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Author(s): Shafiq, M.; Kauhaniemi, K.; Robles, G.; Isa, M.; Kumpulainen, L.

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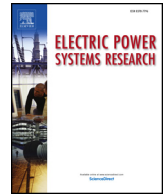
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Online condition monitoring of MV cable feeders using Rogowski coil sensors for PD measurements



M. Shafiq^{a,b,*}, K. Kauhaniemi^a, G. Robles^b, M. Isa^c, L. Kumpulainen^a

^a University of Vaasa, School of Technology and Innovations, 65200 Vaasa, Finland

^b Universidad Carlos III de Madrid, Department of Electrical Engineering, 28911 Leganés, Madrid, Spain

^c Universiti Malaysia Perlis, School of Electrical System Engineering, 02600 Arau, Perlis, Malaysia

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ABSTRACT

Condition monitoring is a highly effective prognostic tool for incipient insulation degradation to avoid sudden failures of electrical components and to keep the power network in operation. Improved operational performance of the sensors and effective measurement techniques could enable the development of a robust monitoring system. This paper addresses two main aspects of condition monitoring: an enhanced design of an induction sensor that has the capability of measuring partial discharge (PD) signals emerging simultaneously from medium voltage cables and transformers, and an integrated monitoring system that enables the monitoring of a wider part of the cable feeder. Having described the conventional practices along with the authors' own experiences and research on non-intrusive solutions, this paper proposes an optimum design of a Rogowski coil that can measure the PD signals from medium voltage cables, its accessories, and the distribution transformers. The proposed PD monitoring scheme is implemented using the directional sensitivity capability of Rogowski coils and a suitable sensor installation scheme that leads to the development of an integrated monitoring model for the components of a MV cable feeder. Furthermore, the paper presents forethought regarding huge amount of PD data from various sensors using a simplified and practical approach. In the perspective of today's changing grid, the presented idea of integrated monitoring practices provide a concept towards automated condition monitoring.

1. Introduction

Improved maintenance technology plays a major role to keep the electrical supply network in reliable operation. The electric grid operates over wide geographical areas on 24/7 basis and is, therefore, exposed to various operational and environmental stresses. The distribution network is the most interactive part of the supply network and a large number of failures initiate from the distribution network components [1]. Therefore, the network companies and solution providers continuously keep on striving for suitable solutions to improve the reliability of the components and continuity of the power supply.

Power transformers and MV cables are key components in distribution networks. These components undergo through TEAM-stress regime, thermal, electrical, ambient, and mechanical stresses, that significantly accelerate the degradation of the electrical insulation [2,3]. Condition monitoring refers to the inspection and identification of the common failure modes of equipment that provides initial data for prognostics based on actual measurements and hence leading to the

execution of preventive maintenance plans. Based on the impact of stresses on the lifetime, operation, and performance of the components, one type of condition monitoring is considered more critical than others. For instance, a limited mechanical operation involved in power transformers is tap-changing or the switching contacts while power lines/cables do not involve any moving elements. The operation of these components is predominantly static where voltage, current, and electrostatic/electromagnetic fields interplay with the conductors and insulation system of the corresponding components. A typical underground cable feeder spans over several kilometers from the substation to the consumers via a number of cable sections, transformers, joints, terminations, and other protective, monitoring and control equipment. The primary focus of this paper is the condition monitoring of MV cable feeders and power transformers using a newly designed Rogowski coil with a bandwidth adapted to the whole system.

Dielectric insulation is the most important part, which is designed according to well-established standard specifications and practices, providing withstand to likely stress levels over the expected lifetime.

* Corresponding author at: University of Vaasa, The School of Technology and Innovations, Vaasa 65200, Finland.

E-mail address: muhammad.shafiq@uwasa.fi (M. Shafiq).

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Nomenclature

List of symbols

ϵ_c	Dielectric permittivity of the cavity
ϵ_i	Dielectric permittivity of the insulation
μ_o	Permeability of free space
Ω	Ohm
A_c	Area of the core of the coil
a	Area of healthy insulation
b	Area of healthy insulation in series with the cavity
c	Area of cavity
C	Capacitance of the coil
C_{ia}	Capacitance of healthy insulation
C_{ib}	Capacitance of healthy insulation in series with the cavity
C_{ic}	Capacitance of cavity
d	Diameter of winding wire
E_a	Electric field due to supply voltage
E_{BA}	Dielectric breakdown strength of XLPE
E_{BC}	Dielectric breakdown strength of cavity
E_c	Dlectric field E_c across the cavity
f_{BW}	Bandwidth of the Rogowski coil
f_c	Resonant frequency of the RCS for cable measurement
f_H	Upper cut-off frequency of RC
f_L	Lower cut-off frequency of RC
f_o	Optimum frequency of RC for cable/transformers
f_r	Resonant frequency of the RCS
f_t	Resonant frequency of the Rogowski coils.
H_1	Effects of medium on the signal
H_2	Effect of sensor
H_3	Effect of sensor DAS
Hz	Hertz
h	Width of the coil turn
i_m	Measured current
$i_p(t)$	Primary current
K_c	Calibration factor for the sensor
L	Inductance of the RCS
l	Length of winding wire
m	Number of straight joints
M	Mutual inductance between coil and conductor
N	Number of turns of the coil
N	Number of transformers
$N_{F1'}$	Number of sensors for SSMS
N_{F1}	Number of sensors for DSMS
nH	Nanohenry
p	Point
P_1	Starting terminal of the winding
P_2	Ending terminal of the winding
pF	Picofarad
ρ	Resistivity of the conductor (winding wire)
R	Resistance of the Rogowski coil
R_{11}	Upstream (source) side sensor-node 1
R_{12}	Downstream (load) side sensor-node 1
R_{21}	Upstream (source) side sensor-node 2
R_{22}	Downstream (load) side sensor-node 2
R_t	Terminating resistor
R_{y1}	Upstream (source) side sensor-node y
R_{y2}	Downstream (load) side sensor-node y
S_m	Signal measured by Rogowski coil
S_p	Primary signals
t_c	Thickness of the cavity

t_i	Thickness of the insulation
U_a	Supply voltage
U_{BC}	Breakdown voltage across the cavity
$V_o(t)$	Output voltage of Rogowski coil

Abbreviations

ADC	Analogue to digital converter
CSC	Closed size component
CC	Covered conductor
D (Table 1)	Detection
dB/m	Decibel/meter
DAS	Data acquisition system
DG	Distributed generation
DGA	Dissolved gas analysis
DOA	Direction of arrival
DSMS	Double side monitoring scheme
DSO	Digital storage oscilloscope
EMCP	Electromagnetic current pulses
EMWR	Electromagnetic wave radiation
End A	End A of the Rogowski coil core
End B	End B of the Rogowski coil core
FFT	Fast Fourier Transform
FPGA	Field programmable gate arrays
GHz	Gigahertz
GBWP	Gain-bandwidth product
GS/s	Giga samples per second
HFCT	High frequency current transformer
HV	High voltage
ICT	Information and Communication Technology
IEC	International electrotechnical commission
IEEE	Institute of electrical and electronics engineers
IT	Information technology
kV	Kilovolt
L (Table 1)	Location
LV	Low voltage
MHz	Megahertz
mm	Millimeter
ms	Millisecond
MS/s	Mega sample per second
mV/A	Millivolt per ampere
MV	Medium voltage
OSC	Open size component
PD	Partial discharge
PRA	Phase resolved analysis
RCS	Rogowski coil sensor
RMU	Ring-main-units
SADC	Successive adjacent data comparison
SNR	Signal to noise ratio
SSMS	Single side monitoring scheme
TDOA	Time difference of arrival
TDR	Time-domain reflectometry
TEAM	Thermal, electrical, ambient, and mechanical
UHF	Ultra high frequency
μH	Microhenry
μs	Microsecond
VHF	Very high frequency
X (Fig. 10)	X branch of the Feeder
XLPE	Cross-linked polyethylene
Y (Fig. 10)	Y branch of the Feeder
Z (Fig. 10)	Z branch of the Feeder

The insulation of medium voltage (MV) and high voltage (HV) equipment are designed according to the IEC 60071—1 & 2 [4] standards that deal with the determination of insulation levels considering the rated withstand and highest voltages that may be encountered during operation. Due to aging, dynamic, and random behavior of the various operational and environmental actors [5] and abnormal situations, defects can emerge in the insulation, which cause an increased rate of deterioration, progresses with time, and eventually leads to failure of components before their lifetime [6,7]. Due to their very nature, insulation defects are incipient and therefore proactive maintenance efforts can be made based on present-day condition of the insulation. Partial discharge (PD) is an indication and, at the same time is the cause of insulation degradation. PD monitoring is a valuable tool for obtaining updated status of insulation that requires a meticulous measurement system and expertise for an accurate prognosis.

Promoting the societal and technological goals under the umbrella of smart grid, gradual upgradation of the network, inclusion of distributed generation (DG), electrical vehicles, energy storage, etc., are predominantly embedded in the distribution grid. The underground cable topology is becoming more meshed and interconnected. There has been a significant increase in the number of connection points (joints, terminations, and tapping) and distribution (secondary) transformers [8]. This means an increased probability of having adverse events on the components that may cause serious insulation degradation promoting the emergence of PD defects and hence leading to complete breakdown of the affected components. The development of the infrastructure is not the whole solution to the modernization of the power grid; predictive technologies must also need a proportional upgrade.

Efficient PD monitoring and diagnostics depend on the performance of the sensors, techniques of measurement, and interpretation of data obtained from sensors. Although a variety of high performance solutions are available for PD monitoring, considering the grid advancements and available solutions, this paper identifies two major gaps that have to be addressed, being the focus of this paper, and they are described below.

