Bashir Ahmed Siddiqui

**New Cost-effective Method for Monitoring
Wideband Disturbances at Secondary Substation**

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Sähkötalo Building, Auditorium SA203, at Tampere University of Technology, on the 4th of May 2018, at 12 noon.

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Abstract

Modern societies are becoming increasingly dependent on reliable and continuous supply of high quality electricity. Maintaining continuous supply of electricity round the clock depends heavily on the efficient and reliable operation of distribution system components. On the other hand, large-scale power outages are increasing in overhead lines due to extreme weather condition i.e. heavy storms and snowfalls. Distribution network operators (DNOs) are facing considerable network investments in the near future due to the ongoing trend of cabling. At the same time, the long fault location and repair times in aging cable networks set new demands for condition monitoring and fault prevention through preventive maintenance. Partial discharge (PD) monitoring is an excellent way to determine the overall health of the MV components and detect developing faults in underground cables. On the other hand, the proliferation of e.g. distributed generation and electronic loads poses new challenges to maintain the power quality (PQ) in distribution networks. Utilizing network condition and power quality information together would improve the allocation accuracy and benefit-cost ratio of network maintenance and renewals. Thus, the importance of condition monitoring is increasing in the distribution networks to facilitate online diagnostic, preventive maintenance, forecasting risk of failure and minimizing outages.

Secondary substations seldom have any remotely readable measurement and control units and the existing measurements in the network are limited to only power quality and MV fault management due to low sampling rate (some kHz). There are also commercially available devices for PD monitoring of underground cables but those capable of continuous on-line monitoring are still relatively expensive and as such, more suited for critical and high risk location. Currently, there are no cost-effective wideband multifunction devices suitable for continuous on-line PD monitoring, PQ monitoring, disturbance recording (DR) and fault location at secondary substation.

This thesis proposes a novel cost-effective secondary substation monitoring solution which includes the monitoring system as well as the monitoring concept to measure various quantities at LV and MV side of secondary substation. Additionally, it can be used in fundamental frequency metering and can be used as disturbance recorder as well. It also locates earth fault which is demonstrated as an application of disturbance recording function. The architecture of the monitoring system includes high frequency current transformer (HFCT) sensors for current measurements at MV side, resistive divider for voltage measurements at LV side, filter & amplifier unit and multichannel data acquisition & processing unit. HFCT sensors not only measure PD but also PQ at the MV side of secondary substation, which is a novel approach. Hence, no sensor having expensive high voltage insulations is needed, which makes the solution cost-effective and reliable. The overall concept is tested and verified through prototype systems in the laboratory and in the field. Secondary substation monitoring solution provides a platform on which various monitoring, control and network automation applications can be built.

Preface

Foremost, I would like to express my sincere gratitude to my supervisor Professor Pekka Verho for providing me an opportunity to work with a challenging and interdisciplinary subject. Thank you for your enthusiastic encouragement, valuable guidance, constant support and allowing me the freedom to make decisions. I am highly indebted to my immediate supervisor, Dr. Pertti Pakonen, for his invaluable support, continuous guidance, meticulous suggestions, astute criticism and recommendations throughout the course of this research work, without his efforts this book would not have been possible. I am also grateful to the preliminary examiners of the thesis, Professor Hans Edin from Royal Institute of Technology (KTH), Sweden and Dr. Pekka Koponen, Senior Scientist from VTT Technical Research Centre of Finland for their constructive comments that have helped me immensely to improve the quality of the thesis.

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Contents

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List of Publications

This thesis is composed of the following six publications:

[P1]   B. A. Siddiqui, P. Pakonen and P. Verho, "Experience of Communication Problems in PLC-based AMR Systems in Finland", in *Proceedings of 5th IEEE Conference on Innovative Smart Grid Technologies - Europe (ISGT-Europe)*, Istanbul, Oct. 2014.

[P2]   B. A. Siddiqui, P. Pakonen and P. Verho, "A Novel Device for Real-Time Monitoring of High Frequency Phenomena in CENELEC PLC Band", *Journal of Smart Grid and Renewable Energy (SGRE) by Scientific Research Publishing Inc.*, May 2012.

[P3]   B. A. Siddiqui, P. Pakonen and P. Verho, "Novel Inductive Sensor Solutions for On-line Partial Discharge and Power Quality Monitoring", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 1, pp. 209-2016, Feb. 2017.

[P4]   B. A. Siddiqui, A. Hilden, P. Pakonen and P. Verho, "A Versatile Solution for Continuous On-line PD Monitoring", in *Proceedings of 5th IEEE Conference on Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Bangkok, Nov. 2015.

[P5]   P. Pakonen, B. A. Siddiqui and P. Verho, "A Novel Concept of Secondary Substation Monitoring: Possibilities and Challenges", in *Proceedings of IEEE Conference on Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Melbourne, Nov. 2016.

[P6]   B. A. Siddiqui, P. Pakonen, P. Verho, "Field testing of a wideband monitoring concept at MV side of secondary substation", in *Proceedings of 23rd International Conference & Exhibition on Electricity Network*, *CIRED*, Glasgow, June, 2017.

Abbreviations

AMR	automatic meter reading
AMI	advanced metering infrastructure
A/D	analog-to-digital
CFL	compact fluorescent lamp
CIC	customer interruption cost
DNO	distribution network operator
DMS	distribution management system
DSM	demand-side management
DOE	department of energy
DER	distributed energy resources
DG	distributed generation
DR	disturbance recording
EV	electrical vehicle
EVM	evaluation module
EMC	electromagnetic compatibility
ENOB	effective number of bits
FFT	fast Fourier transform
FLIR	fault location, isolation and restoration
FPGA	field programmable gate array
HV	high voltage
HF	high frequency
HFCT	high frequency current transformer
HSMC	high-speed mezzanine card
IED	intelligent electronic device
ICT	information & communication technology
IEC	International Electrotechnical Commission
LED	light-emitting diode
LV	low voltage
LVDS	low-voltage differential signaling
MCS	mains communicating system
MV	medium voltage
NIST	national institute of standards and technology
PD	partial discharge
PQ	power quality
PV	photovoltaic
PLC	power-line communication
PCC	point of common coupling
RTDS	real-time digital simulator
RMS	root mean square
SNR	signal-to-noise ratio
SMPS	switched-mode power supply
SCADA	supervisory control and data acquisition
THD	total harmonic distortion
UHF	ultra high frequency

1 Introduction

The electric utility industry is going through significant changes caused by ageing infrastructure of distribution systems, large-scale integration of distributed generation and energy resources and requirements for continuous improvement in the quality of power supplied to the customers. Due to these challenges, distribution network operators are looking for ways to improve the reliability of their assets while minimizing the operational and maintenance cost of the network. The U.S. National Institute of Standards and Technology (NIST) defines smart grid as, "a modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications". The IEEE also defines smart grid as a next-generation electrical power system represented by the increased use of communication and information technology in the generation, delivery and consumption of electrical energy [1]. The U.S. Department of Energy (DOE) has also envisioned smart grid as a network full of monitoring systems [2]. Condition monitoring of distribution network equipment plays a vital role in order to locate the asset that implores the most urgent reliability concern. Through the efficient integration of cost-effective monitoring devices, information collected from the grid can be used to obtain a highly reliable and non-disruptive smart grid system.

The medium voltage (MV) network is an important asset of distribution network and it must guarantee a stable operation of the supply. In Europe, 70 to 80 % of the interruptions are caused due to the failure in the medium voltage network [3]. The most common fault type in distribution network is the single phase to earth fault. It is estimated that almost half of the faults are single phase to earth faults. Early detection of these faults are necessary to avoid long outage duration and damage to equipment and people. On the other hand, underground cables in cities are aging and cabling of medium voltage networks is increasing in rural areas so the likelihood of accident and failure arising from insulation degradation is becoming one of the main challenges against distribution network reliability. Underground cabling is a rising trend in rural areas electricity distribution network and it also plays an important role in enabling the future weather proof smart grid. It is also essential economically to extend the life span of the medium voltage cables. However, it may be difficult to maintain the power supply specifically in rural areas via alternative network configurations during the fault location and repair. The repair times of faults in underground cables are much longer than in overhead lines therefore, incipient faults must be detected before they cause an interruption. In addition, legislative actions and regulatory measures are forcing the network companies to increase proactive network monitoring. Thus, condition monitoring is becoming an important measure in preventing unplanned and long lasting outages. To minimize interruptions to supply, utilities must be able to monitor and locate faults more quickly

and develop condition monitoring in a more preventive direction [4,5]. The best way of detecting incipient faults in underground cable networks is continuous on-line partial discharge monitoring. However, continuous on-line PD measurement for condition monitoring has not been economically possible in medium voltage network due to the high cost of the equipment and resources needed [6].

Traditionally, network monitoring has been focused on high voltage (HV) and medium voltage network at primary substation (in Finland, mainly 400 / 110 kV and 110 / 20 kV). On the contrary, low voltage (LV) network has been monitored quite rarely especially using permanent monitoring devices. The information about power quality is based mainly on the measurements done at HV and MV level together with the case specific measurements done due to customer complaints [7]. There are some commercially available secondary substation monitoring and control units which offer limited power quality monitoring and MV network fault location indication. Due to their relatively low sampling rate (some kHz), they are neither capable of measuring partial discharges nor rapid voltage changes, transients or other higher frequency problems. Additionally, with the increasing low voltage network challenges due to the introduction of new customer equipment, for example, electrical vehicle (EV) chargers, photovoltaic (PV) inverters, other devices with power electronics network interface and heat pumps, there is a growing interest in extending the monitoring of LV network. The introduction of automatic meter reading (AMR) systems has opened new possibilities for DNOs to support network operation e.g. automatic LV-fault indication, isolation and location, network planning and asset management (e.g. exact load profiles for network calculation), power quality monitoring, customer service and load control in addition to providing traditional energy consumption data to utility [8]. Power line communication (PLC) based AMR systems offers a cost-effective way of bidirectional communication between customer and utilities but they are easily disturbed by noises in the LV network. Modern electronic equipment produce high frequency (HF) emissions at their switching frequency and its multiples which seriously affect the operation of PLC based AMR systems. Consequently, monitoring PQ (50 Hz…2.5 kHz) as well as high frequency (2 kHz…150 kHz) disturbances in LV network are another considerable issues for the successful and efficient operation of the grid.

There is an increasing trend of developing and increasing secondary substation automation to enable rapid fault location, isolation and restoration (FLIR) to ensure customer satisfaction. FLIR is currently based mainly on information available from the protective relays located at primary substations. Some companies may have remotely readable secondary substation monitors discussed later in the thesis, which may be used in fault location, but this is quite rare. For example in Finland, after the recent major storms, legislative actions have been taken which force the DNOs to develop their networks so that the set limits for the length of interruptions will not be

exceeded. This places new demands, especially, for existing and new underground cable networks both at medium and low voltage levels, where the fault location and repair is more challenging and takes longer time than on overhead lines. Secondary substation measurements would be extremely useful both in MV and LV network fault location and in giving early warnings of incipient faults. Secondary substation disturbance recordings (MV/LV) would improve the fault location accuracy considerably and speed up the fault isolation and supply restoration both in overhead line and underground cable networks. In addition, monitoring the load currents and harmonics on the secondary substations is useful for planning future network investments and e.g. transformer maintenance. Especially, feeders with industrial customers or high penetration of distributed energy resources (DERs) can be monitored to extract the information about the harmonic current injection at secondary substation. It would be useful in locating potential causes of power quality problems, assessing the transformer loading and aging [9,10] and the compliance with recommendations given e.g. in IEEE Std. 519 or IEC/TR 61000-3-6 [11,12].

Smart Grid concept significantly increases the monitoring need at all voltage levels for efficient and flexible power delivery. The lack of cost-effective wideband monitoring solution for measuring high frequency phenomena is one of the biggest shortcomings preventing the deployment of condition monitoring system extensively in the network. The essential part of condition monitoring system is the coupling device i.e. sensor which collects wide range of real-time signals to investigate about the health of the distribution system components. The cost of the sensor is already high if it contains high voltage insulation, which ultimately dominates the total cost of the measuring system, especially at high voltage levels. Sensors with flexible design, good sensitivity, higher frequency bandwidth and low-cost are the fundamental unit of a wideband monitoring system. Additionally, developments in enabling technology (digital electronics, communication technology, data storage and processing) have made it possible to monitor any parameter of interest efficiently and cost-effectively. A simple cost-effective condition monitoring solution can eliminate issues associated with power quality, MV faults and aging of the distribution system components to prevent blackout and save huge sum of money associated with distribution system failure.

This doctoral thesis highlights the importance of condition monitoring at LV and MV level and deals with the development of cost-effective instrumentation for measuring high frequency phenomena in the distribution network. Moreover, it presents a novel cost-effective secondary substation monitoring solution based on a monitoring system which can be installed at secondary substation, and a monitoring concept for measuring power quality and partial discharges, and performing disturbance recording and fault location at secondary substation. The monitoring system includes high frequency current transformer (HFCT) sensors for current measurements at

MV side, resistive dividers for voltage measurements at LV side, filter & amplifier unit and multichannel data acquisition & processing unit, all developed by the author and the co-authors. HFCT sensors are of utmost importance which enable PD monitoring, PQ monitoring, disturbance recording and fault location cost-effectively at MV side of the transformer. The proposed monitoring solution has not been fully developed as a standalone system in the course of the thesis. However, the performance of subsystems i.e. HFCT sensors and different systems for monitoring LV and MV network have been tested in the laboratory and in the field. Results are promising, thus, by integrating different subsystems, it is possible to develop full-fledged secondary substation monitoring solution.

1.1 Motivation of the thesis

In the continuous improvement of the reliability of the network, DNOs are looking for new cost-effective methods to overcome network challenges due to the climate change, aging infrastructure of distribution systems and demand of high quality electricity. Secondary substation (MV/LV) is an important location for acquiring network data since monitoring can be performed for both LV and MV network at one location. Hence, this is the key motivation of the thesis to come up with a new innovative multichannel solution to monitor a wide range of functionalities i.e. PD and PQ monitoring, disturbance recording and fault location cost-effectively at secondary substation. The innovation comes from the fact that it is based on one measuring unit and few wideband sensors for monitoring different phenomena. The concept has several advantages compared to a separate PD, PQ and disturbance recording systems. A wideband monitoring system having only a few sensors and one measuring unit is less complicated, easier to install and maintain and has lower hardware costs compared to a system having separate sensors and units for each monitoring function. In addition, electromagnetic compatibility aspects related to cabling, shielding and power supplies are easier to manage in a single device which helps in achieving a good sensitivity for PD monitoring. Moreover, a novel concept of monitoring at secondary substation together with multichannel wideband monitoring system can be extremely helpful in building various monitoring and control applications.

1.2 Objective of the thesis

The main objective of the thesis is to develop cost-effective wideband instrumentation for real-time measurement of high frequency phenomena (PLC communication, HF harmonics caused by

electronic loads and partial discharges) in distribution network which is also a challenge in the field. The development of cost-effective instrumentation includes multichannel data acquisition & processing unit and ferrite based wideband high frequency current transformer sensors for measuring PD, PQ and disturbance recording and fault location at MV side of the transformer. The novel approach of measuring PQ at the MV side together with PD also minimizes the extra cost of instrument for condition monitoring of transformer. Another important goal was to study the possibility of developing a multi-mode monitoring concept i.e. few sensors and a single measuring unit for a wide range of functionalities i.e. PD and PQ monitoring, disturbance recording and fault location.

Furthermore, a novel monitoring solution based on HFCT sensors, resistive divider, filter & amplifier unit and multichannel data acquisition & processing unit is proposed which can be installed permanently at secondary substation for measuring various quantities at LV and MV side of secondary substation. The key idea was to investigate the possibilities of incorporating new functions into the wideband multichannel monitoring system based on the performance of HFCT sensors which can measure PD, PQ and fault location at MV side of transformer. In the end, novel secondary substation monitoring concept has been tested in the field to demonstrate the potential of the proposed monitoring solution.

1.3   Author's contribution

The research work for the thesis has been conducted in the Laboratory of Electrical Energy Engineering, Tampere University of Technology, Finland under the supervision of Prof. Pekka Verho and Dr. Pertti Pakonen. Results obtained from the research work have been reported in six publications in the form of conference papers and journal articles; [P1]-[P6]. The author was the primary author of all publications except [P5], in which the author was the second author. The author designed and developed different monitoring devices and ferrite based HFCT sensors, performed extensive laboratory measurements, wrote MATLAB program for post-processing of the raw data as well as compared and analyzed the results by himself. All field measurements and laboratory setups were done jointly with Dr. Pertti Pakonen. Detailed contributions of the author and co-authors can be summarized as follows:

- · [P1] highlights the presence of high frequency disturbances in the PLC frequency range caused by electronic loads which affects the PLC communication of AMR systems. It also discusses the architecture of different AMR systems installed in Finland. The author developed the main ideas of the paper and composed majority of the text in this publications. However, field measurements were carried jointly with Dr. Pertti Pakonen.

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- [P2] presents the development of low-cost intelligent electronic device (IED) for real-time monitoring of high frequency disturbances in PLC network. The main ideas of the paper were developed by the author. The performance of the IED was tested in laboratory using smart meter and data concentrator along with load model based on compact fluorescent lamp (CFL) and light-emitting diode (LED) lamps. The author has designed and developed the standalone low-cost IED and implemented the software interface to process and analyze the data in real-time.

- [P3] presents the development of low-cost ferrite based high frequency current transformer sensors for continuous on-line PD monitoring and PQ monitoring at frequency range below 2.5 kHz. The author developed the main ideas of the paper and performed extensive laboratory measurements and analyzed the data to study the characteristics of different ferrite cores, including sensitivity, saturation current, frequency bandwidth as well as relative errors to design the best possible sensor. A comparison with commercial HFCT sensor, the Rogowski coil and power quality monitor is also made by the author to demonstrate the capability of the developed sensors to measure PD signals together with PQ at the MV side. All the laboratory setups reported in this publication were done jointly with Dr. Pertti Pakonen.

- [P4] describes the development of a versatile cost-effective monitoring system for continuous on-line PD monitoring of MV cables at secondary substation. The author developed the main ideas of the paper. A comparison of resolution and signal-to-noise ratio (SNR) between monitoring system and 8 bit oscilloscope is done. Moreover, laboratory measurements were also done using PD calibrator data and real PD data collected from 20 kV line to demonstrate the capability of the monitoring system to be used efficiently and permanently in the field for detecting PD signals. The filter & amplifier unit used in the data acquisition stage was developed by co-author Antti Hilden.

- [P5] proposes a novel secondary substation monitoring concept for smart grids which can be installed at secondary substation for partial discharge monitoring, power quality monitor, disturbance recording and fault location. The ideas of the paper were developed by Dr. Pertti Pakonen which is based on high frequency current transformer sensors, resistive dividers, filter & amplifier unit and a versatile multichannel data acquisition & processing unit developed by the author and co-authors. Additionally, it discusses the possibilities and challenges of incorporating different monitoring functions into the measuring device and utilizing the data to analyze electrical network during normal operation and different disturbance events.

- [P6] reports the field testing of wideband monitoring concept at MV side of secondary substation to observe what monitoring goals can be achieved based on the potential of the cost-effective HFCT sensor which is the foundation of the novel secondary substation

monitoring concept. The main ideas of the paper were developed by the author. The network simulation model for earth fault detection and field measurements were done jointly with Dr. Pertti Pakonen.

1.4 Thesis outline

The rest of the thesis is organized as follows. Chapter 2 gives an overview of disturbances and source of disturbances in different frequency range. It also discusses the standards dealing with PD, PQ and PLC. Additionally, it presents the latest trend in the field of distribution automation and finally state-of-the-art in distribution network monitoring is discussed. Chapter 3 briefly introduces the environment of secondary substation. This is followed by proposing the secondary substation monitoring solution. It also discusses the pros and cons of placing HFCT sensors at different location in the secondary substation. In the end, preferred sensor location for measurements at LV and MV side is proposed. Chapter 4 presents the development of monitoring system which includes HFCT sensor for PD and PQ monitoring at MV side and monitoring devices. It starts by discussing the frequency bandwidth requirements for PD and PQ monitoring. It further describes the development of ferrite based high frequency current transformer sensors for continuous on-line PD and PQ monitoring at MV side. The effect of winding configurations and air gaps on the amplitude response, transfer impedance, saturation current and relative errors are analyzed under laboratory conditions. Then the performance of the developed sensors is compared with commercially available HFCT sensor, the Rogowski coil and power quality current sensors. Afterwards, the specification of the monitoring device followed by the prototype development of the monitoring system is presented. Thereafter, the performance of the monitoring system is analyzed in the laboratory. Next, implementation of the software interface is discussed which processes the data in real-time. Finally, evaluation of the cost and benefits of the proposed monitoring solution is made. In chapter 5, field testing results of the HFCT sensors for monitoring MV-side quantities i.e. partial discharge monitoring and MV power quality monitoring at 20 kV feeder is presented. Additionally, earth fault detection method is demonstrated through simulation performed in the real-time digital simulation (RTDS) environment. Finally, Chapter 6 concludes the thesis and discusses the future development and research areas.

