertainties and risks related to arcing time and incident energy. In the future, arc-flash protection can be maximized by a combination of passive methods, proactive and reactive techniques, and enhanced by IEC 61850 based communication.

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High Speed Protection Concept to Minimize the Impacts of Arc-Flash Incidents in Electrical Systems of Ships

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***Abstract*—Arcing faults in switchgear are rare events but their consequences may be extremely severe. Personnel can be seriously affected by the heat, pressure, light, and noise associated with the arc flash. From equipment point of view, the direct damage to equipment is significant, but the indirect consequences such as power supply outage and interruptions of production can cause even higher costs. In a ship environment an arc-flash fault can lead to temporary or long term loss of critical control systems. This paper discusses the impacts of arcing faults, and presents options for mitigation, emphasizing the speed of protection. A new concept of closer integration of arc detection and circuit breaker is introduced. Because the pressure impact is especially important in marine vessels, arc elimination technology, enabling arc blast mitigation, is discussed.**

I. INTRODUCTION

An arc flash is the most devastating type of electrical fault. Arc faults are often caused by direct or indirect human intervention. Typical reasons for arcing faults are:

- Direct human error, e.g. bridging of live conductors by tools
- Design error, e.g. incorrect dimensioning
- Inadequate maintenance
- Animals in switchgear
- Contamination
- Ageing of isolation

An electric arc supplies the current path of the short circuit through the air which is ionized and contaminated by the molten metal of the conductors. It is characterized by temperatures of around 20 000 K in its core and high pressure (several bar) which leads to high forces on surfaces like cabinet walls. Electromagnetic forces drive the arc away from the current source such that not only the initial location of the fault is affected.

In case of direct human intervention, the personnel is exposed to several arc-flash impacts. During the first moments there is intensive electromagnetic radiation that can cause burns and eye damage. The high temperature heats the air, and causes another thermal impact in form of convection. The heated air and vaporized metal cause a significant pressure impact. The arc blast can cause collapse of lungs, ear injuries or broken bones due to falling. Flying particles and the toxic impact of the vaporized materials, and hazard voltage create additional risks.

The thermal impact is often the most significant impact. IEEE Std 1584™ provides a methodology to perform incident energy calculations. The calculations are utilized when safe working distance and personnel protective equipment are determined [1]. The calculations can also be used when comparing different arc-flash protection technologies.

While a lot of attention has been paid to safety issues, the impact on equipment and processes has been studied less. However, many arc-flash incidents occur without direct human intervention, and the direct and indirect costs can rise to millions of dollars.

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When developing mitigation to arc-flash impacts, safety as well as asset and process related points of view should be taken into account. Mitigation technology providing good protection for equipment and processes along with personnel safety is well justified.

II. Overview of arc-flash protection or mitigation technologies

A. *Arc fault prevention*

As stated in IEC standard 62271-200, switchgear should be designed, manufactured, installed, operated and maintained so that the probability of internal arc is very low [2]. To eliminate the human factor, education and training of personnel should be emphasized.

There are also technological options, such as use of insulated busbars or selection of the system grounding technology to prevent arc faults.

B. *Arc-resistant switchgear*

Along with personal protective equipment, and withdrawable devices, arc-resistant switchgear is an example of passive protection technology. Figure 1 presents an example of arc-resistant controlgear with a plenum. The plenum facilitates channeling the dangerous superheated air and arc contaminates to a safe and controlled location which is typically external to the electrical equipment room [3]. From a safety point of view, arc-resistant switchgear provides protection to personnel as long as the doors are closed. Unfortunately maintenance work often requires opening the doors. In ships it is more challenging to apply arc-resistant switchgear, because redirecting and channeling the arc exhaust gases may be difficult.

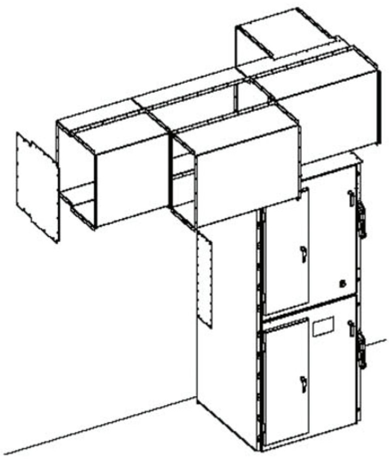

Figure 1. Example of a arc resistant technology [3].

C. *Arc fault prediction by on-line monitoring*

Several technologies have been proposed for on-line monitoring of switchgear. Monitoring of partial discharges or temperature are well known methods but not widely applied. Infrared or ultraviolet radiation on-line or off-line detection technologies have also been investigated. Smoke detectors have already been used in combination with arc-flash protection relays.

On-line analyzing of current has been proposed for preventive arc fault detection in some scientific papers [4], [5]. The harmonic components of the line current could possibly be used as a sign of a phase-to-ground arcing fault.

On-line monitoring may reduce the number of faults caused by failure of equipment, but it cannot prevent arc-flash incidents caused by direct human errors. However, on-line monitoring technologies are being examined, and they have potential to become components of more comprehensive arc-flash protection systems with communication capabilities.

D. *Reduction of fault current*

Arc fault incident energy depends on voltage, distance, current, and arcing time. Reduction of fault current may seem to be an excellent option. The current can be reduced by e.g. choosing several feeding transformers instead of one large unit, or by current limiting reactors. Naturally these solutions increase costs and losses. Current-limiting fuses are a good solution, if a high fault current can be guaranteed. However, in low voltage systems the fault current is often less than 50% of the bolted fault current. For those current levels the operation time of the fuses significantly increases, and the current peak, which occurs within the first half cycle of the current, will not be limited. In fact, it has been proved that lower current can lead to higher incident energy. [2], [6].

In marine applications the arc current is often rather a high-impedance fault than a bolted fault, and the fault current can be similar to those of many working loads [7]. This is another reason why reduction of fault current hardly is a practical arc-flash mitigation option in ship environment.

E. *Reduction of arcing time*

Incident energy is directly proportional to arcing time which makes reduction of arcing time a very efficient means of arc mitigation. Arcing time can be reduced by reducing the operation time of the protection equipment. The total arcing time consists of arc detection time, protection logic operation time, and operation time of the primary protection device, i.e. circuit breaker, fuse or arc eliminator. In state-of-the art arc-flash protection, the arc is detected very rapidly, and most of the arcing time comes from the operation time the circuit breaker.

III. Detection of fault arc

A. *Current based methods*

When using protection relays, traditional over-current based protection requires several cycles to process the measured current data, leading to unacceptably high arcing time. Different protection options, such as zone selective interlocking, bus differential, and instantaneous tripping during maintenance have extensively been discussed in the literature. However, the most effective ways to detect a fault arc are based on different technologies than just analyzing the current.

B. *Detection of pressure*

Protection can be based on detection of the pressure caused by the arc. Pressure and sound sensors were examined and applied in [7], but later on they were removed and photosensors alone were used in surface ship protection applications. However, there are still manufacturers of pressure sensors and protection systems based on detection of the arc blast, although this technology has not been widely applied.

C. *Detection of arc light and overcurrent*

The fastest technology to detect the fault arc is based on detection of arc-flash light. There is a strong correlation between arc fault current and light [8]. An arcing fault can thus be detected practically immediately, within 1ms, by detecting the light. Light can be detected by e.g. using photodiode based point sensors or fiber optic sensors. Figure 2 presents examples of light sensitive sensors.

Figure 2. Point sensor and fiber optic sensor.

There are applications where detection of light alone is a sufficient condition for protection, but in some cases external light sources can activate the light sensors leading to nuisance tripping. This is why optical detection based arc-flash protection systems are normally configured by using dual sensing, light & overcurrent condition for tripping. Because of the light condition, the pick-up current of the over-current can be set very low. The current condition will not cause significant delay to the detection, because it can be based on simple analog comparator or on only a few samples. In case of phase-to-phase arcing fault, the fault current can be detected within 1-2ms [11]. For the detection of over-current the current sensors that are installed for normal protection can be used.

Ground-fault current can also be used as a detection condition. This gives the benefit of early detection of arcing faults, because the majority of faults starts out as ground fault, and rapidly escalate into three-phase fault [9].

When speed is compared, optical sensors are superior to pressure sensors. There is always a short delay in the development and the detection of the pressure compared to detection based on light and over-current.

IV. PROTECTION LOGIC AND SELECTIVE OPERATION

A. *Basic logic of protection*

The logic of protection based on optical detection is illustrated in Figure 3. After the arc is detected by sensors, some type of protection device sends the tripping command to the device in the primary circuit, capable of eliminating the arc.

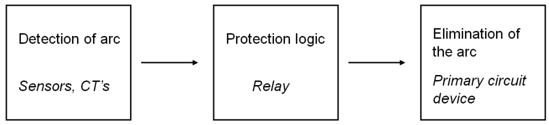

Figure 3. The basic logic of optical arc-flash protection.

B. *Stand-alone devices*

In simple cases where no selectivity is required, a stand-alone arc-flash protection device can be applied. The protection can be based on dual sensing or light only. Figure 4 presents an example of switchgear application where point sensors and 'light only' condition are applied.

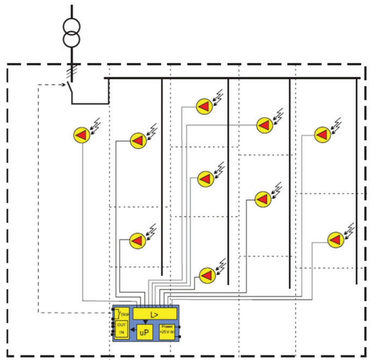

Figure 4. Example of simple protection by a stand-alone device.

C. *Arc-flash protection integrated into numerical relays*

A cost effective solution to selective arc-flash protection is installation of numerical relays equipped with arc-flash protection option. Along with normal overcurrent and ground fault protection the relays are able to trip the appropriate circuit-breakers within a few milliseconds in case arc-flash light and overcurrent is detected. Figure 5 illustrates the principle of arc-flash protection integrated into common numerical protection relays.

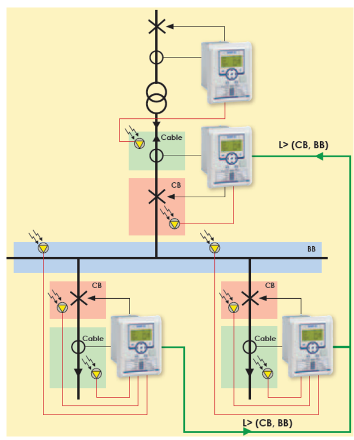

Figure 5. Simplified example of applying integrated arc-flash protection.

D. Dedicated arc-flash protection relays

For complex systems, dedicated arc-flash protection equipment can be applied. A number of point sensors or optical fiber sensors as well as many current transformers can be connected to the protection system via separate I/O units. The arc-flash protection central unit is then able to trip the appropriate circuit breakers, leaving the healthy part of the system in operation. Figure 6 illustrates an example of a protection implementation using dedicated devices.

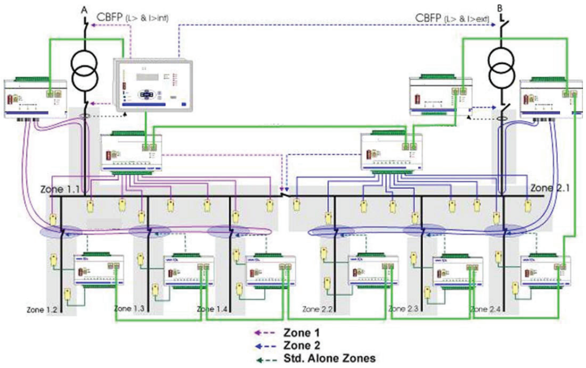

Figure 6. Example of selective protection utilizing dedicated arc-flash protection units.

An interesting detail of the configuration in Figure 6 is that both point sensors and fiber sensors are applied. Less sensitive fiber sensors are installed in CB cubicles in order to minimize the risk of nuisance tripping caused by switching arcs.

V. ADVANCEMENTS IN DETECTION OF LIGHT, ARC-FLASH PROTECTION UNITS, AND CIRCUIT BREAKER INTEGRATION

A. Tests and development of fiber optic sensors

The spectrum of arc light needs to be known to be able to choose optical sensing technology for the detection of the arc. Laboratory tests were defined for different copper electrodes, busbars, and standard switchgear. The currents were changed in a range from 1 kA to 65 kA. The measurements indicate that significant differences can be detected in the wavelengths of 330-530 nm and 770-870 nm. Figure 7 presents the measured characteristics of arc spectra for different busbar materials.

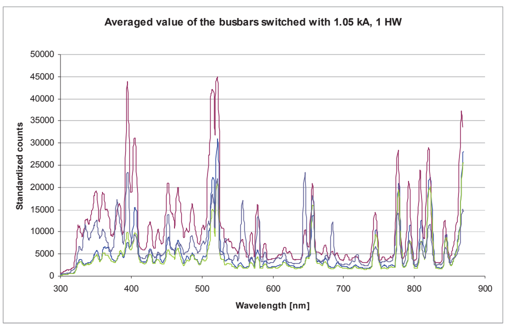

Figure 7. Measured characteristics of arc spectrum on busbars with small distance and different materials.

The results for the uncritical area of 530-770 nm for different busbars are in line with measurements from [10]. An optimal optical fiber should be sensitive in the critical range and not sensitive in the uncritical range. A specific filtering of the uncritical range of wavelengths has lead to an improvement of the sensitivity, so that the radiation from other sources will not activate the sensor.

The transmittance characteristics of various types of optical fibers have been tested. Figure 8 illustrates the impact of the filtering of the uncritical range.

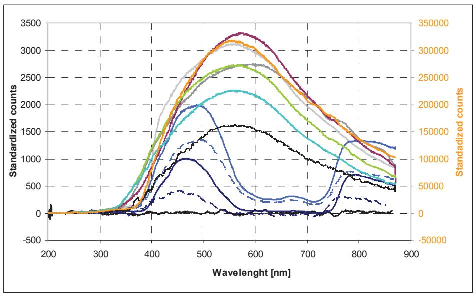

Figure 8. Received signals of the tested fiber optic sensors.

In [7] a totally different approach has been chosen. Instead of rather wide band detection, a narrowband UV filter centered at 325 nm has been chosen, in order to distinguish arc-flash light from ambient visible light.

In addition to optical characteristics, the fiber sensor should have the following qualities:

- able to tolerate rather high temperature,
- mechanical toughness,
- chemical inertness and
- reasonable production costs.

Considering these characteristics the number of fiber sensor types was reduced to three. The measurements showed further that the spectral distributions of arcing faults and switching arcs of circuit breakers are very similar. Therefore an accurate distinction cannot be based on the spectrum of light.

However, the measurements of switching arcs showed that the sensor signal is much lower than in arcing faults. This indicates that the problem with nuisance tripping related to switching arcs can be solved by either using less sensitive sensors or by increasing the distance between the sensor and the circuit breaker.

B. Advancements in dedicated arc-flash protection units

A new arc-flash protection central unit has been developed. Its comprehensive sensor channel specific event-buffering and built-in disturbance recorder provide the user with a lot of useful data from the protection application. The user interface has been developed both for panel use and for the configuration with PC software. Figure 9 present the front panel of the new generation arc-flash protection central unit.

Figure 9. Front panel of an arc-flash protection central unit.

C. New concept for integration into low voltage circuit breakers

So far arc-flash protection systems have been separate from conventional circuit breakers. The interface to the breaker has only been the shunt trip. A new approach is to integrate the current measurement of the low voltage circuit breaker into the system. A communication unit bridges the arc-flash protection system's fast tripping signals to the breaker unit. This concept provides several advantages:

- No separate current I/O modules (collecting over-current detection information) are needed.
- No need to connect the normal current transducers of the power system to the arc-flash protection system which means less wiring.
- Significantly faster tripping of the circuit breaker.

The key issue in the invention is to utilize the current sensors that are integrated into the circuit breakers. This way the time required by the triggering process of the circuit breaker can be reduced. In order to minimize tripping time, also the interface between the arc detection system and the circuit breaker was redesigned. The combination of the new interface and the circuit breaker technology has been initially tested, and the results are very promising.

The improved performance can be seen when comparing the current traces in figures 10 and 11, presenting test results. The tests were carried out by supplying the circuit breaker with overcurrent and triggering the arc flash detection by a flashlight. The clearing time was reduced by more than 50% to about 10 ms.

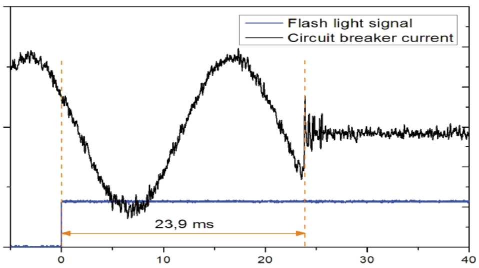

Figure 10. Oscillogram of a CB trip test, standard communication.

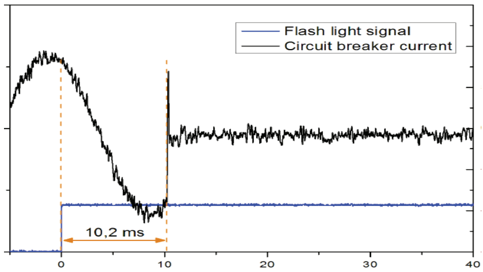

Figure 11. Oscillogram of a CB trip test, the new interface applied.

VI. Mitigation of the Pressure Wave

As stated above, in a ship environment it is difficult to channel the arc blast out of the switchgear. Because the pressure reaches its maximum value within approximately 8..15 ms from arc initiation, very high speed protection is needed.

When arcing time is limited to less than 5 ms the thermal impact of the arc is minimal, and the arc blast is drastically reduced. This is possible by arc eliminator technology which is recognized by the IEC standard [2].

When arc elimination technology is applied, the arc-flash protection relay sends a tripping command both to the arc quenching device and to the circuit breaker. The quenching device creates very rapidly a bolted short-circuit on three phases parallel to the location of the arc fault. This reduces the voltage between the downstream busbars well below the minimum arc voltage and thus instantly quenches the arc. The performance of the low voltage system is demonstrated by the oscillogram in figure 12.

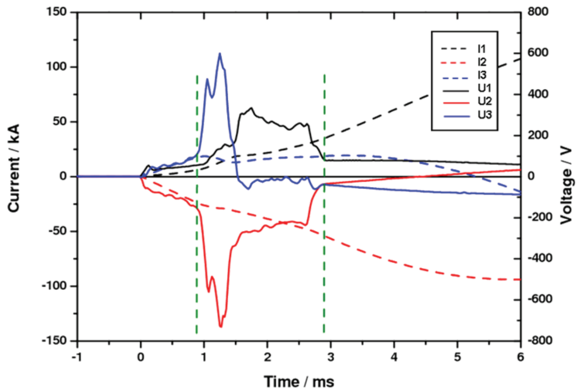

Figure 12. Oscillogram of current and voltage during arc flash extinction (3 phases, U_P = 440 V, I_{CC} =65 kA).

Figure 13 presents a photograph of low voltage busbars after an arc-flash test with similar values as in Figure 12. The damage is minimal. The figure clearly illustrates the effectiveness of minimizing the arcing time.

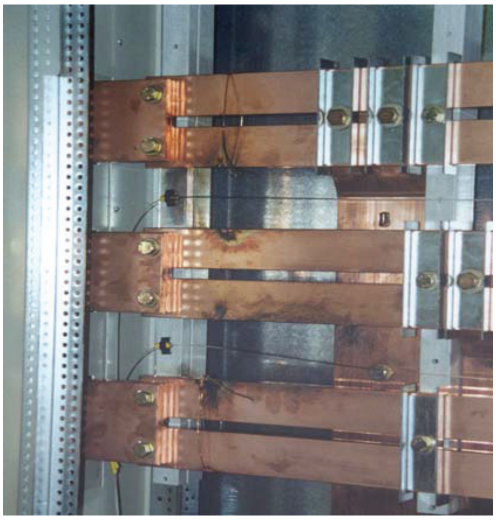

Figure 13. LV busbar after an arc-flash test, quenching device applied.

VII. CONCLUSION

Reduction of the arcing time is the most efficient way to mitigate arcing faults. State-of-the-art mitigation technology, based on optical detection of the arc flash, has been presented. Arc spectrum has been examined in order to develop fiber optic sensors, capable of distinguishing faults from switching arcs. Instead of the spectrum of the arc-flash light, sensor sensitivity level seems to provide a solution.

A new generation arc-flash protection central unit with improved user interface has been introduced, and an innovative concept for low voltage circuit breaker interface has been presented. The new concept is significantly faster than previous technology, and requires fewer components.

Arc quenching technology, effectively mitigating the arc blast along with reducing the thermal impact, has been presented. With arcing time less than 2 ms in low voltage systems, this technology is very feasible in marine applications where maximal protection is necessary.

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Maximal Protection: Lowering Incident Energy and Arc Blast Elements by Minimizing Arcing Time

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Abstract - Arcing faults are rare events, but they often lead to severe injuries. From the economic point of view, the consequences due to direct and indirect costs can be extremely high. There are various options to prevent arcing faults, but faults cannot be totally eliminated. This is why several approaches to mitigate the consequences of arcing faults have been introduced. Several manufacturers have started to produce arc flash protection relays based on optical detection of light energy from an arc. In most applications, the light information is confirmed by overcurrent information before a trip command is initiated to an upstream current breaking device. The tripping of a circuit breaker, for instance, occurs in only a few milliseconds. This seems to be the state-of-the-art technology, leading in most cases to very reasonable incident energy levels. However, it is essential to be able to minimize not only the thermal impact but the pressure wave as well. This paper investigates technology aimed at maximal protection.

Index Terms — Arc flash mitigation, arc eliminator, current limiting fuses, incident energy, pressure wave.

I. INTRODUCTION

Arc flash incidents can cause several types of hazards. In addition to the thermal impact, the blinding radiation and the huge pressure wave, personnel may be subjected to projectiles, shrapnel, hazardous voltage and toxic gases. The most prominent injuries in an arc fault accident are arc burns, but the other arc fault elements, especially those associated with the arc blast component, can not be neglected. From the protection point of view, the difficulty with the pressure wave component is that the pressure reaches its peak value shortly after the arc ignition. Passive protection methods, such as Arc Resistant Switchgear, Controlgear and Personal Protective Equipment, are well justified when appropriately applied.