Firstly, the employed sensors are component specific, a certain type of sensors used for specific type of components [9,10]. For example, acoustic or UHF antenna sensors are commonly used for PD monitoring in power transformers while these types of sensors are not feasible for PD investigations in cables. Similarly, induction sensors are more common for PD measurements in cables. Such constraints limit the possibility to integrate the same type of measurement system for the various power components in the vicinity.

Secondly, most of the methods available at present are for use on individual/single components in the substations or distribution

network. Due to expanding networks, monitoring of individual components is time consuming, expensive and require more expertise, and human resources [11]. There is lack of integrated monitoring solutions in the available literature. The work done in Ref. [12] presenting an integrated monitoring solution, uses only two sensors to find the location of a fault on a cable section of 300 m long among several cable sections interconnected by ring-main-units (RMUs). This methodology is a usual practice based on the two-end measurement technique and does not provide a functionality to monitor multiple sections simultaneously. When considering longer parts of a cable network having several cable sections or longer cable lengths spanning over several kilometers and branches, the PD signals are attenuated during its propagation along the cable and can disappear before reaching the sensors at the far ends. The work in Ref. [13] suggests the need of multiple sensors for longer cable routes where the PD signals may be attenuated during propagation. However, no methodology has been proposed to realize the suggested idea [14].

This paper proposes that multiple sensors have to be installed at suitable locations with appropriate measurement techniques to identify the location of the fault in an effective way. Addressing these gaps, this paper focuses on the cross-component application of the induction sensor (Rogowski coil) by proposing an optimum design that is suitable for both MV cables and transformers. Further, the focus is to propose an integrated monitoring system using the designed sensor by exploiting its simple feature of directional sensitivity that plays a key role in communicating between the consecutive sensors in order to monitor the wider part of the MV cable feeder.

Section 2 in this paper presents a quantitative analysis of the electrical breakdown of insulation defect initiating PDs. Section 3 presents an overview of PD mechanism based measurement approaches and a PD sensor development map. Section 4 provides a comprehensive understanding of the capabilities of the sensors along with limitations for power components. This section also highlights a liberal perspective towards unconventional approaches in order to flourish improved and efficient PD monitoring solutions. Section 5 is aiming at the optimum design considerations of the Rogowski coil taking into account its sensitivity and bandwidth performance for PD measurements in the distribution feeder. Having discussed the Rogowski coil design aspects, Section 6 presents an integrated monitoring scheme for feeders including cables, cable accessories, and transformers. The paper is concluded in Section 7.

2. Partial discharge in power components

Although aging and mechanical damage contribute to insulation

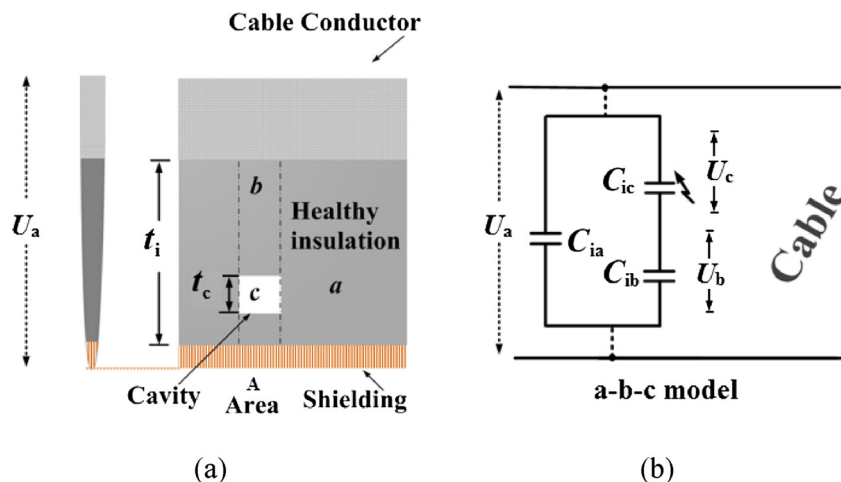


Fig. 1. (a) Physical model of the cavity inside insulation (upper half of the cross-sectional view of cable) and (b) electrical a-b-c model of the cavity inside cable insulation.

deterioration, excessive electric stresses particularly due to sustained or/and impulse overvoltage, overloading, and hence unstable temperature cycling are major causes of insulation degradation while the possible presence of moisture, dirt, salt layer, etc. significantly accelerate this progression. Referring to the IEC 60270 standard, PD is the localized electrical breakdown of a small portion (voids, cracks, bubbles or inclusions) of a solid or a liquid electrical insulation system. The phenomenon is confined to the localized regions of the insulating medium between two conductors at different potential. This discharge partially bridges the phase to ground, or phase to phase insulation [15].

Cavities in the insulation are one of the causes to damage the insulation that is quantitatively elaborated below.

The physical model of the cavity emerging inside the insulation of a MV cable and its surrounding healthy insulation is shown in Fig. 1(a). Assuming that the solid insulation of the cable has a thickness t_i and dielectric permittivity ϵ_i , while t_c is the thickness of disc shaped cavity with the dielectric permittivity ϵ_c . Due to different dielectric constants of the insulation between the electrodes, different capacitances emerge which proportionally divides the voltage applied across the electrodes. To analyze the PD generation, a well-known electrical (a-c) model of the cavity inside insulation is shown in Fig. 1(b). Here C_{ia} , C_{ib} , and C_{ic} are the capacitances of respective sections. The voltage U_a across C_{ia} is essentially divided across C_{ib} and C_{ic} which represents the faulty region. The voltage U_c across C_{ic} is of major concern for PD generation and is expressed as,

$$U_c = U_a \frac{C_{ib}}{C_{ib} + C_{ic}} \tag{1}$$

In terms of respective dielectric permittivity, it can be expressed as,

$$U_c = U_a \frac{1}{1 + \frac{\epsilon_c}{\epsilon_i} \left(\frac{t_i}{t_c} - 1 \right)} \tag{2}$$

The electric field E_a due to supply voltage U_a is uniformly distributed across insulation between the conductors. Based on $U_a = E_a d$, where E_a is the electric field due to potential U_a across the electrodes, the electric field E_c across the cavity can be described as [15],

$$E_c = E_a \left(\frac{t_i}{t_c} \right) \frac{1}{1 + \frac{\epsilon_c}{\epsilon_i} \left(\frac{t_i}{t_c} - 1 \right)} \tag{3}$$

Considering the practical behavior of a partial breakdown of insulation within the particular cavity, if the size of the cavity and relative permittivity are considerably smaller than the solid insulation, as will usually be the case, the E_c will be significantly greater than E_a .

Assuming $t_c = 0.6$ mm inside a 12/20 kV cross-linked polyethylene (XLPE) cable having 6.6 mm thickness (t_i) insulation. For $\epsilon_c = 1$ (relative permittivity) and $\epsilon_i = 2.3$ (for XLPE), the electric field intensity in the cavity is approximately 2.3 times that of the surrounding insulation at a certain applied voltage. The dielectric breakdown strength of XLPE is $E_{BA} = 21$ kV/mm whereas for the air-cavity it is $E_{BC} = 3$ kV/mm. Therefore, for the above-described cavity, the applied voltage U_{BC} at which the breakdown starts to occur can be determined in terms of E_{BC} and dimensional arrangement of the cavity as in Ref. [15],

$$U_{BC} = E_{BC} \left(1 + \frac{\epsilon_c}{\epsilon_i} \left(\frac{t_i}{t_c} - 1 \right) \right) t_c \tag{4}$$

When the voltage across the cavity rises to U_{BC} , a discharge takes place within the capacitive cavity which is called PD inception voltage and it is calculated as $U_{BC} = 9.6$ kV in this case, even when the nominal phase-to-ground voltage is 12 kV for the 12/20 kV cable under test. Once the process is triggered, the insulating materials start to deteriorate progressively and eventually lead to a complete breakdown.

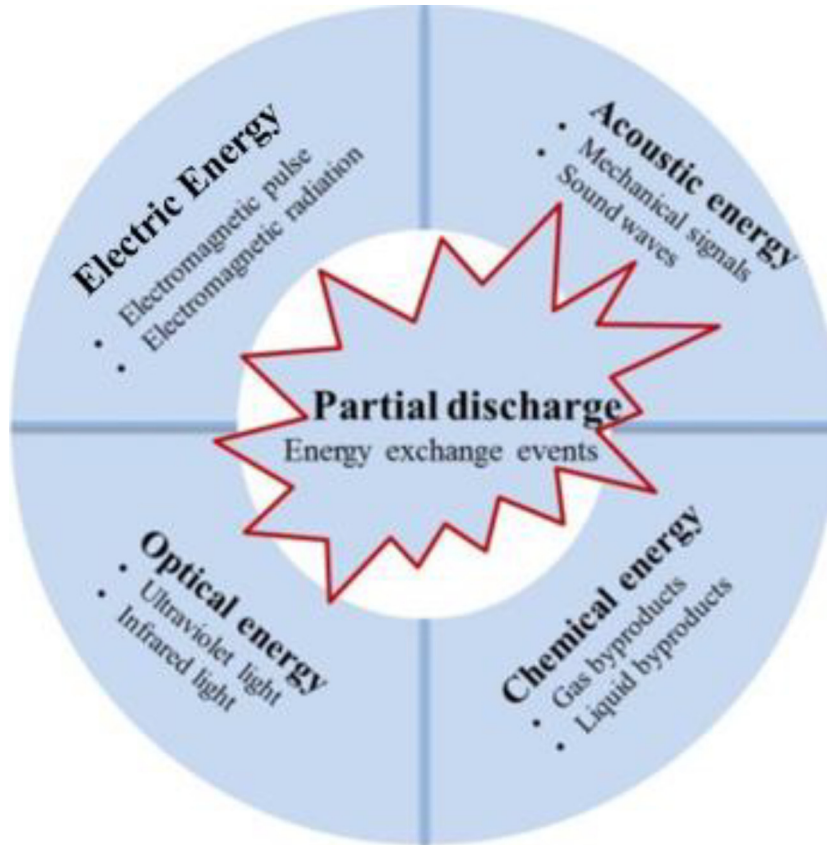


Fig. 2. Energy exchange during PD events and sensing possibilities.