2 Overview of disturbances and control systems in distribution network

This chapter gives an overview of disturbances classified according to their frequency contents which are present in the distribution network. It highlights the sources and consequences of disturbances dealing with PQ, PLC and PD. It also gives an overview of the standards dealing with PQ, PLC and PD. The contents of Section 2.2 is mainly based on [P1] which highlights the presence of high frequency disturbances in PLC frequency range via field measurements. Additionally, it presents the on-going trend in the distribution automation. In the end, state-of-the-art in distribution network monitoring is discussed.

2.1 Power quality issues 0…3 kHz

In recent years, there has been a growing interest in power quality due to the rapid growth of non-linear loads in the distribution network. Climate change and global warming concerns also call for alternative energy resources. Due to which the penetration of distributed energy resources [9], photovoltaic inverters [13], electrical vehicle chargers [14] and other loads based on power electronic have been increasing in the low and medium voltage network. The proliferation of power electronic devices and non-linear loads increases the challenges related to voltage and harmonic levels in LV network. They are usually connected to network using non-linear power electronic interfaces which is likely to increase the harmonic currents flowing in the network. The harmonics generated by DERs and power electronic devices can cause distortion in distribution system voltages and currents. Most significant power quality issues are voltage sags, voltage swells, flicker and harmonics [15]. In Europe, the standard EN 50160:2010+A1:2015 [16] defines the main characteristics of the supply voltage at the customer's supply terminals in public low voltage and medium voltage networks under normal operating conditions. It defines the characteristics of the supply voltage concerning frequency, magnitude, waveform and symmetry of the voltage.

The standard defines that the 10 min root mean square (RMS) value of the supply voltage in low voltage networks under normal operating conditions should always be within the range of U_n + 10 % / - 15 % and that during each period of one week 95 % of the 10 min RMS of the supply voltage should be within the range of $U_n \pm 10$ %. In medium voltage networks 95 % of the 10 min RMS values of the supply voltage should be within the range of $U_c \pm 10$ %, where U_c is the declared voltage. The standard EN 50160, 2010 also defines limit for the magnitude of individual harmonic voltages up to the order of 25. It requires that during one week period, 95 % of the 10

min RMS value of individual harmonic voltage should not exceed the defined limits. Moreover, the total harmonic distortion (THD) will be based on harmonics up to 40th order and it shall not exceed 8 % during 95 % of the week. Regarding signaling voltage, over 99 % of the day the 3 second mean of the signal voltages shall be less than or equal to the values given in Fig. 2.1. Dealing with flicker, the long term flicker severity caused by voltage fluctuation should not exceed 1 for 95 % of the week. The quality of the electricity provided by distribution network operators has to comply with reference parameters set by this standard.
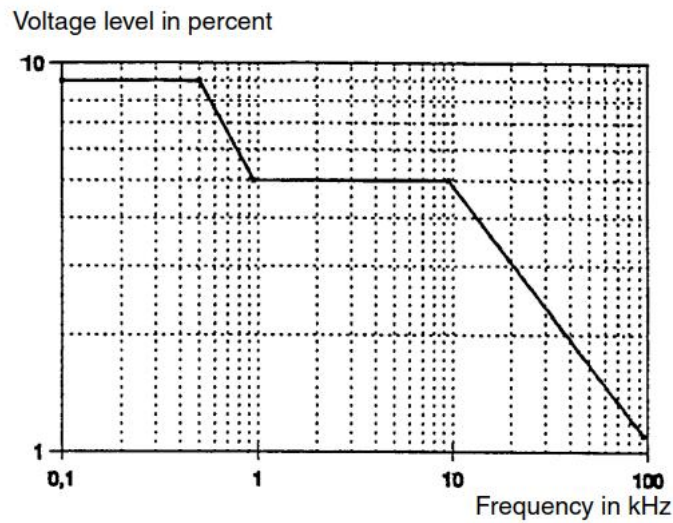

Fig. 2.1. Mains signaling voltage magnitude limit as per EN 50160.

The harmonic components cause various problems in the distribution system, such as power losses and heating of network components e.g. transformers and cables [17]. Harmonics also increase additional losses and heating in transformers and lead to de-rating of the transformer [18]. Additionally, interharmonics (non-integer multiples of the system frequency) and subharmonics (non-integer multiples of the fundamental frequency and their frequency is less than the fundamental frequency) are rapidly becoming a problem due to various kind electronic loads such as, static frequency converters, cycloconverters, induction motors and arc furnaces. They increase losses, overheating phenomenon, voltage fluctuation, flicker, saturation of transformers, and so forth [19,20]. IEC 61000-4-30 defines the methods for measurement and interpretation of results for power quality parameters. The measurement time intervals for parameter magnitudes (supply voltage, harmonics, interharmonics and unbalance) shall be 10-cycle for a 50 Hz power system or a 12-cycle for a 60 Hz power system and RMS method should be used. The 10/12-cycle values are then aggregated over 3 additional intervals i.e. 150/180-cycle interval for 50 Hz and 60 Hz

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system, 10-min interval and 2-hour interval. Aggregations should be performed using the square root of the arithmetic mean of the squared input values [21].

IEEE Std. 519 [11] establishes goals for the design of electrical systems that include both linear and non-linear loads. The limits in this recommended practices are intended for application at a point of common coupling (PCC) between the system owner or operator and a user. IEC 61000-3-2 [94] deals with the limitation of harmonic currents injected into the public supply system. It is applicable to equipment having a rated input current up to and including 16 A per phase. IEEE standard 519 requires that for bus voltage less than 1 kV, any individual voltage harmonic should not be more than 5 % and total harmonic distortion should not be more than 8 %. It also defines harmonic current distortion limit for power systems with voltage levels between 120 V and 69 kV. The IEC framework for harmonic distortion does not define limits for complete installation but a technical report, IEC/TR 61000-3-6 [12] provides guidance to system operators or owners on engineering practices which will facilitate the provision of adequate service quality for all connected customers.

Power quality issues can also have economic impact. In extreme cases, poor power quality can cause enormous financial losses to the network operators as well as customers. For example, the transformer is the most expensive component of the substation which comprises 19 % of the asset share of the whole network [22]. The cost of distribution transformer varies from €3.76k for a 50 kVA transformer to €16k for a 1000 kVA transformer [23]. On the contrary, the value of customer interruption cost (CIC) is much higher than the equipment cost. For instance, CIC values in Finland have doubled from 1994 to 2004 [24]. Similarly, the annual estimated cost of interruptions in USA is approximately $80 billion [25]. European power quality survey reports that most PQ problems are due to the effect of voltage dips (23.6 %), short interruptions (18.8 %), long interruptions (10.7 %), harmonics (5.4 %), transients and surges (29 %) and other PQ related problems (10.7 %) [26]. The survey reports that PQ problems cause a financial loss of approximately €150 billion annually for EU-25 countries [27]. As a result, monitoring power quality in distribution networks is becoming more important for network operators to reduce interruption costs and offer better quality of supply.

2.2 High frequency emissions 2…150 kHz

Disturbances in the frequency range higher than 2 kHz are becoming noticeable in networks due to the introduction of modern devices. There is also growing interest from the international stand-

ard-setting community to gain knowledge in the frequency range 2 to 150 kHz. The term supra-harmonics is used to refer to any type of voltage and current waveform distortion in the frequency range 2 to 150 kHz [93].

The smart grid will integrate several technologies, such as distributed generation, advanced metering infrastructure (AMI), intelligent systems, demand-side management (DSM), etc. [28]. The introduction of AMR has opened new ways for the DNOs in network management. The primary purpose of AMR systems is to provide energy consumption data to the utility but it can also be used for demand side management, disconnection and reconnection of electricity supply, network planning and power quality monitoring. AMR system works as a smart terminal unit and utilize the communication infrastructure to provide information to control center about the faults and health of the low voltage network. The backbone of this monitoring and control is the bidirectional communication infrastructure [29] to transfer real-time information which enables utilities to operate the grid more robustly [91]. Different communication technologies together with power line communication have been proposed for this purpose [91,30]. PLC is a popular and cost-effective technology because it uses the existing power grid infrastructure as a communication medium [31]. Moreover, AMR systems using PLC have been used in Europe since 1980s and are likely to increase in the context of improved energy services and efficiency [32]. In Finland, already 30 % to 50 % of energy meters were estimated to use PLC communication in low voltage networks by the end of 2013 [33].

Tampere University of Technology (TUT) in co-operation with Finnish Energy Industry conducted a questionnaire to Finnish DNOs to get an idea about the communication technologies used in the meter reading (or smart meter communication) and the interference problems experienced so far, especially related to the PLC systems. A total of 18 Finnish DNOs having a total of 1 935 275 energy meters took part in the questionnaire which covers approximately 2/3 of the energy meters in Finland. At the time of the questionnaire, 847 071 meters were remotely readable which corresponds to 44 % of the meters covered by the questionnaire. A total of 13 DNOs answered the questionnaire concerning the communication technologies used by them. Fig. 2.2 depicts the share of different communication technologies used by individual DNO and in all DNOs (in total). This statistic covers a total of 769 578 energy meters in Finland. It is clearly visible that the share of energy meters using PLC was already during the survey very high and it was expected to increase. This survey clearly exhibited that PLC was expected to be one of the potential candidate for AMR systems in Finland [P1,33].
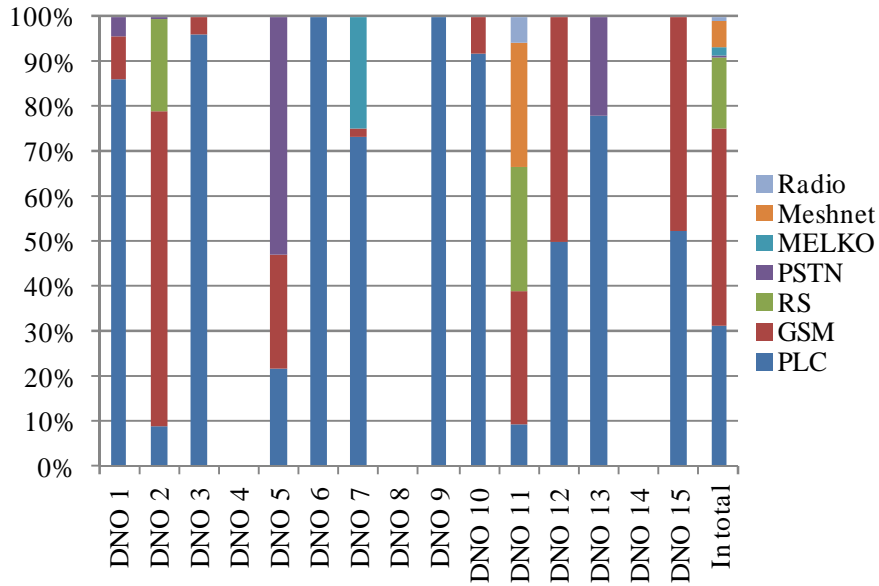
Fig. 2.2. Share of communication technologies used in energy meters by different DNOs.

In Europe, the regulation concerning communications over low voltage network is described by CENELEC standard EN 50065-1 in the frequency range 3 kHz to 148,5 kHz [34]. The allowed frequency range i.e. 3 to 148,5 kHz is further divided into five sub-bands. The use of frequency band 3 kHz up to 95 kHz is restricted to electricity suppliers and their licensees. However, successful communication over PLC is not easy since power lines were not designed for data transmission. All modern power electronic devices use fast switching techniques which create high frequency disturbances in the same frequency range which are chosen for power line communication. One of the most common sources of PLC disturbances in both the survey and the field measurements were found out to be the switched-mode power supplies (SMPS). Switched-mode power supplies have wide applications in various areas mainly because of its low weight, small size, efficiency and wide input voltage range tolerance. Frequency converters are also commonly used in ventilation systems in blocks of flats where many AMR systems are located. They are also used by water circulating pumps of the heating systems which may cause PLC problems. On-site measurements revealed cases where customer's devices equipped with switching-mode power supplies and frequency converters were producing narrowband interference in the frequency range 3…150 kHz which ultimately blocked the communication of large number of AMR systems [P1,35]. An example of the communication failure due to the interference caused by switching power supply of desktop computer is illustrated in Fig. 2.3. The switching frequency of the power supply appears very close to the upper PLC carrier frequency which blocked the communication of the AMR systems.
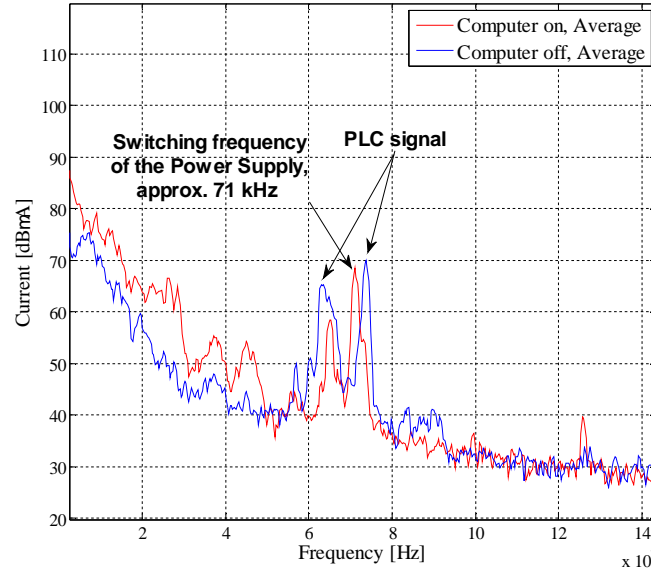
Fig. 2.3. Frequency spectrum showing PLC and interference signals.

There are not many standards setting conducted emission limits for customer equipment in the frequency range 2…150 kHz. For example, IEC/EN 61000-6-3 sets limits only for frequencies below 2 kHz and above 150 kHz [36]. Recently an amendment to IEC 61000-2-2 came in 2017 which defines compatibility level for signals from mains communicating system (MCS) up to 150 kHz. According to IEC 61000-2-2:2002+AMD1:2017, the compatibility level for MCS signals in the frequency band from 3 kHz to 9 kHz is 140 dBμV. The compatibility level for MCS signals in the frequency band from 9 kHz to 95 kHz is equal to 140 dBμV at 9 kHz and decreasing linearly with the logarithm of the frequency to 126 dBμV at 95 kHz. The compatibility level for MCS signals in the frequency band from 95 kHz to 150 kHz is equal to 128 dBμV. All these compatibility levels are related to MCS signal levels between any phase conductor and the neutral conductor (differential mode voltage) measured with a peak detector and with a 200 Hz bandwidth according to CISPR 16-1-1 [37]. Additionally, CISPR 11 applies to industrial, scientific and medical electrical equipment operating in the frequency range 0 Hz to 400 GHz [38]. According to CISPR 11, the conducted disturbances of induction cooking appliances in the frequency range 50 to 148.5 kHz should be below 90 to 80 dBμV (decreasing linearly with logarithm of frequency). However, based on the measurements showed in Fig. 2.3, it can be concluded that the conducted emissions even smaller than those defined in CISPR 11 may block the PLC communication between energy meters and data concentrator.

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PLC data concentrators are mainly located at secondary substations. The presence of high frequency noises close to the data concentrator affects the PLC communication of AMR systems. Measurement of high frequency components produced by e.g., switch-mode power supplies and frequency converters, is a challenge in the real network because neither traditional PQ monitors nor AMR systems are capable of monitoring them because of the low sampling rate. According to Finnish legislation, at least 80 % of the energy meters had to be remotely readable and provide hourly based data already by 2013. As a result, Finland became the first country in the world to have adopted smart metering (hourly metering and remote reading) on a large scale. About 3.4 million electricity metering point are measured every hour and data is transferred via communication network (PLC or GPRS) [39]. Due to communication failure, situations occur where the hourly data is unavailable. It causes a lot of extra work for the DNOs in the imbalance settlement (the consumption during the missing hours has to be estimated and if the data becomes available later, these have to be rectified). Therefore, monitoring of high frequency phenomena in the distribution network is important for efficient operation of the communication infrastructure of smart grid i.e. PLC based AMR systems.

2.3 Partial discharges

The term "partial discharge" is defined by IEC 60270 (Partial Discharge Measurements) as a "localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor". Generally, such discharges appear as sharp pulses having time duration of less than 1 µs [40]. A detailed overview of insulation degradation and PD mechanism can be found in [41,42]. Most common reasons for insulation degradations are material deterioration due to aging and environment, mechanical damage due to installation and physical stress, operational stress (overvoltage) and manufacturing defects (voids and cavities). When PD activity starts, energy is released in different forms, such as electromagnetic radiation (radio waves and optical signals), acoustic noise, thermal energy (change in temperature) and electromagnetic impulses [43]. There are different PD detection methods based on the type of energy released during the discharges. For example, ultra high frequency (UHF) receivers having bandwidth in few GHz range can be used to detect radio waves [44]. The ultra violet radiation can be detected using optical sensors, such as photographic recorders or image intensifiers [45,46]. Piezoelectric effect based transducers or other acoustic transducers can be used to measure acoustic noise [47,48]. Thermal sensors can be used to detect hot spots in the insulation material [49]. Similarly, electromagnetic impulses can be measured by resistive, capacitive or inductive methods [50].

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Partial discharge measurement has long been used as a non-destructive test to evaluate insulation systems design and as a quality control test for new power apparatus. During the past two decades, PD measurement has been widely used as a diagnostic tool to assess the condition of distribution system equipment i.e. cables, transformer, switchgear, etc. Emission of partial discharge signals is a clear indication of insulation degradation in distribution system components. Partial discharge activity occurs at defects, such as air-filled cavities within the insulation material when the electrical field strength exceeds the breakdown strength of the insulation material. PD may deteriorate the electrical strength of insulating material which ultimately leads to the complete breakdown of the cable insulation. PD detection is an important monitoring tool to avoid catastrophic failures of distribution networks and high voltage equipment. Continuous on-line monitoring is more effective way to determine the actual condition of assets in order to detect rapidly developing faults [51]. Continuous on-line monitoring would need a large investment in order to install the measurement system permanently. Therefore, implementation of condition monitoring method at minimal cost is another important concern for DNOs.

2.4 Distribution automation system

Traditionally, distribution automation outside primary substation has been mainly applied for different kind of fault management applications. In the case of overhead line networks this is natural because faults caused by e.g. storms are quite common and there has been a need for fast fault isolation and supply restoration. Two main philosophies can be distinguished in those applications: centralized and local. In centralized applications there are remote controlled switches and there can be also fault indicators in the network, but all the control is made by centralized systems, typically by SCADA/DMS. The first applications were operator driven, but today there are also automatic applications in use. Those applications are strongly dependent on communication between different network locations and the central system. In local applications, the switching operations have been based on local preprogrammed logic which requires local processing, but the advantage is that this kind of a system can work without any communication. However, the necessity of increasing the level of automation in the distribution has been clearly recognized on vendor side [52] as well as on the utility side [53]. This clearly means increasing the amount of monitoring for the measurement, detection and classification of disturbances in the distribution network. Today there are several ongoing trends in this field:

- The focus is moving to cable network, and the term secondary substation automation is used

- There are more sensors along the feeders (in cable network the technical solutions are easier to implement)
- In communication there is more and more capacity available with a reasonable cost
- In addition to fault management there is a need and also possibilities for new applications such as power quality monitoring [54,55] and condition monitoring [56]

2.5 State-of-the-Art in distribution network monitoring

There are already some commercially available secondary substation monitoring and control units and systems [54,55], which are capable of monitoring some or all of the quantities listed below:

- voltage levels (10 minute RMS)
- voltage sags and swells
- phase currents
- hourly averages of active power
- hourly averages of reactive power
- total harmonic distortion (2nd…15th harmonics)
- disturbance recording
- fault indication
- earth fault and short circuit fault location
- temperature (e.g. transformer)

The list omits other quantities for example, phase unbalance, inter-harmonics, supraharmonics and DC in AC networks that all are increasingly important to monitor at the LV-side of substation. Usually, these monitoring units are measuring the voltages and currents at the secondary side of the transformer for PQ measurements and current at MV side for network fault indication. Modern protection and control IEDs used in the distribution network have sampling frequency in the range of 1 – 2 kHz. Due to the relatively low sampling rate of the available monitoring devices, they are neither capable of measuring partial discharges nor rapid voltage changes, transients [57] or other higher frequency problems, which could be useful in case of e.g. studying customer complaints or claims. Additionally, or as the main functionality, currently available secondary substation monitors may have remotely readable and controllable I/O:s for various alarms (door, vibration, flood, transformer proximity) and controls (e.g. disconnector control) [56][38].

Smart meters are becoming more common at the customer end of distribution networks. In Finland, they were installed at practically all customers by the end of 2013, which considerably improves the possibilities of monitoring and estimating the network state (e.g. hourly active power).

Many of the meters also provide some kind of information on simple power quality quantities such as voltage levels. There is, however, a large variation in the implementation of these functionalities and the measuring and recording principles. Usually, it is possible to get only 10 minute RMS values of the voltages (often as a statistical distribution, not a time series) and 1 hour values of the active power. Also reactive power is measured by the meters, but usually it is read to the central system only from meters located at large customers. Portable power quality monitors are also available from different vendor, such as Fluke, LEM and Dranetz but they are mainly used for case specific PQ measurements at LV side.