Safety related indirect medical and legal expenses can be substantial. Along with the safety hazard, arcing faults often cause very high other direct and indirect costs. Direct costs are caused by damage to equipment, and indirect costs include costs due to interruption of the distribution process, and industrial processes. Fires caused by arcing faults can multiply the costs e.g. in marine, oil & gas, and mining applications.

However, there are very fast active protection methods providing extremely effective protection against the thermal impact and significant reduction of the impacts of the blast energy. This paper investigates these new technologies; evaluating their advantages, the possible risks and their applicability. The key technologies discussed include new arc quenching technologies, current limiting fuses and the combination of these and other technologies.

II. ARCING TIME – THE CRITICAL FACTOR IN INCIDENT ENERGY CALCULATIONS

A. *Distance, Voltage and Current*

Arc flash incident energy, as it is defined by IEEE Standard 1584™, takes into account the thermal impact of the arc caused by the radiation and the convection. Incident energy depends on working distance, voltage, current, and arcing time. The working distance and the system voltage are normally factors that can not easily be adjusted. Some methods to reduce the arcing current can be limited by inserting more reactance in the feed or but utilizing several smaller feeding transformers instead of a single large one. However, limiting the current can negatively influence the operation time of the over current protection, and thus lead to longer arcing time and higher incident energy. In fact, the highest incident energy can be caused by the lowest arcing fault current [1]. This very important aspect is covered in more detail in the body of this paper when the use of current limiting fuses is discussed.

B. *Arcing time*

It is quite obvious that the most effective and practical method to reduce the incident energy level is to reduce the arcing time. In practice this means minimizing the operation time of the protection. Figure 1 illustrates the importance of the arcing time as a factor influencing the incident energy level.

Various options to reduce the arcing time, by decreasing the operation time of the protection, have been widely discussed in several other previous published papers. The arcing time includes, in most cases, arc detection time, operation time of protection relays, and the operation time of the primary current interrupting device - often a circuit breaker. The most effective solutions minimize all these arcing time components.

Kumpulainen, L., Kay, J.A., Aurangzeb, M. (2011). "Maximal Protection: Lowering Incident Energy and Arc Blast Elements by Minimizing Arcing Time". Proceedings of 2011 IEEE IAS Petroleum and Chemical Industry Technical Conference, Toronto, September 19–21, 2011, pp. 1–6. Copyright © 2011, IEEE. Reprinted with permission.

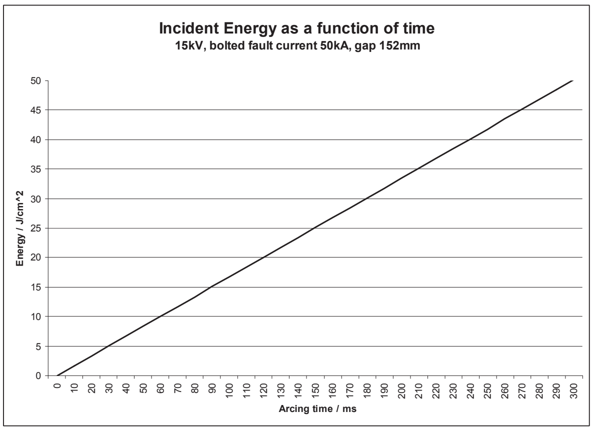

Fig 1. An example how the incident energy is proportional to arcing time.

C. Other perspectives along with incident energy

Incident energy calculations are a tool for evaluation and ultimately reducing the safety hazard associated with the arc flash. The calculations focus mainly on the thermal impact of arcing faults. As outlined above, shortening the arcing time is the most critical factor when mitigating the thermal impact. However, the arcing time is a very essential factor also when mitigating the other dangerous and toxic impacts. The shorter the arcing time, the less toxic copper oxides will be released.

The calculation of incident energy does not take into account the impact of the pressure wave, another significant component of an arcing fault. Other significant issues like the costs related to the damage to the equipment, cost caused by often very long process interruptions, and possible medical and legal expenses are well beyond the scope of incident energy calculations. However, when carrying out arc flash studies, all the aspects should be considered, along with the foundational starting point: arc flash fault prevention.

III. THE PRESSURE WAVE AND ITS IMPACT

From the safety point of view, the arc blast can cause lung damage, temporary or permanent ear injuries, damage to internal organs, and broken bones or concussion injuries if persons are impacted. Additionally the flying particles can cause injuries. The arc blast often causes significant damage to equipment. In some applications, such as marine, mining, and tunnel installations, the pressure wave is especially problematic, because it can be very difficult to redirect the blast energy out of even arc resistant switchgear.

The difficulty in reducing the impact of the pressure wave comes from the fact that the pressure reaches its maximum value very rapidly. Based on what has been published, the peak pressure is reached at ca. 8-30 ms after arc ignition [2], [3], [4], [5], [6], [7]. Some recent tests indicate that 8-15 ms is a good baseline for peak pressure time. This 8-15 ms baseline sets a challenging requirement for protection: the arc must be eliminated within a few milliseconds to provide maximal protection. Figure 2 illustrates the fact that the pressure wave develops with a short delay.

Fig 2. Current and pressure curves after arc ignition [2]

IV. MITIGATING THE IMPACT OF THE PRESSURE WAVE

A. Arc containment

Arc resistant switchgear and controlgear, designed for arc-resistant protection, is typically designed with a heavily reinforced structure to provide the necessary level of structural integrity to retain or control the pressure forces generated, the heat energy produced by the arc and the resultant material vaporization.

Each equipment manufacturer will typically utilize a unique system for arc pressure relief. These systems must open rapidly to reduce the damage resulting from the internal pressure wave associated with the compression stage of an arc fault event.

Arc resistant control equipment designs reduce the hazard/risk category level for normal equipment operating procedures as related to NFPA-70E [8]. This results in a reduced level of personal protective equipment, (depending on the procedure/task performed), while working near medium voltage controllers. Some manufacturers' designs will provide the same arc resistant level of protection even with low voltage control area doors open.

B. Minimal arcing time

Because the pressure reaches its maximum value with a small delay from the original arc ignition, the fastest protection methods are now able to mitigate most of the blast characteristics. A 5ms maximum arcing time target is a suitable goal to insure that the pressure wave will not reach its peak value.

Reduction of the pressure wave naturally decreases the sound wave and thus helps in preventing hearing impairment and reduces the risk of projectiles and shrapnel. Limiting the arcing time to minimal eliminates also the toxic impact, because practically no metal is vaporized and significantly reduces the damage to the equipment.

V. OPTIONS TO ACHIEVE REDUCED ARCING TIME

A. Current Limiting Fuses, Characteristics and Benefits

Current limiting fuses can be very efficient in both limiting the current and reducing the arcing time. In fact, when the fault current is in the current-limiting range, the fuse is able to break the current within half cycle, and reduce the peak current. The reduction of the peak current is a benefit, because high current causes mechanical forces that are detrimental to transformers feeding the current. Figure 3 illustrates the operation a current limiting fuse.

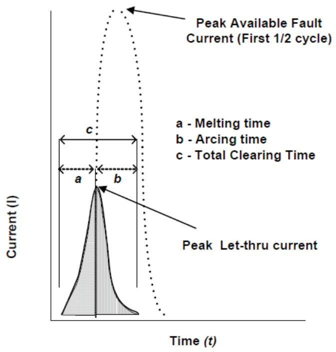

Fig 3. Fuse current let through [9]

The benefits current-limiting fuses have been verified by tests and reported very well in reference [10]. The reduction of damage and arc-fault energy can be tremendous.

B. Current Limiting Fuses, Risks and Limitations

Current-limiting fuses are not a perfect solution. They are very effective in limiting the arc-flash incident energy only if they are in their current-limiting range. This can be seen in the figures 16-42 of IEEE Standard 1584™-2002 [11], and in figures 11-16 of [12]. According to [1], the highest exposed incident energy can be caused by highest or lowest bolted and arcing fault current in contrary to general approach for protective device evaluation. This is especially true in low voltage applications where it is difficult to determine the arcing current level. The current can be as low as 20-40 % of the bolted fault current depending on the system voltage level [13].

As Figure 4 illustrates, the magnitude of the current has a drastic impact on the arcing time when current limiting fuses are applied. In this example, the current 5.5kA versus 2.75kA is compared. A difference of 10ms versus 200ms can be observed.

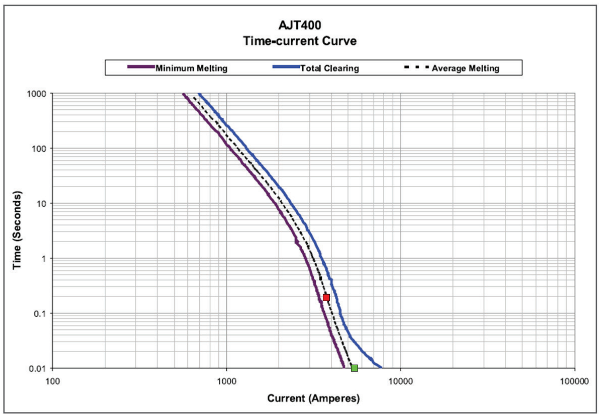

Fig 4. Typical example of the impact of the current on fuse operation time [14]

On the other hand, if the high current can be taken for granted, current limiting fuses can be very effective in reducing the incident energy level, the pressure wave magnitude, and the mechanical stress caused by the high current.

C. Optical arc flash detection

When arcing is stopped by the opening of a circuit breaker or other electro-mechanical device, the arcing time consists of arc detection time, operational time of a protection relay's output contact, and the operation time of the circuit breaker or other current breaking device. Conventional over-current protection based on protection relays, such as zone-selective interlocking or bus bar differential protection, inherently include delays in arc detection.

Significantly shorter arcing time can be provided by optical detection based protection. In optical arc flash detection the arc light is detected within approximately 1ms from arc ignition. In order to prevent nuisance tripping caused by ambient light, the light information is often confirmed by detection of the associated over-current signature. Just like the arc light, the over-current can be detected within approximately 1 ms. Thus, the arc detection time using light and current based detection is approximately 1 ms. The trip time of the relay depends on the output technology utilized in the protection system. With a conventional electro-mechanical output relay the total operation time of the arc flash protection relay is 5..8 milliseconds. When semiconductor outputs (solid state) are used their operating times are typically less than 1ms. Therefore, the total detection and trip time can be less than 2ms. As a result, the arcing time consist almost totally of the operation time related to the opening of the circuit breaker or other current breaking device.

There are various options to put optical detection based arc flash protection into practice. A cost efficient alternative is to integrate it into numerical relays providing normal over-current, ground fault or other protective functions. Separate stand-alone units are also available which are designed especially for applications where a limited number of optical sensors are required. For large control systems, and if selective protection zones are needed, a dedicated arc flash protection system is the best solution. A dedicated system consists of arc flash protection central unit, several light I/O units, current I/O units, and arc light sensors. An example of a typical protection arrangement, using dedicated arc flash protection system, is presented in Figure 5.

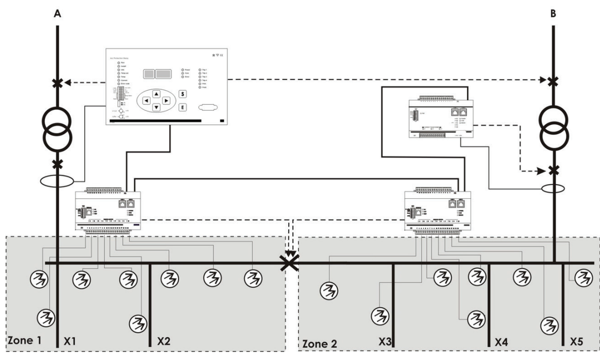

Fig 5. An example of optical detection based arc flash protection

VI. MINIMIZING THE OPERATION TIME OF THE PRIMARY SWITCHING DEVICE

A. *Introduction*

Light and current based arc flash detection combined with normal circuit breakers could provide good protection against the thermal impact of the arc flash. However, in some cases it is desirable to go even further, so that the thermal impact is almost nonexistent and the impact of the pressure wave is also efficiently mitigated. Maximal protection is especially useful in the following environments:

- Where it is difficult to arrange plenums to redirect the arc blast,
- Where a fire can have disastrous consequences, (classified areas), and
- Where it is crucial to minimize electricity distribution process downtime and minimize process outages
- The reduction of equipment damage improves the ability to place the equipment back into service quickly

Such environments can be found in many application segments including marine, mining and tunnel, oil and gas production and transportation, process industries, information technology centers and health care facilities.

Because the peak pressure will typically be reached within 8-15 ms, an extremely short arcing time is required to be able to reduce the pressure wave to a target of approximately 5 ms can set.

B. *Arc elimination technology*

Arc eliminating by means of a short-circuit device (crowbar unit, arc quencher or high speed earthing device) is recognized by IEC Standard 62271-200 [15] as an option to provide highest possible level of protection to persons in case of an internal arc in MV switchgear. The operation principle is simple: when an arc flash fault is detected, the arc eliminator will create an intentional high speed short circuit in the system so that the voltage collapses and the arc is extinguished. Various manufacturers have different technologies in the methods related to the creation of the short circuit, e.g. pyrotechnical pressure element, Thomson coil, micro gas cartridges, or a spring mechanism assisted by an electromagnetic repulsion system.

For suitable arc detection, a current and light based system is needed. The arc detection system is able to trip the eliminator within 1-2ms, and the high speed short-circuit device operates within a few milliseconds. Fast communication between the arc-flash protection relay and the short-circuit device play is vital. A typical arcing time is less than 5ms.

Along with tripping the short-circuit device, the arc detection system sends a tripping command to the normal circuit breaker, and the circuit breaker eliminates the short-circuit current within a few cycles. Thus the elimination of the fault is carried out in two phases: in the first phase the arc is eliminated by the arc eliminator, and then the short-circuit current is eliminated by the circuit breaker. An example of an arc flash protection system equipped with arc eliminators is presented in Figure 6.

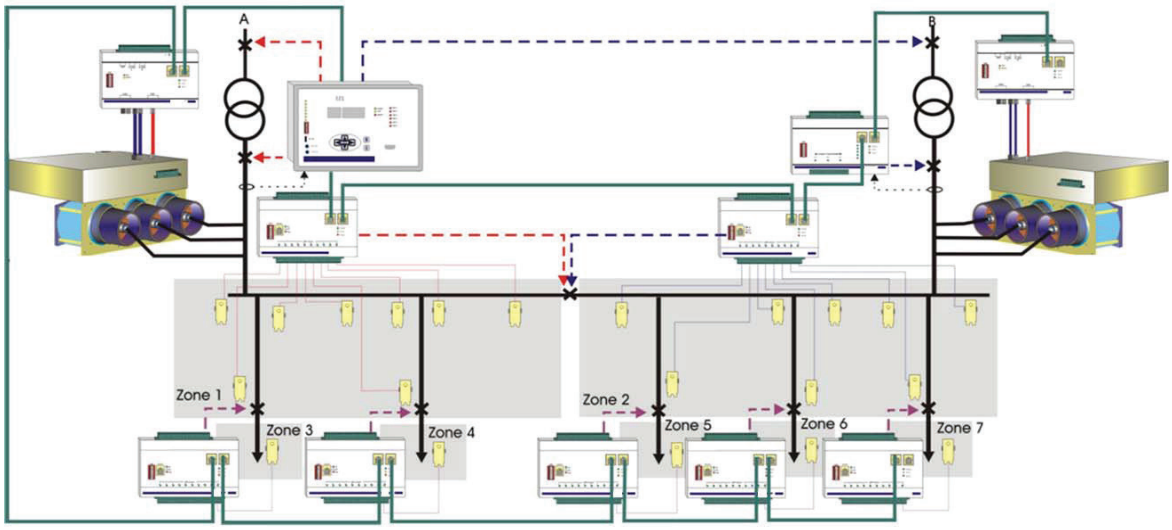

Fig 6. An arc flash protection system equipped with arc eliminators

Test results confirm the effectiveness of arc eliminator technology. The energy release associated with the arc blast is radically reduced, and the burning impact is minimal. As described in a recent 12kV 63kA test report: "No visible burn-marks" were evident.

C. *Evaluating the risks caused by the short circuit*

Arc eliminating systems have been criticized because of the high current they cause. Questions have risen whether the dynamic forces caused by the peak current could damage the feeding transformer or a full short circuit could cause damage to motors close to the arc elimination system.

An external short-circuit can be detrimental to transformers, and the failure rate in laboratory tests is rather high. However, according international reporting on a statistical basis, large power transformers have to face several full and many small short-circuits during their life, but the real life failure rate is low. Thus the report assumes that actual (full) short-circuit current in service is normally (much) smaller than the rated short-circuit current for which the transformer is designed. [16]

Another important aspect is that in MV systems the arcing current is approximately equal to the bolted-fault current anyway [13], [17]. Thus the arc elimination system does not significantly increase the fault current level, and it will not increase the risk of damage due to high current and mechanical stress compared to situation where the arc is not eliminated by a shorting device.

In MV systems, a short circuiting device is beneficial from the transformer and motor point of view related to an arcing fault. This is because the arc detection system will trip the circuit breaker faster than a normal protection relay sensing the over current event only.

When an arc eliminator operates, it will create an intentional short circuit with balanced short-circuit current. There are references to the fact that a controlled, balanced short circuit is less detrimental than asymmetrical currents [18], [19]. In [19] it has been shown that the stresses to interior permanent magnet synchronous machines associated with the asymmetric single-phase fault are noticeably higher than those for the three-phase fault. Very high negative torque and current transients have been reported in induction motors, especially in the cases of asymmetrical faults [20]. [18] even suggests a control strategy that purposely changes asymmetrical faults into symmetrical three-phase short-circuits.

Induction motors are designed with a safety factor to withstand certain levels of short-circuit torque [21]. From a generator perspective, the external short circuit is probably not the case where the highest torque is encountered. An unsynchronized connection to the main network can causes very high torque transients in a generator. [22]. The same applies to induction motors [23].

In low voltage systems the arcing current is lower than the bolted-fault current. Thus in low voltage systems an arc flash eliminator will increase the current of the feeding transformer. However, transformer failures caused by short-circuit events are relatively rare events, and according to IEEE and IEC standards, transformers shall be designed to withstand the electromagnetic forces and the thermal stresses produced during the flow of a short-circuit current [24].

The overall conclusion of the eliminator and mechanical stress related equipment risk evaluation is that the risk level is acceptable, and the benefits of arc eliminators clearly overweigh the negative consequences of the potentially increased current level.

VII. COMBINATION OF TECHNOLOGIES

Although the risks related to the impact on current of an arc eliminator seem to be low, mitigation options have been designed. One interesting option is to combine an eliminator and current limiting fuses. These technologies will compensate each others' drawbacks:

- Along with limiting the arcing time to 2..5 ms, minimizing the thermal impact and significantly reducing the arc blast, the eliminator will guarantee that the current is in the current-limiting range of the fuse which leads to very fast operation of the fuse.
- The current-limiting fuse will break the current within a half cycle and limit significantly the peak value of the current.

Additionally, the combination of these technologies provides a level of protection redundancy.

The combination of arc eliminator and current-limiting fuses provides several benefits including extremely short arcing times, minimized incident energy, a reduced pressure wave, lower peak currents, limited stress to transformers and protection redundancy because of two complementing devices.

VIII. CONCLUSIONS

One approach to reduce arc-flash incident energy is to reduce arcing current. However, it has been shown that lowering the current may lead to higher incident energy level, because of the increased operation time of the protection. In low voltage systems an additional uncertainty comes from the fact that the arcing current is significantly lower than the bolted fault current.

The minimization of arcing time is a very efficient way to reduce incident energy and associated hazard to personnel as well as impact on equipment and processes. The arcing time consists of arc detection time, operation time of the protection logic, and the operation time of the primary device finally eliminating the arc. Examples of how to apply the fastest method to detect the arc, optical detection, have been given.

When applying optical arc-flash detection, the operation time of the circuit breaker is the dominating factor in arcing time, while arc detection and protection logic times are minimal. Arc eliminator technology provides means to reduce the impact of the arc blast along with minimizing the thermal impact of the arc. By creating an intentional short circuit an arc eliminator extinguishes the arc within a few milliseconds, before the pressure reaches its maximum value.

Crowbar technology has been criticized for causing excessive mechanical stress to feeding transformers and motors nearby. Risk of equipment damage due to high current has been estimated low. A combination of arc eliminator and current limiting fuses has been suggested for maximal protection, minimizing the thermal impact, pressure wave, and even the mechanical stress caused by the short-circuit current.

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X. VITA

Lauri Kumpulainen (M'2006), received his Master's degree (1987) and Licentiate degree (2000) in Electrical Power Engineering from Tampere University of Technology. Currently he holds the post of Research Director with Vamp Ltd. One of his He is a member of IEEE, CIGRE, and a member of CIRED Session 3 Advisory Group. He has authored a number of technical papers, especially related to arc-flash protection and the impact of distributed generation.

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Maximizing Protection by Minimizing Arcing Times in Medium-Voltage Systems

John A. Kay, *Fellow, IEEE*, and Lauri Kumpulainen, *Member, IEEE*

***Abstract*—Arcing faults in the forest product industries are real risks that often lead to severe injuries and fires. From an economic point of view, the consequences due to direct and indirect costs can be extremely high as well. There are various opportunities to prevent arcing faults, but faults cannot be totally eliminated. This is why several approaches to mitigate the consequences of arcing faults have been introduced, particularly in the last decade. Several manufacturers have started to produce arc-flash protection relays based on optical detection of light energy from an arc event. In most applications, the light information is confirmed by overcurrent information before a trip command is initiated to an upstream current-breaking device. The tripping of a circuit breaker, for instance, occurs in only a few milliseconds. In most cases, this seems to be the state-of-the-art technology leading to very reasonable incident energy levels. However, it is essential to be able to minimize not only the thermal impact but also the pressure wave. This paper investigates technology aimed at maximizing the protection for the pressure wave.**

***Index Terms*—Arc eliminator, arc fault, arc flash, arc-flash mitigation, current-limiting fuses, forest products, incident energy, pressure wave.**

I. Introduction

ARC flash incidents cause several types of hazards within the forest product industries. In addition to the thermal impact, the blinding radiation, the huge pressure wave, and fire hazards, personnel may be subjected to projectiles, shrapnel, hazardous voltage, and toxic gases. The most prominent injuries in an arc fault accident are arc burns. However, the other arc fault elements, particularly those associated with the arc blast component, cannot be neglected. From the protection point of view, the difficulty with the pressure wave component is that the pressure reaches its peak value shortly after the arc ignition. Passive protection methods, such as arc-resistant switchgear, control gear, and personal protective equipment, are well justified when appropriately applied.