3. PD energy and sensing

Due to the increasing demand for reliability of the developing power grid, an increased interest has been seen in recent times on PD sensor and measurement technology. Particular attention is being given for the advancements of condition monitoring of power cables, power transformers, and switchgear, due to their critical operation and significant costs in terms of both commercial value and repairs. The use of compatible PD sensors can enable tracking and updating the status of the insulation system of the components in order to have a proper maintenance plan for repair, replace, and standby. A true interpretation of the fault depends on the transducer type and its capability to sense the relevant occurrence.

3.1. Mechanism based PD measurement approaches

The measurement methodology of PDs is based on the type of energy exchange that takes place at the localized part of insulation defects such as electromagnetic radiation, sound or noise, thermal radiation, gas pressure, chemical formation, and electromagnetic impulses, which are the indicators of the ongoing PD activity as shown in Fig. 2.

Electromagnetic radiation emitted due to ionization, excitation and recombination can be in the form of electromagnetic radio frequency waves and optical signals. Radiometric techniques have been implemented using ultra high frequency (UHF) receivers (antennas) having bandwidth in the range of GHz [16]. Optical sensors such as photographic recorders, photo-multipliers or image intensifiers can detect the ultra violet radiation emitted during PDs [17]. The energy released during the discharges heats the adjacent insulation material, which results in a small and rapid explosion producing sound or noise (acoustic) waves. Piezoelectric effect based transducers or other acoustic transducers are the most common methods of performing acoustic measurements in power equipment [18,19]. The temperature of the surface of the defective site increases and can be measured by using thermal sensors [20]. There are localized chemical changes during insulation deterioration [21]. Appearance of by-products such as wax in mass-impregnated cables can be determined to monitor PDs. Dissolved Gas Analysis (DGA) is one of the most commonly used chemical method for PD diagnostics [22]. Similarly, an important class of PD sensors measures the electromagnetic impulses. Due to the rapid movement of the charges during the discharge event, voltage and current transient appear in the form of electromagnetic waves. These transients can be measured by resistive, capacitive or inductive methods that are named as very high frequency (VHF) sensors [9].

3.2. PD sensor development

The sensor technology is rapidly moving towards electronic, electrical, and digital instrumentation. A measuring sensor transacts a

complete measurement function from initial detection to final indication of the measured quantity. The initial detection is done by a transducer, which is a sensing element and acts as an interface between measured quantity and sensing device. Intermediate signal processing of the sensed signal is carried out based on the physical and electrical characteristics of the transducer, and the features of the measured signal. Final indication is displayed or recorded by a suitable data acquisition system (DAS). Based on the type of study, the captured data can be analyzed in real time or stored in digital format for further analysis.

Considering the construction map of a PD sensor, Fig. 3 presents its development model along with the measurement system. The measured signal S_m , can be expressed as:

$$S_m = S_p \cdot H \cdot K_c \tag{5}$$

where S_p is the primary PD signal and H is the total effect of medium and measurement system, expressed as:

$$H = H_1 \cdot H_2 \cdot H_3, \tag{6}$$

where H_1 , H_2 , and H_3 are the effects of medium, sensor, and DAS respectively, while K_c is the calibration factor.

Considering inductive sensing, the magnetic field of the PD signal linking through air (medium) induces the voltage in the sensor coil. The magnetic flux leakage causes loss of energy (radiative losses). Such losses are considered small; however, they have to be taken into account for accurate measurements. The effect of the electrical parameters of the sensor is incorporated into the electrical signal. Determining the accurate parameters and designing a matched impedance may cause a loss or add in the measured signal. Similarly, the link between the sensor output and the input of the DAS (digital storage oscilloscope in this study) is of critical importance. The impedance of the sensor's probe to DAS and the sensor circuit may not always match perfectly and hence the probe may affect the measurement. Depending on the type of sensing, proportional compensation is generally accomplished by using calibration techniques. Sensor calibration is required for removal of structural or operational effects on the outputs of the sensor and for standardizing the sensor performance for measurements.

4. Power components and PD monitoring

Common practices and a literature survey reveals that the suitability of a sensor type leans on the type of application or component under test. The bandwidth, sensitivity, noise vulnerability, installation of sensors, etc. are important factors to consider when selecting a sensor type. Apart from these considerations, the structure of the components under test must be taken into account in order to get effective information from the measured data. Considering the structure of the major electrical components, power networks can be divided into two categories,

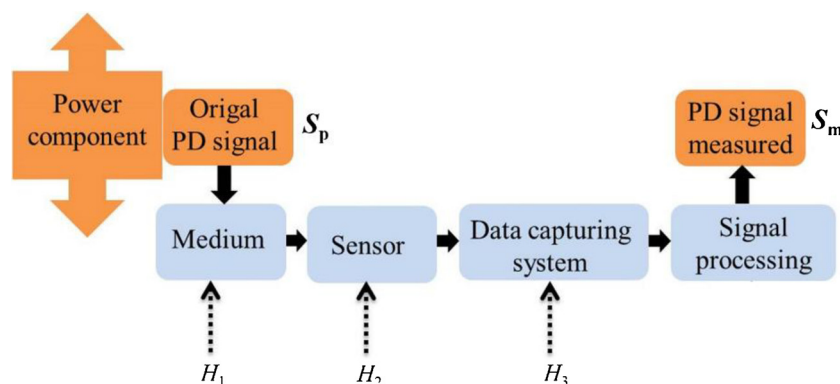


Fig. 3. Design map for PD sensor and measurement.

Closed size component (CSC): the components with definite size that are positioned at a specific place can be categorized as CSC. Power transformers, generators, motors and switchgears can be considered in this group.

Open size components (OSC): the components that are distributed along a wider region (few hundred meters up to kilometers). Mainly, power lines are categorized as OSC.

Various review papers have been published providing comparison of the commonly used PD measurement solutions for different power components [9,10]. The published work mainly presents the advantage/disadvantages of PD sensors and methodologies applied for PD monitoring of individual components. However, there is neither so called a universal sensor solution that can be used reliably for PD applications in different power components nor integrated (multiple components) PD monitoring systems. Based on recent literature survey and the authors' own experience of exploring various features of sensor design for PD measurements, the detection and location diagnostics performance of five accustomed methodologies is presented in Table 1.

It comes out that chemical and optical sensing has limited use for PD diagnosis due to their specific operational nature. Dissolved gas analysis (DGA) based chemical method is frequently used for PD investigation in power transformers and can be applied to the oil-filled paper or oil impregnated paper cables with limited accuracy. Both components generate the same type of gases at similar stresses, however, due to different geometry; the measurement arrangement is quite different in both cases. Hydrogen, methane, ethylene, and acetylene are the major gases that are generated from the decomposition of the oil. Samples for measurement are usually taken from the sealing ends or the joints. Gas concentrations in oil samples are a combination of gases coming from the aging site of the cable insulation to the spot of sampling [23]. Although it is still possible to apply DGA analysis to the oil impregnated paper insulation based cables, the performance of DGA based results for power cables has not reached the degree of sophistication that is obtained from transformers. Therefore, DGA analysis is hard to use for power cable diagnostics. Similarly, due to limited capability, optical measurement methods are not useful for power cable and transformer to carry out PD measurements.

Considering the acoustic environment, during PD activity the discharge events appear as small explosions within the insulation, which initiate mechanical vibrations that propagate through the insulation towards the measurement sensor. These pressure waves are sensed by the microphone based sensing transducer and produces electrical pulses of proportional frequency and amplitude [24]. While propagating from the source to sensors the effects of reflection and refractions, loss of signal energy due to dissipation in the medium, geometrical spreading of the waves, and distance travelled impacts the velocity of wave propagation, amplitude, frequency spectrum of the acoustic signals which can cause serious errors during PD diagnosis [25]. The distance of the PD source plays a significant role in the performance of these sensors. These sensors are suitable for the CSC category with the possibility of installing the sensors at the outer casings of these components. In the case of OSC, the underground cable, substation feeders typically span over tens of kilometers having cable sections of several hundred meters. Here the possibility of installing PD sensors is limited to the cable joints, terminations, or to the power tapping points along these lines. Therefore, the acoustic sensors are not a suitable option for the PD monitoring in OSC.

During PD events, electric energy is transmitted in irradiated and conducted forms that are, i). electromagnetic wave radiation (EMWR) and ii). electromagnetic current pulses (EMCP). VHF–UHF sensors measure EMWR while HF sensors normally measure the EMCP signals. The VHF and UHF ranges are from 30 MHz to 3 GHz and the HF range is from 3 to 30 MHz. In addition to non-intrusive efficacy, notable features of VHF–UHF are the wide band frequency and good sensitivity. VHF–UHF sensors are common for PD monitoring of CSC, however, for medium voltage (MV) cables (OSC), these ranges are not desired. High

frequency components of the PD signal face immense attenuation while propagating along the line. Due to higher attenuation at high frequency components, the signal to noise ratio (SNR) becomes low, therefore it is important to perceive a frequency range of interest. Detailed investigations made on a 260 m long MV cable in Ref. [26] presents sever attenuation for the frequency components above 30 MHz and are embedded with considerable noise making very poor SNR. Similarly, the attenuation of VHF–UHF signals within the transformer varies between 5 and 13 dB/m, depending on the location and therewith the traveling path of the VHF–UHF signals, therefore, measurements in the VHF–UHF ranges are vulnerable to location errors during PD diagnostics [27].