Partial discharge monitoring is one of the most versatile methods of monitoring the condition of high voltage insulations. The condition monitoring of motor and generator stator windings is the most well-known application of on-line PD measurement [51]. Other applications have been developed for gas insulated substations [58], cables [59,60], switchgear [61] and instrument transformers [62,63]. Continuous on-line PD monitoring has been applied in a large scale only in the past 10 years partly due to the lack of effective noise separation techniques and partly due to the lack of cost-effective hardware solutions for collecting, storing and processing the PD data in order to draw the meaningful results [51]. Some portable mobile solutions, such as oscilloscope [64] and spectrum analyzer are available but they are not practical for continuous on-site measurements and permanent installation due to the data storage limitation and the heavy costs of the equipment. Additional research on the development of on-line PD monitoring systems have been done [65,66] but none of them offer cost-effective multichannel monitoring solution which improves the ability to identify PD sources [67]. There are commercially available devices from several manufacturers for PD monitoring of e.g. underground cables, but those capable of continuous on-line monitoring are still relatively expensive and more suited for extremely needed location [68-70]. Periodic on-line-monitoring, on the other hand, often fails to detect rapidly developing faults. The commercial PD monitoring solutions are quite expensive, for example, typical cost of the commercial monitor is €30,000 [68] and the cost varies depending upon the services offered by the vendor.

Sensors are a fundamental and expensive unit of a PD monitoring system as they provide information about the propagation of partial discharges in MV cable networks. They should have high enough sensitivity and wide frequency bandwidth to detect pulses in a noisy environment. The choice of sensor type is very crucial for developing a system capable of detecting PD in MV cables. There are number of coupling techniques available for monitoring PD activity including coaxial cable sensors which can be installed at the cable joints [71], directional couplers which can be placed on either side of the cable joint [72], the Rogowski coil [73] and inductive HFCT sensors which can be clamped either around the cable or the earth straps [74]. The capacitive

coupling needs the high voltage capacitor to be connected to the phase conductor which means cable has to be switched off and power delivery is interrupted. Inductive coupling requires no galvanic contact with the conductor so the sensor does not compromise the reliability of the medium voltage networks. Depending on the switchgear design, the sensor may be mounted around the cable without interrupting the power delivery which makes it a popular choice for both periodic and continuous on-line PD measurement. There are commercially available sensors from several manufacturers for PD monitoring [75,76] but cost-effective sensor solution for monitoring wide range of disturbances is still quite rare for secondary substation monitoring.

To summarize, utilities still have very little measurement and control units beyond primary substation. The medium voltage network is the most critical part of the distribution system. In Europe, most of the interruptions take place in medium voltage networks. Commercially available monitoring and control units as discussed earlier are still monitoring traditional PQ quantities at LV side of secondary substation due to low sampling rate and the high cost and space requirements of MV instrument transformer. Due to wide range of disturbances at LV and MV side of secondary substation, cost-effective implementation of condition monitoring is essential to improve the reliability of the distribution network. The following sections presents the proposed secondary substation monitoring solution for smart grid with multifunctional capabilities i.e. partial discharge monitoring, power quality monitoring, disturbance recording and fault location all contained in one unit. The primary focus of the monitoring solution is to measure cost-effectively at MV side of secondary substation. However, an additional benefit of the novel monitoring solution comes from the fact that it can monitor all the quantities measured by existing monitoring devices as well as other increasingly important quantities which are not measured by existing monitoring devices due to low sampling rate.

3 Secondary substation monitoring solution

This chapter presents the secondary substation monitoring solution which can be installed at secondary substation for measuring various quantities at LV and MV side of transformer. HFCT sensors developed by author have suitable frequency range for monitoring PD and PQ and performing disturbance recording and fault location at MV side which makes the solution cost-effective and reliable. The main idea of this chapter is to show that a novel secondary substation monitoring solution is possible based on the performance of HFCT sensors [P3] and monitoring systems [P2,P4] developed earlier by author for LV and MV applications. The contents of this chapter is mainly based on [P5].

3.1 Secondary substation

Secondary substation which is the focus of this thesis is the interface between the MV and LV network. In Finland, it typically transforms the voltage level from medium voltage (20 kV) to the low voltage level (0.4 kV). The structure of the traditional secondary substation has been very simple as it contains MV busbar, power transformer for changing the voltage levels and LV feeders. The level of automation has also been very low at secondary substation since most of the faults occur in the MV networks. The MV feeders are protected by protection relays located in the primary substation. It is not usual to use expensive protection devices in LV network as used in the MV network. Therefore, fuse is used as a typical fault current protection device in LV network which is placed in every phase of the LV feeder.

Smart grid concept substantially increases the need of monitoring devices for efficient and flexible power delivery. Technological advancement makes it possible to find new applicable and cost-effective condition monitoring and automation solutions. Secondary substation can be used as a data aggregation point to monitor LV and MV grid together with network components i.e. transformer and cables. Secondary substation automation can play a vital role in the evolution of distribution network towards smart grid by incorporating wide range of functionalities together with communication infrastructure. Thus, a novel cost-effective secondary substation monitoring solution is proposed in the next section.

3.2 Proposed monitoring solution

The secondary substation monitoring solution is based on the monitoring system and the monitoring concept which combines functions for PD and PQ monitoring, disturbance recording and fault location into a single unit. The monitoring system includes HFCT sensors for current measurements at MV side, resistive dividers for voltage measurements at LV side, filter & amplifier unit and a field-programmable gate array (FPGA) based multichannel data acquisition & processing unit. The monitoring concept describes what monitoring functions can be included into the monitoring system and how data can be utilized to analyze the electrical network during normal operation and different disturbance events. Detailed discussions can be found in [P5].

3.2.1 Monitoring system architecture

Fig. 3.1 depicts the general architecture of the secondary substation monitoring system. Front end of the monitoring system should have wide frequency bandwidth and high enough dynamic range to handle PD and PQ data. Thus, an 8 channel, 12 bit, 65 MHz analog-to-digital (A/D) converter is selected which was used in the earlier development of PD monitoring system reported in [P4]. Multichannel A/D converter enables various measurements at LV and MV side of secondary substation.
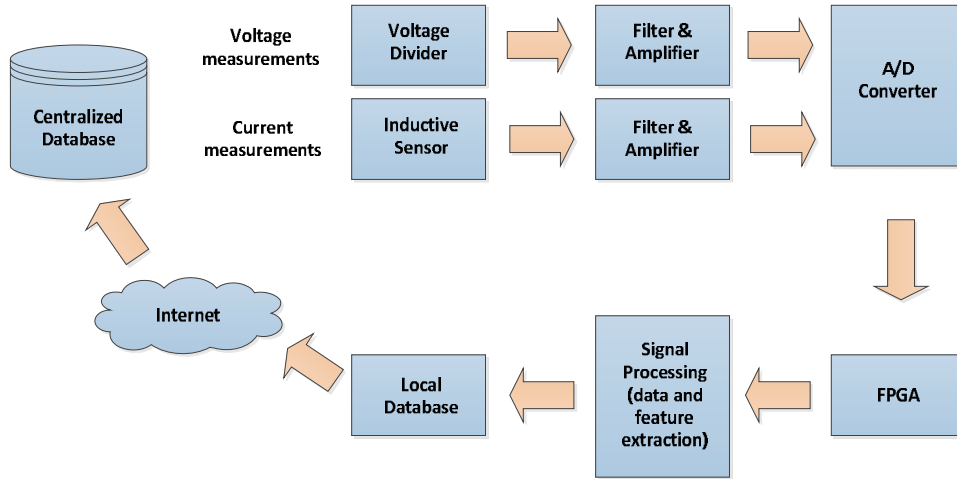

Fig. 3.1. Architecture of the proposed secondary substation monitoring system.

Voltage measurements are implemented using resistive divider at LV side, whereas current measurements are implemented using the HFCT sensors at MV side. Filter & amplifier unit is used to attenuate unwanted signals and amplify signals of interest.

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Signal processing block processes the sampled data to extract the information related to the PD and PQ phenomena and disturbances in the network. It also includes down sampling and frequency domain analysis of the PQ data.

Local data base is used to store bulk data, such as PD, PQ and disturbance recordings from the secondary substation monitor. Centralized database can be used to collect critical information about the network from secondary substation monitors around the network in order to take necessary actions. Communication between the local database and centralized database can be implemented using 3G/4G modem with TCP/IP protocol.

3.2.2 Monitoring concept for measuring LV and MV quantities

Main features of the monitoring concept are presented in Table 3.1. I_L, U_L, I_0 and I_n refer to MV phase currents, LV phase voltages, MV zero sequence (residual) current and LV neutral current, respectively.

Table 3.1. List of LV and MV quantities to be monitored at secondary substation.

Quantity	Frequency range		Monitoring function		Channels used		
MV-side	HF	LF	Primary	Secondary	PD	PQ	DR
I_{L1}	x	x	PD detection and location	LF: 50 Hz current, current harmonics, transformer loading, cable loading, MV faulty phase detection	x	x	x
I_{L2}	x	x			x	x	x
I_{L3}	x	x			x	x	x
I_0		x	MV fault location				x
LV-side							
U_{L1}	x	x	LV Voltage quality, harmonics, disturbance recording	PD 50 Hz voltage reference, HF: PLC/HF interference, transients, MV phase-to-phase voltages, LV faulty phase detection, fault type assesment	x	x	x
U_{L2}	x	x				x	x
U_{L3}	x	x				x	x
I_n		x	LV earth fault resistance and location estimation	Neutral conductor loading, neutral conductor fault		x	x

HFCT sensors are used for measuring MV-side quantities, whereas resistive dividers are used for measuring LV-side quantities. HF at MV-side refers to the HFCT sensor frequency range (130 kHz…45 MHz) for measuring PD signals, whereas HF at LV-side refers to the frequency range (2 kHz…150 kHz) as defined earlier in the thesis. LF also refers to the typical power quality

frequency range (50 Hz…2.5 kHz) as defined earlier for both LV and MV side measurements. It is also possible to measure frequencies up to few megahertz at LV side depending upon the actual sampling frequency. Detailed discussions about how different quantities at LV and MV sides can be monitored is presented in [P5]. The monitoring system has only eight channels, therefore four channels are used at LV and MV side, respectively to measure the quantities that benefit the most.

3.3 HFCT sensors placement

In the secondary substation monitor, partial discharge and power quality measurement is planned to be implemented using HFCT sensors at MV side of the transformer. Based on on-site tests, the sensors should be installed preferably around the cable terminations at the location indicated in Fig. 3.2.
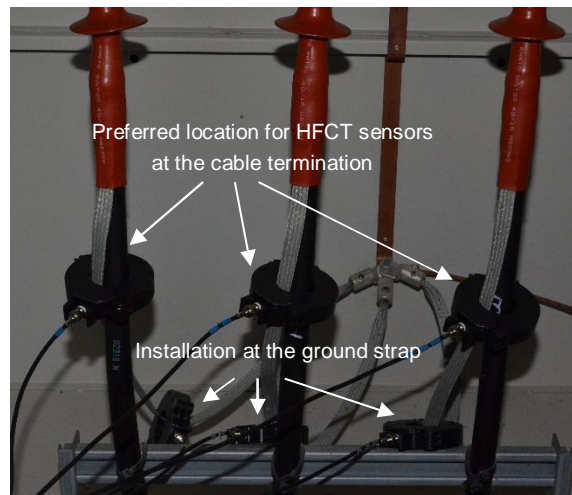
Fig. 3.2. HFCT sensors around phase conductors (recommended method) or ground straps of the cable termination at a secondary substation (more susceptible to interference).

This installation location allows measurement of the PD currents flowing in the phase conductor. On-site measurements at secondary substations have indicated that PD measurement with sensors installed at the ground strap of the termination is more susceptible to interference signals and cross coupling of signals between phases [77]. An example of the cross coupling in a secondary substation measurement is illustrated in Fig. 3.3 and Fig. 3.4. The preferred installation location also allows the measurement of primary 50 Hz current and harmonic currents to estimate the thermal loading of transformer or incoming cable depending on the installation location of the sensors.

If installation to the phase conductor is not feasible due to the secondary substation construction, the sensors may be installed at the ground strap, but the PD data analysis becomes more complicated due to the additional interference and at the same time, the possibility for MV current and power quality monitoring is lost.
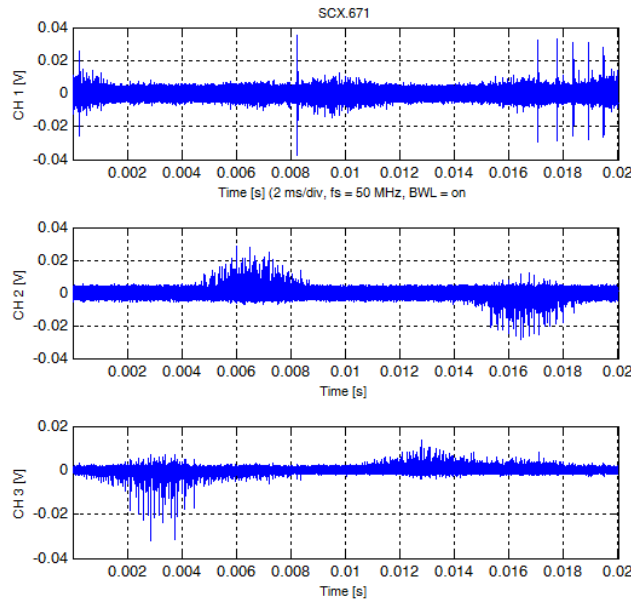

Fig. 3.3. PD measurement using sensors around phase conductors (CH1: L1, CH2: L2, CH3: L3).
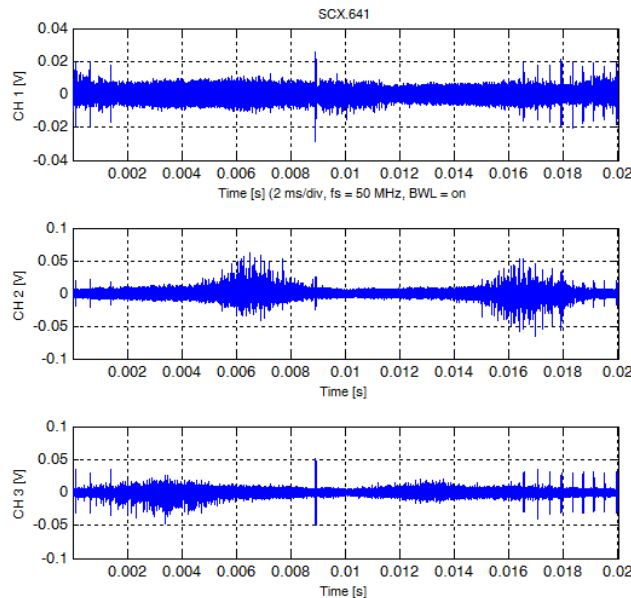

Fig. 3.4. PD measurement using sensors around ground straps of the cable termination at a secondary substation. Signals from one phase are coupled to the other two phases (CH1: L1, CH2: L2, CH3: L3).

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3.4 Proposed sensor locations for secondary substation monitor

The preferred location of the LV and MV sensors for secondary substation monitor is shown in Fig. 3.5. HFCT sensors can be installed either at the cables (or bushings) connecting the MV busbar to the transformer or to the incoming cables of the secondary substation. The former installation location is useful for monitoring the thermal loading and estimating the hot-spot temperature of the transformer, the latter location is feasible for monitoring the loading of the incoming cable and estimating its temperature and temperature variations. Resistive dividers can be used for three phase voltage measurements at LV side. The neutral current measurement I_n can be implemented using a LV current transformer at the neutral conductor between the transformer and LV switchgear.
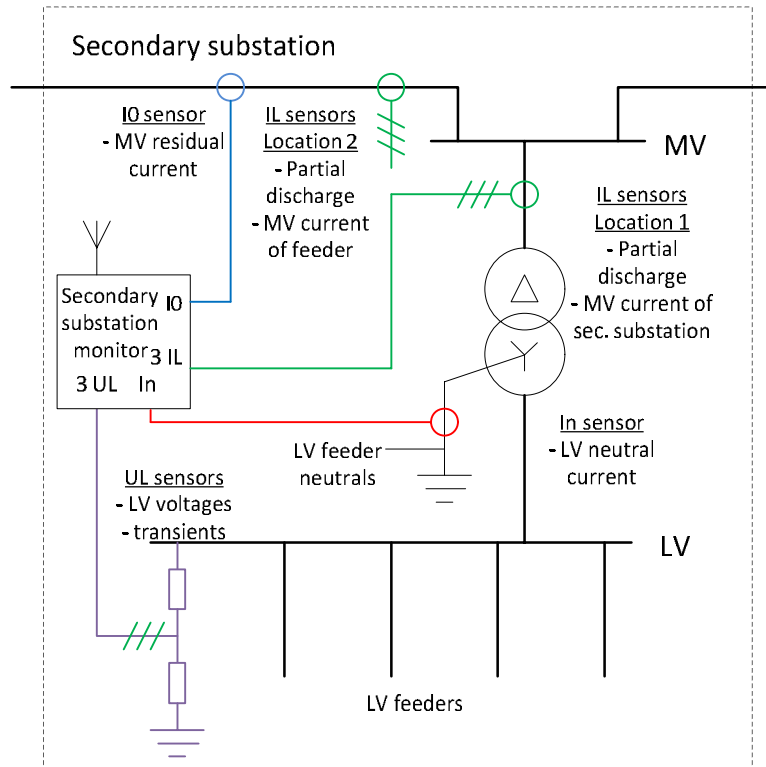

Fig. 3.5. Proposed MV and LV sensor locations for secondary substation monitor.

4 Design and development of monitoring system

This chapter summarizes the development of HFCT sensors and monitoring device. The monitoring device is based on FPGA-based multichannel data acquisition & processing unit. The monitoring system has not fully developed to process the data in real-time. However, experience gained from earlier developments of the IED [P2] and the PD monitoring system [P4] can be merged together to build the processing unit of the secondary substation monitoring system. The contents of this chapter is mainly based on publications [P2-P4]. [P2] deals with the development of IED for measuring HF phenomena in LV networks. Moreover, it also processes the data in real-time using digital signal processing techniques. [P4] deals with the development of monitoring system for PD measurement, whereas [P3] deals with the development of HFCT sensors for on-line PD and PQ monitoring at MV side. It is demonstrated through measurements that the monitoring system has better resolution and signal-to-noise ratio (SNR) than 8-bits oscilloscope. In laboratory environment, it is verified that monitoring system is capable of capturing PD calibrator pulses accurately. Furthermore, a real PD data from 20 kV feeder is also measured successfully using the monitoring system.

4.1 Requirements of the sensors

Sensors are the fundamental unit of the monitoring system. They should have suitable frequency response for measuring wide range of signals. In general, PD signals can extend at least up to hundreds of MHz, but when propagating in cable the highest frequencies are attenuated quite rapidly. According to IEC 60270:2000+AMD1:2015, the recommended upper cut-off frequency of a wideband PD measurement is limited to a maximum of 1 MHz with a bandwidth of 900 kHz. However, larger bandwidths are often used in on-line measurements than in the laboratory. The lower-cut off frequency is some tens or hundreds of kHz and the upper cut-off frequency ranges from hundreds of kHz to tens of MHz [6]. An effective PD sensor should be compact and easy to install, have a high frequency bandwidth, be sensitive to tens of picocoulombs (pC) of PD level and have a high saturation current performance.

The traditional frequency range requirements for power quality monitoring is up to 2.5 kHz. Power frequency current and harmonic currents measurement is useful in estimating the thermal loading of the transformer and/or incoming cable. It may be used also for pinpointing the causes

of PQ problems (e.g. high harmonic voltages or currents and large load variation). Accurate measurement of currents at low frequencies is desirable because low frequency harmonics for example, 5th and 7th, cause additional power losses in the AC transformers and cables [78].

4.2 Construction of high frequency current transformer sensors

Four different ferrite materials were used to develop HFCT sensors at the Tampere University of Technology for PD measurements [79]. Two of the best ones (in terms frequency range, transfer impedance and saturation current) were further investigated so they also allow PQ measurements at frequency range below 2.5 kHz at the MV side [P3]. The novel approach not only reduces the cost of having multiple sensors for each monitoring application but also minimizes the space requirements. Novel sensors were constructed using toroidal ferrite cores. These sensors are compared with a commercial HFCT sensor and the Rogowski coil (developed earlier at TUT [73]) for PD measurements. In addition, they are compared with the commercial power quality current sensors for PQ measurements. Different winding configurations, i.e., 4, 9 and 20 turns were wounded on each ferrite core using enameled copper wire of diameter 0.19 mm. The windings are spread evenly over the core area which helps reducing the leakage inductances. Experiments are also performed using split ferrite cores with different air gaps which reduces the saturation of the magnetic materials. It is recommended to delay this saturation for measuring PD signals if a high current is flowing through the phase conductor. This section focuses on the development of ferrite based HFCT sensors for PD and PQ measurements at the MV side. The effects of winding configurations and air gaps on the amplitude response, transfer impedance, saturation current and relative errors are analyzed under laboratory conditions. All amplitude measurements were performed using Agilent 4295A Network Analyzer combined with S-parameter test set.