Safety-related indirect medical and legal expenses can be substantial. However, the potential long-term psychological impact can be completely debilitating to a worker. Along with the safety hazard, arcing faults usually cause other very high direct and indirect costs. Direct costs are defined by equipment damage, and indirect costs are associated with the interruptions of the distribution and industrial processes. Due to the levels of flammable materials on site of forest product industries, fires caused by arcing faults can multiply the costs.

There are new and very fast active protection methods providing extremely effective protection against the thermal impact and significant reduction to the impacts of the blast energy. This paper investigates these new technologies, evaluating their advantages, the possible risks, and their applicability. The key technologies discussed include new arc-quenching technologies, current-limiting fuses, and the combination of these and other technologies.

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II. Arcing Time—The Critical Factor in Incident Energy Calculations

A. Distance, Voltage, and Current

Arc-flash incident energy, as it is defined by IEEE Standard 1584 [11], takes into account the thermal impact of the arc caused by the radiation and convection. Incident energy depends on working distance, voltage, current, and arcing time. The working distance and the system voltage are normally factors that cannot easily be adjusted. Arcing currents can be limited by inserting more reactance in the power feed or by utilizing several smaller transformers instead of a single large one feeding the system. However, limiting the current can negatively influence the operation time of the overcurrent protection and thus lead to longer arcing time and higher incident energy. In fact, the highest incident energy can be caused by the lowest arcing fault current [1]. This very important aspect is covered in more detail in other sections of this paper.

B. Arcing Time

It is quite obvious that the most effective and practical method to reduce the incident energy level is to reduce the arcing time. In practice, this means minimizing the operation time of the protection. Fig. 1 illustrates the importance of the arcing time as a factor influencing the incident energy level.

Various options to reduce the arcing time, by decreasing the operation time of the protection, have been widely discussed in several other previous published papers. The determination of total arcing time must include arc detection time, operation time of protection relays, and the operation time of the

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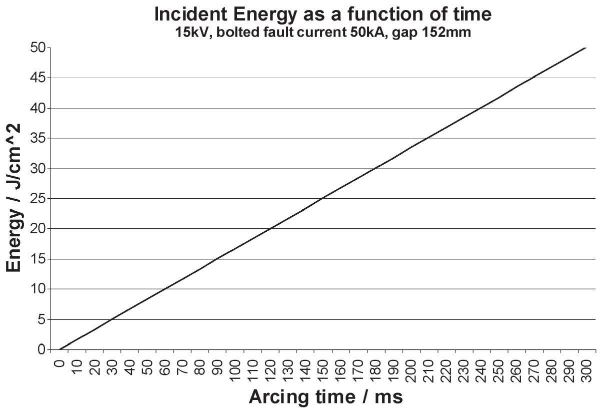

Fig. 1. Relationship of incident energy to arcing time (example).

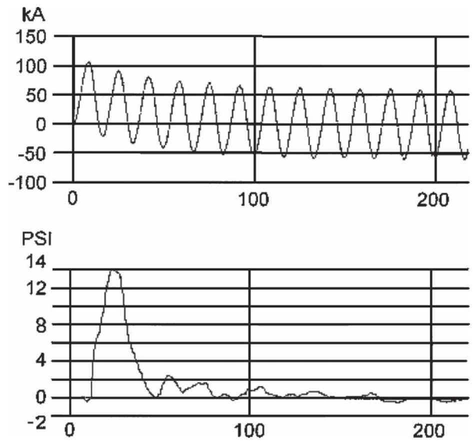

Fig. 2. Typical current and pressure curves after arc ignition.

primary current interrupting device—often a circuit breaker. The most effective solutions minimize all these arcing time components.

C. Other Perspectives Along With Incident Energy

Incident energy calculations are one tool for evaluation and, ultimately, reduction of the safety hazards associated with the arc flash. The calculations focus mainly on the thermal impact of arcing faults. As outlined previously, shortening the arcing time is the most critical factor when mitigating the thermal impact. However, the arcing time is also an essential factor when mitigating other dangerous and toxic impacts. The shorter the arcing time, the less toxic the materials, like copper oxides, will be released.

The calculation of incident energy does not take into account the impact of the pressure wave, which is another significant component of an arcing fault. Other significant issues like the costs related to the damage to the equipment, costs caused by very long process interruptions, and possible medical and legal expenses go well beyond the scope of incident energy calculations. However, when carrying out arc-flash studies, all the aspects should be considered, along with the foundational starting point: arc-flash fault prevention.

III. Pressure Wave and Its Impact

From the safety point of view, the arc blast can cause lung damage, temporary or permanent ear injuries, damage to internal organs, broken bones, and concussion injuries if persons are impacted. In addition, the flying particles can cause injuries. The arc blast often causes significant damage to equipment. In some applications, such as marine, mining, and tunnel installations, the pressure wave is particularly problematic because it can be very difficult to redirect the blast energy out of even arc-resistant switchgear.

The difficulty in reducing the impact of the pressure wave comes from the fact that the pressure reaches its maximum value very rapidly. Based on data which have been published, the peak pressure is reached about 8–30 ms after arc ignition [2]–[7]. Ongoing testing indicates that 8–15 ms is a good baseline for peak pressure time. This 8–15 ms baseline sets a challenging requirement for protection: The arc must be eliminated within a few milliseconds to provide maximal protection. Fig. 2 illustrates the fact that the pressure wave develops with a short delay. The peak pressure reached is defined by the pressure relief of the enclosure.

If the current source to the arcing event is not removed before the pressures begin to rise in any given cabinet, the pressure dynamics acting on the cabinet will take over. If the equipment is arc resistant, then an appropriate and controlled release of arc plasma will occur. In the event of other non-arc-resistant products experiencing an arc fault, if the current is not removed before the peak pressures are reached, cabinet exteriors will be breached. This could result in projectiles being ejected from doors and other components of the structure. Even with circuit breakers operating in their most instantaneous mode, there can be reduced incident (thermal) energies, but the pressure wave impacts will still occur. Standards like NPFA-70E [27] do not directly take into account any projectiles or the results of the pressure wave. Its intent is to focus on the electric shock and thermal aspects of working around electrical energy.

IV. Mitigating the Impact of the Pressure Wave

A. Arc Containment

Arc-resistant switchgear and medium-voltage (MV) motor controls, designed for arc-resistant protection, are typically designed with heavily reinforced structures. These types of enclosures provide the necessary level of structural integrity to retain or control the pressure forces generated, the heat energy produced by the arc, and the resultant material vaporization.

Each equipment manufacturer will typically utilize a unique system for arc pressure relief within the enclosure [2]. These systems must open rapidly to reduce the damage resulting from the internal pressure wave associated with the compression stage of an arc fault event.

Arc-resistant control equipment, tested and compliant to one of the various testing guides and standards, reduces the

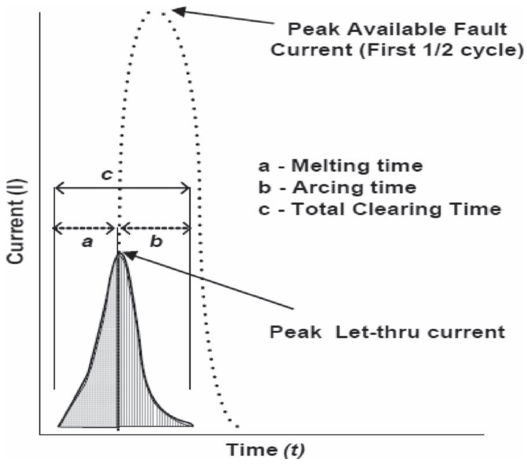

Fig. 3. Fuse current let through [9].

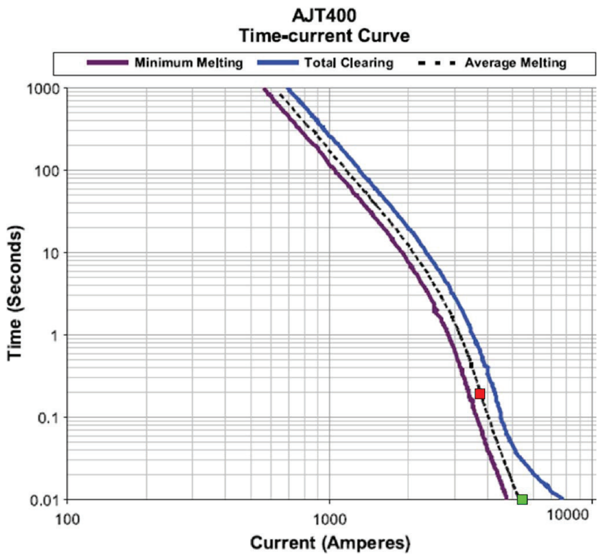

Fig. 4. Typical example of the impact of the current on fuse operation time [14].

hazard/risk category level for normal equipment operating procedures typically to the lowest level as defined by safety standards like NFPA-70E [8]. This reduced hazard/risk category results in a reduced level of personal protective equipment required (depending on the procedure/task performed) while working near MV controllers. Some manufacturers' designs will provide the same arc-resistant level of protection even with low-voltage control compartment doors open.

B. Minimal Arcing Time

Because the pressure reaches its maximum value with a small delay from the original arc ignition, the fastest protection methods are needed to mitigate most of the blast characteristics. A 5-ms maximum arcing time target is a suitable goal to ensure that the pressure wave will not reach its peak value.

The reduction of the pressure wave naturally decreases the sound wave and thus helps in preventing hearing impairment and reduces the risk of projectiles and shrapnel. Minimizing the arcing time also eliminates the toxic impacts because very little metal or other material is vaporized. This also significantly reduces the level of damage to the equipment.

V. Options to Achieve Reduced Arcing Time

A. Current-Limiting Fuses—Characteristics and Benefits

Current-limiting fuses can be very efficient in both limiting the current and reducing the arcing time. In fact, when the fault current is in the current-limiting range of the fuse, the fuse is able to break the current within a half cycle and reduce the peak current. When applied appropriately, current-limiting fuses can be very effective in reducing the incident energy level, the pressure wave magnitudes, and the mechanical stresses caused by the high currents. Fig. 3 illustrates the operation a current-limiting fuse.

The benefits of current-limiting fuses have been verified through many tests and well documented [10]. The reduction of damage and arc-fault energy can be tremendous. However, one must also review the risks and limitations imposed by using fuses.

B. Current-Limiting Fuses—Risks and Limitations

Current-limiting fuses are unfortunately not a perfect solution. They are very effective in limiting the arc-flash incident energy *only* if they are operating in their current-limiting range. This can be seen in Figs. 16–42 of IEEE Standard 1584-2002 [11] and in [12, Figs. 11–16]. The highest incident energy exposures can be exhibited when the bolted-fault current is very high or very low [1]. This can result in arcing fault currents that are contrary to the general approach for protective device evaluation. This is particularly true in low-voltage applications where it is difficult to determine the arcing current level. The current can be as low as 20%–40% of the bolted-fault current, depending on the system voltage level [13].

As Fig. 4 illustrates, the magnitude of the current has a drastic impact on the arcing time when current-limiting fuses are applied. In this example, the current 5.5 kA versus 2.75 kA is compared. A difference of 10 ms versus 200 ms can be observed.

C. Optical Arc-Flash Detection

When arcing is stopped by the opening of a circuit breaker or other electromechanical device, the arcing time consists of arc detection time, operation time of a protection relay's logic and output contact, and the operation time of the circuit breaker or other current-breaking devices. Conventional overcurrent protection based on protection relays, such as zone-selective interlocking or bus bar differential protection, inherently include delays in arc detection.

The abnormal current characteristics and the light energy from the arc are presently the first easily detectable elements of

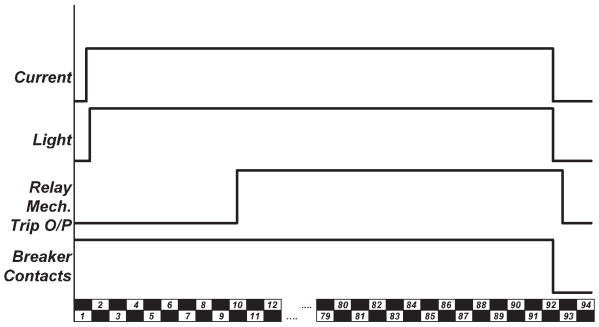

Fig. 5. Latency (in milliseconds) for mechanical trip relay and circuit breaker.

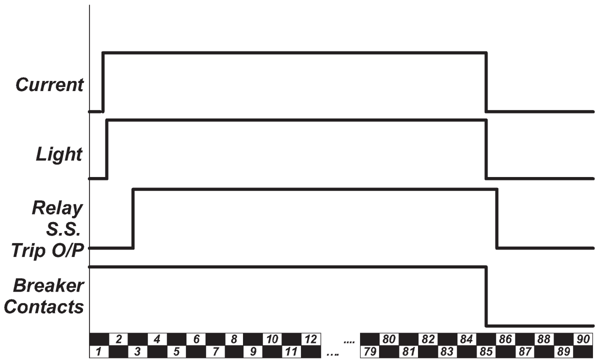

Fig. 6. Latency (in milliseconds) for solid-state trip relay and circuit breaker.

an arc event. Significantly shorter arcing time can be provided by utilizing optical-detection- and current-detection-based protection. In optical arc-flash detection, the arc light is detected within approximately 1 ms from arc ignition (Fig. 5).

In order to prevent nuisance tripping caused by ambient light, the light information is confirmed by detection of the associated overcurrent signature. Just like the arc light, the overcurrent can be detected within approximately 1 ms. Thus, the arc detection time using light- and current-based detection is approximately 1 ms. The trip time of the relay depends on the output technology utilized in the protection system. With a conventional electromechanical output relay, the total operation time of the arc-flash protection relay could be 5–8 ms. When semiconductor outputs (solid state) are used, their operating times are typically less than 1 ms. Therefore, the total detection and trip time can be less than 2 ms. As a result, the arcing time consists almost totally of the operation time related to the opening of the circuit breaker or other current-breaking devices (Fig. 6).

There are various options to put optical-detection-based arc-flash protection into practice. A cost-effective alternative is to integrate it into numerical relays providing normal overcurrent, ground fault, or other protective functions. Separate stand-alone units are also available, which are designed particularly for applications where a limited number of optical sensors are required. For large control systems, and if selective protection zones are needed, a dedicated arc-flash protection system is the best solution.

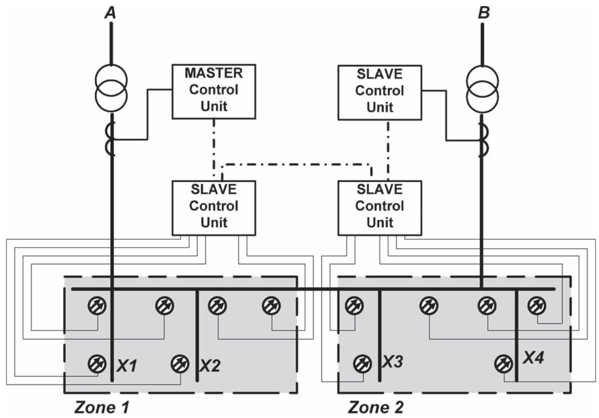

Fig. 7. Example of optical/current-detection-based arc-flash zone protection.

A dedicated system consists of an arc-flash protection central unit, several light I/O units, current I/O units, and arc light sensors. An example of a typical zone protection arrangement, using a dedicated arc-flash protection system, is presented in Fig. 7.

For optimal protection, some optical sensors could overlap various zones of protection. This provides for some redundant overlapping of protection in the event of a failure to open the upstream isolation means of a zone detecting a fault. The alternate zone sensor would generate a time-delayed failure protection trip signal to all other upstream isolation devices.

D. Using MV Circuit Breakers

For low-voltage circuit breakers with integral trip units, the manufacturer's time–current curves include both tripping time and clearing time.

IEEE 1584-2002 [11] reminds the user that, for relay-protected breakers, such as MV breakers, the relay's curves only show the relay operating time in the time-delay region. For relays operating in their instantaneous region, the IEEE 1584 standard recommends that you should allow 16 ms on 60-Hz systems for operation.

The ANSI/IEEE C37.04 [28] standard no longer stipulates the traditional three-, five-, or eight-cycle classes nor it gives assumed values for "contact parting time" associated with a particular interrupting time. Instead, the total rated interrupting time is now stated in terms of absolute time in milliseconds. Clause 5.6 in C37.04 [28] defines "rated interrupting time" as "the maximum permissible interval between the energizing of the trip circuit at rated control voltage and rated operating pressure for mechanical operation, and the interruption of the current in the main circuit in all poles."

However, C37.04 [28] states that the rated total interrupting time has to be based on the worst case conditions, which means that the actual published interrupting time of any circuit breakers will have a wide range. Circuit breaker vendors will typically now provide the individual ranges for the mechanical opening time and arcing time, thus the total interruption time. They may also provide normalized values for each of

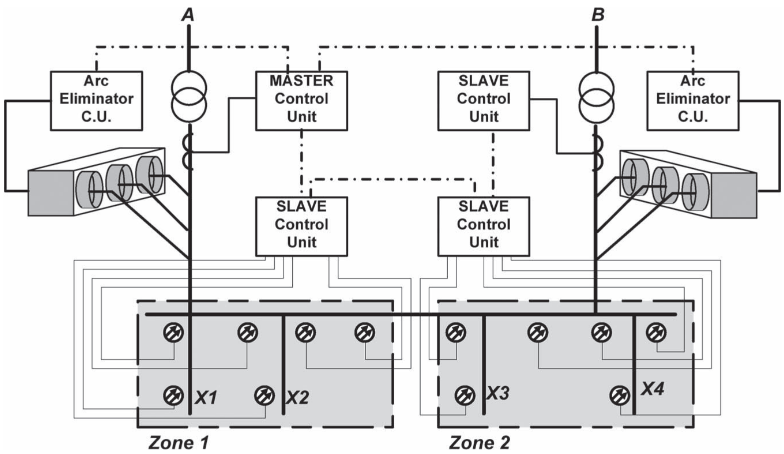

Fig. 9. Arc-flash protection system equipped with arc eliminators.

cartridges, arcing chambers, or spring mechanisms assisted by an electromagnetic repulsion system.

For suitable arc detection, a current- and light-based system is needed. The best arc detection systems are able to initiate a trip within the eliminator within 1–2 ms, and the high-speed short-circuit device operates within a few milliseconds thereafter. Ultrafast communication between the arc-flash protection relay and the short-circuit device plays a vital role. A typical total arcing time can be less than 5 ms.

Along with tripping the shorting device, the arc detection system sends a trip command to the circuit breaker, and the circuit breaker eliminates the short-circuit current within a few cycles. Thus, the elimination of the fault is carried out in two phases: In the first phase, the arc is eliminated by the arc eliminator, and then, the short-circuit current is eliminated by the circuit breaker. An example of an arc-flash protection system equipped with arc eliminators is presented in Fig. 9.

Test results confirm the effectiveness of this technology along with the associated protection elements. The energy release associated with the arc blast is radically reduced, and the burning impact is minimal. As described in a recent 12-kV 63-kA test report, "no visible burn-marks" were evident.

C. Evaluating the Risks Caused by the Short Circuit

Arc-eliminating systems have been criticized in some areas of the world because of the high current they cause. Questions have risen whether the dynamic forces caused by the peak current could damage the feeding transformer or a full short circuit could cause damage to motors close to the arc elimination system (Fig. 10).

IEEE Standard C57.12 [25] sets the requirement for short-circuit withstand capability and provides construction guidelines for specific transformer short-circuit withstand levels. This standard states that a transformer shall withstand 2 s of bolted fault at the current terminals. Testing to verify through-fault withstand capability is normally performed on a design basis, with the length of the test limited to 0.5 s for up to 30-MVA three-phase transformers.

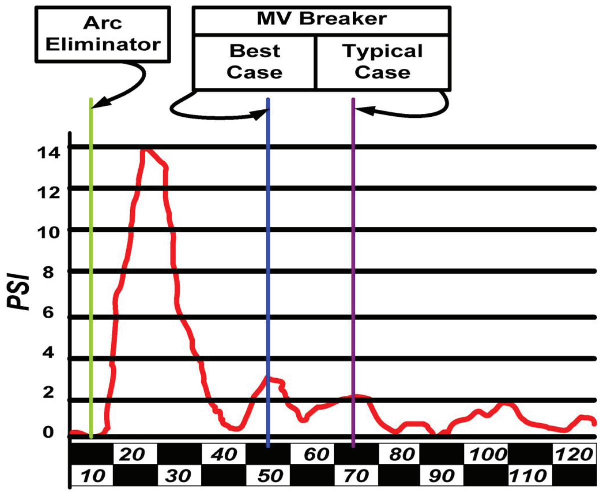

Fig. 10. Comparison of arc clearing times (ms) to pressure rise.

IEEE Standard C57.12.00 [25], clause 7.1.1, states the following:

> "*Liquid-filled transformers shall be designed and constructed to withstand the mechanical and thermal stresses produced by external short circuits... The external short circuits shall include three-phase, single line-to-ground, double line-to-ground, and line-to-line faults on any one set of terminals at a time.*"

IEC Standard 60076-5 [26] also requires that a transformer be designed to handle short-circuit currents and an additional strength verification test or theoretical evaluation of the ability of the transformer to withstand the dynamic effects of short-circuit events must be performed.

Certain external short circuits can be detrimental to transformers. However, according to international reporting on a statistical basis, large power transformers have to face several full and many small short circuits during their life, but the real life failure rate is low. The highest fault current will not always lead to the highest forces in a winding. Superimposed fields of other windings may create higher stresses. Thus, the report assumes that actual (full) short-circuit current in service is normally (much) smaller than the rated short-circuit current for which the transformer is designed [16].

Another important aspect is that, in MV systems, the arcing current is roughly equal to the bolted-fault current [2], [13], [17]. Thus, when used on MV systems, arc elimination methods do not significantly increase the fault current level compared to the arcing current. These methods do not increase the risk of damage due to high current and mechanical stress compared to situations where the arc is not eliminated by a shorting method.

In MV systems, a short-circuiting device is beneficial from the transformer and motor point of view related to an arcing fault. This is because the arc detection system will trip the circuit breaker faster than a normal protection relay sensing the overcurrent event only.