Inductive (HF) sensing is being used since long as a rigorous solution for detection and location of PD faults in cables. In transformers, induction sensors have already been in use for PD monitoring with emphasize on the location of faults [28]. Moreover, recent advances have enabled efficient location indication of insulation defects based on current measurement methodologies. This includes extracting the location based information of the faults from current pulses measured through transformer bushings and line neutral along with phase resolved analysis (PRA) technique [29,30]; further details are given in Section VII. Due to substantial developments in current sensing applications integrated with Machine Learning and Neuro-Fuzzy techniques, the adoption of inductive sensors can be a step forward towards a 'universal' sensor for PD monitoring distribution network components.

5. Rogowski coil for efficient PD monitoring

Because of their non-intrusive application that provides a good possibility for online measurement without disconnecting the component's supply and operation, high frequency current transformer (HFCT) and Rogowski coil sensor (RCS) are the most commonly used inductive sensors. However due to the flexibility of the physical design and robust operational features, RCS are preferred over HFCT in many applications [31,32]. Compared with HFCT, air-core construction of Rogowski coil does not have the limitations of magnetic saturation and therefore higher bandwidth can be achieved if needed. Furthermore, the preferred capabilities of Rogowski coils can be seen in the special report presented by the working group of IEEE Power Engineering Society in 2010 [33].

5.1. High frequency Rogowski coil sensor

5.1.1. Laboratory Implementation

A Rogowski coil consists of an air-core wound with a conductor of suitable diameter. The winding is done from End A of the core towards End B and then a return loop made through the center of the core (End B) back towards End A. Both the winding terminals P_1 and P_2 are available at the same end and therefore enable the coil to be openable to put around the power line under test (see Fig. 4). The geometrical parameters of the Rogowski coil are shown in Fig. 5(a) where a is the internal diameter, b is the external diameter, h is the width of the coil

Table 1

Performance comparison of PD diagnostic methods for distribution network. Components (D: detection, L: location).

Measurement methods	Task	Cables/CC lines	Transformer	GIS
EM-Waves measurements	D	–	+	+
	L	–	+	+
Electrical measurements	D	+	+	+
	L	+	+	–
Acoustic measurements	D	–	+	+
	L	+	+	+
Chemical measurements	D	+	+	+
	L	–	–	–
Optical measurements	D	+	+	+
	L	–	+	–

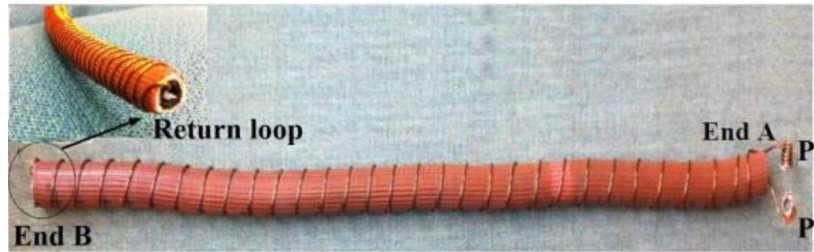


Fig. 4. Basic construction of Rogowski coil.

turn, d_w is the diameter of the wire used in the winding, and N is the number of turns. Considering the electrical parameters of the coil, R , L , and C are the resistance, inductance and capacitance of the coil. As an external component, R_t is the terminating resistor. Electromagnetically induced output voltage $V_o(t)$ of the coil is directly proportional to the time derivative of primary PD current $i_p(t)$ as shown in the electrical model of Fig. 5(b).

Damping of unwanted oscillations induced due to the electrical parameters of the coil using a selected matching terminating resistance R_t , integration of $V_o(t)$ to get the current signal i_m , and finally the calibration of the sensor prototype using a commercial sensor to get the primary signal i_p , are the stages that bring the full scale laboratory implementation of the RCS, as shown in Fig. 6. The development of the sensor and the experimental investigation was carried out in the HV laboratory at Aalto University.

5.1.2. Performance parameters

Although Rogowski coil sensors are commercially available, continuous research on the sensor is ongoing. This paper addresses further improvements with regard to the design, performance, and application aspects. The amplitude and frequency are the most imperative characteristics of PD signals, which depend upon the size of the insulation defect, applied voltage, material properties, the location of the defect near conductors/insulation, and the environmental conditions. A suitable design of the measuring sensor plays a significant role in order to get the reliable traces of the ongoing PD activity.

Considering the design aspects, the electrical parameters determine the amplitude and frequency behavior of the sensor while the electrical parameters are derived from the geometrical parameters as,

$$R = \rho \frac{4l}{\pi d^2} \tag{7}$$

$$L = \frac{\mu_0}{2\pi} N^2 h \ln \frac{b}{a} \tag{8}$$

$$C = \frac{2\pi\epsilon_0(a+b)}{\ln\left(\frac{2\sqrt{A/\pi}}{d}\right)} \tag{9}$$

Being l and d the length and diameter of the cable, respectively, ρ is the resistivity of the wire and $A = (b - a)h/2$. Finally, M is the mutual inductance given by,

$$M = \frac{\mu_0}{2\pi} N h \ln \frac{b}{a} \tag{10}$$

The amplitude behavior of the sensor refers to the sensitivity while the frequency behavior establishes the bandwidth of the sensor. The sensitivity can be described in V/A at certain frequency which represents the output voltage $V_o(t)$ measured by RCS in response to the primary current (i_p) flowing through the under test components and can be expressed as:

$$V_o(t) = M \frac{di_p}{dt} \tag{11}$$

where M is also termed as the sensitivity of RCS and μ_0 is the permeability of free space. The resonant frequency of the Rogowski coil indicates the range of the bandwidth and is specified in MHz. The Rogowski coil acts as an RLC type filter with resonance frequency f_r determined by,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

The resonance frequency of Rogowski coil can also be observed practically using the Fast Fourier Transform (FFT) of the response of the Rogowski coil for a short duration pulse of few nano-seconds. The bandwidth of the Rogowski coil is given by $f_{BW} = (f_H - f_L)$ where f_H and f_L are the upper and lower cut-off frequencies. The resonant frequencies of two RCS prototypes tested in Fig. 7, can be obtained from the frequency domain plots shown in Fig. 8.

In addition, directional sensitivity is a useful feature of Rogowski coil, which enables it to identify the direction of arrival (DOA) of the current pulse based on the measured polarity of the incoming. It is common to record the PD data during the whole power frequency cycle that provides the opportunity to make phase resolved analysis (PRA). The positive PD pulses appear during the positive half-cycle while the negative half-cycle contains negative PD pulses. When the Rogowski coil measures a PD pulse with the negative polarity, it means that the

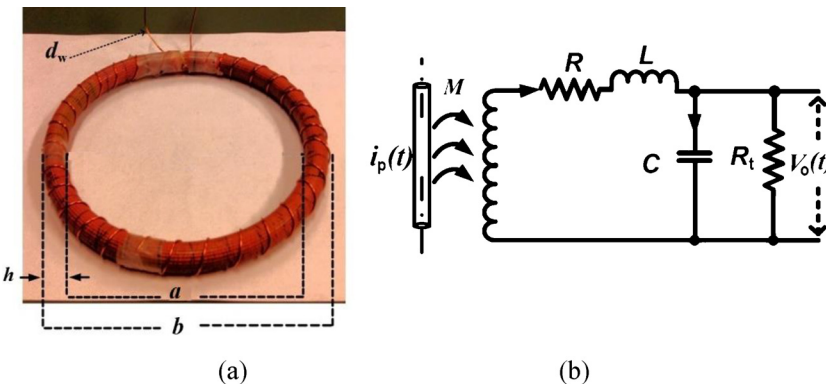


Fig. 5. Modelling of Rogowski coil. (a) Geometrical parameters model (b) lumped parameters model.

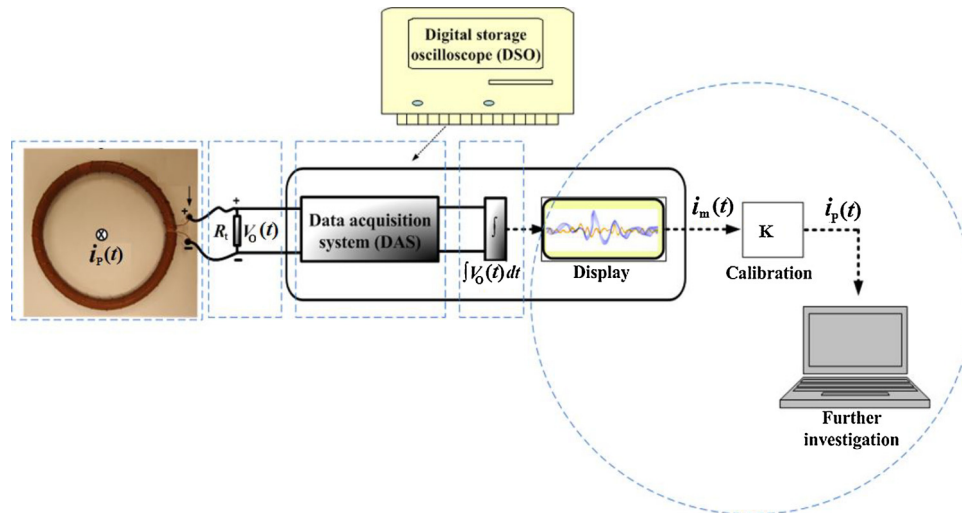


Fig. 6. Full scale laboratory implementation of RCS.