4.2.1 Solid core HFCT PD sensors

For simplicity, only two ferrite cores M1 (core 1) and M2 (core 2) are considered in this section. Fig. 4.1 depicts the frequency responses i.e. amplitude ratios as the function of frequency of solid core sensors M1 and M2 with different winding configurations wounded evenly around the core. As shown in Fig. 4.1, the frequency response of sensors M1 and M2 with 4 turns winding configuration are not flat over higher frequencies but their sensitivity is better than other winding configurations. With 20 turns, the frequency response of sensors M1 and M2 have similar flat response over a wider bandwidth until their sensitivity starts to increase 3 dB to 5 dB at high frequencies, respectively then drops and finally resonance frequencies are reached. In comparison, sensors M1 and M2 with 9 turns winding configuration have flat response over a much wider

bandwidth until resonance frequencies are reached. Moreover, they exhibit good overall sensitivity as well as low resonance peaks when compared with 4 and 20 turns winding configurations. The resonance peaks of all sensors appear in the frequency range 75 – 90 MHz which already gives good frequency range in the higher end to measure PD signals. To summarize, solid core sensor M1 with 9 turns winding configuration shows high enough sensitivity, flat amplitude ratio response between 30 kHz (-3dB cut off) to 45 MHz (-3 dB cut off) as well as low resonance peak which makes it an excellent choice for PD monitoring.
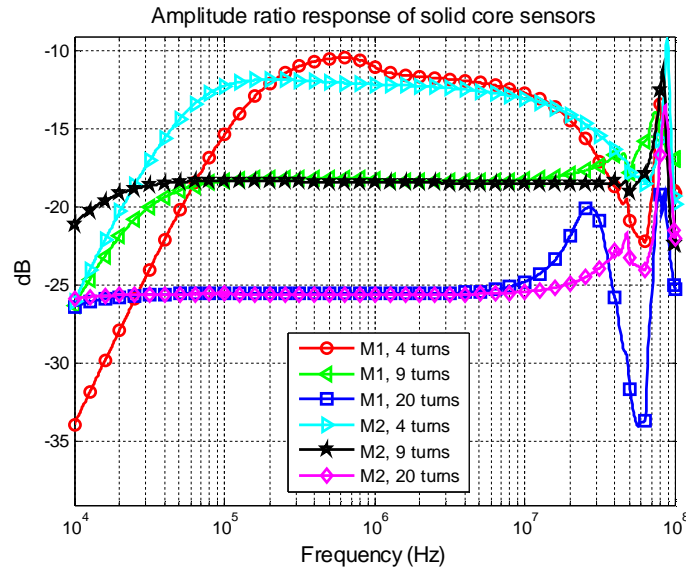
Fig. 4.1. Amplitude ratio response of solid core sensors M1 and M2 with different winding configurations.

4.2.2   Split core HFCT PD sensors

The solid core sensors have shown good frequency bandwidth to monitor PD signals but the significant disadvantage of using solid core structure is that they require power interruption before installing the sensors. Moreover, they cannot bear high currents because of the core material saturation. Split core sensor solves these issues but it affects the frequency response of the sensor and can be less accurate than a solid core sensor. Investigations are done to study the effect of split ferrite core by increasing the size of air gaps. Since sensor M1 and 9 turns winding configuration showed the best solid core amplitude ratio response so it will be used to demonstrate the effect of air gaps. Fig. 4.2 shows the comparison of the amplitude ratio responses of the sensor M1 with solid and split cores with three different air gaps i.e. 0.1 mm, 0.2 mm and 0.3 mm. It can be observed that the lower -3dB cut-off frequency increases to around 85–130 kHz with respect to different air gaps compared with 30 kHz in case of solid core sensor. However, the amplitude

ratio response is still quite flat over the frequency range of interest. To conclude, the working frequency range of sensor M1 with respect to different air gaps (as set by the lower and upper - 3dB cut-off frequency) is between 85 kHz to 45 MHz which is quite promising range to detect PD signals.
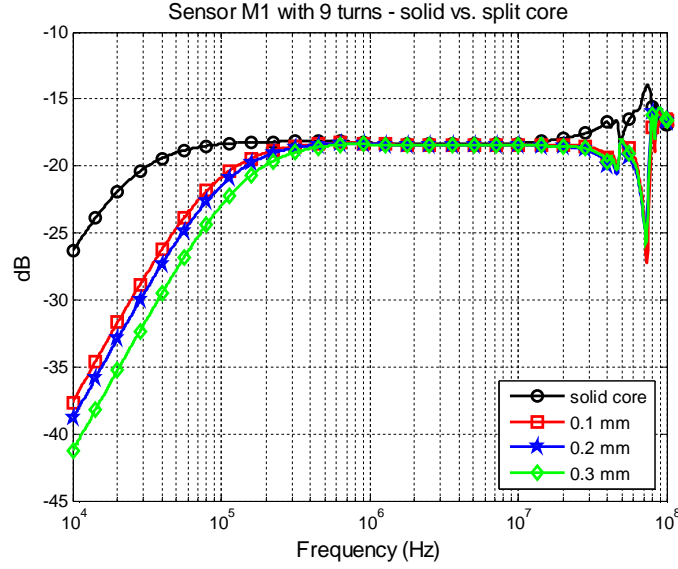

Fig. 4.2. Amplitude ratio responses of sensor M1, solid core and split core with different air gaps.

4.2.3   High frequency transfer impedance

The length of the air gap affects the sensitivity and the lower cut-off frequency of the sensor (as demonstrated earlier). Passband transfer impedance was measured to study the effect of air gaps on the sensitivity of the sensors M1 and M2. Additionally, a comparison of the transfer imped-ances (sensitivity) with the commercial HFCT and the Rogowski coil is made. The result suggests that the transfer impedance of the developed sensors (M1 and M2) reduces as the air gap increases which is mainly because of the imperfect contacts between the two halves of the core. In compar-ison, the transfer impedance of the sensor M1 with 0.3 mm air gap (5.9 Ω) is higher than the sensor M2 (5.72 Ω), commercial HFCT (3.45 Ω) and the Rogowski coil (1.45 Ω). To summarize, it can be stated that the smaller the air gaps the higher the sensitivity and the lower the lower cut-off frequency.

4.2.4   Saturation test

The air gap tunes the permeability of the core material so that the saturation takes place for a

higher current [92]. Hence, a saturation test is conducted and a comparison of the saturation currents is made among the sensors M1 and M2, commercial HFCT and the Rogowski coil. The result suggests that the saturation current of sensor M1 with 0.3 mm air gap (100 A) is higher than sensor M2 (67.3 A) and commercial HFCT (64 A), whereas the Rogowski coil does not saturate because of an air core.

4.2.5 Comparison of frequency responses

Finally, the performance (in terms of sensitivity and amplitude ratio response) of the sensors M1 and M2 with 9 turns and 0.3 mm air gap is compared with the commercial HFCT sensor and the Rogowski coil as illustrated in Fig. 4.3. The sensor M1 has a good sensitivity, lower -3 dB cut-off frequency (130 kHz) and flat amplitude ratio response which extends up to 45 MHz. The sensor M2 has also a flat amplitude ratio response but the lower -3dB cut-off frequency is around 230 kHz which is quite high in comparison with M1. On the other hand, the commercial HFCT sensor has the lowest -3 dB cut-off frequency (70 kHz) but the amplitude ratio response is flat only up to 15 MHz. Moreover, the sensitivity is considerably lower when compared with sensors M1 and M2 in the passband region. In comparison, the Rogowski sensor has the lowest sensitivity and unstable amplitude response at higher frequencies. In addition, the resonance peak of the Rogowski sensor appears in the PD frequency range which may affect the measurement.
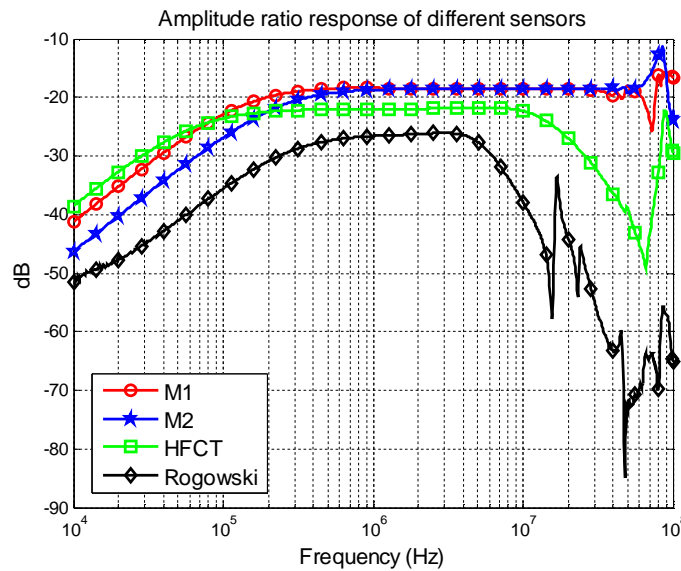

Fig. 4.3. A comparison of amplitude ratio responses among developed sensors M1 and M2, the commercial HFCT and the Rogowski coil.

To summarize, the split core sensor M1 with 9 turns and 0.3 mm air gap seems to be the best candidate for PD measurement because of the higher transfer impedance (5.9 Ω), saturation current (100 A) as well as the wider frequency bandwidth between 130 kHz and 45 MHz. To verify the performance of sensor M1, a laboratory measurement is performed using a PD calibrator and the real PD data captured by measuring a 20 kV feeder line at a substation which is demonstrated in Section 4.6.3. Detailed discussion, comparison and test setup dealing with the frequency response, passband transfer impedance and high current saturation test are presented in [P3]. Further discussions about other ferrite cores can be found in [79].

4.3   HFCT sensor for MV power quality measurements

The following section demonstrates the capability of sensors M1 and M2 for MV power quality measurements. As demonstrated earlier that the split core sensor with 9 turns winding configuration and 0.3 mm air gap seems to be the best candidate therefore, same configurations is used for PQ analysis. The performance of the sensors M1 and M2 is studied at frequency range 50…2500 Hz against primary current 0.2…10 A in terms of relative amplitude error and phase error. The measurement setup consists of an arbitrary waveform generator, a current amplifier, 4-channel digital oscilloscope and a reference shunt box. The reference shunt box has different resistors to monitor different current levels. The shunt box is used as a reference sensor since it provides accurate current measurement without any phase error. More information about the laboratory setups can be found in [P3].

4.3.1   Relative errors and comparison with power quality current sensors

As represented by Fig. 4.4 even at a low primary current of 0.2 A sensor M1 has an amplitude error of less than 3 % compared with shunt for all frequencies and the error gradually decreases with increasing current for all frequencies. On the contrary, sensor M2 has an amplitude error of approximately 12 % to 15 % at 0.2 A current for all frequencies. The reason for high amplitude error is the high lower -3 dB cut-off frequency which affects the sensitivity of the sensor at lower currents. However, amplitude error tends to be lower with increasing current for all frequencies which is already quite good at 5 A.

Fig. 4.5 shows the phase angle error of both sensors M1 and M2 as a function of current for each frequency. With a low 0.2 A primary current at 50 Hz, the error for both sensors M1 and M2 compared with shunt is about 0.3 degrees and 0.45 degrees, respectively. Additionally, the phase angle error of the sensors M1 and M2 is less than 0.7 degrees and 0.6 degrees, respectively for all

current values at frequencies up to 350 Hz (7th harmonics). For higher frequencies, phase angle errors of both sensors increases further with increasing current which is caused primarily by oscillatory field fluctuations due to the mechanical resonance of the coils at high current. However, the overall phase angle error of sensors M1 and M2 is less than 2.5 degrees and 3.5 degrees, respectively.
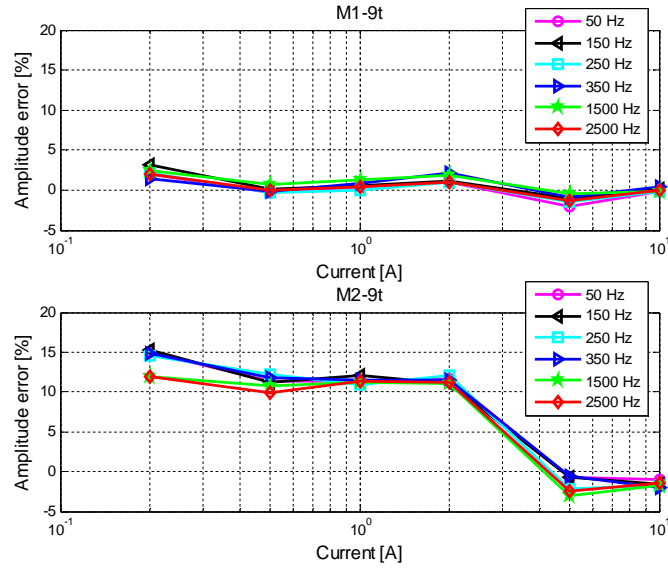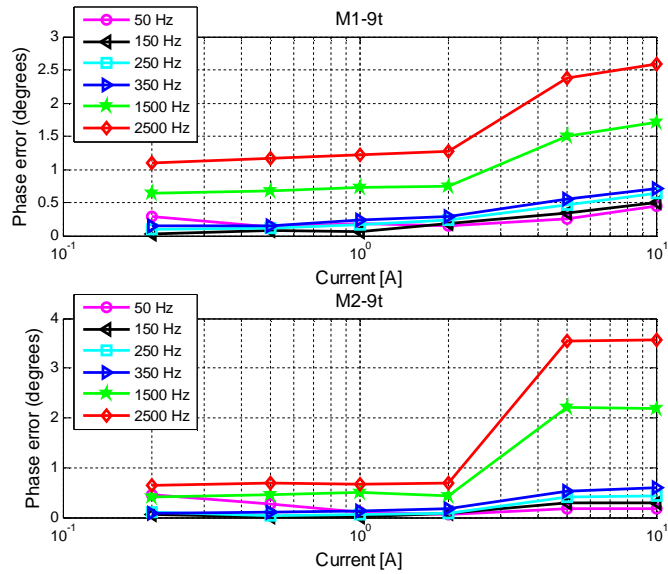

Fig. 4.4. Relative amplitude error of sensors M1 and M2.

Fig. 4.5. Phase angle error of sensors M1 and M2.

Both the amplitude error and phase angle error is promising for monitoring power quality compared with the commercially available power quality current sensors such as, Fluke (i1000s), LEM Flex (RR3020/RR3030) and Dranetz (TR2510A). Fluke has the phase shift error of more than 3 degrees and amplitude error of 3 % in the range 48 Hz to 65 Hz [80]. LEM has phase angle error of ±1 degrees (45 to 65 Hz) [81]. Dranetz has phase angle error of 1.5 degrees (40 Hz to 5 kHz) and amplitude error of 2 % in the range 1 A…5 A [82]. Consequently, the accuracy of the sensors M1 and M2 is quite adequate for indicative power quality measurements even at low currents 0.2 A…1 A. Phase angle error of sensor M1 is less than 0.7 degrees for all current values at frequencies up to 350 Hz. Amplitude error is 3 % at primary current 0.2 A for all frequencies but the error decreases even further with increasing current. Hence under laboratory conditions, split core sensor M1 seems to be the best choice also for PQ measurements.

4.4   Specification of the monitoring device

The output signal of the coupling device which is typically in an analog form is converted into a digital form using A/D converter which is necessary to perform automated analysis of the signal by software algorithms. The sampling frequency of the A/D converter must be high enough to sample the signal properly. The sampling rate must be at least 2 f_{max}, or twice the highest frequency component [83] in order to avoid aliasing and to completely represent the signal. The partial discharge phenomenon is highly stochastic in nature and the amplitude distribution of the PD pulses emerging from a single discharge source is wide and resembles the Weibull or exponential distribution [84,85]. As a result, 8 bit A/D converter used by many general purpose oscilloscope is not sufficient to record the correct shape of PD pulses. Practical experiences have also shown that 12 bits or more is required to capture the dynamic behavior of PD pulses [86].

A high bandwidth is required to record the correct shape of the PD pulses. However, there are no clear guidelines described in the literature for the oversampling ratio used for PD measurement. A sampling frequency of 6 or 8 times is recommended in [87]. According to [88], a sampling rate of at least 5 MS/s is required when a PD detector with a bandwidth of 40 to 400 kHz is used. Online measurements of hydro generator stator windings using a commercially available measuring systems have been reported in [89]. For a bandwidth of 25 MHz of the input signal, a sampling rate of 100 MS/s were used resulting an oversampling ratio of 4.

The measuring systems are characterized by their bandwidth, resolution, noise floor and sampling rate. All of these factors are the driving force behind the performance of the system. A compromise has to be made between the dynamic range of the PD measurement and the accuracy of the

PQ measurement, since the same A/D converter is used for both measurements. However, a high sampling rate which is used by default for PD monitoring can be used to achieve extra bits of resolution for PQ monitoring. Oversampling is a popular and cost-effective method of improving the resolution of A/D converter. This can be achieved by oversampling the input signal then digitally filtered to remove the quantization noise and then decimating it. The result is an improved SNR which increases the A/D converter's effective number of bits (ENOB). For example, a 12 bit A/D converter sampling at 1.28 MHz yields an effective resolution of 16 bits at frequencies below 2.5 kHz [90].

4.5 Prototype of the monitoring system

The hardware of the monitoring system presented here is based on HFCT sensors, filter & amplifier unit and FPGA-based multichannel data acquisition & processing unit. To reduce the development cost, custom made components are integrated to build the platform. Moreover, it is also difficult to find commercial products fulfilling the requirement of the proposed design. The prototype of the monitoring system is presented in Fig. 4.6. An 8 channel, 12 bit, 65 MHz A/D converter is interfaced with high speed FPGA via high speed mezzanine card (HSMC) connector. Filter & amplifier unit is powered by 9 V battery. A 100 MHz arbitrary waveform generator is used to clock the A/D converter. HFCT sensor with the test cable can be observed in the measurement chain.
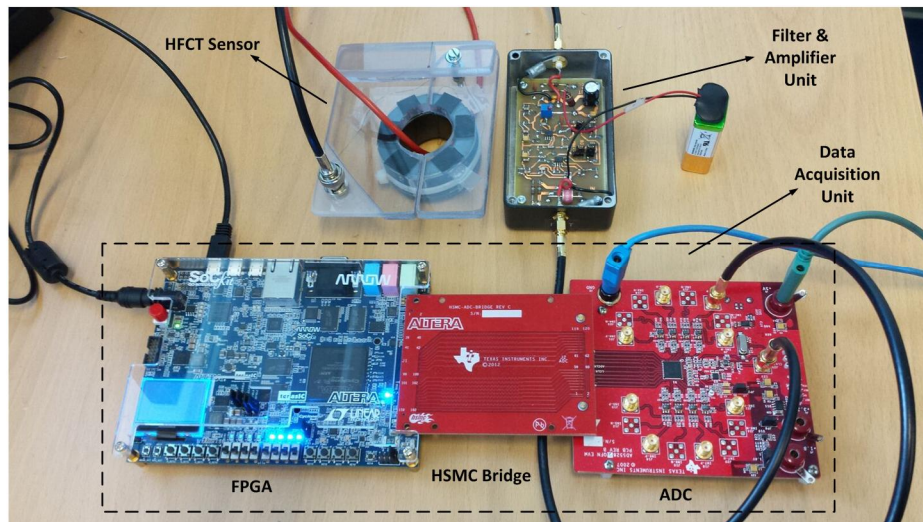

Fig. 4.6. Prototype of the monitoring system.

4.6 Performance analysis

A comparison between the monitoring system and an 8-bit oscilloscope (LeCroy LT364L, MFG date 12-June-2000) in terms of resolution and signal-to-noise ratio is made to show the better sensitivity of the monitoring system.

4.6.1 Resolution of the monitoring system

The dynamic range requirements for capturing PD signals is quite high because the discharge may originate close to the sensor or travelling far from the sensor and the magnitude of the discharge pulses even on one site may have a large variation. Therefore, a high-resolution front end is necessary. Many general-purpose oscilloscopes use an 8-bit A/D converter, which is insufficient to record the dynamic behavior of the PD. Fig. 4.7 represents a comparison of the PD calibrator pulse of 10 000 picocoulombs captured by monitoring system and 8-bit oscilloscope. The PD pulse measured by the monitoring system is quite smooth compared with the oscilloscope because 12-bit A/D converter has 4096 quantization levels, whereas 8-bit A/D converter has only 256 quantization levels.
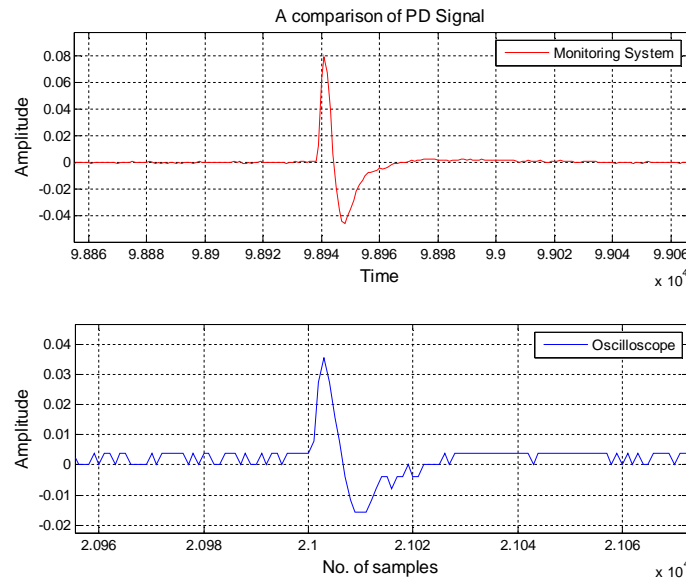

Fig. 4.7. PD calibrator pulse measured by monitoring system and the oscilloscope.