When an arc eliminator operates, it will create an intentional short circuit with balanced short-circuit current. There are references to the fact that a controlled balanced short circuit is less detrimental than some asymmetrical currents [18], [19]. It has been shown that the stresses to interior permanent-magnet synchronous machines, subjected to asymmetrical single-phase faults, are noticeably higher than those for three-phase faults [19]. Very high negative torque and current transients have been reported in induction motors, particularly in the cases of asymmetrical faults [20]. Reference [18] even suggests a control strategy that purposely changes asymmetrical faults into symmetrical three-phase short circuits.

Induction motors are designed with a safety factor to withstand certain levels of short-circuit torque [21]. From a generator perspective, the external short circuit is probably not the case where the highest torque is encountered. An unsynchronized connection to the main network can cause very high torque transients in a generator [22]. The same applies to induction motors [23].

In low-voltage systems, the arcing current is lower than the bolted-fault current. Thus, in low-voltage systems, an arc-flash eliminator can increase the current of the feeding transformer. However, transformer failures caused by short-circuit events are relatively rare events, and according to IEEE and IEC standards, transformers shall be designed to withstand these electromagnetic forces and the thermal stresses produced during the flow of short-circuit current [24].

The overall conclusions, related to an eliminator and mechanical-stress-related equipment risk evaluation, are that the risk level is acceptable and the benefits of using arc eliminators clearly overweigh the negative consequences of the potentially increased current level.

VII. Combination of Technologies

Although the risks related to the impact on current of an arc eliminator seem to be low, mitigation options have been designed. One interesting option is to combine an eliminator and current-limiting fuses. These technologies will compensate each other's drawbacks.

1) Along with limiting the arcing time to 2–5 ms, minimizing the thermal impact, and significantly reducing the arc blast, the eliminator will guarantee that the current is in the current-limiting range of the fuse, which leads to very fast operation of the fuse (assuming that there is a high-enough system short-circuit current to cleanly open the fuse).
2) The current-limiting fuse will break the current within a half cycle and limit significantly the peak value of the current.
3) The combination of these technologies provides a level of protection redundancy.

The combination of arc eliminator and current-limiting fuses provides several benefits, including extremely short arcing times, minimized incident energy, a reduced pressure wave, lower peak currents, limited stress to transformers, and protection redundancy because of two complementing devices.

VIII. Conclusion

One approach to reduce arc-flash incident energy is to reduce arcing current. However, it has been shown that lowering the current may lead to higher incident energy level, because of the increased operation time of the protection. In low-voltage systems, an additional level of uncertainty comes from the fact that the arcing current is significantly lower than the bolted-fault current.

The minimization of arcing time is a very efficient way to reduce incident energy and associated hazard to personnel as well as impact on equipment and processes. The arcing time consists of arc detection time, operation time of the protection logic, and the operation time of the primary device finally eliminating the arc. Examples of how to apply the fastest method to detect the arc (optical detection) have been given.

When applying optical arc-flash detection, the operation time of the circuit breaker is the dominating factor in arcing time, while arc detection and protection logic times are minimal. Arc eliminator technology provides a means to reduce the impact of the arc blast along with minimizing the thermal impact of the arc. By creating an intentional short circuit, an arc eliminator extinguishes the arc within a few milliseconds before the pressure reaches its maximum value.

Short-circuiting technologies have been criticized, without documented support, for causing excessive mechanical stress to feeding transformers and nearby motors. Risk of equipment damage due to high current has been shown to be low. The track record from installations has proven the reliability and suitability of this technology. A combination of arc eliminator and current-limiting fuses has also been suggested for providing maximal protection, by minimizing the thermal impact, pressure wave, and even the mechanical stress caused by the short-circuit current.

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Preemptive Arc Fault Detection Techniques in Switchgear and Controlgear

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***Abstract*—Earlier and continuous detection of potential failure points within electrical control equipment can facilitate a more proactive and complete arc fault prevention system. When these new sensor systems are interconnected to predictive protection systems communicating with supervisory control and data acquisition or programmable logic controller systems, online predictive monitoring is now a very real option available to increase the safety and reliability of switchgear and controlgear (motor control centers). A number of different new sensor technologies, for preemptive continuous monitoring, are evaluated based on extensive studies and actual user experiences. The most significant new technologies are examined more thoroughly. In these tests, equipment has been subjected to some common causes of arc fault events. Analytical results are provided for associated prearc conditions to establish conclusions for applying any of these new sensor technologies.**

***Index Terms*—Arc flash, online monitoring, sensors.**

I. Introduction

THE DIELECTRIC strength of air is, in standard conditions, about 3×10^6 V/m (3 kV/mm). Dry ambient air is a reasonably good insulator, thus substantiating the global use of air-insulated switchgear and controlgear. However, when the temperature of air is raised to between 2000 K and 3000 K (3140–4940 F), air becomes conductive owing to thermal ionization. At approximately 6000 K (10 340 F), air becomes a very conductive ionized plasma consisting of not only nitrogen and oxygen molecules but also ionized atoms and electrons. The ionized air, along with ionized material from the electrodes, forms the conductive plasma channel between the electrodes. This is fundamentally how an electric arc flash acts.

The impacts of an arc flash are well known, and recently, the economic consequences have gained more attention along with the hazards to personnel. Several arc fault mitigation options have been introduced into the market. Fig. 1 graphically portrays the various principles related to passive and active methods. Most of the active mitigation approaches are based on detection and rapid elimination of the arc fault. Passive systems generally rely on containing the energy.

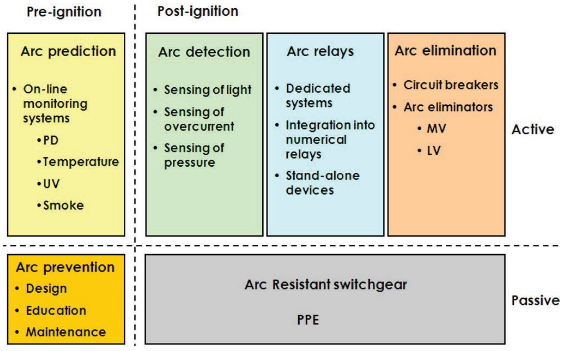

Fig. 1. Arc fault mitigation principles.

This paper examines the opportunities to detect the conditions leading to an arc flash, enabling preemptive action. Various sensor technologies are evaluated, and some of the most interesting technologies are examined in laboratory tests.

II. Causes of Arcing Faults

A. *Estimation of Causes*

Because statistical information on arcing faults is limitedly available, the estimation of causes is based on single source and practical experience. According to [1], the majority of the examined arcing events had been caused by faulty connections. Other common causes are degradation of insulation and contamination. It is obvious that many arcing faults start without direct human interaction and that many of them develop gradually.

B. *Mechanisms Gradually Leading to Arc Ignition*

The mechanism of how a faulty connection develops and ultimately leads to an arcing fault is well described in papers [2] and [1]. A faulty connection has higher resistance than a healthy connection and will heat up excessively when normal load current flows through it. Heating leads to expansion, and any presence of moisture and other contamination causes oxidation and corrosion. The oxidation further increases the resistance of the joint. During low-load or no-load periods, the connection cools off. Repeated heating and cooling cycles, as well as any vibration on the connection, increase the joint resistance

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that propagates into a failure at this connection point. Finally, the temperature rises to levels that cause the melting of the connection materials, and eventually, an arc fault results.

Degradation of insulation is another major cause of arc faults. The lifetime of any electrical insulation depends on the thermal, electrical, ambient, and mechanical stresses [3].

Thermal stresses may result due to repeated overloading operation or due to a loose joint. Electrical stresses on insulating materials are caused by partial discharge (PD) and overvoltage. PD is a localized discharge which does not bridge two electrodes [4]. It starts either on the surface of the insulator/insulation due to contamination or inside the insulating materials due to voids or cracks. In air-insulated switchgear applications, surface discharges are more prominent. PD further leads to localized chemical contamination (ozone and nitric acids). These contaminants can easily deteriorate certain insulation materials both chemically and mechanically. Damage continues to increase until it causes phase-to-ground or phase-to-phase arcing fault.

Overvoltage is another common electrical stress on insulating materials. Every type of insulating material has a puncture voltage rating at which its insulation strength breaks down permanently. The voltage level at which a localized "puncture" of the insulating medium occurs is the dielectric strength or puncture voltage. When enough voltage is applied, any insulating material will eventually succumb to the electrical "pressure," and electron flow will occur through it. Once current is forced through any insulating material, breakdown of that material's molecular structure has occurred. After breakdown, the material may or may not behave as an insulator since the molecular structure of the material has been altered by the breach. Even lower overvoltage levels will cause gradual deterioration of the insulation which can lead to PD and, ultimately, an arcing fault.

Ambient stresses are the results of excessive ambient temperatures, moisture, gas, and chemicals present in the environment. For example, electrical equipment used in corrosive environments and in petrochemical industry processes will have a shorter life expectancy than the same equipment installed in a fresh air environment.

Sometimes, mechanical vibration in the surrounding environment of the electrical equipment causes mechanical damage to material. Small cracks in the insulation material can cause initiation of PDs and finally lead to destruction of the insulation.

C. *Immediate Causes of Arc Ignition*

From the safety point of view, gradually developing faults can be considered less hazardous to personnel than those caused by direct human interaction, because, in gradually developing faults, it is less likely that there are humans in the dangerous area. However, many arcing faults ignite immediately, without giving signs (e.g., emissions) that prediction could be based on.

Slipped or forgotten tools and equipment malfunctions during maintenance work are examples of direct human interaction potentially leading to an arcing fault.

Foreign objects or animals can also lead to an immediate fault. These types of faults are more challenging to predict by online monitoring systems. One type of monitoring option might include motion detectors that can automatically switch protection modes to an instantaneous maintenance setting.

Because online monitoring systems can only cover part of the arcing faults, they should not be the only means to reduce arc-flash-related risks.

III. Phenomena Indicating a Developing Fault

A. *Electromagnetic Emissions*

Normal load current flowing through a loose connection can also cause microsparks and the ionization of the air molecules in the surroundings (plasma creation). Surface discharge and corona can also ionize the insulating air around the electrode and create plasma. All these phenomena are sources of electromagnetic radiation.

When an electric current flows through a conductor, it produces an electromagnetic field around it. The propagation and frequency of the electromagnetic radiations depend on the rise time of the current waveform. Internal PDs cause surge of electrons (current) in the dielectric material. The initial rise time of the current waveform produced by PD is sufficiently small to extend the frequency spectrum to the radio frequency (RF) region [5]. These are called RF emissions. PD pulses are somewhat random and vary in terms of rise time depending on the nature of the PD, location, and material. Hence, the spectrum of the RF emissions is within a wideband spectrum. According to [6], the most suitable frequency bands for preventive maintenance purposes are as follows:

1) high-frequency (HF) band: 3–30 MHz;
2) very high frequency (VHF) band: 30–300 MHz;
3) ultra high frequency (UHF) band: 300 MHz–3 GHz.

B. *Acoustic (Ultrasonic) Emissions*

PDs also cause mechanical vibrations within the electrical equipment. An acoustic signal is emitted as a result of such vibrations.

However, the acoustic signal from a PD source is immune to electromagnetic noise. The frequency of the signal highly depends on the type of PD. In switchgear applications, most of the PDs are surface discharges so the range of acoustic signal is in the ultrasonic region. They can be detected by piezoelectric transducers, fiber optic acoustic sensors, accelerometers, and sound-resonance sensors usual using a frequency band between 10 and 300 kHz.

Ultrasonic detection has been successfully used to locate the PD source inside of the test object. Particularly combined with electrical measurement techniques, acoustic measurement can be useful. However, one of the main issues to overcome is the background sound signal which is very common in many industrial installations. These disturbances may distort the useful signal [7].

C. *Optical Emissions*

Optical ultraviolet (UV) signals are produced as a result of various ionization, excitation, and recombination processes during PDs. Every material emits light of different wavelengths as a result of these phenomena. Intensity and wavelength of these optical signals largely depend on different factors such as insulation material, temperature, PD intensity, and pressure.

The optical spectrum of hydrogen or nitrogen depends on the dominant surrounding materials. PD emissions mainly lie in the UV, visible, and infrared (IR) regions. At the cable terminations inside the switchgear, corona emits the light spectrum range of around 280–405 nm at the medium and high voltage levels. The spectrum of a strong camera flash is between 400 and 700 nm (visible light). Roughly speaking, the light emitted is proportional to the amount of charge transferred due to the PD.

There are two kinds of optical PD detection techniques: direct detection of optical PD signals and detection of the change of an optical beam. A method called optoacoustic measurement catches sonic or ultrasonic range acoustic emissions caused by the PD which results in the deformation of the optical fiber. The main advantage of this method is its immunity to electromagnetic interferences and its high sensitivity compared to conventional electrical techniques [8]–[10].

D. HF Current Components

PD is basically a surge of electrons and, hence, a current pulse. These current pulses are superimposed on the normal load current frequency. These pulses have a very small rise time and an HF. Normal current measuring devices, such as magnetic current transformers (CTs), are not sensitive enough to record such HF pulses, but more sensitive equipment can measure such current components.

Both serial and parallel low-current arc faults have been examined in [11]. The characteristics of arc faults could be found particularly in the HF domain. However, single characteristics of arc faults can also occur in load currents, and thus, it is difficult to find a suitable threshold value in order to determine a specific alarm level.

E. Harmonic Current Components

Because current is regularly measured and analyzed, it would be very convenient to use normal phase current measurements for discovering developing faults. According to low-voltage (LV) investigations reported in [2], it is generally possible to design preventive arc fault protection based on the detection of the harmonic components (third, fifth, and seventh harmonics) within the current. However, this approach has not gained general acceptance. However, similar to analysis of HF current components, it could be one criterion in a multiple-criterion alarm system.

F. Thermal Emissions (IR Emission and Thermal Ionization)

Serial arcing across loose contacts or terminations, ionization, excitation of atoms, and recombination of ions to form a molecule due to PDs are mainly responsible for the heating phenomena. In the case of loose contacts, as discussed in Section II-B, heat is produced due to increased resistance. Ionization may exist only if there is a sufficient air gap. If there is no ionization, there is no ultrasonic emission.

In LV equipment, corona does not exist, because the corona inception voltage is more than 1 kV [12]. Thus, for LV switchgear applications, thermal effect is more prominent than others.

In the case of high-voltage and medium-voltage (MV) switchgears, heat is produced due to serial arcing and corona in addition to the increased contact resistance. Heat produced due to these phenomena lies in the range of IR spectrum of electromagnetic radiation. It can be measured by IR thermometers, thermocouples, bimetallic sensors, etc. For arc fault prediction purposes, online monitoring of temperature is more noteworthy than time-based temperature inspection. This technology is now commercially available through many vendors. The development of wireless sensors has reduced wiring and installation costs. Self-powered sensors provide lower maintenance costs than those requiring batteries.

One of the drawbacks of thermal sensors is the large number of sensors required to provide adequate protection. A single general alarm of a switchgear compartment is seldom adequate. Instead, each contact should be supervised individually. This results in a more complex and costly system.

High temperature causes thermal ionization of materials. Clearly, gases ionize thermally before metals. Some thermal ionization sensors have been implemented for switchgear applications, e.g., that in [1], but they are not common commercially yet.

G. Chemical Emissions

During the process of ionization, a neutral item or molecule loses or gains electrons, thereby acquiring a net charge. These ions combine with the ions of other atoms to produce a molecule which is a by-product of PD. The most common by-products of PD, in air-insulated switchgear, are ozone (O_3) and nitrogen oxide (N_2O). When these compounds react with the moisture and water molecules, they form nitric acid (HNO_3) [12]. Nitric acid is very dangerous for most of the dielectrics and insulators used in switchgear and controlgear. Nitric acid plays a major role in the decomposition of the chemical structure of the insulating materials. These gases can be detected online by using online analyzers, but the chemicals (like nitric acid) are difficult to detect in the air-insulated switchgear. In gas-insulated switchgear (GIS), the change in chemical composition of the SF6 can easily be detected.

IV. Measuring Sensors

A. RF Antenna

An antenna transforms electromagnetic signals into electric signals (current or voltage). For online monitoring purposes, antenna-type sensors are widely used for PD detection in the higher frequency range (HF/VHF/UHF). Since there are many practical constraints for sensor installation, practical antenna designs can differ depending on the application. Different types of antennas are used for different frequency ranges (e.g., loop, biconical, log-periodic, and stick antennas). The characteristics of various types of antenna for GIS applications have been studied and reported in detail in [13].

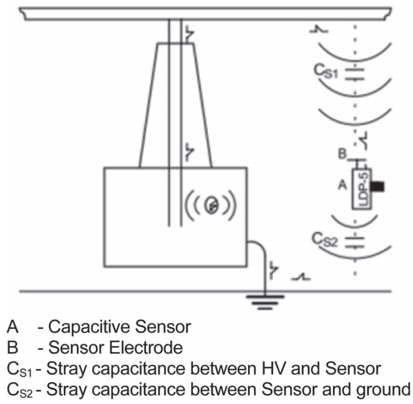

Fig. 2. Principle of capacitive sensor [14].

B. Coupling Capacitor

Coupling capacitors are used to transfer PD energy from a PD source to the measurement setup. Sometimes, this technology is used in proximity sensors for current or voltage measurement. Epoxy–mica-encapsulated capacitive couplers are the most popular sensors, particularly for transformers and rotating machines. Commercially available epoxy–mica couplers (80 pF up to 2 nF) have been widely used.

The main shortcoming of coupling capacitors is that the capacitors have to be designed in order to withstand the 50-/60-Hz high voltage levels of the equipment, and they should be manufactured to have low inductance in order to have an appropriate HF response. These two considerations are the reasons for their relatively high price compared to RF-CT-type detectors, for example. On the other hand, their advantage is that the pulse signals are usually strong because they can be placed close to PD spots. Additionally, the PD activity in each phase can be determined [14]–[16].

C. Capacitive Sensor

Stray capacitance between the high-voltage parts within the equipment and the electrode of the capacitive sensor works as a coupling capacitor. Its working principle is shown in Fig. 2.

D. HFCT

The working principle of an HF CT (HFCT) is the same as that of a normal 50-/60-Hz CT. The magnetic field around a wire (e.g., ground connection or live wire) caused by the HF current induces a voltage in the winding of the HFCT. This sensor is one of the most popular inductive sensors in condition monitoring technologies for all kinds of applications on power system equipment due to its portability, its cost effectiveness, its nonintruding characteristic, and the independency of the frequency of the measured signal [13].

Using a ring type of ferrite core, the basic structure of an HFCT consists of six or seven turns of copper wire over the ring core. Ferrites, being ferromagnetic ceramics with very high resistivity and permeability, are attractive materials for HF applications [17]. An HFCT is particularly useful in coupling for ground rods or cables. The closed- or split-core versions of HFCT are commercially available. The HFCT can detect PD in the range of several hundred megahertz.

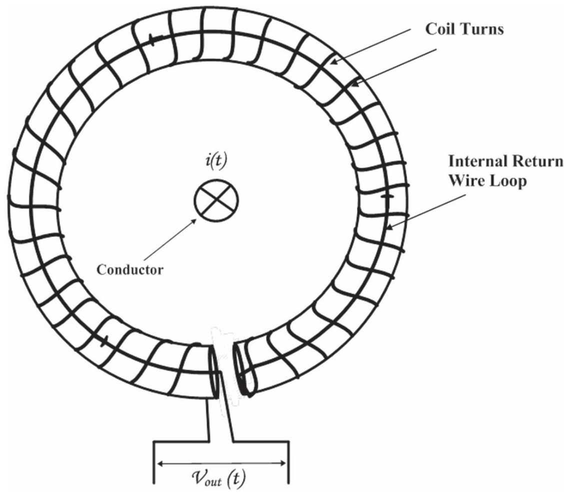

Fig. 3. Operation principle of Rogowski coil.

E. Rogowski Coil

The operating principle of the Rogowski coil is very similar to that of the HFCT. It is designed with two wire loops connected in electrically opposite directions, in order to prevent the effect of external noise and interference. It operates on the principle of Faraday's law of electromagnetic induction. The air-cored coil is placed around the conductor, where current pulses produced by PDs are to be measured. The changing current produces a magnetic field, and the rate of change of current induces voltage in the coil [18].

A Rogowski coil works on the inductive principle and is a sensitive sensor for the PD frequency bandwidth of between 1 and 4 MHz. Fig. 3 illustrates the operation principle of the Rogowski coil.

F. Piezoelectric Ultrasonic Sensor

Piezoelectric sensors rely on the piezoelectric effect created by a PD. These are directional sensors which can give proper results if installed in the proper direction of PD. This type of sensor normally operates in the 100–130-kHz frequency band which is the optimum frequency range of PD in air-insulated switchgear [19].

Commercially available acoustic detection for PD localization, which is applicative for transformers, has been successfully applied. For PDs in air insulation, an air pickup ultrasonic probe is a sensitive way of measuring PD activity. For this sensor to work, there must be a clear air path from the sensor to the discharge site. Delays of a few milliseconds are common [19]. In standard conditions, sound travels at 340 m/s in air, so a distance of 1 m would produce a delay of 3 ms between the electromagnetic signal and the acoustic signal.

Internal discharges in insulating materials do produce ultrasound signals, but these will generally not be picked up when using an ultrasonic probe. The attenuation in the insulation and poor coupling of the air/solid interfaces mean that acoustic signals, which originate inside the insulation, are generally not accessible via ultrasonic methods [19], [20].

G. UV Sensor

When light particles (photons) hit certain semiconducting material, electrons are emitted from the material, or the electrical resistance of the material is changed. This is the basic principle of UV sensors. Such sensors are only sensitive to the light having wavelength in the UV region. PD phenomenon or arcing in the switchgear always emits light in the UV region. UV sensing is specified to the UV spectrum, i.e., 10–400 nm.

H. Thermal Sensors

There is a wide variety of thermal sensors. Some sensors work on the principle of resistance change of the material, whereas others work on electron emission due to heat. Such sensors are less sensitive. If these sensors are kept in contact with the insulation, they may melt themselves due to excessive heat produced as a result of arcing. If they are kept at a larger distance, they may not sense the temperature accurately; rather, they may sense the room temperature only [21].

Second, a number of sensors will be required for the complete protection of the switchgear application. Hence, a lot of wiring is required which may be impractical. It is hardly justified to install sensors in every possible fault location. Therefore, sensors like thermocouples cannot be used for the arc prediction technologies.