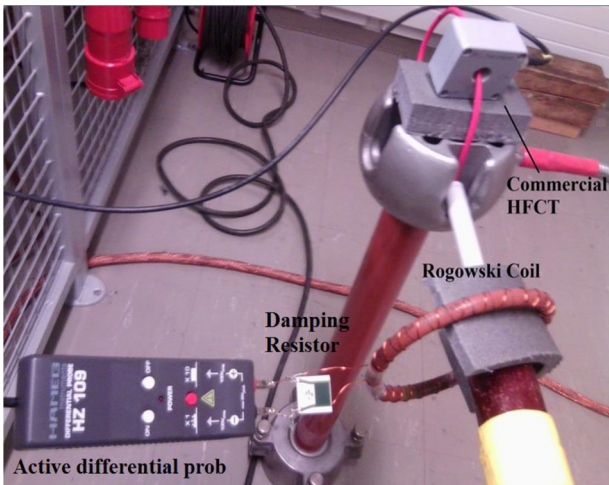


Fig. 7. Experimental setup for investigation of Rogowski coil prototypes.

direction of the PD pulse is into the Rogowski coil as shown by a cross in the center of the coil in Fig. 6. Similarly, the PD pulse measured with positive polarity means that the DOA of PD pulse is coming out of the Rogowski coil.

The design of a Rogowski coil to measure partial discharges can be addressed in two different ways depending on the application. Rogowski coil sensor can be designed in resonance operation without terminating resistor if the main purpose is to detect the partial

discharges and the direction of arrival of the PD pulses in a certain asset. In this case, the response of the coil is not damped and it is very oscillating. The other way is to use the Rogowski coil with a terminating resistor when the objective is to detect the pulses along with the information about their shape. The later design is more complicated since we need to define the bandwidth of the sensor where it is self-integrating and to use an optimization method to define the geometrical parameters.

Both cases are explained in the paper in sections V.B. and V.C., respectively. In both cases, it is necessary to have an idea of the band of frequencies in which the partial discharge has energy. This band is closely related to the transmission line from the discharge site to the location at which Rogowski coil is installed which, from personal experiences and studies, it is found that the bandwidth from 1 MHz to 30 MHz [34,35] is suitable for a wide range of electrical equipment.

5.2. Design consideration for a Rogowski coil

The impact of the change in the geometrical parameters of the Rogowski coil can be analyzed by testing two coils with different designs. The measurement setup shown in Fig. 7 is used to test two prototypes of the Rogowski coil (Coil 1 and Coil 2). A commercial HFCT is used to measure the primary PD pulse to provide reference measurements. Fig. 8 presents the time and frequency domain response of both coils. It can be observed that Coil 1 has a resonant frequency of 26.8 MHz while Coil 2 has a resonant frequency of 60.7 MHz. Additionally, the resonant peak of Coil 1 is larger than the peak of Coil 2. This behavior, shown in Fig. 8a, was determined applying a sinusoidal

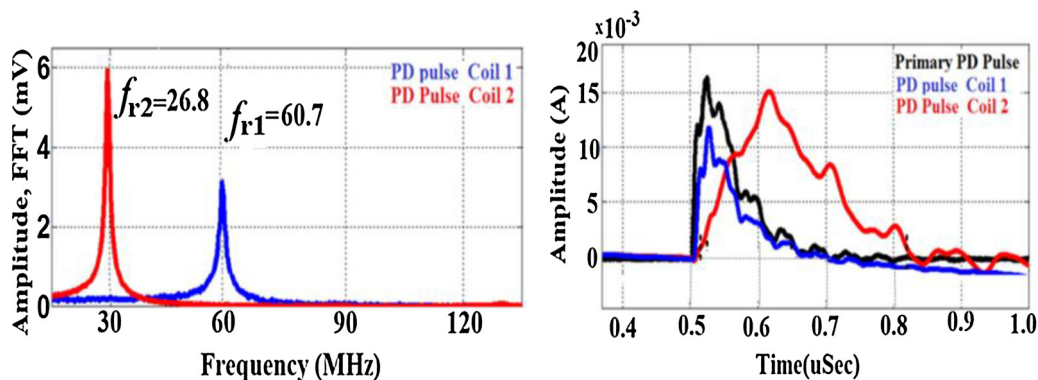


Fig. 8. Performance comparison of Rogowski coil. (a) Frequency domain, (b) time domain.

input voltage with a function generator to the primary conductor passing through the Rogowski coil. The conductor was a short 50 Ω coaxial cable with a low-induction resistor connected to the other end so this voltage can be considered proportional and in phase with the current. The resulting sinusoidal voltage at the output of the Rogowski coil was measured with an oscilloscope. The frequency of the function generator was changed gradually obtaining different points for the V/I transfer function. The frequency with the highest output voltage was identified as the resonant point. At that instant, the ratio between the output voltage and the injected current was 19 mV/A for Coil 1 and 9.51 mV/A for Coil 2. This means that an ideal current pulse passing through the coils would give a larger response for Coil 1 so this coil would have larger sensitivity. These values will be considered as the sensitivities of the coils. Since the resonant frequencies depend on the geometry of the coil, the design of a Rogowski coil should be done taking into account the type of signal to measure and its frequency response. The bandwidth of the Rogowski coil would have to be centered in a resonant frequency determined by the frequency spectrum of the input signals. If partial discharges were to be measured with these coils, they would need to have a reasonable amplitude at the resonant frequencies to reach a sensitivity of 19 mV/A and 9.51 mV/A, respectively. The frequency spectrum of an ideal PD pulse can be considered flat from low frequencies up to high frequencies and therefore the sensitivity of a Rogowski coil with a resonance frequency in the frequency range of a PD pulse can be high enough to measure it.

Tables 2 and 3 provide a comparison of the designed geometrical parameters, experimentally determined electrical parameters, and the observed operation performance parameter for PD measurements. In this comparison, the number of turns of Coil 2 is twice that of Coil 1 while the other parameters are the same. It has been observed that the sensitivity of Coil 2 becomes two times higher while the resonant frequency has decreased to 40% of that of Coil 1. It should be noted that changing one geometrical parameter affects both the sensitivity and resonant frequency in a certain proportion. More importantly, the same percentage change in different geometrical parameters (changing one geometrical parameter at a time); provide a different percentage change in the sensitivity and resonant frequency. Similarly, other parameters such as a , b , and h can be changed, based on requirements of physical design of the coil.

5.3. Optimized design of a Rogowski coil with terminating resistor

By investigating the flexibility of the RCS design and identifying the methodology of its performance evaluation, a suitable design of the RCS with an optimum sensitivity and bandwidth can be developed so it can measure the shape of PD signals from both cables and transformers even when the pulses have different spectral characteristics. An appropriate way is to determine an optimum bandwidth that can encompass the PDs from cables and power transformers that lead to select a suitable range of the geometrical parameters of the coil which has been considered to be from 1 MHz to 30 MHz as explained before.

To develop the intended design of the Rogowski coil, we propose to maximize an optimization function based on the geometrical parameters of the coil. Since the requirements of the sensor is to have maximum bandwidth and maximum gain, the objective would be to maximize the gain-bandwidth product (GBWP) considering certain boundaries constraint for the geometry. The design presented in Section V-B does not include the external components i.e., the resistance of the terminating resistor. This resistor connected at the output of the Rogowski coil plays an important role in modifying the bandwidth of the sensor [36] since it splits the double complex pole that creates the resonance into two poles at low and high frequencies, f_L and f_H , respectively that would be the new bandwidth. Then, the transfer function between voltage V_o and current i_p would have a flat frequency response between those two frequencies with a constant gain or sensitivity. Considering the model of the Rogowski coil represented in Fig. 5,

the transfer function is given by the following expression [36],

$$V_o(s) = \frac{R_t Ms}{LR_t Cs^2 + (L + RR_t C) s + R + R_t} I(s). \tag{13}$$

There are five design parameters: a , b , h , N , and R_t that will determine the best GBWP with the lower and upper bounds as shown in Table 4. The internal diameter of the coil a has been set to a minimum of 100 mm to be able to enclose the bus bars while the external diameter b has an upper bound set to 300 mm so that the coil does not interfere with other devices close to the measuring point. These same criteria have been applied to the width of the turns h , which would be restricted between 10 mm and 40 mm so the coil can be easily bent and clamped around the bars.

There are also some other constraints in the design: the external diameter must be larger than the internal and the decision has been to set $b > a + 10$ mm; and the poles of the transfer function (Fig. 9) must be real to ensure that the resonance has been eliminated; additionally, the desirable theoretical limits of the bandwidth must be $\frac{1}{2\pi} < f_L$ and $f_H < \frac{1000}{2\pi}$ in MHz. Notice that, though the bandwidth seems to be very wide, the effective limits of the band where the frequency response is flat are narrower due to the fact that the transfer function is second order with real poles. As a figure of merit, we have considered that we have an output voltage proportional to the input current when the phase shift in the frequency response is lower than 10°.

The metaheuristic method of finding the optimum GBWP is based on particle swarm optimization with a swarm size of 2000 particles and variable inertia that provide the set of optimized parameters as given in Table 5.

From Fig. 9, the gain for this Rogowski coil is 0.94 V/A and the effective bandwidth, considered as the limits where the phase shift is below 10 degrees, ranges from 700 kHz to 29 MHz which is suitable for a wide range of electrical assets as was the objective of this design. Partial discharges propagated through cables with energy below 700 kHz, being quite unusual, could still be measured with the designed sensor though they would be attenuated and shifted due to the resulting frequency response. The same would happen with pulses with energy above 29 MHz.