4.6.2　Signal-to-noise ratio

In addition, signal-to-noise ratio of the monitoring system and oscilloscope is calculated via (4.1) using the data shown in Fig. 4.7 as 38 dB and 12 dB, respectively, which clearly shows better sensitivity of the monitoring system.

$$SNR_{dB} = 10log_{10}\left(\frac{V_{signal}}{V_{noise}}\right) \qquad (4.1)$$

4.6.3　Laboratory test and analysis

To further verify the performance of the overall monitoring system, a real PD data captured earlier by measuring 20 kV feeder is used. Time-domain representation of the real PD data measured inductively by HFCT sensor and recorded by the monitoring system and oscilloscope is depicted in Fig. 4.8. PD pulses captured by monitoring system and oscilloscope are the same.
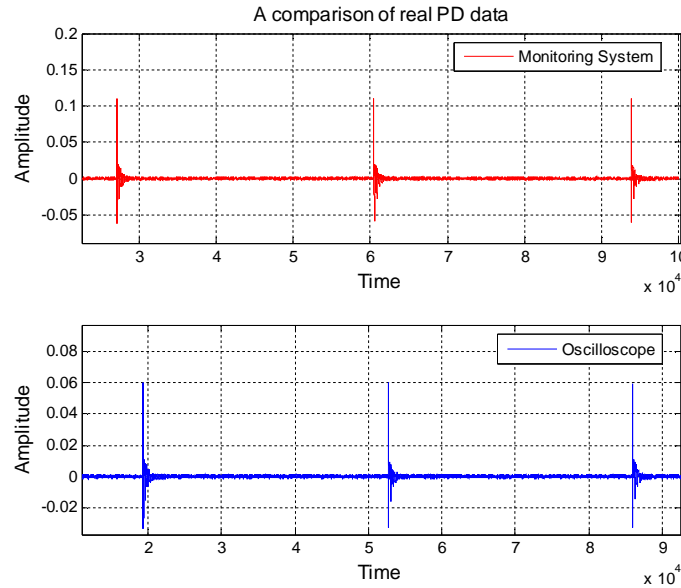

Fig. 4.8. Time-domain representation of the real PD signals captured by monitoring system and oscilloscope.

Frequency-domain analysis reveals the frequency distribution of PD pulses. A comparison of the frequency spectrum of the data captured by both systems is illustrated in Fig. 4.9. The spectrum of both systems show identical distribution of the frequencies extending up to 1 MHz, which gives quite good frequency range for detecting PD signals.
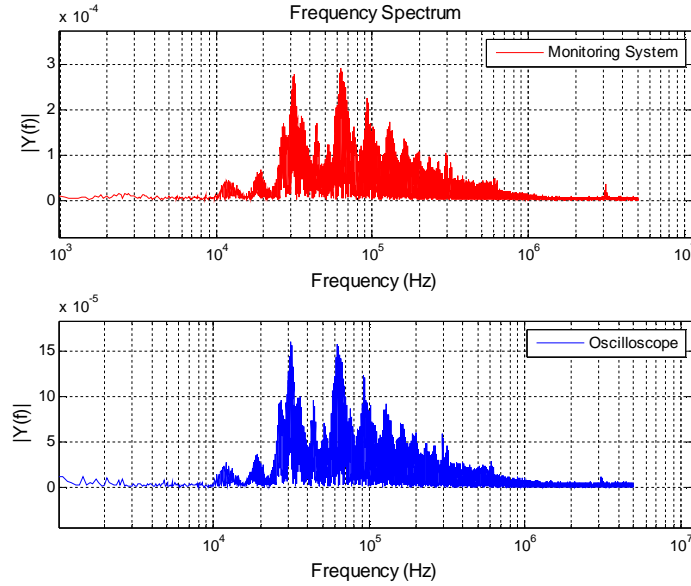
35

Fig. 4.9. Frequency-domain representation of the real PD signals captured by monitoring system and oscilloscope.

4.7   Implementation of software interface

This section highlights the cost-effective standalone IED developed by author for real-time monitoring of high frequency phenomena in CENELEC PLC band. The main idea of this section is to emphasize on the software interface which can be used as a reference for the future development of the data processing unit of secondary substation monitoring system. The IED is based on digital signal processor interfaced with 4 MHz A/D converter. An optimized algorithm to process the sampled data in real-time using digital signal processing technique is implemented on the IED. Full details on the design and development of the IED can be found in [P2].

An efficient fast Fourier transform (FFT) is implemented on the IED to meet the real-time challenges. Fig. 4.10 represents a comparison of frequency spectrum of the known signal i.e. 80 kHz computed by the IED and spectrum analyzer. The spectrum analyzer is typically an expensive device compared with the cost-effective monitoring system. Nevertheless, it has captured the 80 kHz signal quite accurately. Another peak at 160 kHz is not detected by the IED since the signal peak is below the noise floor of the IED.
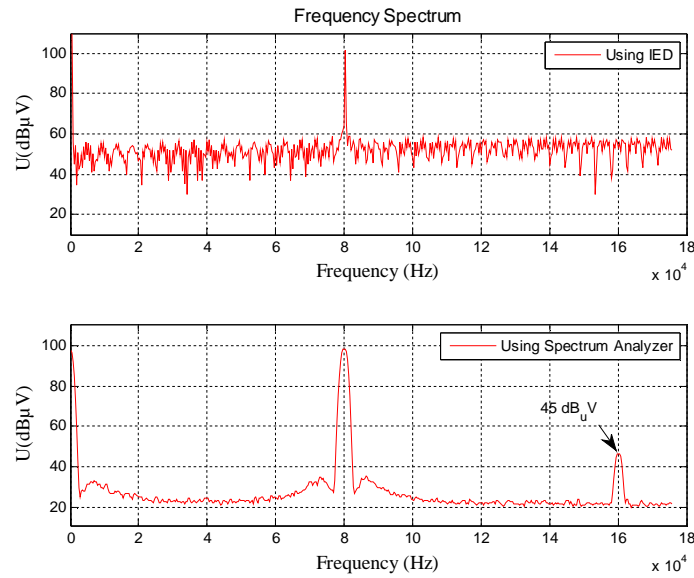
Fig. 4.10. FFT spectrum analysis between the monitoring system and spectrum analyzer.

A load model based on CFL and LED lamps is developed [P2] to further test the capability of the IED to monitor real signals. The load model is connected between smart meter and data concentrator to create high frequency disturbances in the network. Fig. 4.11 shows the frequency domain analysis of the data captured by the IED.
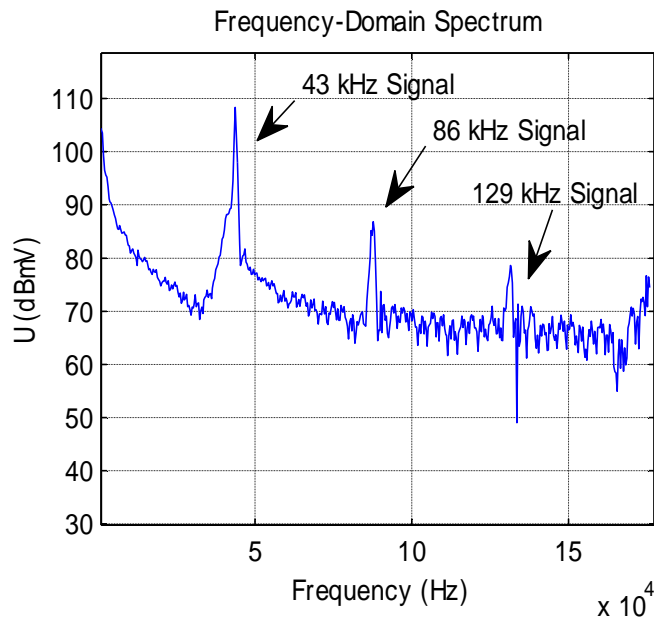

Fig. 4.11. Frequency-domain analysis computed by the IED.

High frequency disturbances produced by compact fluorescent lamps polluting the whole PLC band can be observed in both spectrums. The fundamental harmonic is present at 43 kHz followed by a second harmonic at 86 kHz and third harmonic at 129 kHz.

4.8 Evaluation of the cost and benefits of the monitoring solution

It is too early to make a detailed cost-benefit analysis since the system is not yet fully developed and deployed in the distribution network. However, benefits of the proposed monitoring solution can be estimated quantitatively. The most important feature of the secondary substation monitoring solution is the cost effectiveness. This section compares the cost of the secondary substation monitoring solution with the commercially available monitoring solution. Additionally, it presents a simple analysis about the cost savings which can be achieved by DNOs through implementing this kind of monitoring solution.

According to Finnish Energy Authority [23], the cost of secondary substation automation equipment e.g. remote control, fault indication and communication are €3100, €1200 and €4800, respectively. The cost of commercial secondary substation monitor is some thousands of euros. The cost of monitoring at MV level is quite high, for example, the cost of a typical commercial PD monitor is €30,000. Similarly, the cost of a HFCT sensor for PD measurements could be thousands of euros depending upon the characteristics of the sensor.

The manufacturing cost of the secondary substation monitor is difficult to estimate at this point since the cost of commercializing the product is not known. Additionally, unit price of components is different than the price of the evaluation modules which offer additional features but might not be useful for custom design. Moreover, unit price can be even cheaper if order is made in bulk. The following estimation is made based on the price of the evaluation modules used to develop the product. The cost of the FPGA-based data acquisition & processing unit which includes FPGA kit, A/D converter, header adapter card for interfacing A/D converter with FPGA and filter & amplifier unit was about €700. The material cost of developing wideband HFCT sensor was approximately €50. Additionally required components are power supply, timer circuit for FPGA, flash memory and communication module for data transfer. Hence, the ballpark estimate of manufacturing standalone secondary substation monitoring solution is €2000.

In comparison with the commercial PD monitor, the cost of secondary substation monitoring solution is much cheaper. Additional benefits of monitoring PQ and locating earth faults at MV side using the same system make it ideal and cost-effective solution for distribution network operators

to achieve improvements in supply performance and asset management with good cost efficiency. On the other hand, existing secondary substation monitoring solutions cannot measure transients or HF disturbances due to low sampling rate. The proposed monitoring solution implements wide range of functionalities i.e. PD and PQ monitoring, disturbance recording and fault location cost-effectively at secondary substation. It also solves the complexity of having different sensors and measuring unit for monitoring different applications. Consequently, the proposed monitoring solution will enable preventive maintenance of network assets and power quality.

New(ish) relays have fault location functionalities but generally their accuracy and usability has not been good enough which increases the outage time as well as customer interruption cost. Identifying immediately the asset that needs the most urgent maintenance will save unplanned outages and interruptions costs. Secondary substation monitoring solution will shorten the fault location and clearance time together with customer interruption cost saving. The proposed monitoring solution can also diagnose HF disturbances in the LV network which are often the reasons for PLC communication failure of the AMR systems. This saves DNOs a lot of extra work in imbalance settlement. Moreover, it saves extra cost of hiring professional services i.e. power quality experts to diagnose and mitigate the problems.

5 Field testing of the proposed monitoring concept

This chapter presents the field testing results of the wideband HFCT sensor which lays the foundation of the novel monitoring concept since it can measure PD, PQ and locate earth faults at MV side of secondary substation using RMS based detection method. Measurements are performed at 20 kV feeder for PD and PQ monitoring. Additionally, a commercial power quality sensor is used to compare the PQ results. Moreover, a cost-effective way of detecting phase-to-earth fault in the MV network using HFCT sensors is demonstrated using the real-time digital simulator (RTDS).

Test results presented in this section deals only with the MV-side quantities which are shown in the Table 3.1. As a result, HFCT sensors are installed at primary substation to study the potential of the wideband sensor for PD and PQ monitoring. Detailed discussions and field testing results are presented in [P6].

5.1 HFCT sensors specification

As demonstrated earlier, split core HFCT sensor M1 with 9 turns winding configuration and 0.3 mm air gap seems to be the best candidate for PD measurement. It has the highest transfer impedance (sensitivity) and saturation current (100 A) compared to HFCT sensor M2 and commercial HFCT sensor. The amplitude ratio response is flat between 130 kHz to 45 MHz which gives an excellent range for partial discharge monitoring of underground cable networks. Moreover, it has shown an adequate performance for PQ measurements compared with HFCT sensor M2 and commercial power quality current sensor in terms of relative amplitude error and phase angle error. The overall relative amplitude error is less than 3 % at primary current 0.2 A…10 A at frequency range 50 Hz…2500 Hz which provides same or better accuracy than commercial power quality current sensor. Thus, split core HFCT sensors M1 is used in the field for PD and PQ monitoring and the term HFCT sensor is used in this chapter.

5.2 Partial discharge monitoring

HFCT sensors were installed around live 20 kV feeder phase conductors for PD measurements. The installation of the HFCT sensors and LEM sensor around the phase conductor is depicted in Fig. 5.1.
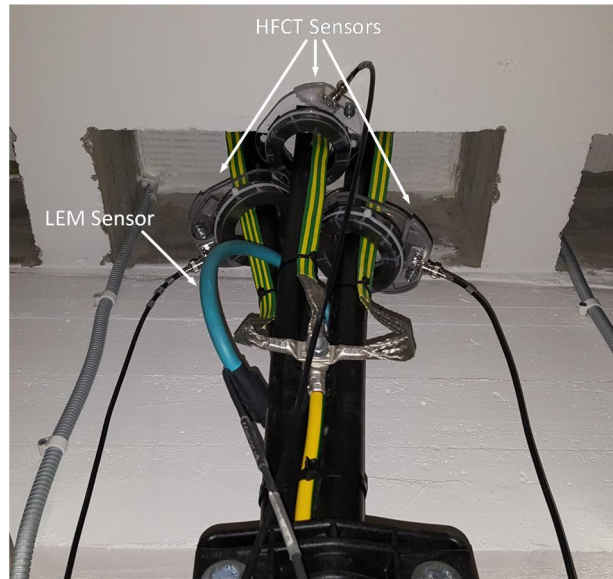
Fig. 5.1. Installation of the sensors around 20 kV feeder.

Fig. 5.2 presents high frequency information extracted from the measurement data using a digital first order Butterworth high-pass filter having a corner frequency of 25 kHz.
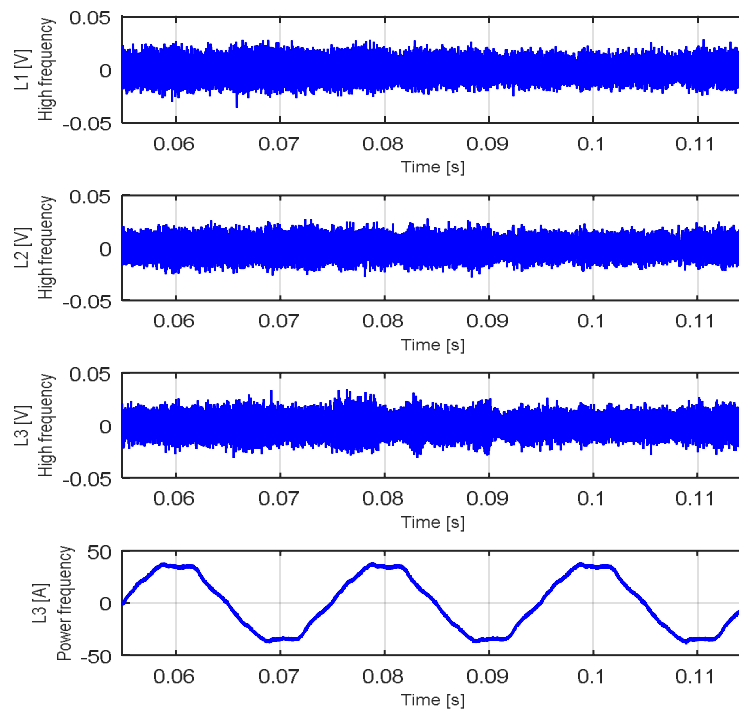

Fig. 5.2. Partial discharge measurement performed at 20 kV feeder.

Due to high-pass filtering the 50 Hz and harmonic frequencies are absent in channels L1…L3 but high frequency signals can be easily observed. In this case, only very small partial discharge activity can be observed in phase L3.

Fig. 5.3 illustrates another example of PD measurements performed at two 20 kV feeders simultaneously on a 110 / 20 kV primary substation having a double-busbar system. Feeder 1 with a load current of 26 A and feeder 2 with a load current of 80 A were connected to different busbars. In feeder 2, phase L3, high frequency impulses occurring at regular intervals caused by some power electronic devices can be witnessed. Feeder 1, phases L1 and L3 have no sign of partial discharges and high frequency disturbances.
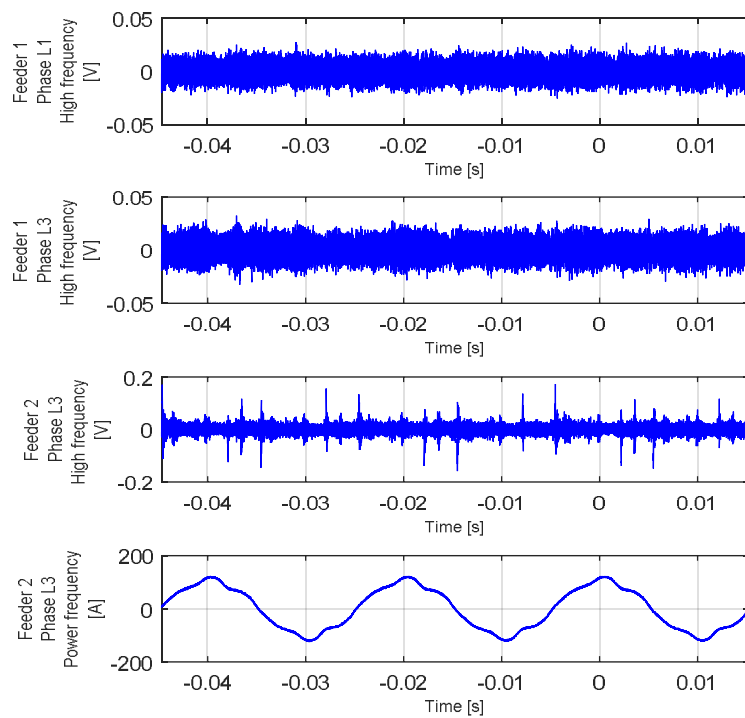

Fig. 5.3. Partial discharge measurement performed at two 20 kV feeders on a 110 / 20 kV primary substation.

5.3 MV power quality monitoring

The data used earlier for PD measurements in Fig. 5.2 are used to extract the PQ information. Three HFCT sensors were measuring the phase L1…L3 currents and LEM was measuring only phase L3 current. Fig. 5.4 depicts the time-domain representation of the currents measured at 20 kV feeder by HFCT sensors and the commercial power quality current sensor, LEM Flex (RR3030). HFCT waveforms represent the derivatives of the phase currents while LEM waveform is already integrated by the sensor's built in analog integrator.
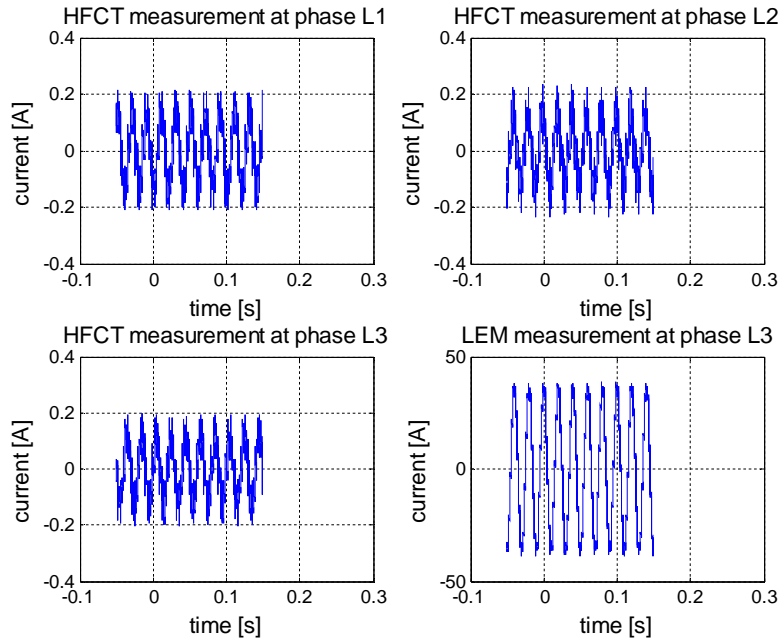

Fig. 5.4. Current measured at 20 kV feeder using HFCT and LEM sensors.