There are sensors which can measure IR radiations emitted due to heat. Conventional IR thermal sensors and thermographs can be used to locate a hot spot created due to loose contacts and PD. Such IR thermal cameras are very expensive and not yet practical to implement for online condition monitoring.

There are IR sensors available in the market, which can be installed in the switchgear permanently for the online monitoring purpose. They provide a reference voltage as an output signal [16]. On the other hand, the measurement of all three contacts on a main bus bar section, by using only one sensor, is not very practical because the observation of all three bus points simultaneously is difficult due to various bus orientations [22].

Fiber optic temperature monitoring technology is also available in the market. The physical principle is based on the change of the properties of the light as the temperature of the sensing tip changes [23]. At least one manufacturer has developed a thermal ionization detector which detects the presence of certain ions in LV switchgear applications [21].

I. D-Dot Sensor

The D-dot sensor (Fig. 4) is a simple coaxial wideband PD sensor made from a standard straight bulkhead SMA jack. The probe measures the change in electric displacement (flux) density D ($dE/dt/dV/dt$), hence the name D-dot [24]. The sensor can be installed into the wall of a switchgear compartment by a mounting plate.

Fig. 4. D-dot sensor.

J. Comparison of Sensor Technologies

Table I presents a comparison of sensor technologies based on literature survey [1], [14], [19].

V. LABORATORY MEASUREMENTS

A. Selection of Technologies and Sensors

PDs and temperature-related phenomena (rise of temperature and thermal ionization) were estimated to be the most feasible physical phenomena for detecting developing faults in switchgear. Along with them, the waveforms of current or voltage may provide rather easily accessible information for early warnings, because analysis of these electrical quantities does not necessarily require additional sensors, CTs, or voltage transformers.

For phase 1 testing, PD technologies were chosen, and thermal sensing and analysis of current and voltage waveforms were postponed to be tested in phase 2. The aim of the laboratory measurements is to gain deeper understanding of the phenomena and, finally, to develop prototype sensors for sensing developing faults. Results of the phase 2 testing will be reported in a later paper.

For detecting PD, an HFCT, an RF loop antenna, a D-dot sensor, and a Rogowski coil were chosen, based on sensitivity and applicability requirement and on experience of the laboratory on these sensors. All the sensors were noncommercial, designed for the laboratory.

B. Test Setup

An experimental setup was arranged in a laboratory. Four sensors (HFCT, RF loop antenna, flexible Rogowski coil, and D-dot sensor) were used to measure PD signals. Fig. 5 illustrates the HFCT and loop antenna sensors.

The circuit diagram of the experimental setup is shown in Fig. 6, and the switchgear compartment is shown in Fig. 7.

The outgoing end of the breaker was kept open circuited. An RF antenna was contained inside the switchgear compartment in order to minimize the external noise. A PD source was created by removing the insulation of the stranded conductor at both ends and connecting it to the load termination of the breaker.

TABLE I
COMPARISON OF SENSOR TECHNOLOGIES

Sensor type	Advantages	Disadvantages
RF Sensor	• No connection to the HV equipment is required • Can be used on-line • No coupling device required • Inexpensive, small • Suitable for PD measurement	• Works only near the PD source • Highly sensitive for a wide range of signals • Sensitive to reflected signals • Direction sensitive
Coupling Capacitor	• Frequency range is 1-500 MHz (wide range) • Very high sensitivity • Can detect surface and internal discharges • Availability	• Requires high insulation level • High price • Each sensor is designed for a certain application
Capacitive Sensor	• No physical connection to the HV is required • No coupling device • Very inexpensive • Easy to use • Possibly portably	• Requires direct line-of-sight • Not very sensitive • Sensitive to noise
High Freq. CT	• Robust to external noise • No insulation is required if used around the ground wire. • Can be used on-line • No coupling capacitor required • Very sensitive	• Usually insulation is required to protect from the high voltages if used on the live wire • Costly
Rogowski Coil	• No physical connection • Very high band width • Can be used on-line • Ease of use, non-intrusive • Very sensitive	• Costly
Piezoelectric Ultrasonic Sensor	• Easy and inexpensive • Can detect surface PDs • Immune to electromagn. interference. • Steel or fiber rods can be used to propagate the ultrasonic emissions from the PD source to the transducer. • Very sensitive	• Directional • Sensitive to background sound Signal often attenuated • Electrostatic forces may affect the measurements • Delay
Ultraviolet Sensor	• Very inexpensive and sensitive • Easily implemented	• Difficult to calibrate • External light may create problems
Thermal Sensors	• Inexpensive, available, easy to implement • Temperature of individual phases can be compared	• Calibration for different environments • Placement often difficult • Wiring unless wireless sensors • High number of sensors required
Thermal Ionization Detector	• Reliability • Number of sensors required	• Availability
D-dot sensor	• Very compact, cheap • Wideband spectrum • Very sensitive	• Directional • Sensitive to noise

C. Test Results

The signal-to-noise ratio of the measured signals was low. This is why the signals were processed with wavelet transform filtering. Fig. 8 presents an example of a measured signal (D-dot sensor) before and after filtering. The figure illustrates how noise has been reduced to filter out the good data. It is also noticeable that lower frequency components have been filtered out.

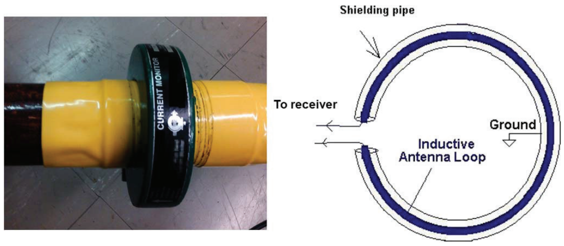

Fig. 5. HCFT and loop antenna sensors.

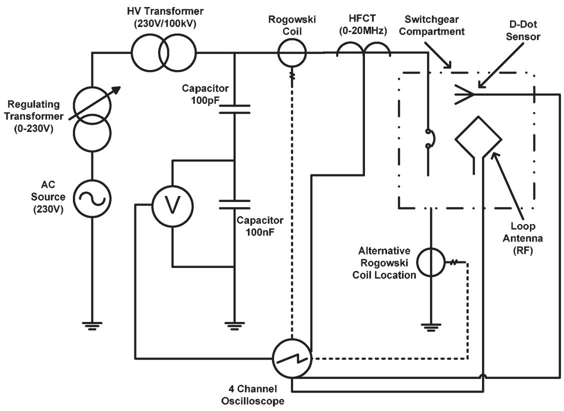

Fig. 6. Diagram of the test setup.

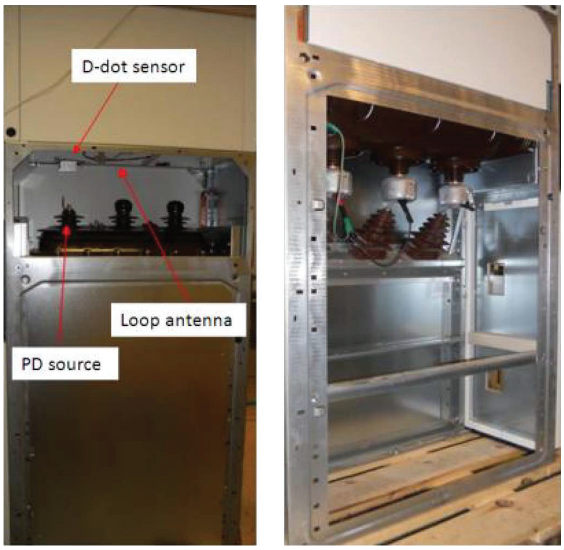

Fig. 7. Top and bottom parts of the switchgear compartment used in the test.

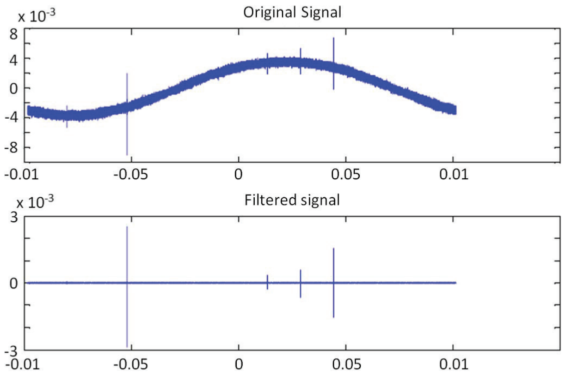

Fig. 8. Original and filtered signals (D-dot sensor).

According to these tests, the D-dot sensor and the Rogowski coil had better signal-to-noise ratio than the HFCT and the loop antenna. It seems that they can be applied for PD measurements in switchgear applications. However, PD sensing requires significant signal processing which makes practical application somewhat more difficult.

D. Further Measurement Needs

Further laboratory testing is focusing on the detection of two other major causes of arc faults: loose connections and defect cable terminations. Along with PD-sensing-based detection, thermal sensors and current- or voltage-waveform-based early detection methods should be examined. In order to avoid excessive cabling or number of sensors, general warning type of thermal detection should be investigated.

Although previous reports regarding detecting developing faults based on analysis of electrical quantities are not very promising, it is justified to further examine these options because they do not require any additional sensors. If existing measurements and relays can be utilized, these methods can be cost effective. A very interesting option could be a combination of several detection technologies, adding redundancy and reducing the risk of false alarms.

VI. Connection of Online Monitoring to Supervisory Control and Data Acquisition or PLC Systems

Online monitoring systems are currently connected to information systems in the control room. Examples of separate communication solutions are given in [23] and [25].

A cost-efficient alternative to a connection to upper level control and monitoring systems would be a connection via an integrated arc-flash protection system. Modern arc-flash protection relays already include digital and analog inputs for receiving the signals from sensor systems, and they include various standardized communication options, like Ethernet I/P, IEC 61850, IEC 103, IEC 101, Modbus, Profibus, DNP3, DeviceNet, and SPA.

VII. Future Combination of Proactive and Reactive Arc-Flash Protection

A. Reactive Protection

The risk of arcing faults cannot yet be totally eliminated by only preventive measures, such as better design or online monitoring. Some arcing faults are still caused by direct human interaction or by other nonpredictable events. This is why particularly the safety aspect requires reactive protection, which operates immediately when the arc flash can be detected.

Conventional protection approaches, based on measurement of electrical quantities and relay algorithms, often lead to rather long arcing times and relatively high incident energy levels. Protection based on optical detection of arc-flash light provides the fastest protection. Normally, the light condition is confirmed by very rapid (< 1 ms) detection of overcurrent, in order to prevent nuisance tripping caused by ambient light. This dual-sensing (light and overcurrent) protection principle is provided by several manufacturers with arc detection times being typically less than 2 ms. When a semiconductor output is applied instead of conventional relay output, the total arc-flash detection and trip time is typically less than 3 ms. Conventional relay output causes an additional mechanical delay of a few milliseconds, but also in that case, the relay latency time is a small component in the overall arcing time, because the operation time of the circuit breaker is typically some tens of milliseconds.

One of the benefits of optical-detection-based arc-flash protection systems is that the number of sensors needed is limited. When applying point-type sensors, typically, three sensors per structure are needed, one for the bus compartment, another for the breaker compartment, and the last for the cable compartment. With the use of loop-type fiber optic sensors, the number of sensors is even lower.

When an arc eliminator (short-circuiting device) is added to the protection system along with an arc-flash relay and a circuit breaker or fuses, minimal arcing time and very low incident energy levels can be achieved. However, so far, this technology has not been widely applied, while the protection system consisting of arc-flash relays and circuit breakers is a de facto standard in many countries.

B. How to Combine Proactive and Reactive Protection

Modern arc-flash relays are equipped with versatile communication options, enabling connection to almost any automation systems. These communication channels can be used to transfer information from online monitoring to upper level in circuit testing systems (ICT). Measurement data from online monitoring can be routed to analog inputs of protective relays, and alarm data can be routed to digital inputs on protective relays or programmable logic controller (PLC) systems.

C. Reliability Benefit of Online Monitoring

Continuous-monitoring-based systems are state-of-the-art maintenance technologies. Even if the safety-related benefit may be small, there are reliability benefits that may justify the implementation of proactive protection.

VIII. Conclusion

An extensive information survey on existing and potential methods for prediction or early detection of arc faults in MV and LV switchgears has been carried out. A number of sensor technologies have been discussed and compared. Most of the preemptive arc fault detection techniques are based on monitoring phenomena caused by PDs or thermal impact.

Four noncommercial PD sensors were tested in a laboratory setting. The tests indicated that Rogowski-coil-based sensors and D-dot sensors are superior to HFCT or loop antennas because they have a better signal-to-noise ratio. In any case, significant signal filtering is required, which makes practical application more difficult, but this can be overcome by today's microprocessor-based integrators. A single sensor technology system will not cover all of the possible potential fault areas.

A potential option would be the combination of several detection technologies into an integrated system. A combination of PD detection, simple thermal indication, and indication based on analysis of current or voltage waveforms would add redundancy and reduce the risk of false alarms. With the computing power of many of the newer arc-flash detection and motor and feeder protection relays, the combination of these inputs could be incorporated to provide an ever broader level of system protection.

The risk of arcing faults may never be totally eliminated by incorporating preventive measures, such as better equipment designs or by adding additional online monitoring. Some arcing faults will still be caused by direct human interaction or by other nonpredictable causes. This is why very fast, effective, and reactive protection, operating when the preemptive effects of an impending arc are detected, is justified along with proactive protection. This combination of protection provides the best overall protection of the equipment as well as the personnel working around the equipment and should be considered for a broader level of equipment and personnel protection.

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Preemptive Arc-Fault Detection Techniques in Switchgear and Controlgear—Part II

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***Abstract*—The significant benefits of preemptive arc-flash protection and the online condition monitoring of electrical equipment are quite well known. Our continuing research focuses on the development of new advanced sensor technologies that are cost-effective, reliable, and efficient for the early detection of faults in order to predict impending arc-flash occurrences in medium-voltage and low-voltage switchgear and controlgear. More extensive and detailed measurements regarding significant defects that lead to an arc-flash event have been completed since the original work in Part I was completed. A more detailed analysis of the results of this additional testing is presented in this paper. It has been documented that the two major noncontact causes that lead to an arc-flash event in switchgear are insulation degradation and thermal stresses. This paper covers the detailed measurement results under both of these conditions. New sensor technologies for both the partial discharge measurement and the thermal detection are introduced and evaluated. An effective signal processing technique, which is needed for extracting the essential indication of a developing fault, is also presented. Finally, this paper outlines how a preemptive arc detection system can be connected to protection, the programmable logic controller, or the supervisory control and data acquisition.**

***Index Terms*—Arc flash in switchgear, discrete wavelet transform (DWT), nonintrusive sensors, online condition monitoring, proactive techniques.**

I. Introduction

An ELECTRIC arc is an unintentional discharge of electricity through air due to the ionization of air molecules. The resultant damages, which are due to arc faults, have been widely reported and understood [1], [2]. There is a difference between the arc-fault current and the available bolted fault current. Bolted fault current is the maximum possible fault current level that can pass through the equipment. It is calculated with zero fault impedance values. For medium-voltage (MV) applications, the arc-fault current is slightly lower than the bolted fault current, but for a low-voltage (LV) system, the arcing current is often significantly lower. Thus, the arc-fault level relative to the bolted fault current level can widely vary from case to case. In the worst case, this fault level may be equivalent to the lightly overloaded connected loads. Hence, the protection scheme may fail to recognize the fault [3].

The causes of arc-flash incidents can be divided into two general categories: the immediate and slowly developing causes. These two causes have been explained in detail in [2]. The immediate causes of arc faults include unintentional contact due to direct human or animal interaction, e.g., tool slippage, animals bridging two phases, etc. Hence, it is very challenging to predict such faults.

The major causes of slowly developing faults are bad connections, insulation degradation, and thermal stresses. Bad connections further lead to thermal stresses [2], [4]. Various types of online sensors for the detection of slowly developing faults have been already developed. This paper focuses on the early detection of slowly developing electrical faults that may lead to an arc flash in switchgear and controlgear. Novel sensors have been tested in the laboratory and compared with a high-frequency current transformer (HFCT) to confirm their sensitivity and reliability. Based on various factors, the differential electric field (D-dot) sensor and the thermal ionization detector (TID) have been selected for industrial implementation. An outline of a typical implementation has been given, and the connection to the upper level monitoring and the control system is discussed in this paper.

II. Discharge Transient Signals

High-voltage (HV) and MV equipment is designed in such a way that the local electric field stress never exceeds a critical value at which insulation breakdown occurs. Despite careful dimensioning, imperfections such as voids may occur in insulation. Breakdown strength and the permittivity of air are much lower than solid dielectrics. Because of this, local electric field enhancement in the air-filled voids or cracks occurs. Under this condition, sudden ionization may occur inside the void or crack, resulting in the generation of positive ions and electrons. When the applied voltage becomes lower than the breakdown strength, the localized electric field is extinguished. The time interval between the ignition and the extinction is extremely short (less than 0.1 μs) [5]. In case of surface discharge and corona discharge, the ionization of the surrounding air takes place if the localized electric field exceeds the dielectric strength. Similarly, the ionization of the air molecules (plasma)

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between the loose contacts occurs if the electric field exceeds the dielectric strength of the air between the contacts. These phenomena are sources of electromagnetic radiation.

Transients are superimposed into the voltage and current waveforms through electric circuits and through airborne electromagnetic radiation. The propagation of electromagnetic waves depends on the frequency spectrum of the radiation. Due to their small rise time, the spectrum of such radiation is in the RF region [6].

III. Selection of Sensors

Sensors are the basic and essential part of an online monitoring system. Sensor characteristics and the location of sensors affect the measured results significantly. The following factors are considered for the selection of the sensor for further consideration for the online monitoring of the switchgear and the laboratory measurements:

1) cost-effectiveness, including the number of sensors and input/output devices;
2) sensitivity and reliability;
3) compactness and ease of use;
4) compatibility with the application;
5) connectivity of the sensor to protection, monitoring, and the control system [supervisory control and data acquisition (SCADA)].

In MV switchgear, insulation degradation and loose contacts slowly lead to a condition that could create a high-power arc flash. Surface discharge or cracks, and voids in the insulation material play significant roles in damaging the insulation. Serial low-power arcing is very common across loose contacts. Therefore, it can be concluded that in MV switchgear, partial discharge (PD) and arcing can be prominent. In LV switchgear, thermal or environmental degradation of insulation is more likely to cause an arc. PD and arcing across loose contacts are not prominent in LV switchgear [1], [3].

On the basis of the reliability and characteristics of the different sensors given in [2], the experience of our research group in various technologies, and by considering the aforementioned factors, the following nonintrusive sensors have been selected for further examination in the laboratory. Fig. 1 shows the pictures of various sensors, and Table I represents the frequency band of these sensors. The following sensor technologies were used for the PD and arcing measurements at MV levels:

1) D-dot sensor;
2) Rogowski coil;
3) loop antenna;
4) HFCT - a reference sensor for comparison.

Thermal monitoring in the LV switchgear was done using the TID. Its figure is shown in the following section.

HFCTs are one of the most reliable sensors being used for the PD measurement in different electrical equipment, including transformers, rotating machines, and gas-insulated switchgear. However, this technology is costly due to the HV insulation and low inductance requirements. However, it was a good choice to confirm the reliability and accuracy of the other sensors. For our research, a commercial HFCT was used to validate the reliability of the other sensors.

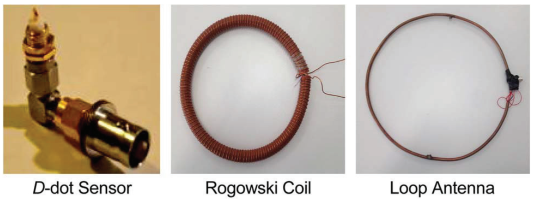


Fig. 1. Sensors used in the laboratory measurements.

TABLE I
Properties of the Sensors Used

Sensor	Lower Cut Off Frequency	Upper Cut Off Frequency
HFCT	1 Hz	100 MHz
D-dot Sensor	1 Hz	18 GHz
Rogowski Coil	1 kHz	150 MHz
Loop Antenna	1 kHz	100 MHz

$$i(t) = kC\frac{dE(t)}{dt}$$

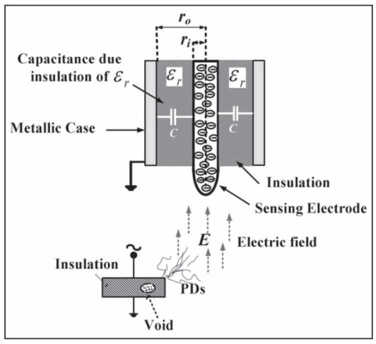


Fig. 2. Working principle of the D-dot sensor.

IV. Development of Selected Sensors

A. D-dot Sensor

The D-dot sensor that is used in our measurements is shown in Fig. 1. It is a coaxial sensor made from a standard straight bulkhead subminiature version A (SMA) jack. The working principle has been already explained in [2] and is shown in Fig. 2. The normal electric field in the energized equipment generates a surface charge density on the center conductor of the sensor. At zero frequency, the center conductor is held at zero potential through the terminating resistance; however, at higher frequencies (e.g., for the PD or the arcing) with a changing electric field, the current is induced in the center conductor due to the surface charge [7]. The output of a D-dot probe is proportional to the derivative of the electric field with respect to time dE/dt and is thus recorded by the oscilloscopes as dV/dt.

The D-dot sensor is a very inexpensive and robust solution for the discharge measurement within the switchgear. It is very small in size and can be installed almost anywhere inside a switchgear compartment. It can be installed on the side metallic sheets of the switchgear or just by drilling a hole in

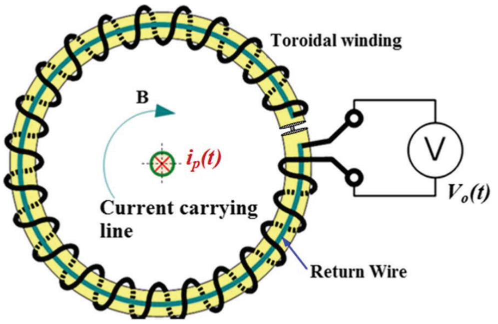


Fig. 3. Construction of the Rogowski coil.

the metallic plate (i.e., flush-mounted). The diameter of the sensor can be as small as 1.5 cm. It has a high bandwidth (up to 18 GHz), which makes this sensor sensitive enough for most types of discharges inside the switchgear [8]. It is immune to any external discharges if it is installed in a closed and grounded metallic compartment because earthing helps to ground the external noise. However, it may capture some other high-frequency signals and system frequency signals due to its high bandwidth. This noise can be identified and eliminated by the discrete wavelet transform (DWT) analysis.