6. Integrated monitoring scheme for cable feeder using Rogowski coil sensor

The HV and MV cables with extruded insulation and their accessories are designed, tested, and installed, complying with the IEC 60840 [37] to ensure reliable operation of the cable system during likely stresses. Similarly, IEC 60076 [38] deals with the insulation system of power transformers considering not only oil, bushing, winding and terminal insulation but also the clearances between the live parts as well as with the air. However, regardless of all improvements in material and production technology, the defects emerge and cause initiation of PD signals that are to be measured and analyzed to predict the progressing threats before failure.

A typical distribution network consists of a large number of components distributing power to the consumers. For instance, Energex (an Australian power distribution utility) operates 300 HV/MV substations where each substation runs of 6–12, 11 kV feeders, 80–50 MV/LV transformers that serve 50,000–100,000 customers [39]. Fig. 10 shows a typical primary substation (HV/MV transformer) having four cable feeders supplying several secondary substations (MV/LV transformer).

Table 2
Geometrical design parameter of RCS prototypes.

RCS type	a	b	H	n
Coil 1	155.0 mm	131.0 mm	12.0	30
Coil 2	155.0 mm	131.0 mm	12.0	60

Table 3
Electrical parameters of RCS prototypes.

RCS type	C (pF)	L (μH)	M (nH)	Resonant frequency (f_r)	Sensitivity
Coil 1	5.7 pF	1.20 μH	9.51 nH	60.7 MHz	9.51 mV/A
Coil 2	15.2 pF	2.33 μH	19.0 nH	26.8 MHz	19.0 mV/A

Table 4
Lower and upper bound to determine the optimized design of Rogowski coil.

Parameter	Lower bound	Upper bound
a	100 mm	∞
b	100 mm	300 mm
h	10 mm	40 mm
N	3 turns	∞
R_t	10 Ω	∞

Here feeder F_1 is branched into feeder Z and Y at T-Junction J_1 supplying power to two different locations of customers. The sensors installed at the nodes (joints, cable sections, and transformers) are shown in Fig. 10.

6.1. Integrated condition monitoring system for MV cable feeder

Along the cable feeder, the components that are most vulnerable to insulation faults and are focus of this work are cable sections, joints, terminations, tapping points, and transformers as shown in Fig. 10. A comprehensive condition monitoring model is presented in Fig. 11. The data measured from multiple RCSs is transmitted to the processing computer using Information and Communications Technology (ICT) solutions. Advances in digital electronics and computers realize the implementation of high-performance yet low-cost measuring instruments. The PD analyzer can now utilize the combination of FPGA (field programmable gate arrays) and computer based system for implementation of the complicated digital part without compromising ease of use [40].

Matlab based algorithms can be developed with the features of data comparison (polarity of the PD signals), fault detection, location, and quantification. The polarity of the first peak represents the polarity of the measured PD signal. The algorithm mainly aims at analyzing the data obtained from each sensor individually as well as pairing with the

Table 5
Optimized parameters of the Rogowski coil.

Parameter	Value
a	100 mm
b	221 mm
h	36 mm
N	194 turns
R_t	182 Ω

sensors. It is based on a successive adjacent data comparison (SADC) approach. This approach performs a comparison of the PD data of one sensor with that of the adjacent sensor and then with the next adjacent sensors. The SADC array can be described as (R_{11}, R_{12}) , (R_{12}, R_{21}) , and (R_{21}, R_{22}) and so on. Based on the DOA technique developed in Ref. [41], the faulty parts of the feeder can be identified. If the cable section between a pair of any consecutive sensors (R_{y1}, R_{y2}) is identified as the faulty section, the algorithm will carry out further diagnostics. The overall framework for PD monitoring and diagnostics is shown in Fig. 12, which highlights the use of different available techniques for detection and location of the PD signals and sources in transformers, cable, and cable accessories.

When a cable section is identified as the faulty part, it needs further diagnostics to find the location of the defect. Time-domain reflectometry (TDR) and time difference of arrival (TDOA) techniques are commonly used to locate the faults on cables [12,42]. The accurate information of the wave propagation velocity of the cable plays an important role to improve the accuracy of location of the fault. If the node sensors declare a transformer as the source of captured PD signals based on DOA observation, the location of the PD defect is the next stage to accomplish the diagnosis. Here again the PRA is the front end technique to assess if these are corona, surface or internal discharge activity that usually correspond to terminal, contacts, bushing, and windings. When the PD pulses propagate from the source location to the measuring sensor, attenuation and dispersion due to the transmission line are embedded on the signals. Therefore, for deeper investigation of possible defects located within the transformer windings, the transfer function technique can identify the fault location based on the shape of the PD pulse [43]. Similarly, machine learning based pattern recognition techniques developed with a test and training approach is another solution for speedy fault location in transformers [29,30].

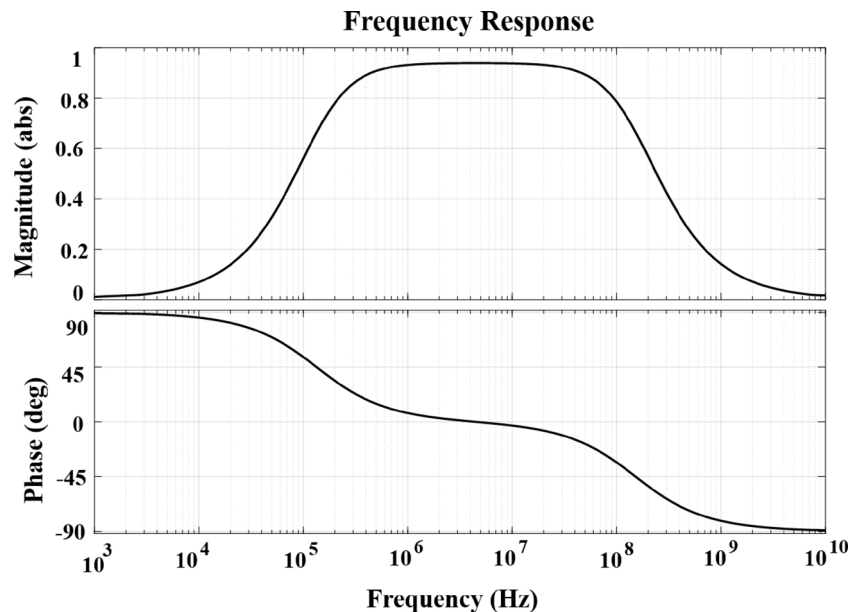


Fig. 9. Frequency response of the designed Rogowski prototype.

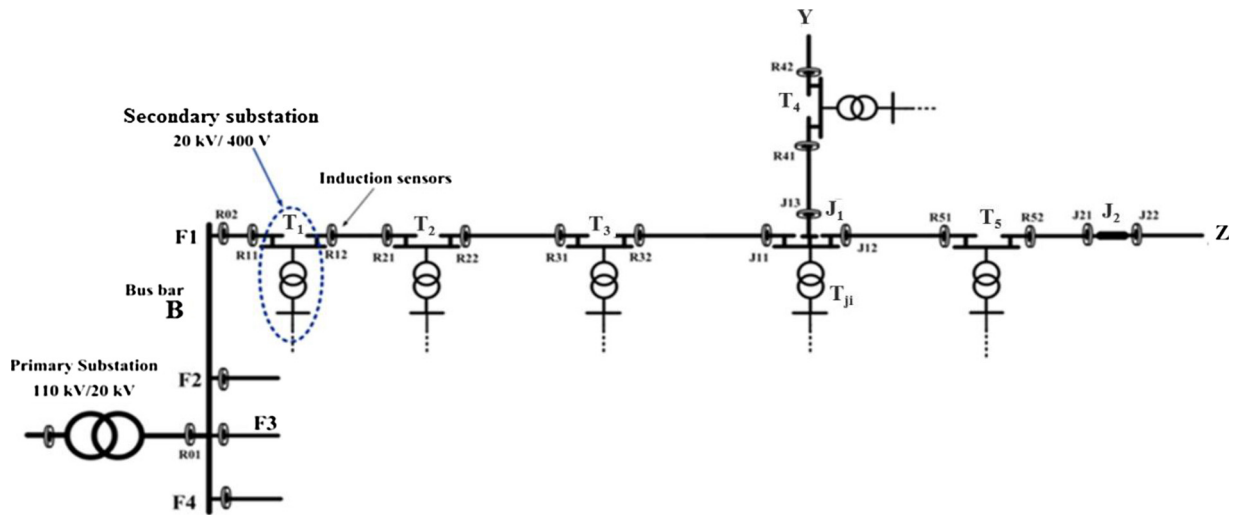


Fig. 10. Integrated PD monitoring scheme of cable feeder using Rogowski coils.

6.2. Major considerations for the implementation

Periodic and continuous monitoring are commonly used approaches for condition assessment of electrical components. Periodic monitoring is traditionally performed one to four times per year depending on the acuteness, economic worth, intensity of incoming threat, and rate of defect progression based on previous observations [44]. Periodic monitoring is performed mostly in both on-line and off-line modes. The insulation defects may manifest in between two consecutive periods and the unavailability of trend establishing data may cause a failure before the next inspection. Especially in today's grid operational scenario where the stress profile is changing and the impacts are still unknown to the existing insulation system, which was not designed for the emerging domain of non-standard stresses. The need for continuous monitoring has never been as critical as it is today. Continuous monitoring is generally carried out in online mode. The sensors are permanently installed and the data is recoded locally (on site recording instruments) or remotely (using wireless links interfaced with sophisticated information technology based solutions). Two major considerations for practical implementation of the proposed monitoring scheme are discussed below.

6.2.1. Economic considerations

Limiting the sensors' requirement, with double side monitoring scheme (DSMS) for a cable feeder (shown in Fig. 10) with n number of transformers, m number of straight joints, and p number of branched joints (with 3 branches), the required number of sensors can be determined as:

$$N_{F1} = 2n + 2m + 3p. \tag{14}$$

The number of sensors can be reduced to,

$$N_{F1'} = n + m + 3p, \tag{15}$$

i.e., that refers to single side monitoring scheme (SSMS) with no change in branched nodes. However, the major drawback of this installation scheme is the reduced reliability of PD location for transformers while fault detection will still be done effectively.