For further analysis, let's have a closer look at the output of the HFCT sensor and LEM sensor measured at phase L3 as shown in Fig. 5.5. The HFCT sensor output is also integrated to get the actual power frequency current. The integrated output of HFCT sensor is quite identical to the LEM output. LEM output has more noise because of its larger measurement range of up to 300 A compared to that of the HFCT sensor (100 A).
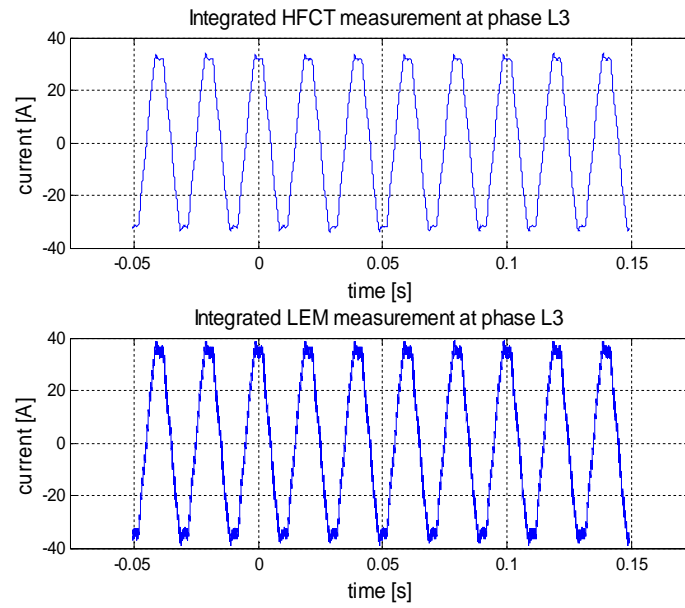
Fig. 5.5. Integrated current waveforms of the HFCT and LEM sensor.

Fig. 5.6 illustrates the frequency spectrum calculated from 200 ms time window specified by IEC 61000-4-7:2002+A1:2008 for harmonic measurements. The fundamental frequency harmonics can be observed in the output of both sensors.
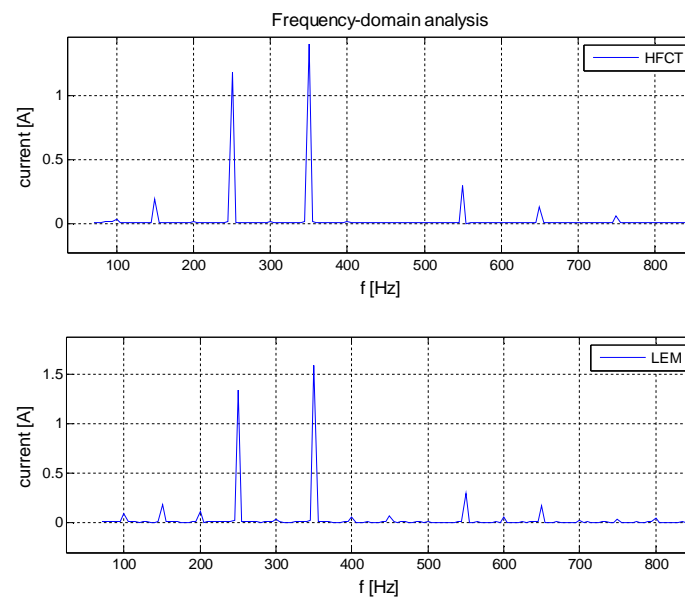

Fig. 5.6. Frequency domain analysis of the current measured by HFCT and LEM sensor.

5.4   Earth fault location in MV network

The primary purpose of disturbance recording is to capture as much data as possible in order to investigate a disturbance event afterwards. In general, recording starts when triggering condition is fulfilled and a predefined number of cycles of the waveform data before and after the triggering moment is recorded. Traditionally, disturbance recordings function is used in order to analyze the operation of protection, but it can also be used in the analysis of e.g. voltage dips and swells. In this thesis, fault location has been used as an example of the application of disturbance recording function.

RMS-based detection scheme is proposed in this thesis but it requires more research to verify its feasibility. In this method, HFCT sensors measure three phase currents as well as residual current to detect the earth fault. Such a detection scheme significantly reduces the costs of measuring at MV side since no voltage measurements are needed.

The MV residual current I_0 triggering criterion is used to capture the waveform related to earth fault events in the MV network. An earth fault in a medium voltage feeder causes the residual current to increase in the feeder upstream from the fault and based on the data captured at the secondary substations, it is possible to locate between which secondary substations the fault has occurred. This helps in decreasing the duration of interruptions by enabling quicker fault location, isolation and supply restoration.

Let us consider a radial distribution network simulation performed in the RTDS environment. The single line diagram of the network model used for the earth fault simulation is presented in Fig. 5.7. M2…M4 shows placement of the HFCT sensors at each secondary substations. M1 is located at MV substation. In this case, the fault is located near the first secondary substation.

Let's have a closer look on Fig. 5.8 which illustrates the integrated waveforms of the cases when fault occurred in all three phases L1…L3 and measured at M1. A change in the current amplitude of the faulty phase can be observed in all cases. An increase in the residual current can also be noticed.
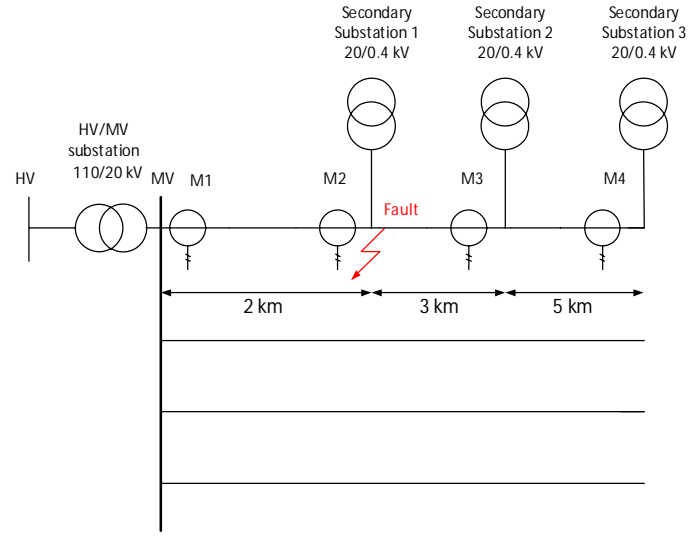
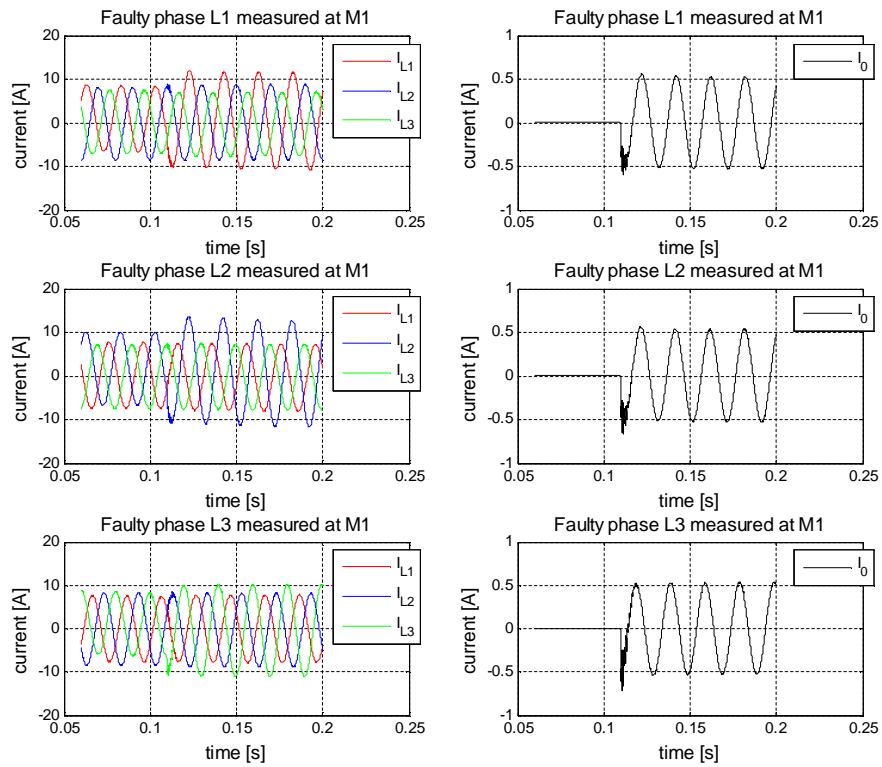**Fig. 5.7.** Network model used in RTDS simulation for earth fault detection

Fig. 5.8. Integrated phase currents and residual currents measured at M1 in case of faults at phases L1…L3.

Location of the fault can be estimated based on the proposed monitoring concept that the wide-band monitoring system should be installed at each secondary substation [P5]. For location estimation, let's use the fault in phase L1 only and measurements from all locations i.e. M1…M4.

Table 5.1 represents the RMS current of the MV feeder when fault is simulated in phase L1 only and measurements were performed at all locations. Since M1 is located upstream from the fault so the change in the faulty phase current I_{L1} and I_0 is clearly visible. M2 is located upstream of the fault and very close to the fault location, a higher I_{L1} and I_0 can be observed. On the contrary, M3 is located downstream of the fault, therefore, no significant change in the faulty phase current I_{L1} is seen, whereas I_0 has small change. Similarly, M4 neither shows any notable changes in faulty phase current I_{L1} nor the residual current I_0. Based on the measurements, it can be concluded that M2 has the highest RMS value, hence the fault is located close to secondary substation 1 upstream of the measurement.

Table 5.1. RMS current of the faulty phase L1 measured by HFCT before and after the fault

Location M1	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.59	5.93	5.17	0.0020
After fault	7.88	6.10	5.20	0.37
Location M2	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.61	5.96	5.20	0.0027
After fault	7.91	6.10	5.22	0.40
Location M3	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.42	5.96	5.18	0.0016
After fault	5.24	6.12	5.21	0.10
Location M4	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.48	6.02	5.24	0.0013
After fault	5.35	6.14	5.25	0.06

5.5 Summary

This chapter presented the field testing of the wideband HFCT sensors installed around live 20 kV feeder phase conductors for PD and PQ measurements. According to test results, they have successfully captured PD and high frequency phenomena occurring in the MV network without experiencing any saturation when the maximum load current was 80 A.

It gives additional possibility of monitoring primary 50 Hz and harmonic currents which is a novel approach. The PQ performance of HFCT sensor is adequate. It has shown similar results compared with the commercial power quality sensor in terms of time-domain and frequency-domain analysis.

Cost-effective implementation of earth-fault detection and location is also demonstrated using RTDS. Based on the RMS current measurements, detection of the faulty phase of the feeder as well as the location of the earth-fault in the MV network is possible using the wideband HFCT sensors.

A successful testing of the HFCT sensors has been carried out in the field for measuring MV-side quantities of the proposed monitoring concept. The performance of the HFCT sensors has been satisfactory considering the fact that they can monitor PD, PQ and locate earth faults using the same sensor which significantly reduces the cost of monitoring at MV side.

6 Discussion and conclusion

Condition monitoring is becoming an increasingly significant factor to improving the reliability of distribution network. However, the lack of cost-effective monitoring solutions for measuring wide range of disturbances especially at MV side restrains the deployment of condition monitoring system extensively in the network. Sensor with high voltage insulation is another essential and equally expensive component which increases the cost of monitoring system even further. This thesis focused on the development of cost-effective wideband instrumentation for real-time measurements of high frequency phenomena in the distribution network. Another important goal was to study the possibility of developing a multi-mode monitoring concept based on few wideband sensors and a single measuring unit for a wide range of functionalities i.e. PD and PQ monitoring, disturbance recording and fault location, which significantly reduces the cost and complexity dealing with installation and maintenance. The idea of combining different monitoring functions into a single unit is driven by previous research done at TUT on on-line PD measurement, power quality monitoring and fault location.

Secondary substation is an ideal location for data acquisition since both LV and MV networks can be monitored. Consequently, a novel cost-effective wideband secondary substation monitoring solution is presented in this work which includes a multichannel monitoring system and a monitoring concept to measure various quantities (shown in Table 3.1) at LV and MV side of secondary substation. The monitoring system includes FPGA-based multichannel data acquisition & processing unit, filter & amplifier unit, wideband HFCT sensors for MV-side measurement and resistive dividers for LV-side measurement. Multichannel data acquisition interface is developed using an 8 channel, 12 bit, 65 MHz A/D converter so that four channels measure at LV side and four at the MV side. Additionally, the monitoring concept describes what monitoring functions can be incorporated into the monitoring system and how data can be utilized to analyze the electrical network during normal operation and different disturbance events.

The author has successfully developed a cost-effective instrumentation for monitoring high frequency phenomena and a multi-mode monitoring concept which is based on wideband HFCT sensors and a single measuring unit for monitoring wide range of functionalities i.e. PD and PQ monitoring, disturbance recording and fault location. Most novel part of the thesis is the development of wideband cost-effective HFCT sensors which made the realization of multi-mode monitoring concept possible. Wideband HFCT sensors not only monitor PD and PQ but also record disturbances and locate earth faults at MV side of secondary substation, which is a novel approach. They are fundamental units of the wideband secondary substation monitoring solution which sig-

nificantly reduces the cost of monitoring at MV side of secondary substation. The proposed monitoring solution is not fully integrated into a single unit. However, overall concept is tested and verified through prototype systems in the laboratory and in the field which are summarized below.

An intelligent electronic device (IED) is developed for real-time monitoring of high frequency phenomena in the distribution network. The IED provides a versatile environment to study and analyze the behavior of LV network in real-time. Furthermore, a versatile and complete monitoring solution composed of FPGA, multichannel A/D converter, filter & amplifier unit and HFCT sensors was developed for on-line PD monitoring. Laboratory measurements using time-domain and frequency-domain analysis have demonstrated that the monitoring system has successfully captured the PD calibrator pulse as well as real PD data from 20 kV feeder. The monitoring system has eight channels but four were used for PD measurements. The design concept from both devices can be extended further for monitoring and real-time processing of the data measured at LV and MV side of secondary substation.

Ferrite cores are used to develop cost-effective wideband HFCT sensors. Split core HFCT sensor M1 with 9 turns winding configuration and 0.3 mm air gap seems to be the best candidate for PD and PQ monitoring. A successful field testing of the wideband HFCT sensors (M1) was carried out at 20 kV feeder phase conductors for PD and PQ monitoring. In addition, RMS-based method for detecting earth fault in MV network was demonstrated using the RTDS. HFCT sensors (M1) have showed promising results in detecting PD and high frequency signals from phase conductors without experiencing saturation. Power quality measurements also showed adequate performance compared with the commercial power quality monitor. The performance of wideband HFCT sensors (M1) fulfilled the expectations considering the fact that the same sensor can monitor PD and PQ and locate earth faults.

Secondary substation monitoring plays a vital role in improving the power grid reliability and flexibility. Along with the communication infrastructure, it creates the foundation on which various monitoring, control and network automation applications can be built. Through prototype systems, it is demonstrated that the performance of subsystems of the wideband secondary substation monitoring solution were adequate in the laboratory as well as in the field. Thus, it is possible to integrate different subsystems to develop a standalone secondary substation monitoring solution. The proposed secondary substation monitoring concept would fundamentally improve the possibilities of predicting and preventing component failures at secondary substations and connected feeders. Information on the voltage level and quality at secondary substations would be useful in network operation (e.g. to increase the hosting capacity of DG) and network planning. Additionally, fault location would also help automatic fault location, isolation and restoration process.

6.1 Future development and research

The performance of HFCT sensors to monitor PD and PQ together with locating earth faults at the MV side of secondary substation makes it possible to develop versatile and cost-effective condition monitoring solution. The development of the secondary substation monitoring solution to work as a standalone system in the field will be continued after the submission of the thesis. Future work will concentrate on the development of data processing unit to process the data in real-time from eight channel. Further research to develop the analysis method, e.g., what information should be recorded, how to extract the useful information from raw data dealing with different monitoring applications is needed. The development of communication infrastructure is another potential research area to transfer the data between local database and centralized database. Furthermore, implementation of IEC 61850 based substation automation would allow exchanging information with commercial IEDs for improving the power grid reliability in more efficient manner.

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Publications

Publication I

B. A. Siddiqui, P. Pakonen and P. Verho, "Experience of Communication Problems in PLC-based AMR Systems in Finland," in *Proceedings of 5th IEEE Conference on Innovative Smart Grid Technologies Europe (ISGT-Europe)*, Oct. 2014.

Experience of Communication Problems in PLC-based AMR Systems in Finland

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Abstract— **According to Finnish legislation, at least 80% of the energy meters had to be remotely readable and provide hourly based data by the end of 2013. The expansion of AMR system has certainly set higher demand for the reliability of the communication link when hundreds of meters establish communication link with data concentrator. This paper discusses the architecture of different Automatic Meter Reading (AMR) systems and gives some insight to the level of conducted disturbances which may cause PLC communication problems in commonly used AMR systems. It also proposes potential solutions to overcome the PLC communication problems. On-site measurements have been carried out to study the behavior of different system in real networks with various electronic loads. The results indicate that large number of PLC links failed to operate in the field due to the high frequency noise generated by electronic loads at frequencies close to the PLC carrier frequency. The presence of high frequency disturbances in the PLC frequency range caused by customer loads obstructed the communication of AMR systems which is a matter of concern for DNOs.**

Index Terms— **Power Line Communication, Automatic Meter Reading, High Frequency Interference, Switched-Mode Power Supply, Frequency Converter**

I. INTRODUCTION

The idea of sending communication signals over power line is as old as the telegraph itself. Power Line Communication (PLC) is currently an emerging technology, consequently gaining much attention for various applications such as Internet, home entertainment, home automation and enabling easy deployment of Automatic Meter Reading (AMR) systems which is of most interest because of its rapid growth in the recent era. The inherent communication infrastructure presented by power line makes it a favorable solution for AMR systems. PLC-based AMR system is a technology to gather and transfer data from energy meter to data concentrator using power line. It may also be used to update energy meter parameters or software or to control customer loads. Therefore, reliable operation of the AMR system is important. AMR systems using PLC network have been used in Europe since 1980s and is likely to increase in the context of improved energy services and efficiency [1].

In recent years, a large growth in the usage of electronic loads i.e. variable speed drives (VSDs), fluorescent lamp with electronic ballast, switch-mode power supplies (SMPS), uninterruptible power supplies (UPS) etc. have been observed in the power networks. All these devices use fast switching technique which produces high-frequency distortion in the distribution network. On the other hand, due to the introduction of remotely readable energy meters, power network is used increasingly as a communication medium in addition to the power distribution. The power lines were not designed for data transmission and as a result they exhibit unpredictable levels of channel noise, signal attenuation and distortion which seriously affect the performance of the communication system. In Europe, the available frequency range for PLC in low voltage (LV) network is regulated by CENELEC standard EN 50065-1 [2]. It specifies the allowed maximum frequencies and signaling levels in the LV network. However, standardization in the frequency range 3…150 kHz to limit the emissions by customer equipment is practically non-existent so far. This is one of the reasons why PLC may be disturbed by the emission of customer equipment.

This paper discusses the architecture of different AMR systems installed in Finland which uses different MAC layer protocol. It also presents practical cases of disturbances found in the PLC-based AMR systems which affected the communication between energy meters and data concentrator. Additionally, it proposes some potential solutions to the interference problems.

II. COMMUNICATION TECHNOLOGIES USED BY FINNISH DNOS

In April 2011, Tampere University of Technology (TUT) in co-operation with Finnish Energy Industry conducted a questionnaire to Finnish Distribution Network Operators (DNOs) to get an idea about the communication technologies used in the meter and the interference problems experienced so far, especially related to the PLC systems. A total of 18 Finnish DNOs having a total of 1 935 275 energy meters took part in the questionnaire which covers approximately 2/3 of the energy meters in Finland. At the time of the questionnaire, 847 071 meters were remotely readable which corresponds to

44% of the meters covered by the questionnaire. A total of 13 DNOs answered the questionnaire concerning the communication technologies used by them. Fig. 1 depicts the share of different communication technologies used by individual DNO and in all DNOs (in total). This statistic covers a total of 769 578 energy meters in Finland.

It is clearly visible that the share of energy meters using PLC was already during the survey very high and it was expected to increase to be the dominant communication technology by the end of 2013. A more detailed analysis of the questionnaire is presented in [3]. The survey clearly exhibits that PLC is the potential candidate for AMR systems in Finland. It also brings a challenge for AMR manufacturer to ensure reliable communication link between meter and data concentrator.
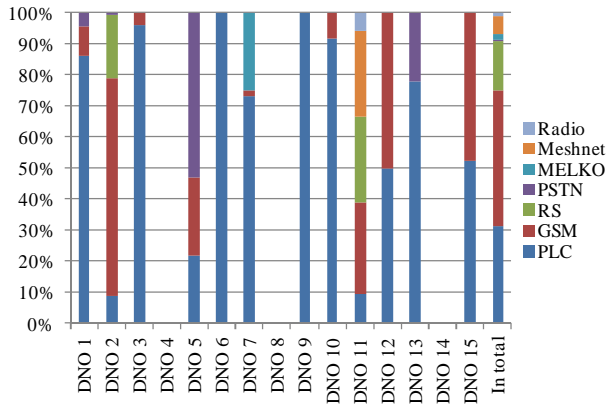
Figure 1. Share of communication technologies used by different DNOs in energy meters.

III. AMR SYSTEM ARCHITECTURE

AMR refers to the collection of data from electronic meters and then automatically transmit the collected data via communication medium without human intervention. A general AMR network consists of a master node (data concentrator) polling several slave nodes (energy meters) to collect data and transfer it to the central unit. The following section discusses most common modulation schemes as well as medium access control protocol used in AMR systems.