B. Rogowski Coil

A Rogowski coil is an air-cored induction sensor. The coil's winding is constructed with two wire loops that are electrically connected in "opposite" directions. The coil is installed around a current-carrying conductor (power phase or ground connection). The voltage that is induced in the windings of the coil due to the changes in the magnetic field around the current-carrying conductor is given by

$$V_o(t) = -\mu_o A_c n \frac{di_p(t)}{dt} = -M_c \frac{di_p(t)}{dt} \quad (1)$$

where μ_o is the permeability of free space, A_c is the cross-sectional area of the core, n is the number of turns, i_p is the primary current, and M_c is the mutual inductance. The basic construction of the sensor is given in Fig. 3.

The "opposite" connection of the wire loops leads to a better compensation of the effect of any external noise. Discharge transients cause current pulses to be superimposed on the power supply. Transients tend to ground through any closest ground path. Therefore, a Rogowski coil can be installed either on live phases or on ground terminals in order to measure transient pulses. Rogowski coils can be designed to measure the high-frequency discharge pulse with certain accuracy. Resonant frequency, bandwidth, and sensitivity are the key parameters to be considered when designing the coil. If the Rogowski coil is to be installed on a phase conductor, it must be designed at an insulation level of the nominal voltage. This can make the coil design more costly. Installing the coil on the grounding conductor (cable sheath) does not require higher insulation strength.

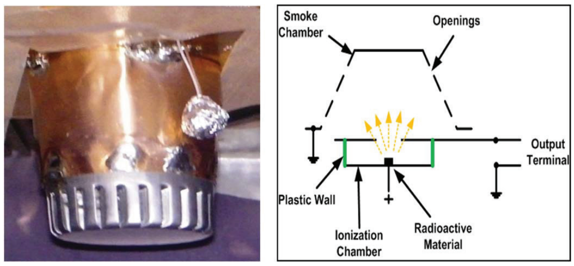


Fig. 4. TID and its operating principle.

C. Loop Antenna

RF antennas transform electromagnetic energy into electrical energy. Discharge transients are sources of electromagnetic emissions. These emissions can be detected by RF antennas through Faraday's law of electromagnetic induction. The output of the loop antenna is proportional to the changing magnetic field. The changing magnetic and electric fields are directly proportional to each other. Hence, it is correct to state that the loop antenna measures the changing electric or magnetic fields, which is similar to the D-dot sensor.

Various types of antennas are available commercially. They can be also easily designed and constructed. This is a very inexpensive and robust solution. Antennas can be installed at a certain location from the possible faulty points inside the switchgear. Proper signal processing is necessary to eliminate high-frequency noise from the captured signal in order to get useful information from the measurement.

D. TID

In the LV switchgear, one of the most dominant causes of high-power arc faults is a bad connection. Bad connections lead to heating and ultimate damage to the connection, possibly leading to an arc and fire in the switchgear. Heating causes the surrounding air to ionize, creating positive and negative ions. Fig. 4 shows the TID and its operating principle. The detector contains two chambers: an ionization chamber (interior) and a recombination or smoke chamber (outer). Both are maintained at a certain potential difference and both act as two electrodes. The radioactive material that is contained in the interior chamber causes the ionization of the air inside the ionization chamber. The smoke chamber contains the ions that are created by the thermal effects outside the detector. In a normal condition, there is a very small current flow (in picoamperes) between the electrodes due to recombination, and this causes a constant potential at the center conductor (the detector output). During a prominent thermal effect, the potential at the center conductor varies and can be calibrated in terms of temperature. An electronic amplifier is involved to amplify the measured signal. Potential problems can be identified much earlier than the melting point of copper. It is also a low-cost solution and a proven technology [4], but this technology has not been yet widely promoted commercially. Some manufacturers have incorporated smoke and thermal detectors as a part of arc protection systems in switchgear.

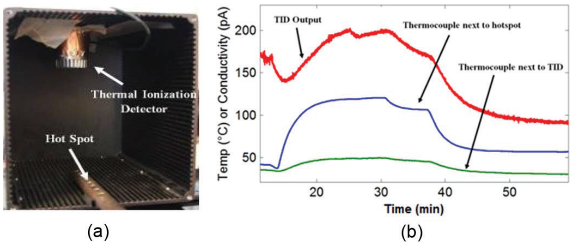


Fig. 5. Setup 1. (a) Thermal monitoring. (b) Measured results.

V. Measurement Setup

The measurements were carried out using three different setups. Setup 1 was implemented for thermal monitoring. Setup 2 was utilized for the PD measurement (the PD in voids and the surface discharge) inside the switchgear. Setup 3 was implemented for the arcing (low power) across a very small arc gap (0.2 mm).

A. Thermal Monitoring (Setup 1)

The sensor was developed in the university's HV laboratory by using the radioactive material that is contained in the domestically used ionization-type smoke detectors. The measurement setup was arranged in such a way that a hot spot was created in a metallic enclosure. The hot spot was fabricated by using a copper tube and a soldering iron. The soldering iron, having controlled the temperature, was placed inside the copper tube. The TID was installed at the ceiling of the enclosure, whereas the hot spot was placed at the base of the enclosure. Two calibrated thermocouples were installed in the enclosure, i.e., one next to the hot spot and the other next to the TID. The setup is shown in Fig. 5(a).

The temperature of the hot spot was varied and its effect on the output of the TID and the thermocouples was studied, as shown in Fig. 5(b). Due to the diffusion in the surrounding air, the temperature of the hot spot and the temperature at the TID surface are totally different. However, the TID behaved similar to the thermocouple that is installed next to the copper tube. It shows that the TID is very sensitive to the thermal ionization effects. Practically, thermal sensors cannot be installed very close to all the joints in the LV switchgear; therefore, the TID is another choice for the thermal monitoring in the LV switchgear. TIDs can be installed at the ceiling inside an LV switchgear enclosure to monitor a section of the switchgear.

B. PD Measurements (Setup 2)

PD measurements were carried out inside the switchgear panel. The circuit breaker was put in the closed position, and the outgoing side of one phase was open-circuited, whereas the other two phases were grounded. PD sources were connected to the open end of the phase. The switchgear was placed on a wooden base and its enclosure was grounded through a single point. The PD source was energized through an LV regulating transformer and a 0.23/100-kV transformer. Fig. 6 shows the circuit diagram of the setup. The D-dot sensor was fixed inside the upper portion of the switchgear compartment

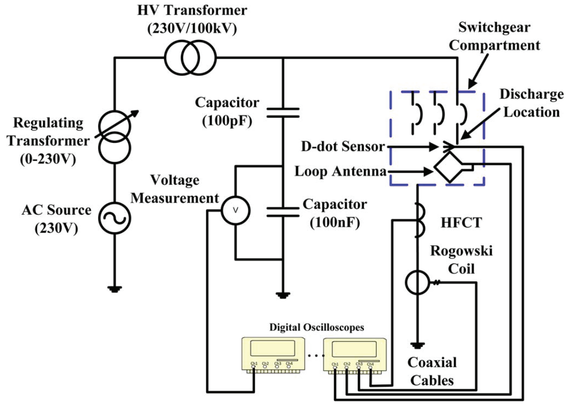


Fig. 6. Setup 2: circuit diagram.

at a distance of 13 cm from the discharge location. The loop antenna was placed in the same area at a distance of 16 cm from the discharge point, whereas the HFCT and the Rogowski coil were installed around the ground connection of the switchgear. The location of the sensors is illustrated in Fig. 7(a). The HV transformer and the capacitive divider circuit for the voltage measurement are shown in Fig. 7(b). Discharge pulses were measured at various voltage levels by the given sensors.

The sensors were connected to the digital oscilloscopes through a 50-Ω coaxial cable to a 50-Ω channel input of the oscilloscope. Data were captured at a sampling frequency of 20 GHz using a 16-bit digital oscilloscope. The measurements were carried out under the following discharge conditions, which are also depicted in Fig. 8:

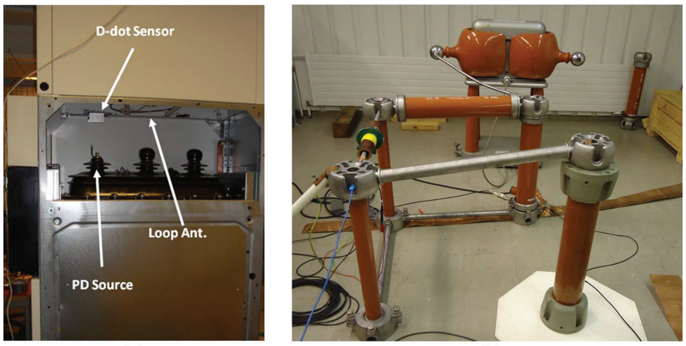
1) the PD in the void;
2) the surface discharge at the insulator surface.

The voltage was gradually increased until it started to produce PD signals. The discharge transients are superimposed on the electrical parameters (the voltage and the current), causing airborne electromagnetic radiation. The transients passing through the electrical network are much stronger than the electromagnetic signals passing through air. Moreover, the signals are attenuated while passing through the air more than by passing through the conductors.

C. Arcing Measurements (Setup 3)

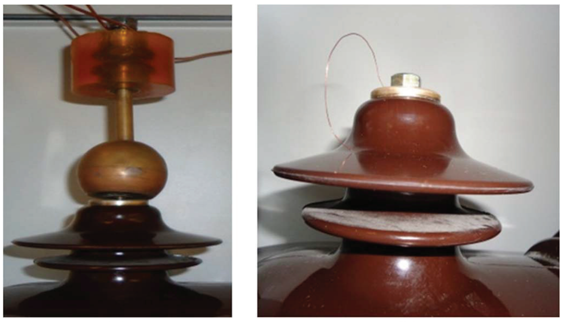
The behavior of the arcing across loose contacts is similar to the low-energy arcs (sparks) across a small arc gap. In this way, both of them cause RF electromagnetic emissions. In order to study the response of various sensors under the arcing across loose contacts, a very small arc gap (rod–sphere) of 0.2 mm was implemented. The system was energized by an LV regulating transformer and a 0.23/100-kV transformer. Fig. 9 shows the circuit diagram, and Fig. 10 represents the physical placement of the different sensors (about 1 m away from the arc source). This measurement setup also includes the capacitive divider for the voltage measurement.

The sensors were connected to the digital oscilloscopes through a 50-Ω coaxial cable to a 50-Ω channel input of the



(a) (b)

Fig. 7. (a) Location of the sensors inside the switchgear panel. (b) HV transformer and the capacitive divider.



(a) (b)

Fig. 8. PD sources. (a) PD in the voids in an epoxy insulator. (b) Surface discharge over an insulator.

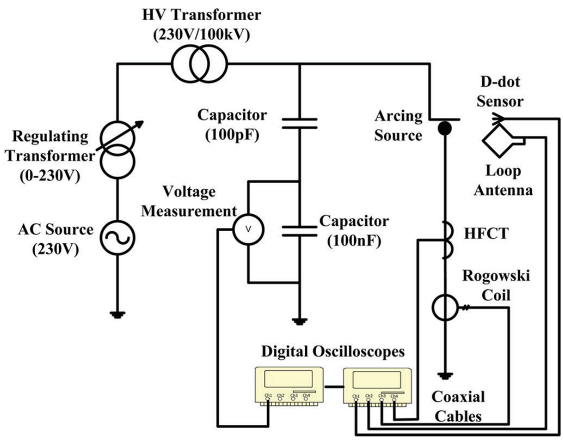


Fig. 9. Setup 3: circuit diagram.

oscilloscope. Data were captured at a sampling frequency of 20 GHz using a 16-bit digital oscilloscope.

VI. Signal Processing

A. DWT

A wavelet is a small waveform with limited duration and a zero mean value. It starts from zero, oscillates in amplitude,

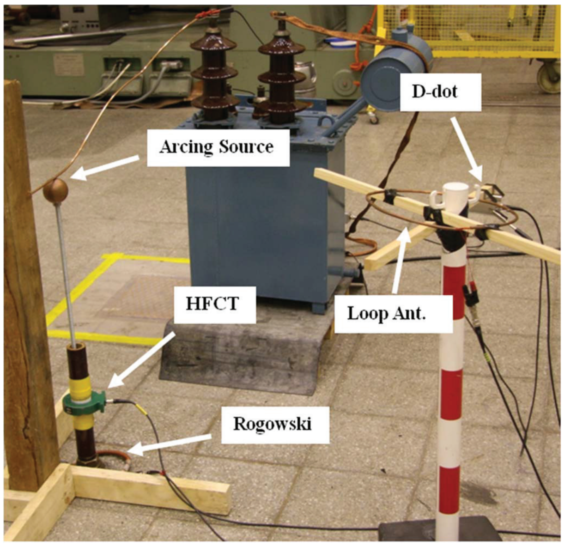


Fig. 10. Arc gap and placement of the sensors.

and decays to zero again. A WT is a tool that is widely used to denoise images. Currently, it is being used for the analysis of transient (nonstationary or time varying) signals in electrical and electromagnetic applications. It works similar to the Fourier transform (FT), which breaks up a signal into sine waves of various frequencies. The WT breaks up a signal into shifted and scaled versions of the original (or mother) wavelet. The WT can be applied to either continuous signals or discrete (digital) signals, and hence has two types, i.e., the continuous wavelet transform (CWT) and the DWT. The DWT was used for our digitized data that are recorded by the oscilloscopes. The DWT is an effective method of the WT for discrete signals. Unlike the CWT, the DWT is faster and does not generate redundant data [9].

The online measurements are not pure fault transient signals, but they also contained varying electromagnetic noise, such as the discrete spectral interference, periodic pulses, random pulses, white noise, and reflected signals from the walls of the compartment. The DWT has to be applied on measurements before proceeding to the analysis of the data.

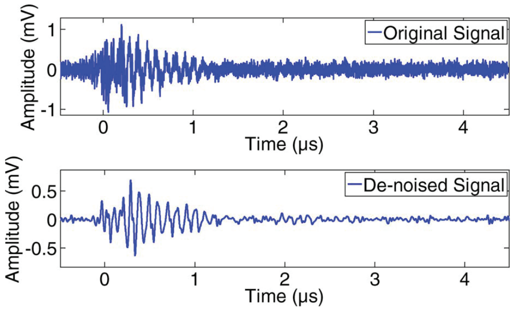


Fig. 11. Original and denoised signals of the D-dot sensor.

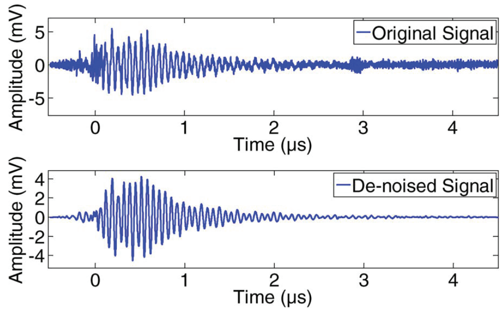


Fig. 12. Original and denoised signals of the Rogowski coil.

B. Denoising in DWT

Arcing and PD signals are transient pulses of very small rise time and have a wideband spectrum. It has been elaborated in [10] and [11] that the DWT is the most effective way to denoise such signals. The procedure to apply the DWT starts with the selection of the mother wavelet according to the signal and noise characteristics. The mother wavelet, having the closest resemblance to the original signal, is preferred for the denoising from interference. Among the wavelets that are available, the Daubechies wavelet family has almost all of the required properties, such as compactness, limited duration, orthogonality, and asymmetry, for the analysis of fast transient and irregular PD pulses [10]. Therefore, the Daubechies wavelet family was selected to denoise the PD measurements in this paper. After the selection of the mother wavelet, the number of levels are defined up until which the original signal is to be decomposed into the approximation and detail coefficients. The components corresponding to the PD signals, the interference, and the random noise are identified at each level by visual inspection and knowledge of frequency characteristics. A threshold level is defined for each level to filter the noise. The components that correspond to the interference and the random noise are discarded. Denoised signals are composed of cutting the low-level noises in the useful signals by thresholding and by adding up all the useful signals. The reconstruction of the signals based on the selected components gives an interference-free signal.

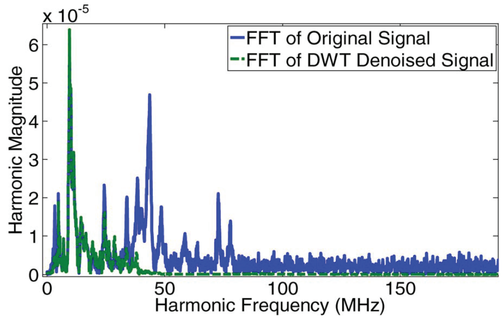


Fig. 13. FFT of the D-dot sensor signal (original and denoised).

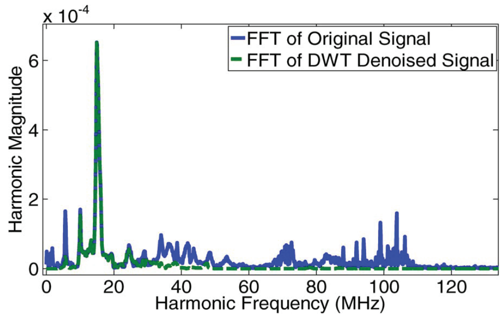


Fig. 14. FFT of the Rogowski coil signal (original and denoised).

C. Comparison Between Original and Denoised Signals

The signals captured by the D-dot sensor and the Rogowski coil were denoised by using the DWT. The Daubechies mother wavelets were selected, and the signals were analyzed up to nine decomposition levels. The useful signals were identified to be the decompositions 6, 7, and 8 in both signals. Hence, the denoised signals were reconstructed by adding these compositions. The denoised and original signals from the D-dot sensor and the Rogowski coil are plotted on the same time scale in Figs. 11 and 12, respectively. The figures show that the captured signals contain a lot of high-frequency noise before and after the initiation of the discharge signal, whereas the denoised signals do not contain such noise. The fast FT (FFT) spectra of the original and denoised signals of the D-dot sensor and the Rogowski coil have been plotted in Figs. 13 and 14, respectively. The FFT of the original signals show that the spectra have dominant frequencies up to 100 MHz. The FFT spectra of the denoised signals show that the useful signal lies roughly in the range of 5–30 MHz. The other higher frequencies that are visible in the FFT of the original signal correspond to various types of noise.

This confirms that the WT technique successfully denoised the actual PD signals from the interference, the electric and magnetic field coupling, and the reflections in the measurement system. In order to get a clear idea about the nature of the fault, it is necessary to perform such denoising before analyzing the signals and finding the fault characteristics.

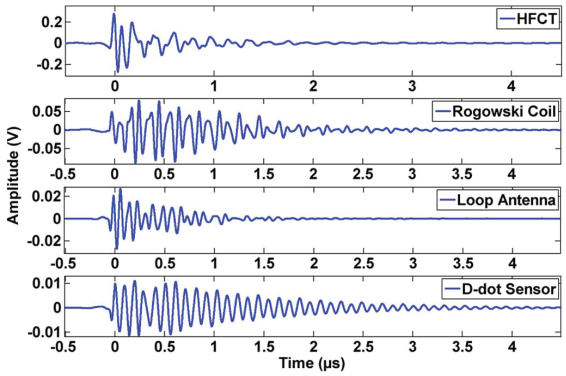


Fig. 15. PD in the voids in an insulator.

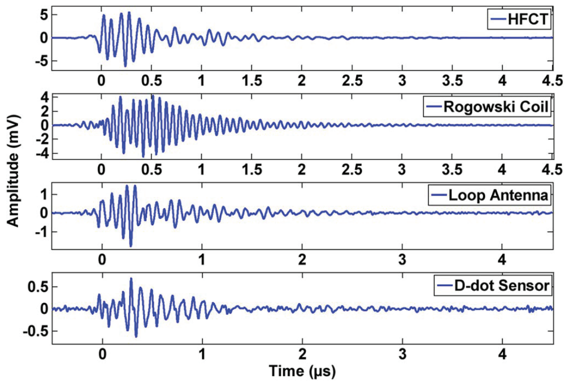


Fig. 16. PD over the insulator surface.

VII. Analysis of the Measured Results

A. Time-Domain Comparison Between Signals of Different Sensors

The signals that are captured by all the sensors were plotted in Fig. 15. Since the HFCT and the Rogowski coil were installed around the ground connection, the signals that they captured have higher amplitudes. The HFCT is the most sensitive in this case followed by the Rogowski coil, the loop antenna, and the D-dot sensors, respectively. The HFCT and the Rogowski coil measure the change in discharge current di/dt, whereas the loop antenna and the D-dot sensor measure the changing magnetic field and electric field, respectively. Since all the sensors have a different bandwidth and a different sensitivity, a direct proportionality between their measurements cannot be determined. Due to the difference in the measured parameter and bandwidth, the measured signals slightly differ from each other. However, it is clear that all the sensors responded to the same discharge. This proves the reliability and usability of the sensors used.

The sensors are considered good, although they capture the signals with lower amplitude. The important thing is that, if the amplitude of the useful signal is lower, the amplitude of the noise must be relatively much smaller, as is the case with the loop antenna and the D-dot sensor.

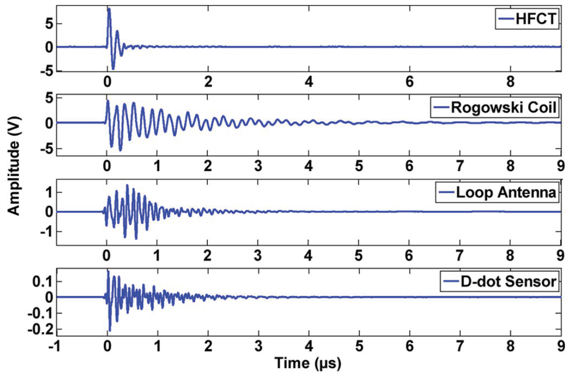


Fig. 17. Arcing at a 0.2-mm arc gap (rod–sphere).