6.2.2. Data processing

A high frequency DAS is needed for reliable measurement of PD signals. Therefore, the issues related to the size of data storage/processing in the proposed integrated monitoring scenario put significant limitations. PD activity (shown in Fig. 7) captured in the laboratory

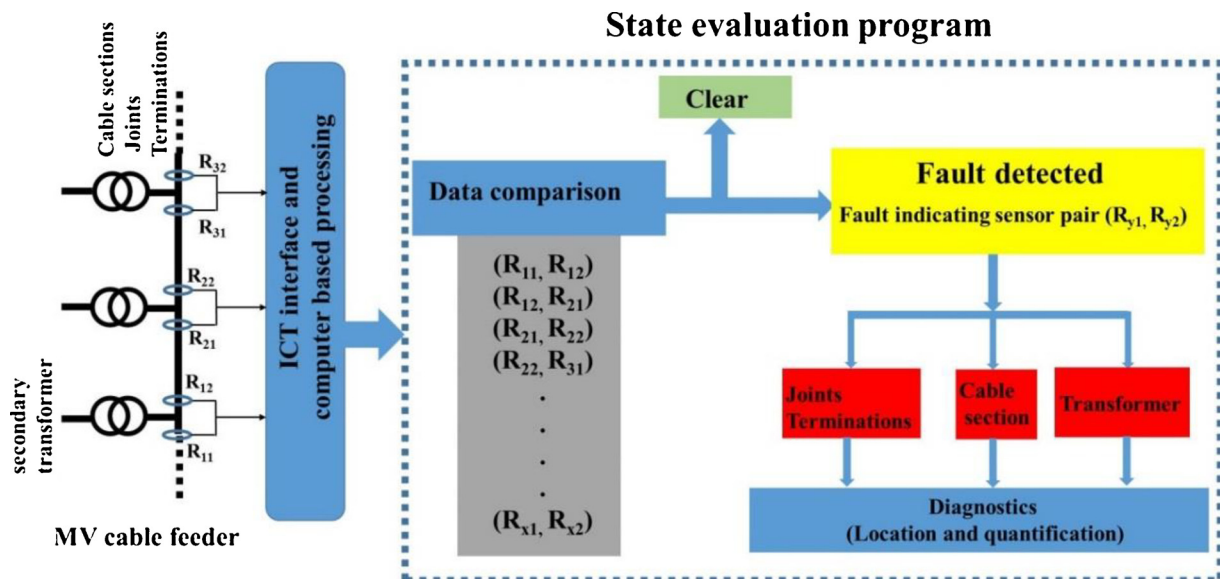


Fig. 11. Integrated condition monitoring model for MV cable feeder.

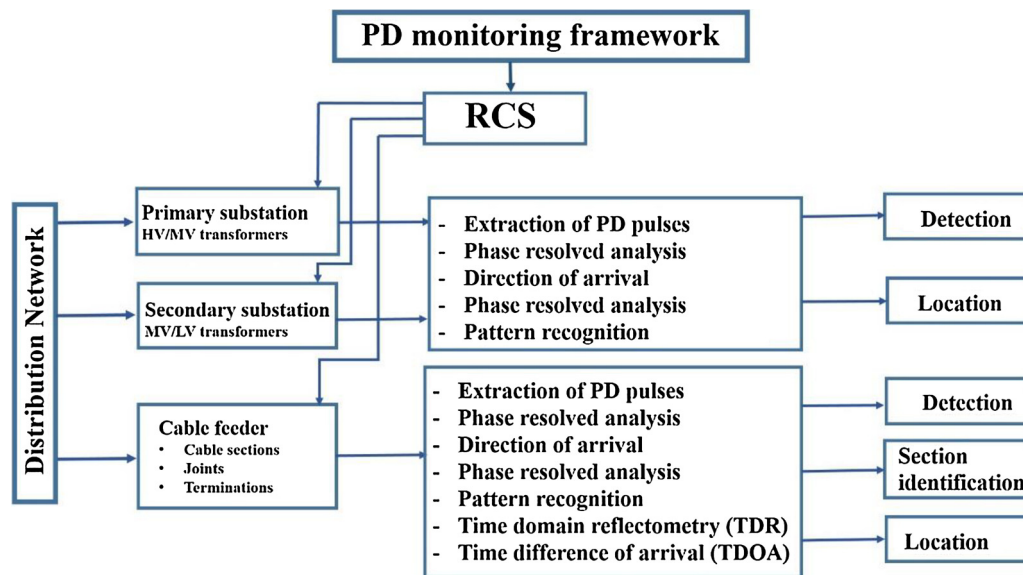


Fig. 12. Framework for monitoring and diagnostics using Rogowski coil sensor.

setup by a 60.7 MHz RCS system during a power supply cycle (20 ms in Fig. 13) with a DSO having 12-bit analogue to digital converter (ADC) and 2.5 GS/s sampling rate, needed approximately 70 Mbyte when stored as an ASCII data file. When such data of four sensors was processed with computational software, it needed considerable time even for very basic analysis. Implementing the proposed scheme for an entire feeder or substation requires a large number of sensors, this means a huge amount of data during online monitoring is fairly challenging.

For real application, a practical consideration should be made. The sampling rate should be selected according to the bandwidth of the measurement sensor with respect to Nyquist sampling frequency. Therefore, based on the resonant frequency of the Rogowski coil of 60.7 MHz, a sampling rate of 125 MS/s was selected to capture the PD signals. This has reduced the number of samples significantly to 5%.

In order to make the monitoring system more agile a smart data processing solution can be implemented based on the very nature of the PD activity. The PD data during a complete power cycle presents the PRA in order to recognize the type of PD defect whereas individual PD pulses with parameters, amplitude, polarity, peaks, pulse width, and rate of rise or fall, are required to analyze the PD defect and its location. Therefore, data for a complete cycle is proposed. Similarly, it is proposed that a limited number of PD pulses can be ‘picked’ during each cycle based on a set threshold for peak values of the pulses.

Considering the above-mentioned measured data, the PD pulse width is in microsecond (μ s) range. The pulse width of the captured PDs were between 0.1 μ s–0.5 μ s. The pulse of 0.5 μ s width takes approximately 60 samples. Based on laboratory investigation each power cycle may have few pulses of significant intensity/amplitude. Extracting two pulses from each half cycle, the number of samples required to capture the useful PD data during 1 s is 12,000, which means 0.0168 MB. If we extend the monitoring time to an hour and then to 24 h around the day, this data becomes 80.64 MB for one sensor. Similarly, for continuous monitoring of a part of the network using for instance 10 sensors over the whole year, the amount of data to be processed will be 2060 GB. A complete year of monitoring of several components can be done with this amount of data. Nevertheless, the data should be processed prior to saving it so that it would not be necessary to store the entire data but the critical data that provide the statistical trends and relevant parameters. As the PD activity is usually a continuous degradation process, monitoring of 1 sample per hour should be a suitable resolution that will have no effect on the reliability of the monitoring.

7. Conclusions

The paper aims at developing efficient non-intrusive and integrated monitoring solution for distribution network components with emphasize on cables, cable accessories, and transformers. The paper combines several aspects of PD monitoring including the mechanism of PD activity, the selection of a compatible and optimized design of a Rogowski coil for PD measurement, the installation of the sensors and the diagnostic possibilities. The design of the coil is based on the maximization of the gain-bandwidth product because it is considered important to have the output of the sensor proportional to the input. This makes it possible to study the characteristics of the pulse to extract the features of the partial discharge for identification of the failure. However, other objective functions can be applied in the design to give prevalence to other features of the measurement: for instance, if the interest of the measuring system is the simple detection of low energy PD, the gain of the coil jeopardizing the detection frequency band should be maximized.

Based on the simple directional feature of Rogowski coils, the proposed technique of measurement and integrated sensor installation scheme presents a modest solution for detection and location identification of PD site in MV cable feeders. The presented monitoring scheme is studied for cable feeders; however, it can be equally used for covered

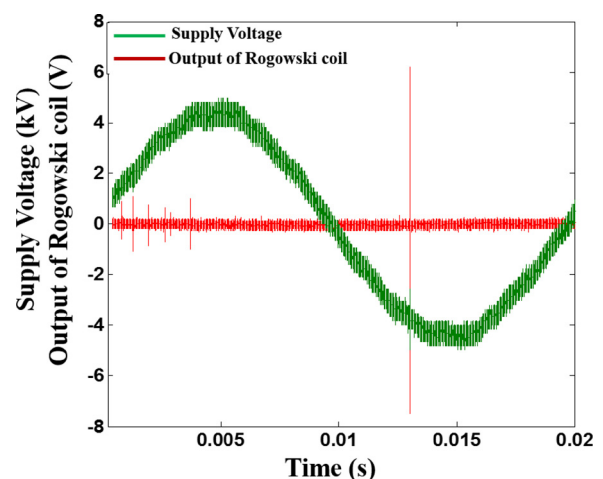


Fig. 13. PD measured during a power supply cycle using high sampling DAS.

conductor (CC) distribution feeders in which PDs are caused by falling trees. The presented concept will add and contribute to the ongoing development of grid automation and the ability of the power grid to adopt the infrastructural growth with increased reliability.