A. Modulation Schemes

Power lines exhibit highly variable and unpredictable levels of channel noise, signal attenuation and impedance. Furthermore, the permissible signal levels for communication defined by the European standard EN 50065-1 restrict the transmission power and limit the bandwidth. However, the standard does not specify which modulation technique should be used. Therefore, to achieve reliable communication in this potentially hostile environment, appropriate modulation scheme is necessary. Three commonly used digital modulation techniques for PLC are:

1) Frequency Shift Keying (FSK): The simplest form of frequency shift keying is binary FSK. BFSK uses two

discrete frequencies to represent logic 0 and 1. BFSK is widely used modulation scheme for communication over powerlines. This modulation technique is very resilient to narrow band interference [4].

2) Phase Shift Keying (PSK): The most basic form of PSK is the binary PSK where logic 0 and 1 are represented by 180° phase shift. Platt [5] outlined that both BFSK and BPSK are robust yet simple but FSK scheme performs better over any phase delay introduced into the channel.

3) Orthogonal Frequency Division Multiplexing (OFDM): OFDM is a robust modulation technique proposed by Open PLC European Research Alliance (OPERA). OFDM techniques have offered great advantage in countering interference across signals, and are helpful for high-speed transmission in an environment of multipath and fading channels.

Several systems based on different modulation schemes have been developed as discussed in [6]. Most vendors, however, do not specify the modulation schemes or other technical details of the PLC system in public documentation. However, one commercial product based on Spread FSK (S-FSK) modulation and polling scheme is discussed here [7].

B. MAC Layer Protocol

Many standardized or proprietary MAC layer protocols are available for AMR application. Despite the AMR systems widespread use, it is difficult to find information on medium access method used by different vendors. This section explains different routing protocol used in the AMR system.

Many AMR systems employ a general polling/broadcast mechanism as a centralized medium access method. The polling protocol is based on automatic repeat request (ARQ) where messages are sent with an error detecting code following a timer for retransmission in case of failure [8]. When energy meter receives the polling message, it immediately transmits the data to the concentrator unit. It also transmits an acknowledgement (ACK) which indicates successful transmission as well as end of the transmission. In case of failure, energy meters keep repeating the retransmission procedure until reaching some predefined time period. This summarizes the polling mechanism of most common AMR systems installed in Finland.

Recently AMR systems of a new routing protocol have been installed in Finland where both meter and data concentrator can initiate the communication. They use carrier sensing multiple access (CSMA) protocol where a node sense the carrier before transmitting on a shared transmission medium. The presence of carrier wave on the transmission medium is used to determine whether other nodes are transmitting because each access node connected to the network does not transmit any carrier wave except their own packet transmission. If the carrier wave is sensed on the communication channel, the channel is called 'busy' otherwise, it is 'idle'. If the channel is sensed as idle, access node starts to communicate immediately. On the contrary, if the channel is sensed as busy, access node waits for the transmission in progress to get over before initiating its own transmission.

One advantage of using the latter system is that, in case of network reconfiguration (if a customer has to be fed from another secondary substation in case of network construction, services or black out) there is no need to re-configure the data concentrator unit for establishing connection with customer energy meter. Both meters and concentrator unit can establish connection with each other which is not the case with the former system. Regardless of different MAC layer protocol, both AMR systems have experienced PLC link failure.

IV. MEASUREMENT METHODOLOGY

All the measurements reported in this paper were made with a Rhode & Schwarz ESPI-3 test receiver/spectrum analyzer, ESH2-Z3 passive voltage probe and EZ-17 current probe. For practical reason, all measurements have been done with a resolution bandwidth of 1 kHz, which is a good tradeoff between adequate frequency resolutions and short sweep time for both 0…150 kHz and 0…1 MHz bands. The EMC standard defines the measurement bandwidth of 200 Hz for frequencies up to 150 kHz and 9 kHz for frequencies 150 …30 MHz [9]. In practice, 200 Hz bandwidth requires such a long sweep time even for 0…150 kHz band that it makes it impossible to make a single sweep measurement between the transmission bursts of the PLC system to identify underlying disturbance signals. In EMC standards, the emission limits are usually given for quasi-peak detector. However, peak detector has been used for measurements in this paper which is available in most spectrum analyzers. At pulse repetition frequencies of greater than 10 kHz, the measurements of quasi-peak and peak detector are within a range of a couple of dB [9] so the effect of different detector on results can be considered very small.

V. DISTURBANCE CASES AND ON-SITE MEASUREMENTS OF ELECTRONIC LOADS

One of the most common sources of PLC disturbances in both the survey and the field measurements were found out to be the switched-mode power supplies (SMPS). SMPS have wide applications in various areas, mainly because of its low weight, smaller size, efficiency and wide input range tolerance. Frequency converters are also commonly used in ventilation system in block of flats where many AMR meters can be found. For example, ventilation fans use frequency converters and there may be frequency converters also in water circulating pumps of heating systems which may cause PLC reading problems. Authors investigated practical cases where customer's equipment equipped with switching power supplies were producing narrowband interference in the frequency range 3…150 kHz which ultimately blocked the communication. One case is also investigated where frequency converters prevented the PLC reading of a large group of meters in a block of flats. Following section presents on-site measurement results carried out for different AMR systems to identify the source of disturbances.

A. On-site Measurements of PC Power Supply

Switched-mode power supplies are commonly found in personal computer and laptops. In this case, switching power supply of desktop computer in a printing press prevented the PLC communication of AMR meters for all the customers

connected to that particular feeder. The current and voltage behavior of the conducted disturbances were measured at the main distribution board of the press. Fig. 2 shows the disturbance voltage signal with amplitude 66 dBμV present at approximately 71 kHz due to the switching frequency of the power supply.

Fig. 3 shows the spectrum of the conducted current with and without the power supply connected to the network. It also shows the lower and upper PLC frequency. It is evident from the figure that the switching frequency is very close to the PLC carrier frequency of about 75 kHz. Although the amplitude level of the disturbance signal is not very high it blocked the communication. The AMR system based on CSMA protocol sensed this signal as a carrier wave, thus considered the channel as busy and never initiated the communication. After disconnecting the supply from the mains, the communication started immediately.
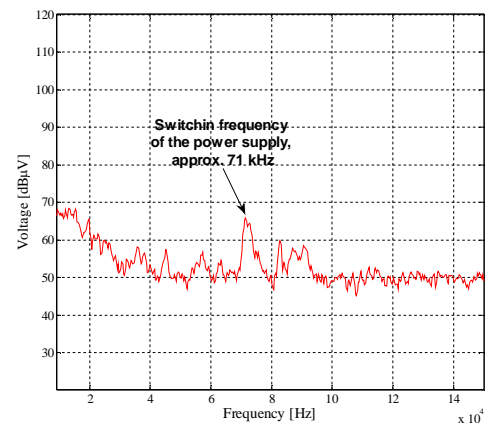

Figure 2. Disturbance caused by single phase switched-mode power supply of desktop computer.
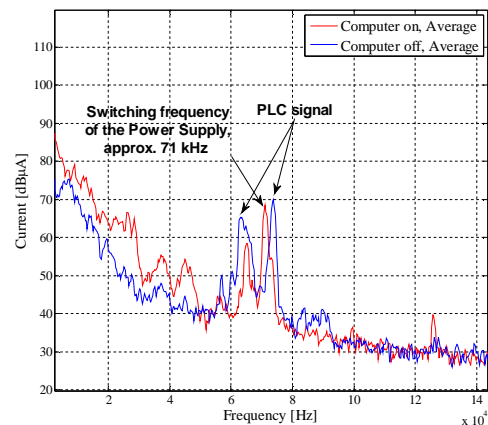

Figure 3. Frequency spectrum showing PLC and disturbance signals caused by switching power supply of desktop computer.

B. On-site Measurements of Ethernet Router

The switching power supplies can cause significant amount of interference in the frequency range 0…150 kHz. In

this case intact power supply of Ethernet router found in a block of flats prevented the PLC communication of AMR meters. The current and voltage behavior of the conducted disturbances were measured at the feeding point of the main distribution board of the block of flats. Fig. 4 shows the voltage disturbance level of about 85 dBμV present at approximately 72 kHz.
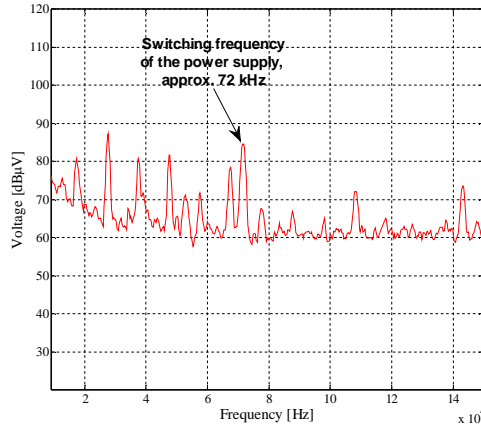

Figure 4. Disturbance caused by single phase switched-mode power supply of Ethernet router.

Fig. 5 shows the spectrum of the conducted current with and without the Ethernet router supply connected to the mains. Both PLC frequencies are also visible in the spectrum. The disturbance signal present at 72 kHz is again quite close to the upper PLC frequency of 75 kHz. Due to the presence of this signal, the CSMA protocol based AMR system did not initiate the communication at all considering the channel as 'busy'. After disconnecting the router from the mains, the PLC communication started immediately.
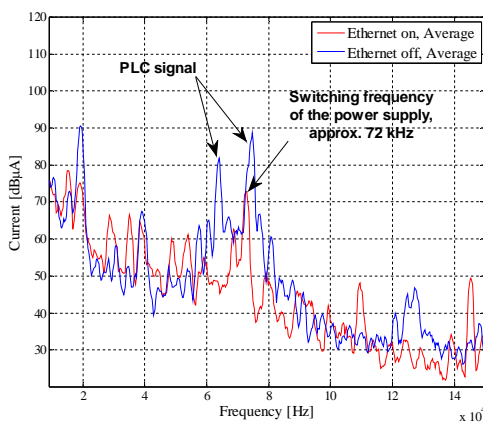

Figure 5. Frequency spectrum showing PLC and disturbance signals caused by switching power supply of Ethernet router.

C. On-site Measurements of Cellular Base Station

In this case interference was caused by 4G/LTE cellular phone base station switched-mode power supply which prevented the PLC communication of AMR meters which use simple polling protocol. All the measurements were performed at the main distribution board of the secondary substation close to the terminals of the concentrator. Fig. 6 shows the max hold measurements done with peak detector when the base station is on and off (also the PLC signals are shown in the figure). It also shows a single sweep measurement from a moment when the PLC-concentrator is not transmitting. With switched-mode power supply base frequency, about 44.5 kHz, the disturbance voltage measured with 1 kHz resolution bandwidth is about 104 dBμV and with second harmonic frequency, 89 kHz, the disturbance voltage is about 75 dBμV. The problem seems to be the second harmonic frequency which hits right between the PLC frequencies. Although the disturbance voltage is not very high but it was adequate to block the communication between meter and data concentrator. There have been several similar disturbance cases in Finland where data concentrator was unable to receive the signal from meters.
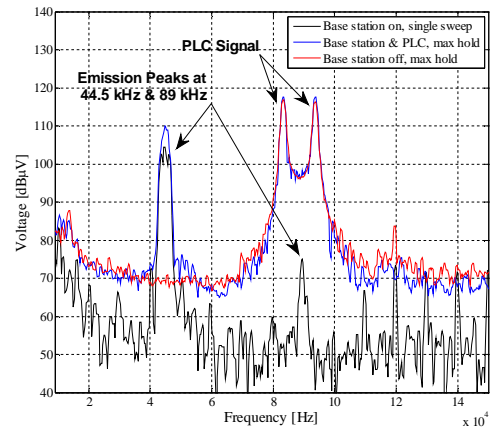

Figure 6. Cellular base station power supply noise voltage frequency spectrum.

D. On-site Measurements of Frequency Converter

In this case air ventilation frequency converters of a parking hall were interfering the PLC reading of newly installed AMR meters in a block of flats which also use polling protocol. The parking hall had six frequency converters (5.5 kW each) located in the main distribution room. Fig. 7 shows the disturbance voltage frequency spectrum measured at the main distribution board of the parking hall close to the secondary substation when all the frequency converters were on and off. Due to their high conducted disturbances the meter reading was blocked in several adjacent blocks of flats. It can be noticed from the figure that around the PLC frequency range, the disturbance voltage is slightly lower than at frequencies above 150 kHz but high enough to prevent the communication.
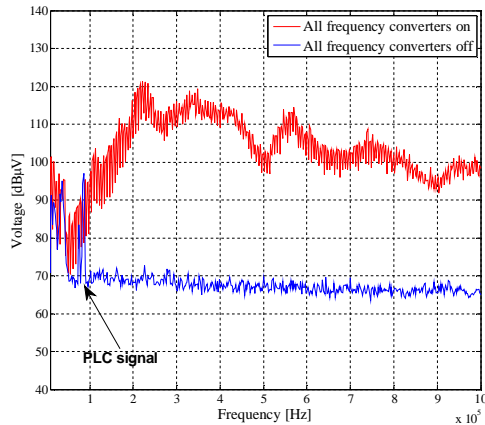
Figure 7. The conducted interference voltage frequency spectrum when all frequency converters were on and off.

VI. Potential Solutions to Interference Problems

So far, there are not many standards setting conducted emission limits for electrical apparatus in the frequency range 2…150 kHz. For example, IEC/EN 61000-6-3 sets limit only for frequencies below 2 kHz and above 150 kHz [10]. According to CISPR 11, the conducted disturbances of induction cooking appliances in the frequency range 50 to 148.5 kHz should be below 80 to 90 dBμV. Based on the measurements, it can be concluded that even conducted emission clearly smaller than those defined in CISPR 11 still interfered the PLC communication.

One way to reduce the effect of disturbances is to install an EMC filter between the device causing the disturbances and the network. Although the commercially available EMC filters are often designed to attenuate conducted disturbances at frequencies above 150 kHz their attenuation is still relatively high at frequencies 60…95 kHz, where, for example, most of the AMR meter PLC systems operate.

Standardization on the frequency range 2…150 kHz is currently under development and in that work the need of smart meter PLC should be taken into account. One possible solution is to define conducted disturbance limits low enough to guarantee the operation of AMR meter PLC systems on the whole frequency range. If it is not possible, another possibility might be to allow higher disturbance emissions at some frequencies not so relevant to PLC and to define lower limits only for the frequency range of e.g. 50…95 (or 148.5) kHz, at which most of the AMR meter PLC systems operate.

Data concentrators are mainly located at secondary substations. It is clearly evident from the measurement results that the presence of high frequency noise close to data concentrator affects the PLC communication of a large number of meters. Measurement of high frequency components produced by, e.g., switch-mode power supplies and frequency converters is a challenge in the real-network because AMR systems are not capable of monitoring them. One solution from network operator end could be to add a real-time monitoring device as discussed in [11] at secondary substation for monitoring high frequency phenomena in LV network. It can continuously monitor the LV network to identify the disturbance source. Due to the computation power of real-time monitoring device, the concept of wideband measurements could also be applied at secondary substation for other purposes for example, partial discharge monitoring and condition based maintenance of underground cable, cable accessories and transformers. These monitoring functions can play a vital role in improving the performance of the power systems by helping the operators in network planning and operation, fault location and maintenance.

VII. Conclusion

HF disturbances caused by different electronic loads are problem for the PLC signals. HF disturbances often originate in loads which use switching techniques and these products are increasing rapidly because of the advantages they offer. The switching frequencies of these products are in the same frequency range which is regulated by CENELEC for LV PLC communication.

Many AMR systems vendors have introduced different MAC protocol to provide a reliable communication link. However, the used protocols have not been publically documented. In this paper, interference cases for AMR systems using CSMA as well as polling protocol were studied by on-site measurements. Both systems failed to offer reliable communication link already at a relatively moderate HF disturbance levels produced by electronic loads, specifically single phase switched-mode power supplies. The presence of HF disturbances close to PLC frequencies were interpreted as carrier wave by CSMA based AMR systems which resulted in silent mode but the communication was established as soon as the disturbance source was removed from the mains. Polling based AMR systems did not interpret the noise as carrier and tried to establish the communication but could not succeed due to the noisy channel. MAC protocol uses different error control method to check the consistency of the delivered message and to recover the data determined to be corrupted. In the studied cases, the system could not even use error detection scheme because of its failure while establishing the communication link. Based on the measurements, conducted disturbances even lower than those specified e.g. in CISPR 11 cause PLC malfunction in AMR systems regardless of the used MAC protocol.

According to the questionnaire made to Finnish DNOs, it seems that by the end of 2013 approximately 30…50% of the approximately 3 million energy meters in Finland will use PLC communication in LV network. The deployments of smart meter using PLC have been already widely applied in other countries as well. Thus, it is important to maintain the network in a condition where the PLC system can operate successfully.

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Scientific
Research

A Novel Device for Real-Time Monitoring of High Frequency Phenomena in CENELEC PLC Band

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ABSTRACT

This paper proposes the design and development of a novel, portable and low-cost intelligent electronic device (IED) for real-time monitoring of high frequency phenomena in CENELEC PLC band. A high speed floating-point digital signal processor (DSP) along with 4 MSPS analog-to-digital converter (ADC) is used to develop the intelligent electronic device. An optimized algorithm to process the analog signal in real-time and to extract the meaningful result using signal processing techniques has been implemented on the device. A laboratory environment has setup with all the necessary equipment including the development of the load model to evaluate the performance of the IED. Smart meter and concentrator is also connected to the low voltage (LV) network to monitor the PLC communication using the IED. The device has been tested in the laboratory and it has produced very promising results for time domain as well as frequency domain analysis. Those results imply that the IED is fully capable of monitoring high frequency disturbances in CENELEC PLC band.

Keywords: Power Line Communication (PLC), Digital Signal Processor (DSP), Analog-to-Digital Converter (ADC), Fast Fourier Transform (FFT), High Frequency (HF) Interference.

1. Introduction

Recent technological developments have enabled the evolution of devices that uses power line communication (PLC) to send and receive control signals with some degree of reliability. The primary purpose of power line is to carry power not data which means reliable communication over power lines are difficult due to noise created by loads and devices connected to the PLC network. All power electronic devices generate and emit unwanted electrical signals (EMI noise) that can lead to a performance degradation of PLC network. They generate high frequency conducted and radiated EMI noise and draw distorted line currents due to the sharp edges of the switching waveform with high du/dt. The most common high frequency noise sources are compact fluorescent lamps (CFL), switched power supplies, frequency converters and AC motors that can cause significant amount of reduction in signal-to-noise ratio (SNR) in PLC network [1]. For Western Europe, the regulation concerning communications over low voltage network are described in CENELEC standard EN 50065-1 entitled "Signalling on low-voltage electrical installation in the frequency range 3 kHz to 148.5 kHz". The allowed frequency range i.e. 3 to 148.5 kHz is further divided into five sub-bands.

The use of frequency band 3 kHz up to 95 kHz is restricted to electricity suppliers and their licensees [2]. The object of the standard is to limit interference caused by signal transmission equipment to sensitive electronic equipment.

The frequency range in the 'traditional' harmonic range up to 2 to 3 kHz has been under investigation for several years and large amount of knowledge has been gathered through the years on this issue. However, little or no attention has been paid to the frequency range above the low-frequency harmonic range, or at least between 2 to 150 kHz. This is probably due to the apparent absence of well documented cases of interference found within this frequency range [3]. Another more fundamental reason is the lack of appropriate measuring equipment to record and analyze high frequency phenomenon in PLC network. Conventional monitoring equipment such as, oscilloscope, network analyzer and spectrum analyzer are not optimized for PLC application because they cannot do any post-processing on the measured data which is necessary to monitor the behavior of PLC network. Some previous work carried out on this topic have been presented in [4, 5] but they are currently unavailable and work presented in [6] has a limited functionality for a specific platform. One main reason for concern is the possible interference

of high frequency distortion with power line communication e.g., automatic meter reading (AMR). The frequency range used for PLC i.e. 3 to 95 kHz is the same range that is often used for switching in switched mode power supplies, high frequency (HF) ballasts, etc. It is a considerable issue for the successful and efficient operation of an AMR. Therefore, long term measurements and real-time analysis of high frequency interference to monitor the power quality of the PLC network has become more essential than ever before. This paper discusses the development of a novel and low-cost intelligent electronic device (IED) for continuous monitoring of power quality and high frequency phenomena in PLC network.

The rest of the paper is organized as follows. Section 2 briefly explains the hardware architecture of the IED. Section 3 discusses about the prototype development of the IED. Section 4 describes the design flow and efficient signal processing algorithm implementation on a low-cost digital signal processor (DSP) to meet the real-time challenges. Section 5 talks about the detailed laboratory setup to test the PLC and other high frequency signals with the IED. The experimental results obtained by IED are discussed in Section 6. Finally, the paper is summarized in Section 7.

2. Hardware Architecture

The hardware architecture of this novel and low-cost IED is based on the development idea proposed in [7]. **Figure 1** shows the modified block diagram of the architecture. The hardware architecture includes signal conditioning, data acquisition and DSP block. Analog signal coming from the LV network needs signal conditioning before an acquisition unit can reliably and accurately acquire the signal. The signal conditioning block includes steps like signal decoupling from the LV network, attenuation, filtering and amplification. Data acquisition block is equipped with ADS7881, a 12-bit analog-to-digital converter to sample the analog signal. Afterwards, a high speed floating-point DSP C6713 with an operating frequency of 225 MHz is used to apply signal processing algorithms to mathematically manipulate the digital data.