TABLE II
Frequencies of the Signals Captured by the Different Sensors Under Various Types of Discharges

Type of Discharge	HFCT	Rog. Coil	Loop Ant	*D*-dot
PDs in Epoxy Insulator	3-20 MHz	3-25 MHz	5-25 Mhz	3-20 MHz
Surface Discharge Over the Insulator Surface	5-35 MHz	5-40 MHz	5-40 MHz	5-40 MHz
Arcing at 0.2 mm Gap Distance	1k-10 MHz	1k-13 MHz	1k-25 MHz	1k-27 MHz

The outputs of the different sensors under the surface discharge condition and arcing have been plotted in Figs. 16 and 17, respectively. In the case of the PD over the insulator surface, the sensors behaved similar to the PD in voids, but there is clearly a different output of sensors in the case of arcing. Arcing causes a high-energy impulse in the system; hence, the output of the sensors is much higher. The HFCT is designed to measure the low-frequency and high-frequency current pulses; this is the reason less oscillations are observed in the HFCT signal due to the dominance of the low-frequency current pulse.

B. Frequency-Domain Comparison

The FFT of the denoised signals from each sensor under the different types of discharges were plotted in order to study the frequency response of the three sensors. Table II shows the frequency ranges of the signals captured under each discharge condition. Due to the difference in design parameters, measured variables, and difference in sensitivity, the frequency spectrum of various sensors slightly differ, e.g., the FFT or arcing signals captured by the HFCT and the Rogowski coil have lower frequencies compared with those captured by the loop antenna and the D-dot sensor due to their current-measuring capability; hence, the effect of the lower frequency arcing pulse was dominated.

The frequencies of the surface discharge are the highest, and the frequencies of the arc signals are the lowest, even some are in the range of kilohertz. Generally, it is understood and believed that the frequency spectrum of the PD is higher than that of the arcing. Such is observed in Table II. It can be concluded that all the sensors are consistent and confirm the reliability of each other to detect certain faults.

C. Cumulative Energies and Peak-to-Peak Values

The apparent charge and rise time of the discharge pulse cannot be measured or calculated using RF sensors. The peak value V_P and peak-to-peak value V_{PP} of the signal voltage give some idea about the intensity of the discharge, but the exact relationship between these values and the apparent charge is still very complex. Another parameter, which is the cumulative energy of the measured signal, can provide more insight concerning the extent of the discharge. This is because some signals may not have higher amplitude, but they may last longer. Thus, the peak-to-peak value might be less, but the cumulative energy can be much higher. As such, the cumulative energy could be considered a more reliable parameter than the peak-to-peak value.

The power and energy across the input resistor of the oscilloscope can be calculated as follows:

$$P_i = \frac{U_i^2}{R} \tag{2}$$

$$E_i = \frac{\Delta t}{R} U_i^2 \tag{3}$$

where Δt is the sample duration, R is the input resistance of the oscilloscope, and U_i is the sample voltage. Equation (3) gives the energy of one sample. If all the sample's energies are summed, the total energy of the captured signal is obtained, as shown in the following:

$$E_{\mathrm{Tot}} = \frac{\Delta t}{R} \sum_{i=1}^{N} U_i^2 \tag{4}$$

where N is the number of samples.

The peak-to-peak values V_{PP} and cumulative energies E_{Tot}, which is also abbreviated as E_C, of all the signals captured by the different sensors have been calculated, enabling the characteristics of the sensors to be compared. Table III(a)–(c) shows the comparison between the peak-to-peak values and cumulative energies of the signals measured by the HFCT, and the Rogowski coil, the loop antenna, and the D-dot sensor, respectively. Only ten random samples have been taken from the measurement chain of the arc discharge. For the purpose of comparison, the ratio of the peak-to-peak values and cumulative energies of the signals has been calculated. If the two signals are consistent in nature, their peak-to-peak value ratios and energy ratios will be also consistent. Any effect or change in the radiation pattern will affect the two parameters measured by both the sensors in the same extent. Therefore, the ratio will remain the same. If the ratio changes, the two measured signals are not consistent with respect to each other. The results clearly show that the ratios are almost constant, although the peak-to-peak values and cumulative energies of the various samples are different. This proves that all three sensors measured the same signals as the HFCT does. Hence, all these sensors can give satisfactory results for the online monitoring of the switchgear.

TABLE III
COMPARISON OF THE PARAMETERS MEASURED BY THE HFCT AND VARIOUS SENSORS

(a)

	HFCT		Rogowski Coil		Ratio	
	V_{PP1} (V)	E_{C1} (nJ)	V_{PP2} (V)	E_{C2} (nJ)	V_{PP1}/V_{PP2}	E_{C1}/E_{C2}
M1	13,207	92,05	10,109	187,39	1,306	0,491
M2	13,681	95,13	10,400	198,25	1,316	0,480
M3	13,768	96,29	10,489	202,32	1,313	0,476
M4	12,867	86,66	9,824	176,23	1,310	0,492
M5	13,793	97,56	10,531	202,80	1,310	0,481
M6	13,794	100,59	10,547	204,97	1,308	0,491
M7	12,863	87,23	9,856	177,74	1,305	0,491
M8	12,852	86,93	9,839	176,85	1,306	0,492
M9	12,760	85,77	9,759	174,74	1,307	0,491
M10	13,554	97,25	10,375	198,19	1,306	0,491

(b)

	HFCT		Loop Antenna		Ratio	
	V_{PP1} (V)	E_{C1} (nJ)	V_{PP2} (V)	E_{C2} (nJ)	V_{PP1}/V_{PP2}	E_{C1}/E_{C2}
M1	13,207	92,05	2,864	8,251	4,610	11,156
M2	13,681	95,13	2,970	8,916	4,606	10,670
M3	13,768	96,29	2,971	8,907	4,633	10,810
M4	12,867	86,66	2,769	7,784	4,647	11,132
M5	13,793	97,56	2,979	8,952	4,629	10,899
M6	13,794	100,59	2,953	8,813	4,671	11,414
M7	12,863	87,23	2,812	8,043	4,574	10,845
M8	12,852	86,93	2,792	7,844	4,604	11,083
M9	12,760	85,77	2,779	7,800	4,592	10,995
M10	13,554	97,25	2,854	8,312	4,750	11,700

(c)

	HFCT		*D*-dot		Ratio	
	V_{PP1} (V)	E_{C1} (nJ)	V_{PP2} (V)	E_{C2} (nJ)	V_{PP1}/V_{PP2}	E_{C1}/E_{C2}
M1	13,207	92,054	0,384	0,099	34,40	933,78
M2	13,681	95,127	0,397	0,108	34,50	883,02
M3	13,768	96,286	0,399	0,109	34,52	880,21
M4	12,867	86,656	0,373	0,092	34,53	937,27
M5	13,793	97,560	0,401	0,110	34,41	890,71
M6	13,794	100,592	0,399	0,109	34,57	921,67
M7	12,863	87,226	0,375	0,095	34,34	916,23
M8	12,852	86,935	0,375	0,093	34,28	931,13
M9	12,760	85,769	0,373	0,091	34,25	941,32
M10	13,554	97,247	0,366	0,097	36,99	1001,15

VIII. OUTLINE OF THE CONNECTION OF ONLINE MONITORING TO PROTECTION AND SCADA SYSTEMS

The essential purpose of the online monitoring of switchgear and controlgear is to prevent high-energy faults. An online monitoring system should be able to analyze the measured data and provide appropriate information to upper level systems, such as the protection system, the programmable logic control system, the distributed control system, or the SCADA system. Based on the required signal processing capacity that is presented, it seems justified to have a separate processing unit, which collects the information from the sensors and sends the

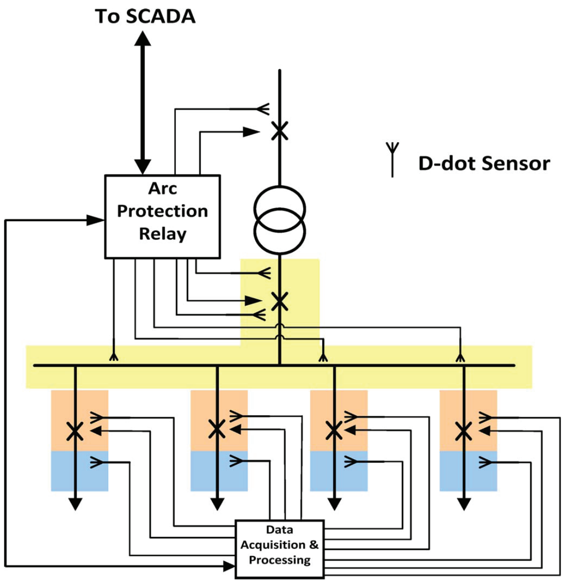


Fig. 18. Typical industrial implementation for MV switchgear.

filtered information to either of the remote systems that are monitored or to the central control station (e.g., through the SCADA).

The information to be sent can be an analog signal, indicating, e.g., the level of PD activity, or it could be a digital information as well, e.g., categorized into "alarm" and "trip" categories. An "alarm" signal could be an early warning, giving an opportunity to check other possible indications of developing fault and to change the power system switching state to isolate the zone of the developing fault. On the other hand, the detected high temperature or PD activity could activate a trip signal in a protection relay. Because protection relays collect information on the basis of the electrical quantities of the system and the unconventional sensors (PD or thermal), it would be relatively simple to set up multicondition criteria for relay operation. A more detailed specification of possible protection system settings is beyond the scope of this paper.

Fig. 18 shows a possible implementation of a typical MV distribution system. In this figure, only the D-dot sensor has been implemented; however the thermal sensors can be also combined in the same system. The data acquisition and signal processing unit acquires data at a certain data rate and performs the signal processing of the data before sending to the upper level systems via the protection relay.

IX. Conclusion

To determine the performance and further development of an online monitoring system that is able to detect slowly developing faults in switchgear, five different types of sensors were tested in a laboratory. All the sensors used in this research were developed by the authors.

A TID was used to study the thermal effects in LV systems. The output of the TID was compared with the thermocouples installed at different locations in the enclosure. Results show that the TID installed at the ceiling of the enclosure is as sensitive as the thermocouple installed next to the hotspot. It is impractical to install a sensor very close to the hotspot; therefore, the TID is a good choice.

Electromagnetic emissions, which resemble the impacts of the defects in MV insulation, were created, and the output signals of the sensors were recorded. Because the recorded signals include a lot of noise, a denoising method had to be applied in order to extract the useful information from the measured data. A DWT was applied for this purpose, and both the principle of the technique and the results have been presented.

The measured signals have been analyzed through different ways. The time-domain and frequency-domain analysis of the measurements indicate that all the sensors captured the same fault; however, there was a time and frequency shift between the measured signals due to the difference in design and measurement parameters. Comparison between the peak-to-peak values and the cumulative energies with respect to the HFCT show the consistency and reliability of each sensor. Finally, the connection of the online monitoring system to the protection or SCADA system has been outlined.

Comparisons of the size, cost, ease of use, sensitivity, and reliability of different sensors show that the D-dot sensor is the most favorable sensor for the discharge (PD or arcing) monitoring in air-insulated MV switchgear. The TID is proposed for LV switchgear.

The results of this paper, thus far, outline the capabilities and practical usefulness of preemptive sensing technologies and signal processing techniques. When used in combination with other existing protection technologies, an effective preemptive protection system may be achieved.

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Research Article

Benefits and performance of IEC 61850 Generic Object Oriented Substation Event-based communication in arc protection

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Abstract: Internal arc fault in switchgear is an especially challenging fault type. High-power faults may lead to a serious hazard to personnel, significant damage to equipment, and extensive system outage. As the nature of arc faults is explosive, very fast protection is required. This study first presents a state-of-the-art technology for effective arc protection and then focuses on communication in arc-flash protection systems. Developments based on IEC 61850 Generic Object Oriented Substation Event communication are introduced including verification of the performance of the new system architecture.

1 Introduction

High-power arcing faults in switchgear are very hazardous and devastating. Personnel can be seriously affected by the radiation, heat, pressure wave, and the flying particles associated with the arc flash. These impacts can also destroy the switchgear and cause substantial economic losses either by directly destroying components of the system or indirectly, by causing process outages or medical and legal expenses. The exploding nature of arcing faults requires far more efficient protection than what traditional overcurrent protection is able to provide.

Various approaches to arc-flash protection have been presented and commercialised. The most common methods have been discussed in [1, 2]. Since the energy released in arc-flash faults is proportional to the duration of the arc [3], minimisation of the arcing time is a very effective means in mitigating consequences of the fault [4]. The arcing time can be reduced by fast detection of the arc and by fast elimination of the arc.

The protection approach based on very fast detection of light has been adopted by several manufacturers and is now widely used all over the world. In most applications, the existence of the arc is verified by simultaneous detection of some other arc-related phenomena along with the intense light, the most common secondary phenomena being overcurrent. The protection scheme based on the simultaneous detection of overcurrent and light provides extremely fast operation [2]. The dominant component determining the arcing time in this type of protection is the operation time of the circuit breaker, which is some tens of milliseconds, whereas in the case of traditional overcurrent protection the dominant component is the operation time of the relay.

Along with the speed requirement, reliability and security are primary requirements for arc protection systems. These requirements apply to both individual components as well as to the whole system including the necessary communication and self-supervision of the system.

This paper presents a short overview of state-of-the-art arc protection technology, and then focuses on the communication aspects of arc protection systems. The progress beyond the state-of-the-art is presented in the analysis of the applicability of IEC 61850 Generic Object Oriented Substation Event (GOOSE)-based communication for arc-flash protection. In addition to theoretical evaluation, a system using this approach is introduced, and its performance is evaluated.

2 Arc protection based on simultaneous detection of light and overcurrent

2.1 Importance of the arcing time

A number of arc-flash mitigation approaches have been introduced and applied. Most of the methods are based on either limiting the fault current or reducing the arcing time. Since the incident energy of an arc fault is proportional to the arcing time, the minimisation of the arcing time is the most common arc mitigation technique. The arcing time and the released energy can be very efficiently reduced by the dual-sensing method, based on simultaneous detection of light and overcurrent. The detection time is minimal and the arcing time consists almost only of the operation time of the primary circuit device, in most cases the circuit breaker, extinguishing the arc. This approach has been adopted by several manufacturers, and it is already a de facto standard in some countries.

2.2 Fast detection of light

The tests carried out in [5] revealed a strong correlation between the power of the arc and the intensity of the observed light. High-power arc faults can thus be detected practically immediately by using light sensitive sensors such as a photodiode (point type of sensor and lens sensor) or an optical fibre (loop type of sensor). Optical sensors provide an extremely fast and clear indication of an arc flash [6]. The detection time is <1 ms [7–10].

Fibre sensors are more cost effective because larger areas can be covered with just a single loop sensor. On the other hand, point sensors provide more accurate location information of the arc, enabling more selective protection. Fig. 1 shows examples of fibre sensor and point sensor installations.

There is no exact universal threshold value which could always differentiate between light emanating from arc faults and the light coming from other sources. A vast practical experience has shown that the sensitivity of ∼10,000 lux provides excellent results. Sensors with the sensitivity of ca. 10,000 lux with specific spectrum very likely detecting the light in all relevant arc fault situations within metal-enclosed switchgear while at the same time the risk of false activation is low. This is especially true in cases where the detection of the arc is also verified by the detection of overcurrent.

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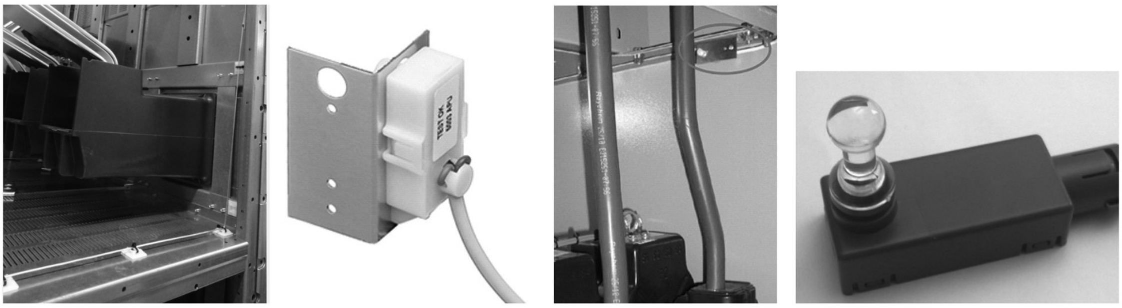

a b c d

Fig. 1 *Fibre sensor and point sensor installations*

a Fibre sensor installation, the attached fibre circulating in the switchgear compartment
b Point sensor and a mounting plate
c Point sensor and the mounting plate installation inside the switchgear
d Another type of point sensor

2.3 Fast detection of overcurrent

To eliminate the possible nuisance tripping caused by external light, detection of (instantaneous) overcurrent is often required in parallel with the detection of light. Together, these two conditions provide an extremely fast and very secure arc-flash detection scheme [6]. The basic logic of this very common protection approach is presented in Fig. 2.

The current can be measured utilising normal current transformers (CTs) which are already available as they are used in traditional overcurrent protection. It has been claimed that current measurement slows down arc fault detection [7], but actually this is not necessarily the case. In arc protection applications, special methods are applied in order to enable extremely rapid detection of overcurrent. Detection times of 0.5–2.5 ms have been reported in the literature. In [11], an algorithm employing instantaneous sampled current values is described and 1 ms detection time is demonstrated for three-phase faults. Another approach [9] takes advantage of the discontinuity of the current waveform (change in d*i*/d*t*) in order to achieve very fast overcurrent detection. In [12], peak-to-peak waveform detectors are utilised for eliminating delays associated with conventional root-mean-square calculations. Fast detection of overcurrent is also possible by applying an analogue comparator, as described in [13]. Since most arc faults initiate as single-phase faults [14], it is justified to include the detection of phase-to-Earth faults as well. If the arc is detected and eliminated before it escalates into a high-power three-phase fault, the damage will be substantially lower.

In almost every conceivable case, in both medium voltage (MV) and low voltage (LV) systems, the trip condition of simultaneous detection of light and overcurrent has proven to be successful. However, some LV circuit breakers (air–magnetic type) emit light while operating, which creates a risk of nuisance tripping. The problem can be solved by installing special type of light sensors which are either less sensitive or designed for limited wavelength range, or by using pressure sensors instead of light sensitive sensors.

2.4 System architecture of a state-of-the-art arc protection system

In the case of a very simple installation, the arc protection system can be just with two components: a protection relay and an optical sensor. If the overcurrent condition is applied, the protection relay can be equipped with an input for high-speed overcurrent detection, as described above. However, in most MV and LV switchgear applications the arc protection scheme is more complicated and the system consists of a slightly wider range of components: light sensors, current sensors (normally existing *s* are utilised), input/output (I/O) units for collecting the information from sensors, an arc protection central unit, and a set of cables for communication and auxiliary power distribution. A simplified example of a selective arc protection scheme is presented in Fig. 3.

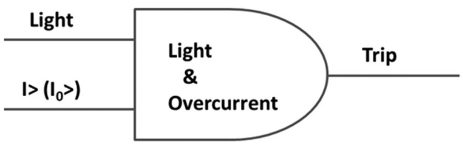

Fig. 2 *Principle of dual-sensing-based tripping*

The system architecture of the arc protection scheme presented in Fig. 3 is centralised and thus the central unit (VAMP 321) is always required. The central unit monitors the system (i.e. provides self-supervision) and maintains the horizontal communication in the system. The central unit can also perform a trip based on the light sensors connected to the central unit itself or based on the information received from the I/O units. The role of the I/O units is two-fold: one to serve as input units for light or current inputs and two to trip contact outputs. All the units in the system are connected together and linked to the central unit of the system by using modular communication cables. The used communication protocol is a proprietary non-standard protocol. The size and number of the packets is kept to a bare minimum in the protocol. Basically only data regarding sensor activations, device addresses, and protection zones are transferred. This enables very short operation times. The central unit is also able to communicate vertically, e.g. with supervisory control and data acquisition (SCADA) system by using standard protocols.

The operation principle of the system presented in Fig. 3 is fairly simple. The current is measured by the normal CT in the incoming feeder and the CT is connected to the high-speed overcurrent detection input of the central unit. The light is detected by the optical sensors (arc sensors) connected to either the central unit or I/O unit. The light detection information also includes the information on which light sensor (which protection zone) has activated, enabling selective tripping of appropriate circuit breakers.

3 IEC 61850 GOOSE-based communication in arc protection systems

3.1 Existing arc protection applications utilising IEC 61850-based communication

Thus far Ethernet-based communication, and IEC 61850-based technology in particular, has not been commonly applied in arc protection systems. However, zone-selective interlocking (ZSI, reverse interlocking) is a common application closely related to arc protection. IEC 61850 and GOOSE have successfully been utilised in ZSI applications, but the operation time of ZSI is longer than

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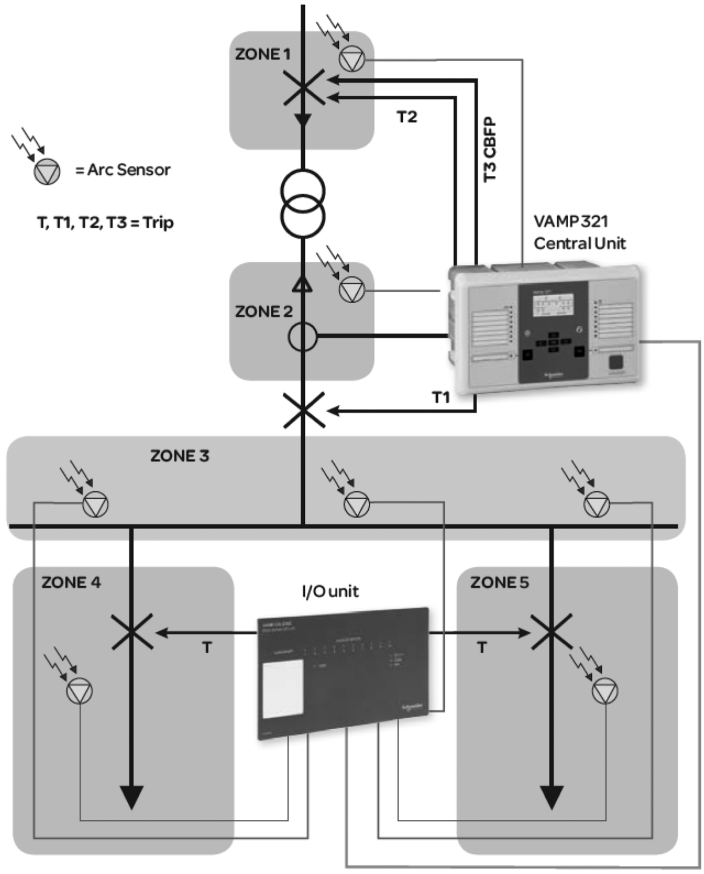

Fig. 3 *Simplified example of a selective arc protection system utilising state-of-the-art technology*

what can be reached by using light/overcurrent-based arc protection [15].