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References

- [1] Pavlos S. Georgilakis, Nikos D. Hatzigiorgiou, A review of power distribution planning in the modern power systems era: models, methods and future research, *Electr. Power Syst. Res.* 121 (2015) 89–100.
- [2] C. Sumereder, M. Muhr, Estimation of Residual Lifetime—Theory and Practical Problems, Graz University of Technology, Portoroz, 2005 November.
- [3] G.C. Montanari, D. Fabiani, P. Morshuis, L. Dissado, Why residual life estimation and maintenance strategies for electrical insulation systems have to rely upon condition monitoring, *IEEE Trans. Dielectr. Electr. Insul.* 23 (June (3)) (2016) 1375–1385.
- [4] IEC60071-1, Insulation co-ordination Part 1: Definition principles and rules, (2006).
- [5] M. Muhr, et al., Aging behaviour of cross-linked polyethylene (XLPE) as an insulating material for high (HV) and extra-high voltage cables (EHV), *Electrical Insulation and Dielectric Phenomena, CEIDP'04* (2004).
- [6] I.L. Hosier, J.E.A. Koilraj, A.S. Vaughan, Effect of aging on the physical, chemical and dielectric properties of dodecylbenzene, *IEEE Trans. Dielectr. Electr. Insul.* 23 (6) (2016) 3389–3396.
- [7] D. Martin, Y. Cui, C. Ekanayake, H. Ma, T. Saha, An updated model to determine the life remaining of transformer insulation, *IEEE Trans. Power Deliv.* 30 (1) (2015) 395–402.
- [8] S. Repo, et al., The IDE4L project: defining, designing, and demonstrating the ideal grid for all, *IEEE Power Energy Mag.* 15 (3) (2017) 41–51.
- [9] M.M. Yaacob, et al., Review on partial discharge detection techniques related to high voltage power equipment using different sensors, *Photonic Sens.* 4 (4) (2014) 325–333.
- [10] M. Hikita, S. Okabe, H. Murase, H. Okubo, Cross-equipment evaluation of partial discharge measurement and diagnosis techniques in electric power apparatus for transmission and distribution, *IEEE Trans. Dielectr. Electr. Insul.* 15 (2) (2008) 505–518.
- [11] C. Kane, A. Golubev, Advantages of continuous monitoring of partial discharges in rotating equipment and switchgear, *Annual Pulp and Paper Industry Technical Conference* (2003) 117–122.
- [12] P. Wagenaars, Integration of Online Partial Discharge Monitoring and Defect Location in Medium-Voltage Cable Networks, PhD Dissertation, Eindhoven University of Technology, 2010.
- [13] L. Renforth, R. Mackinlay, M. Seltzer-Grant, Deployment of distribution on-line partial discharge monitoring devices on medium voltage electricity networks, *CIRE2009 – 20th International Conference and Exhibition on Electricity Distribution – Part 1*, Prague, Czech Republic, 2009, pp. 1–4.
- [14] W. He, H. Li, D. Liang, H. Sun, Z. Sun, B. Liu, An improved directional sensor for on-line partial discharge measurement in overhead covered conductors, *Electr. Power Compon. Syst.* 44 (14) (2016) 1543–1550.
- [15] C. Smith, Partial Discharge and Insulation Failure, IPEC Ltd., 2005.
- [16] M.D. Judd, Radiometric partial discharge detection, *International Conference on Condition Monitoring and Diagnosis (CMD 2008)*, Beijing, China, 2008, pp. 1025–1030.
- [17] R. Schwarz, M. Muhr, Modern technologies in optical partial discharge detection, *Annual Report – Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2007)*, Vancouver, Canada, October, 2007, pp. 163–166.
- [18] J. Rubio-serrano, M.V. Rojas-moreno, J. Posada, J.M. Martínez-tarifa, G. Robles, J.A. Garcia-souto, Electro-acoustic detection, identification and location of partial discharge sources in oil-paper insulation systems, *IEEE Trans. Dielectr. Electr. Insul.* 19 (October (5)) (2012) 1569–1578.
- [19] M. Siegel, M. Beltle, S. Tenbohlen, S. Coenen, Application of UHF sensors for PD measurement at power transformers, *IEEE Trans. Dielectr. Electr. Insul.* 24 (February (1)) (2017) 331–339.
- [20] M. Ghaffarian Niasar, et al., Partial discharges in a cavity embedded in oil-impregnated paper: effect of electrical and thermal aging, *IEEE Trans. Dielectr. Electr. Insul.* 22 (2) (2015) 1071–1079.
- [21] D.M. Hepburn, I.J. Kemp, A.J. Shields, J. Cooper, Degradation of epoxy resin by partial discharges, *IEE Proc. Sci. Meas. Technol.* 147 (3) (2000) 97–104.
- [22] G.C. Stone, Partial discharge diagnostics and electrical equipment insulation condition assessment, *IEEE Trans. Dielectr. Electr. Insul.* 12 (5) (2005) 891–904.
- [23] D. Couderc, P. Bourassa, J.M. Muiras, Gas-in-oil criteria for the monitoring of self-contained oil-filled power cables, Millbrae, CA, *Proceedings of Conference on Electrical Insulation and Dielectric Phenomena – CEIDP '96*, vol. 1, 1996, pp. 283–286.
- [24] Boya, Carlos, et al., Identification of multiple partial discharge sources using acoustic emission technique and blind source separation, *IEEE Trans. Dielectr. Electr. Insul.* 22 (3) (2015) 1663–1673.
- [25] P. Kundu, N.K. Kishore, A.K. Sinha, Simulation and analysis of acoustic wave propagation due to partial discharge activity, *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Kansas City, 2006, pp. 607–610.
- [26] T. Marco, Partial Discharge in Power Distribution Electrical Systems: Pulse Propagation Models and Detection Optimization. PhD Diss, Alma, 2010.
- [27] S. Coenen, S. Tenbohlen, S.M. Markalous, T. Strehl, Attenuation of UHF signals regarding the sensitivity verification for UHF PD measurements on power transformers, *IEEE International Conference on Condition Monitoring and Diagnosis (CMD 2008)* (2008) 1036–1039.
- [28] V. Bolhuis, J. Peter, et al., Comparison of conventional and VHF partial discharge detection methods for power transformers, *11th International Symposium on High Voltage Engineering. IET vol. 5*, (1999).
- [29] J.A. Mazhab, A. Akbari, Partial discharge localization in transformer windings using multi-conductor transmission line model, *Electr. Power Syst. Res.* 78 (6) (2008) 1028–1037.
- [30] M.G. Niasar, Partial Discharge Signatures of Defects in Insulation Systems Consisting of Oil and Oil-Impregnated Paper, Licentiate Thesis, Royal Institute of Technology, Sweden, 2012.
- [31] M. Shafiq, L. Kütt, M. Lehtonen, T. Nieminen, M. Hashmi, Parameters identification and modeling of high-frequency current transducer for partial discharge measurements, *IEEE Sens. J.* 13 (3) (2013) 1081–1091.
- [32] M. Shafiq, G.A. Hussain, L. Kütt, N.I. Elkalashy, M. Lehtonen, Partial discharge diagnostic system for smart distribution networks using directionally calibrated induction sensors, *Electr. Power Syst. Res.* 119 (2015) 447–461.
- [33] L.A. Kojovic, working group, Practical Aspects of Rogowski Coil Applications to Relaying, *IEEE PSRC Special Report*, (2010).
- [34] B. Sheng, et al., Partial discharge pulse propagation in power cable and partial discharge monitoring system, *IEEE Trans. Dielectr. Electr. Insul.* 21 (3) (2014) 948–956.
- [35] J.C. Chan, H. Ma, T.K. Saha, Time-frequency sparsity map on automatic partial discharge sources separation for power transformer condition assessment, *IEEE Trans. Dielectr. Electr. Insul.* 22 (4) (2015) 2271–2283.
- [36] G. Robles, J.M. Martínez-Tarifa, J. Sanz, B. Tellini, C. Zappacosta, M.V. Rojas-Moreno, Designing and tuning an air-cored current transformer for partial discharges pulses measurements, *IMTC 2008 – IEEE Instrumentation and Measurement Technology Conference Vancouver, Canada, May 12–15, 2008*.
- [37] I.E.C. 60840, Power cables with extruded insulation and their accessories for rated voltages – Test methods and requirements, (2004).
- [38] IEC/TS 60076-14, Power transformers – Part 14: Design and application of liquid-immersed power transformers using high temperature insulation material, Edition, (2009).
- [39] N. Higgins, V. Vyatkin, N.C. Nair, K. Schwarz, Distributed power system automation with IEC 61850, IEC 61499, and intelligent control, *IEEE Trans. Syst. Man Cybern. C: Appl. Rev.* 41 (1) (2011) 81–92.
- [40] R.N. Wu, C.K. Chang, The use of partial discharges as an online monitoring system for underground cable joints, *IEEE Trans. Power Deliv.* 26 (3) (2011) 1585–1591.
- [41] M. Shafiq, L. Kütt, M. Isa, M. Hashmi, M. Lehtonen, Directional calibration of Rogowski coil for localization of partial discharges in smart distribution networks, *Int. Rev. Electr. Eng.* 7 (5) (2012) 5881–5890.
- [42] J. Granado, C. Álvarez-Arroyo, A. Torralba, J. Rosendo-Macías, J. Chávez, M. Burgos-Payán, Time domain analysis of partial discharges envelope in medium voltage XLPE cables, *Electr. Power Syst. Res.* 125 (2015) 220–227.
- [43] M. Homaei, S.M. Moosavian, H.A. Illias, Partial discharge localization in power transformers using neuro-fuzzy technique, *IEEE Trans. Power Deliv.* 29 (5) (2014) 2066–2076.
- [44] A report of the IEEE/PES Task Force on impact of maintenance strategy on reliability of the reliability, risk and probability applications subcommittee, “the present status of maintenance strategies and the impact of maintenance on reliability, *IEEE Trans. Power Syst.* 16 (4) (2001).