In [16], GOOSE technology has been applied for arc protection, but GOOSE messages are limited to relay-to-relay communications in the light-/overcurrent-based arc protection system. GOOSE messaging could also be applied for the communication between other components of the arc-flash protection system: sensors, input/output units, relays, and circuit breakers.

GOOSE messaging was applied in [17] to send protection and metering information from light sensors to upstream relays in a LV switchgear application. According to this paper, the performance of a GOOSE-based solution can be as good as the performance of a direct serial communication.

3.2 Performance requirements

The nature of arc faults sets demanding requirements for the protection system. The protection has to be extremely fast, reliable, secure, and stable. IEC 61850-5 [18] sets transfer time requirements for signals. The requirements are divided into seven classes: TT0…TT6. However, even the strictest classification, TT6, applied in trips and blockings, allows for transfer times up to 3 ms. According to Sevov *et al.* [19] modern IEC 61850 implementations can transfer messages between relays with delays of about 2–4 ms.

In [20], it is stated that communication using IEC 61850 is definitely faster than hard wired signals as the hard wired signals must go through an output contact on the sending relay and then again on an input contact on the receiving relay. This is undoubtedly true in systems which use electromagnetic relays to transfer the hard wired signals. However, this argument does not necessarily hold for the systems where semiconductor inputs/outputs can be used for the hard wired signals. In fact, the existing approaches are the ones which set the speed challenge for the GOOSE-based communication. The most demanding arc protection applications are those which utilise an arc eliminator device, which in turn is used to create an intentional short circuit within a few milliseconds. In these applications, while aiming at mitigation of the pressure impact along with the thermal impacts of the fault arc, every millisecond counts. In considering these applications, the 3 ms requirement set by IEC 61850 [18] is too long.

To avoid delays caused by other network traffic, virtual local area networks (VLAN) have been used to separate the priority and non-priority traffic on the network [17, 19]. Another means to enable very fast communication is to utilise high-speed fibre media for networking the devices [21, 22].

3.3 Cyber security and GOOSE-based communication

Cyber security has become an important or even a must-have part of protective relays. Utilities and power users must protect their processes from hackers [23, 24]. Cyber security is a rapidly changing field which is quite new to the power and automation industries, where the technologies are in early stages of development [25, 26]. References [27, 28] list a number of weaknesses of GOOSE and show how they can be exploited in cyber-attacks with devastating consequences, e.g. denial-of-service. Since the IEC 61850 standard has been used from applications contained within substations to a wider range of applications [24], it is easy to see the increasing importance of cyber security. Practical experience has shown that though IEC 61850 is a standardised protocol, multi-vendor environments are

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often problematic. The same applies to the installing of intelligent electronic devices (IEDs) from different manufacturers within the same cyber security system [29].

One of the main challenges in applying GOOSE in arc protection is how to retain the speed while providing adequate cyber security. Security can be increased by authentication and encryption of the GOOSE messages. However, in arc protection applications the operation time is exceptionally critical and it is difficult to implement security for GOOSE messages without degrading the performance because encryption and other security measures tend to increase communication delays [24, 26, 27]. Reference [30] sees encryption unacceptable in time-critical applications and states that authentication is the only security measure included as a requirement. Message authentication code (MAC) is one option to provide security. According to Sarralde and Yarza [29], even just simple authentication based on MAC for the critical messages must be analysed in each situation to determine whether the increased delay is acceptable.

VLAN provides logical separation by creating a separate virtual network segment [31]. Two advantages of VLANs are the separation of the traffic between the segments and the increased security [32]. When using port-based VLANs a specific port or a group of ports is assigned to belong to a VLAN while in tag-based VLANs a VLAN identifier (tag) is sent as part of the message [32]. It is possible to apply VLAN tagging so that each GOOSE message becomes a virtual cable with the message contents virtually wired only to the other IEDs that need the data [33]. VLAN messages also include a priority flag which prioritises data flows through network switches [32]. When GOOSE messages are equipped with both ID tags (authentication) and priority tags, Ethernet switches are able to authenticate, redirect, and prioritise the messages.

Physical isolation of the communication network is an effective means to improve cyber security. Systems can be divided into multiple security zones and the use of removable media can be limited in the station computers [24]. The same principle could be applied in, e.g. universal serial bus ports of IEDs. However, as stated in [34] the Stuxnet virus served as a reminder that physical isolation cannot guarantee total security.

The proprietary system described in Section 2 differentiates between the arc protection network and the upper level communication network (e.g. connection to SCADA) by two means. First, the protocol in the arc protection communication is proprietary, and secondly the system has separated the vertical and horizontal communications in different networks.

A similar system can also be implemented when using IEC 61850-based approach having two individual processors in the central unit. One processor is used for vertical communication (i.e. SCADA system) and the other for horizontal communication (for I/O units). The processors do not share any memory directly, while they have two independent network stacks and two physically different Ethernet connectors for the different networks. Also it should be noted that due to the nature of GOOSE messages they are not routable and thus on default will not pass gateways or firewalls.

4 Practical implementation of GOOSE-based communication in arc protection

4.1 System architecture of the developed IEC 61850-based solution

This section describes the architecture and the operating principles of a new IEC 61850 GOOSE-based arc protection system. The key idea of the implementation is to respond to the challenging performance and cyber security requirements by physical isolation, i.e. by having a dedicated LAN cable for the arc protection system, isolated from the substation LAN (IEC 61850 station bus). This solution provides two crucial benefits. The background traffic in the substation LAN has no impact on the performance of the arc protection system, and physical isolation is a strong means against cyber-attacks.

The new system has the same four basic components as the previously described system: sensors, I/O units for collecting information from the sensors, central units, and cables. However, in this system architecture the central unit is no longer required for maintaining the system. The new I/O units enable the use of a distributed architecture. The communication and system self-supervision are decentralised. This is one of the main benefits of this architecture, which also makes the system more robust. A new concept of an optional arc terminal device is introduced to the system. This device has a role somewhat similar to that of the central unit of the previous system; it can be used as a user-interface to the arc protection system, as well as an information collection, logging, and communication device. The Arc Terminal can also be used as a gateway for transmitting information to upper level information systems, e.g. SCADA. However, it must be emphasised that the arc terminal provides physical isolation of the networks which is very good from both performance and cyber security points of view. In case of a simple standalone system where there is no need to communicate information vertically, the arc terminal can be replaced with a simple local monitoring and configuration display.

The key component of the new system is the I/O unit, utilising Microchip PIC32MX microcontroller hardware. Fig. 4 illustrates the basic principle of the new system architecture based on new I/O units and a dedicated LAN cable. Fig. 4*a* shows the system in a completely independent configuration and Fig. 4*b* shows the system with the arc terminal and SCADA connection included. The latter example utilises two physically separated LANs.

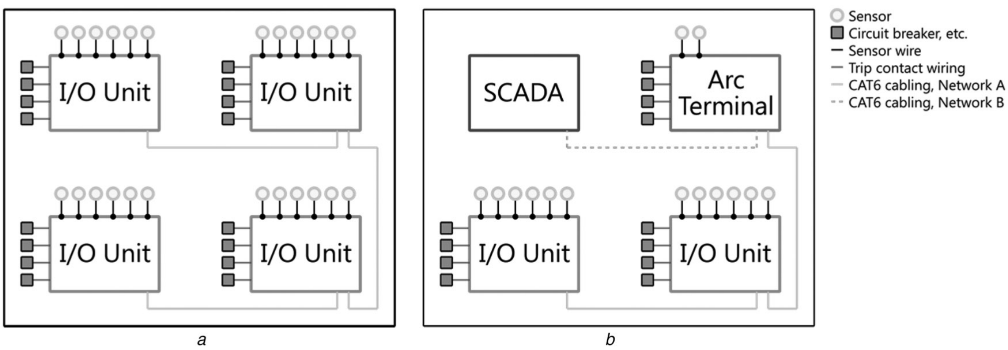

Fig. 4 *Illustration of the new system architecture*
a Independent configuration
b System with Arc Terminal and SCADA connection

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The inputs of the new I/O units can be light sensors or current sensors. The outputs can be electromagnetic relays or very fast semiconductor outputs to deliver trip signals to circuit breakers (CBs). A selective arc protection system can be implemented by dividing the protection into the so-called groups. In this approach the concept 'protection zone' is applied by using the term 'group'. A single group consists of a fixed set of sensors and CBs which are tripped when the arc is detected in the group in question. A single group could contain just a single light sensor or dozens of light sensors and several current sensors. Theoretically, each sensor could be configured to send its information to multiple groups, and CBs could be controlled by signals from different groups. This provides flexibility for the system.

IEC 61850 GOOSE communication operates over Ethernet and the new arc protection system uses standard Ethernet cables with RJ-45 connectors. Each I/O unit has a built-in Ethernet switch and two Ethernet connectors which can be used to daisy chain the I/O units. As the communication is Ethernet based, all the topologies supported by Ethernet are also supported by the system.

4.2 Communication: GOOSE over Ethernet

In the older arc protection system described in Section 2 there are two different kinds of communication systems: faster high priority messaging for zone activation and slower lower priority messaging for other data transfer. A similar approach has also been taken with the new system, where GOOSE messaging is used for the group and sensor activation information and another set of messages is used for other data transfer such as transferring settings.

One advantage of applying GOOSE is that it is a standard protocol and various other devices could be connected to the system. Another advantage is that GOOSE uses broadcast messaging and this works well with distributed systems architecture. The GOOSE protocol is also relatively simple, and it can be fairly easily implemented on embedded devices while still retaining good performance regarding the time constraints.

When comparing the previously described proprietary communication pathway with GOOSE messages, the latter requires large amounts of additional protocol-mandated data to be transferred in order to transfer just a single bit of payload data, i.e. sensor activation detected. Larger amounts of data naturally require more processing power. However, once there is enough processing power, increasing slightly the amount of payload data has only negligible effect on the total transfer and processing times. In addition to the zone/group activation signals, one could transfer, e.g. additional information regarding device self-diagnostics and information about which sensor channel detected the activation.

In the developed architecture, the GOOSE protocol is mainly utilised in the horizontal (internal) communication in the arc protection system: to transfer status information or time-critical trip or block commands. GOOSE portion of the IEC 61850 protocol is not intended for transferring system configuration information. For this purpose, a lower priority communication channel with IEC 61850 over manufacturing message specification (MMS) and transmission control protocol/Internet protocol (TCP/IP), or another protocol could be used. The MMS and TCP/IP portion of the IEC 61850 can also be used for the vertical communication in the arc protection system: for communication between the arc terminal and SCADA.

A major advantage of the new architecture is that extensive arc protection systems can be built. Each of the devices in the new system has a built-in Ethernet switch, which is acting as a repeater. Cable lengths up to 100 m are supported for each link and thus the range can easily be extended to at least several hundreds of metres. However, each additional hop causes a small delay to the end-to-end message transfer times and these accumulate among the device chain. Also transferring the auxiliary power over the modular cable poses its own limitations to the cable lengths.

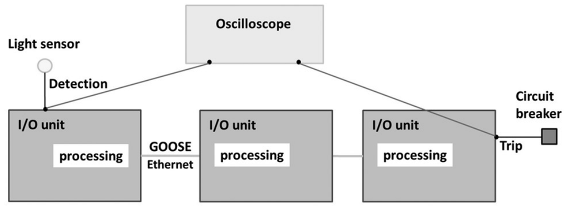

Fig. 5 *Simplified illustration of the test setup*

4.3 Aspects of cyber security

As GOOSE messages are very vulnerable to attacks in the cases where the attacker is able to gain physical access to the communications medium, the first priority should naturally be aiming to prevent this. Conventionally, this is done by border fences, strong doors, and locks on the site where the system is located (e.g. power station or substation). A common argument is that if the attacker has physical access to the network, e.g. inside the substation, the attacker could cause more harm by far simpler means than starting to attack the GOOSE network.

Another way of increasing the cyber security of the system is to limit the network to inside the physically protected area, i.e. no direct connections from the network to the world outside the building/room. If a connection is absolutely required for monitoring the system from the outside, a specifically designed device serving as a secure gateway should be used. In the gateway device, the local and external networks can be physically isolated from each other, and two individual central processing units (CPUs) can be used to transfer data between the networks. To further increase security, the system could be implemented so that the individual CPUs share no common memory and use completely independent network stacks.

5 Performance of the communication of the developed system

5.1 Setup of the performance tests

A series of laboratory tests was conducted in order to evaluate the performance of the described communication system. Since the focus was on the performance of the communication, 'light only' detection principle was applied, i.e. trip purely from light sensor activation without measuring current. The presence of overcurrent information would have slightly increased the traffic in the communication channel. However, increased traffic was included in the test cases by causing multiple simultaneous light sensor detection events.

The performance was evaluated by measuring the time from the detection of light to the moment when the trip signal output was activated on the receiving I/O unit and sent to the appropriate circuit breakers. A strongly simplified illustration of the test setup is presented in Fig. 5 in order to provide an overview of the setup.

The tests were conducted with multiple configurations. This enabled the evaluation of the performance of GOOSE messaging through several I/O units including cases where additional carefully timed traffic was intentionally introduced in order to stress the communication channel.

The test setups consisted of a number of optical sensors, six light detection I/O units (the main components of the tests), one monitoring unit, and communication cables. This setup simulated a real-life MV substation configuration, illustrated in Fig. 6. The light was produced by either a dedicated flashtube-type camera flash or by a light-emitting diode (LED) flash. The measured signals were the detection of light at the input connector of an I/O unit and the trip signal to the circuit breaker, measured at the semiconductor output of another I/O unit. The signals were

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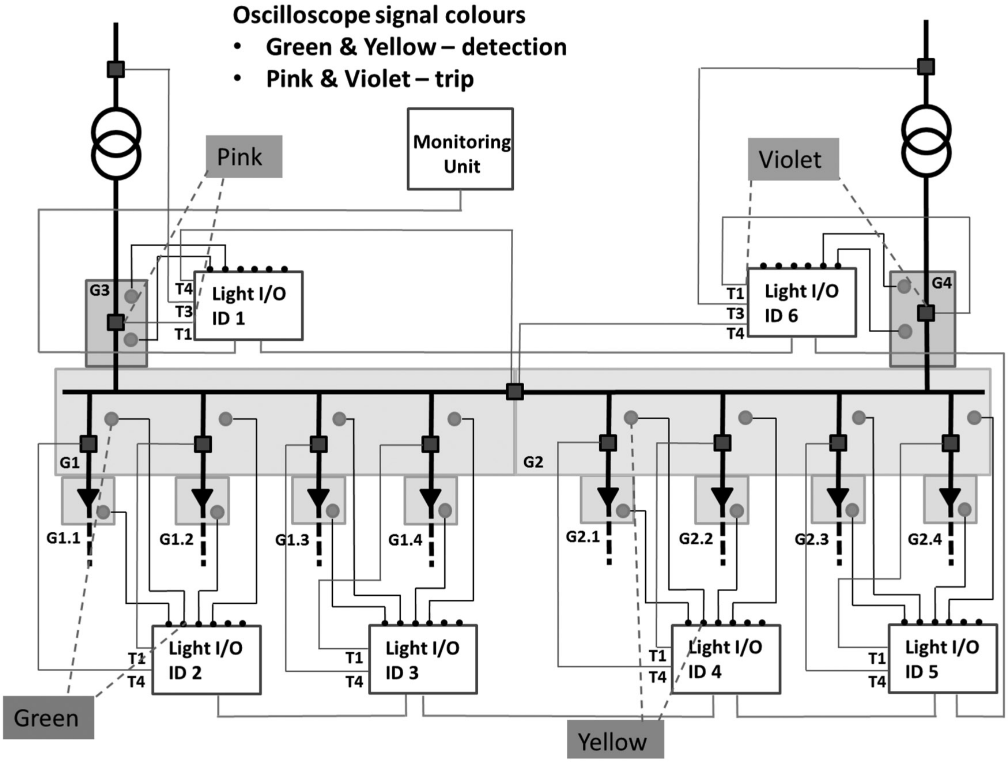

Fig. 6 *Measurement setup, simulating MV substation*

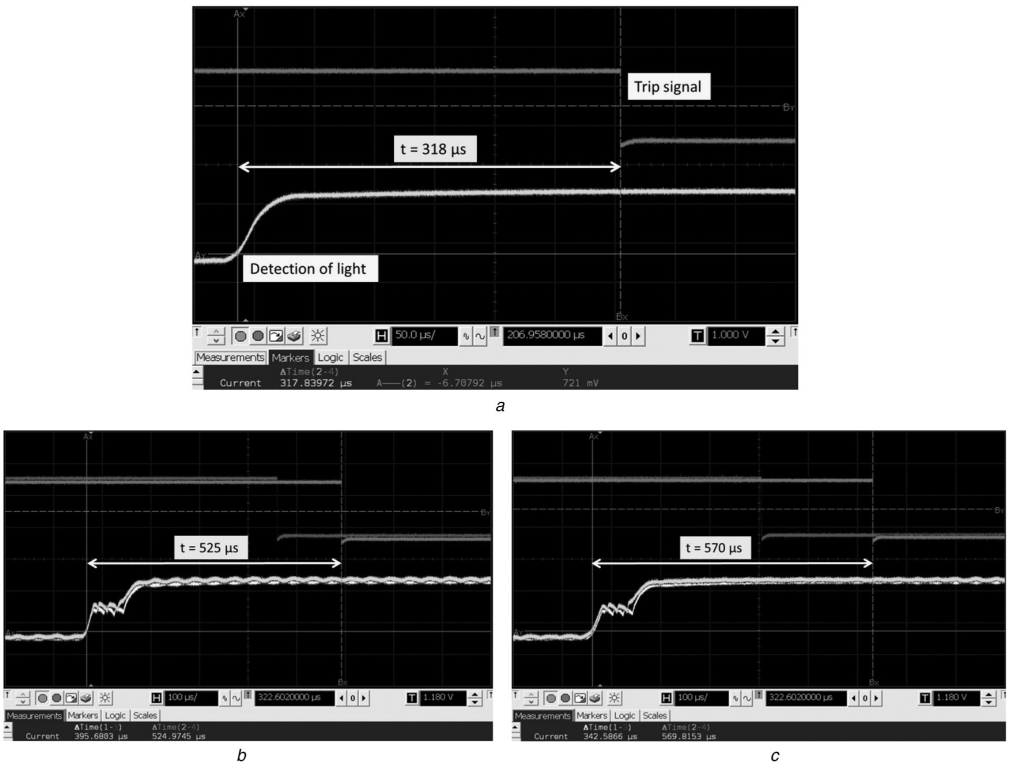

Fig. 7 *Typical measurements of cases A, B, and C*

a No other traffic in the communication channel
b Some traffic in the communication channel
c A lot of traffic in the communication channel

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Table 1 Summary of the numerical results of the measurements of test setups A, B, and C

Case	Mean, μs	Minimum, μs	Maximum, μs
case A	319	278	357
case B	528	359	625
case C	563	372	657

measured at the connectors of the I/O units by an oscilloscope, and the time between these signals was recorded.

5.2 Results of the communication tests

Each test setup was measured ten times, and the mean, minimum, and maximum values were recorded or calculated. The most relevant setups were the following three cases:

(A) Remote trip (detection in I/O unit ID 2 and trip from unit ID 1), communication through four other I/O units, no other traffic in the communication channel. Light source: LED flash.
(B) Remote trip, some traffic in the communication channel, caused by the activation of another light detection input at exactly the same time (I/O unit 4). Light source: flashtube-type camera flash (takes longer than the LED to reach the required light intensity).
(C) Remote trip, a lot of traffic (activation of eight sensors, i.e. simulated 'bus fault' situation) in the communication channel. Light source: flashtube-type camera flash.

Fig. 7 presents typical results of the measurements of each case. Colours of the oscilloscope recordings correspond to the colours marked in Fig. 6. Table 1 presents a summary of the numerical results, i.e. delays from detection of light to the trip signal, of the different test cases. It must be emphasised that the I/O units are equipped with semiconductor outputs instead of mechanical relay outputs. The semiconductor outputs enable extremely fast tripping.

5.3 Analysis of the test results

The test results indicate that the new GOOSE-based communication system is very fast. The mean operation time in all the examined cases was <0.6 ms. The worst measured value was recorded when there was a considerable amount of traffic in the communication channel. Even in this case the measured value was <0.7 ms. The tests strongly indicate that the presented approach provides adequate communication speed.

6 Conclusions

Minimisation of arcing time is a very effective approach in reducing the released energy, the safety hazard, and damage caused by high-power arc faults in MV and LV switchgear. Detection of light provides extremely fast arc fault detection, and the detection is often confirmed with very fast detection of overcurrent. When applying this type of protection approach, the dominant component determining the arcing time in typical applications is the operation time of the circuit breaker.

Practical implementations of arc fault protection systems consist of multiple components, requiring peer-to-peer communication. This paper has investigated the applicability and benefits of IEC 61850-based communication for this purpose including a short discussion on cyber security aspects. The introduced GOOSE communication-based system has many benefits including the following:

- The communication is based on an established standard.
- GOOSE messages can be prioritised and supervised. The system includes extensive self-supervision.
- Physically extensive protection systems are possible, since the new I/O units operate as Ethernet switches.
- The central unit is not necessary; in its place an optional gateway/terminal unit can be used.
- High number of protection groups (zones) enables selective protection.
- As generally in IEC 61850 applications, the simplified wiring reduces costs.

The GOOSE-based approach also includes potential drawbacks. The most obvious challenges, when comparing the existing, proprietary non-standard communication solution with the GOOSE-based system, are performance and cyber security. Owing to the high-performance requirements set by arc protection applications, we strongly recommend physically separated LAN for the arc protection system. When a dedicated LAN is used, background traffic in the station bus does not have an impact on the performance of the communication in the arc protection system. Physical isolation also considerably mitigates cyber security concerns, eliminating direct GOOSE-based attacks.

The performance of the developed system has been verified by laboratory testing. The tests indicate that the performance is very good. Even in the worst case a communication delay of <1 ms was achieved. Future work will cover the testing of the performance of a more complete system including I/O units for overcurrent detection.

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