A high pass filter and voltage divider circuit as shown in **Figure 2** has been developed as a front-end module to couple with LV network to attenuate the voltage signal to ±2.5 volt. It is the common input voltage range for data acquisition unit.
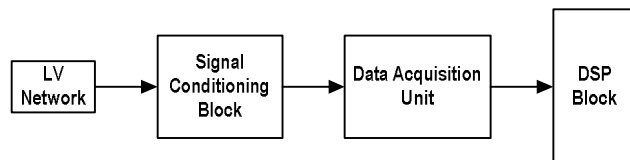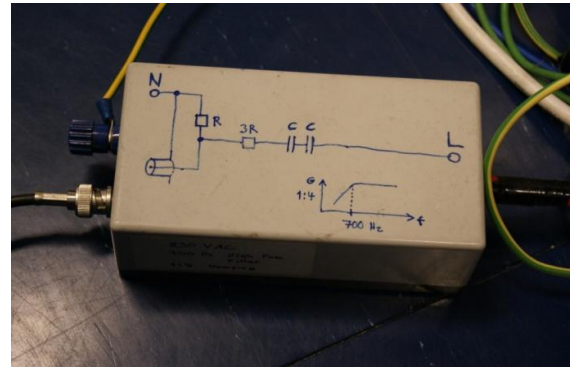

Figure 1. Development approach of the IED

Figure 2. Front-end module for LV network

3. Prototype of Intelligent Electronic Device

The prototype of intelligent electronic device following the hardware architecture discussed in section 2 has been developed which is shown in **Figure 3**. The data acquisition block has been interfaced with DSP using 5-6K Interface board developed by Texas Instrument. The 5-6K board is intended to maintain a compatible interface with the TMS320 series of DSP according to the guidelines set forth in the TMS320 Cross-Platform Daughter Card Specification (SPRA711) [8]. Additional power of ±12 V and +5 V are required to power up the interface board which is necessary for the analog front end and analog power rail of the ADS7881, respectively.

4. Software Interface

Main novelty of the device comes in the software part where the objective is to capture and process the signal in real-time continuously for a longer period of time (days or weeks). The software interface has been developed to collect and process the samples as quickly as possible. **Figure 4** depicts the DSP design implementation flow diagram of the IED. It starts with initializing the necessary functions for board support libraries, DSP and ADC interfaces, resetting interrupt and timer. The most efficient way of accomplishing real-time processing is by using a timer, hardware interrupt and a software interrupt. The algorithm is written to collect 1024 continuous samples of analog signal then computing FFT then performing additional post-processing on the FFT data. As soon as 1024 samples are stored into the Buffer, ADC interrupts the DSP which trigger software interrupt (SWI) and go back to fill another set of data to the Buffer. During the time another set of 1024 samples are stored into the Buffer, the SWI executes the inter service routine (ISR) which includes the scaling and computation of signal processing algorithm of the sampled data. The only time constraint is that all the data inside software interrupt service routine must be processed before the active Buffer fills up. It is much easier to meet the real-time constraints with this implementation.
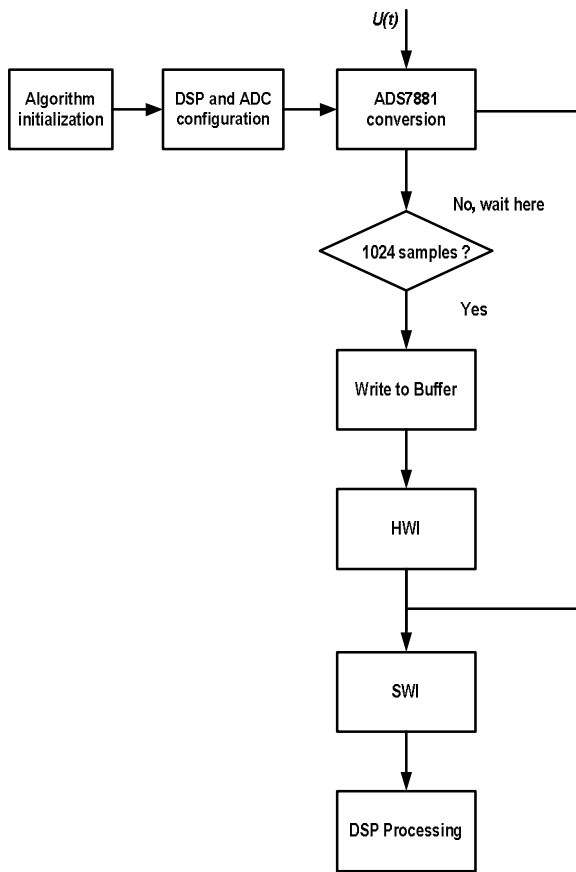
Figure 4. DSP design implementation flow of the IED

Continuous monitoring of the PLC network is another major aspect of this novel device. It is not possible to meet such goal due to the limited amount of memory available on the DSP. To overcome this issue, a laptop has been attached to the IED which works as a data storage unit. A C code is written to transfer the processed data to the laptop through JTAG emulation.
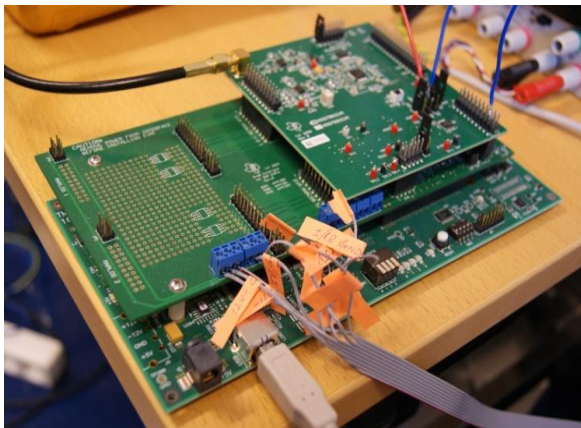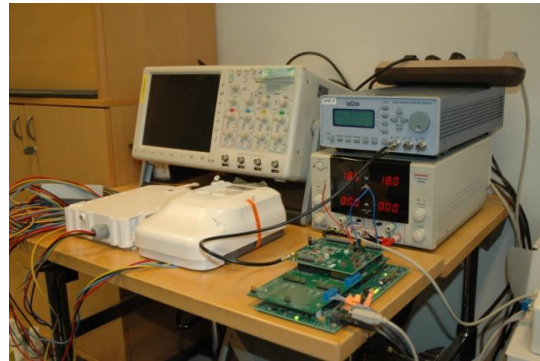

Figure 3. Prototype of the intelligent electronic device

Figure 5. Connection setup in the laboratory

4.1. Frequency Domain Analysis

Time domain waveform does not provide sufficient information about the signals. Therefore, frequency domain analysis is necessary to draw the meaningful result. The waveform assessment is indeed a challenging and time consuming task. It requires an appropriate method and tool especially if real-time processing is a big concern. There are quite a few methods of waveform parameters estimation but, arguably, one of the most popular tools is discrete Fourier transform (DFT), especially its fast algorithm version called fast Fourier transform (FFT). An efficient FFT algorithm is implemented on the IED to meet the real-time challenges. Typical FFT algorithms assume complex input and output data. Most of the time domain data are real valued. A simple solution to this problem is to pad N-length zero-valued sequence as imaginary component with real-valued signal to make it a complex input to compute the FFT. However, this method is obviously inefficient. The algorithm used in this application assumes N-point real sequence as N/2-point complex valued sequence then it computes N/2-point complex FFT on the complex valued sequence. In the first step, only N/2 points of the N-point sequence are computed. Since the FFT of a real-sequence has symmetric properties, the remaining N/2 points FFT are easy to compute with equations. Complete description of the algorithm along with equations can be found in [9].

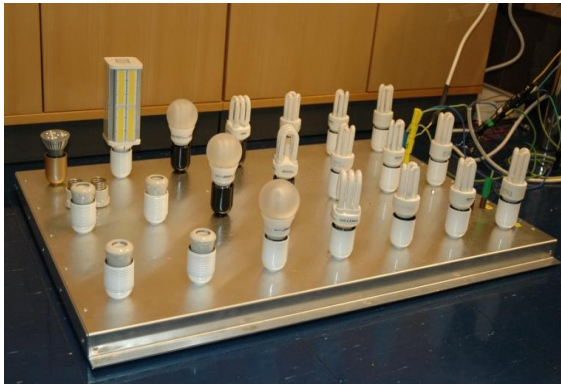**Figure 6. Smart meter and concentrator setup**

SGRE

Figure 7. Load model based on CFL and LED lamps

5. Experimental Setup

The prototype IED has been tested in the laboratory. A setup using smart energy meter and data concentrator which acts as a central unit has been used. These meters are fully electronic and smart which record the consumption of electric energy and send that information to the utility for billing purposes. They communicate over low voltage network using power line communication. **Figure 5** shows the necessary connection setup to power the signal conditioning, data acquisition and DSP block of the IED. **Figure 6** shows the smart meter and concentrator setup used to test the PLC communication using the prototype IED. Modern energy saving lighting can emit high frequency interference in the frequency range chosen for PLC communication. A low-power load model based on CFL and LED lamps as shown in **Figure 7** is developed to test the capability of IED to detect the high frequency phenomena in PLC network. A block diagram showing the experimental setup among LV network, smart meter, concentrator and load model is shown in **Figure 8**. Prototype IED is used to monitor the adverse interaction between PLC communication signals and noise generated by the load.
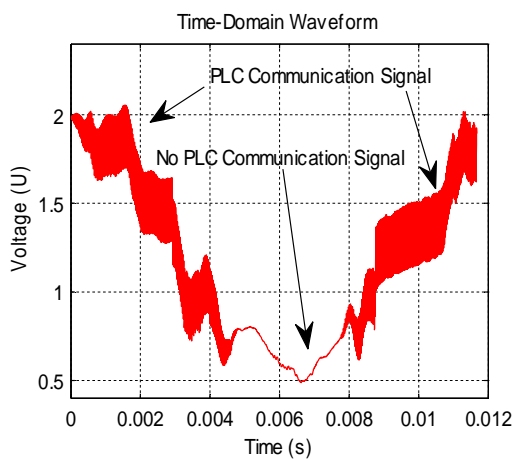

Figure 10. Time-domain waveform captured by the IED

6. Results

This section explains about the results computed by the prototype IED. Matlab has been used to plot all the figures for better presentation. Before making any measurements with the load setup, a reliability test of the IED along with the software algorithm implemented on the IED has been made by comparing the FFT spectrum of the known signal computed by the IED and measured by Rhode & Schwarz spectrum analyzer ESPI-3. **Figure 9** shows the spectrum of 80 kHz signal computed by IED and measured by spectrum analyzer. The spectrum analyzer is typically a more expensive piece of test equipment when compared with this low-cost IED. Despite the low sampling frequency and dynamic range, IED has detected the 80 kHz signal quite accurately comparing to the spectrum analyzer which is evident from the graph.

After successful reliability test, IED was connected with the load setup to monitor the behaviour of the PLC network. **Figure 10** depicts the time-domain waveform (without scaling) of 50 Hz signal captured by the IED. It is clearly visible that PLC signals are modulated over 50 Hz cycle and communication between meter and concentrator is going on in most of the cycle. No communication is going on between meter and concentrator for a short duration of time which is also indicated in the waveform.

Frequency-domain analysis gives description about the distribution of energy in the signal as a function of frequency. It is necessary to determine other high frequency components present in the signal which act as a noise. **Figure 11** and **Figure 12** shows the frequency domain analysis of the load network computed by the IED. It can be observed from the graphs that the IED is capable of monitoring frequencies up to 175.78 kHz with the current system implementation. High frequency phenomena can be observed in both the spectrum through the whole PLC band. The primary source of the noise is the load model which has CFL and LED lamps
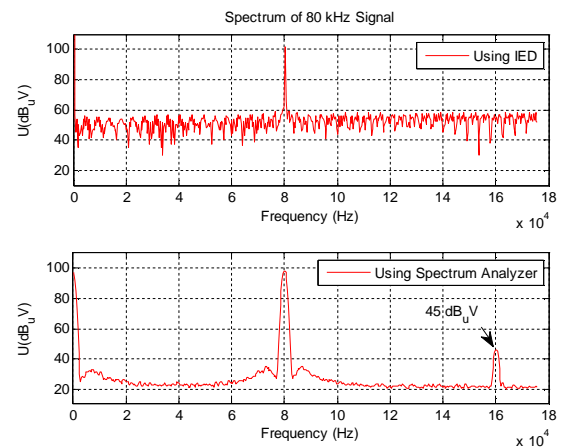

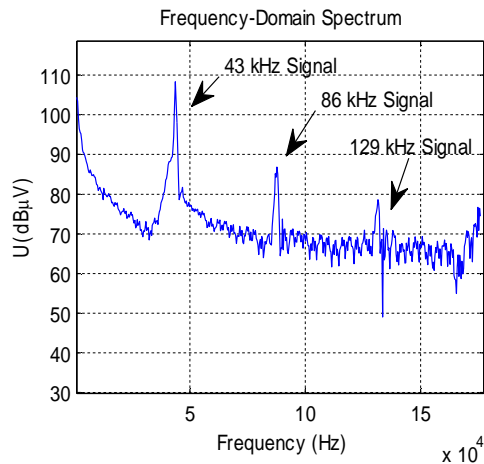**Figure 9. Spectrum analysis using IED and spectrum analyzer**

Figure 11. Frequency-domain spectrum computed by the IED

connected with it. The operating frequency of a CFL is often just above 40 kHz. The high frequency components above 40 kHz in both the spectrum are the emission caused by the switching element in the CFL. In **Figure 11**, the fundamental harmonics can be seen clearly at 43 kHz, followed by a second harmonic at 86 kHz and a third harmonic at 129 kHz. Harmonics can easily pollute the network which is a big concern for successful PLC communication. Other high frequencies present at 12 kHz and 115 kHz as shown in **Figure 12** are probably due to other power electronic devices connected to the distribution network.

As is known, the noise floor limits the smallest measurement that can be taken with certainty since no measured amplitude can, on average, be less than the noise floor. According to the EMC standard EN 55011, conducted emissions from RF equipments should be below 56 dBμV at 150 kHz and decrease to 46 dBμV at 500 kHz. The IED has been designed to meet the following measurement limits. Noise floor of the IED is around 45 dBμV which can be observed from **Figure 12**.
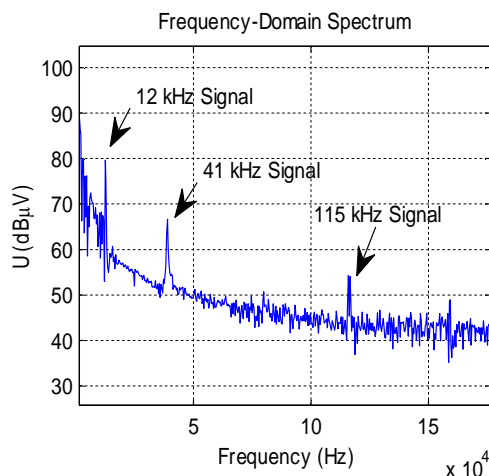

Figure 12. Frequency-domain spectrum computed by the IED
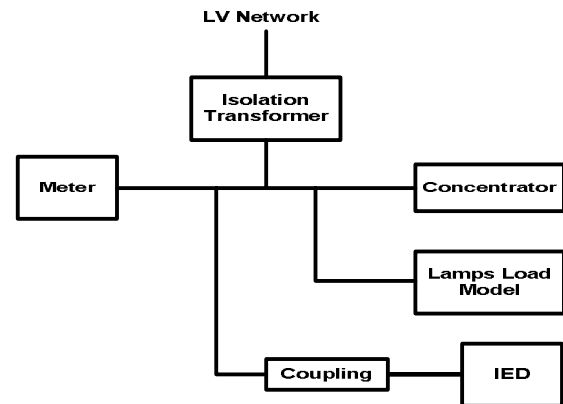

Figure 8. Block diagram showing the experimental setup

It can be further analyzed from **Figure 9** that spectrum measured by spectrum analyzer has second harmonic at 160 kHz which is not found in the spectrum computed by IED because its amplitude is just below the noise floor of the IED. The result proves that IED is capable of monitoring the lowest possible interference set forth by the EMC standard.

7. Conclusion

The design and development of a novel intelligent electronic device for real-time monitoring of high frequency disturbances in PLC network is presented in this paper. The prototype IED has been tested in the laboratory with adequate equipments. The test results have shown very efficient performance in the robust distribution network and computed very accurate results. The IED provides a versatile environment to study and analyze the behavior of LV network in general and PLC network in particular. Moreover, it can be used as a cost-effective platform to develop tools for electrical utilities to monitor the PLC network to solve the practical issues related to disturbances and PLC communication problems. The future prospect of the IED is to make index calculation from the FFT data to extract the valuable information to classify the quality of the signal. The IED will be installed in real field for longer durations of time to monitor the time-variant behavior of the PLC network.

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Publication III

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Novel Inductive Sensor Solutions for On-line Partial Discharge and Power Quality Monitoring

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ABSTRACT

Networks of medium voltage have spread over a long distance through underground cables. The aim to prolong the life span of existing network assets increases the need for condition monitoring to prevent unplanned and long lasting interruptions. Continuous on-line partial discharge (PD) measurement is an excellent way to determine the overall health of the medium voltage (MV) components and to detect developing faults in underground cables. A sensor is an essential part of the PD monitoring system which measures the high frequency PD signals. PD sensors can be used to measure power frequency current and harmonic currents on the MV side to estimate the thermal loading of transformer or incoming cable provided that the sensors have a suitable frequency response for measuring low frequency signals as well. A novel inductive sensor is described in this paper which allows both PD measurements as well as power quality (PQ) measurements at frequency range below 2.5 kHz. Authors did experiments on different ferrite cores in order to design the best possible sensor which can be used for both PD and PQ measurement. Characteristics of the sensors, including sensitivity, saturation current, and frequency bandwidth, as well as relative errors are provided and analyzed under laboratory conditions. At the end, developed sensors are compared with a commercial HFCT sensor, the Rogowski coil and power quality current sensors to show the capability of the sensors to be used for PD and PQ measurements.

Index Terms - Cable insulation, ferrite cores, high frequency current transformer, partial discharges, Rogowski coil, power quality, harmonics.

1 INTRODUCTION

THE medium voltage (MV) network plays a significant role with respect to supply interruptions experienced by the customer. As underground cables in cities are aging and cabling of MV networks is increasing also in rural areas, condition monitoring is becoming an important tool for preventing unplanned and long lasting interruptions. It may be difficult to maintain the power supply especially in rural areas via alternative network configurations during the fault and repair. Thus, it is important to detect and locate incipient faults before they cause a supply interruption. The network companies are also being forced by legislative actions and regulatory measures to increase the proactive network monitoring in order to prevent unplanned and long lasting interruptions. Partial discharge detection is an important monitoring tool for avoiding the catastrophic failures of power networks and high voltage equipment. The best way to detect incipient faults in an underground cable network is continuous on-line PD monitoring.

Power quality monitoring is becoming increasingly important in power networks at all voltage levels due to the increase of sensitive electronic devices connected to the network. New devices such as distributed energy resources (DER) and electric vehicles (EV) are usually connected to power network using nonlinear power electronics interface which is likely to increase the harmonic currents flowing in the network. Harmonics increase losses and heating in transformers and lead to derating of the transformer [1]. Generally the high temperature decreases the life expectancy of the transformer. As a consequence of local hot spots, the degradation (depolymerisation) of the paper insulation accelerates making the paper more brittle and the water contained in the insulation may vaporize forming gas bubbles. These may lead to increased partial discharge activity. Monitoring the load current is also important in cables since the temperature has an effect on the partial discharges occurring in cables, terminations and joints (increasing temperature increases ionization and thus PD). Load and temperature variations may also cause changes in PD activity due to interface delamination induced by thermal

expansion/contraction. Thus, power frequency and harmonic current monitoring gives important information for interpreting the PD measurement results of transformers and underground cables.

Sensors are a fundamental unit of PD monitoring system as they provide information about the propagation of partial discharges in MV cables network. They should have both high sensitivity and wide frequency bandwidth to detect pulses in a noisy environment. The choice of sensor type is very crucial as there are a number of coupling techniques available for monitoring of PD activity including: a) coaxial cable sensors which can be installed at the cable joints [2], b) directional couplers which can be placed on either side of the cable joint [3], c) the Rogowski coil [4], d) inductive HFCT transformers which can be clamped either around the cable or the earth straps [5]. The classical capacitive coupling of the PD signal needs the high voltage capacitor to be connected to the phase conductor which means cable has to be switched off and power delivery is interrupted. On the contrary, inductive coupling requires no galvanic contact with the conductor so the sensors do not compromise the reliability of the medium voltage network. Therefore, the sensor can be mounted around the conductor without interrupting the power delivery which makes it a popular choice for on-line PD measurement.

There are commercially available sensors from several manufacturers for PD monitoring but the novel sensor solutions proposed in this paper combines PD and PQ monitoring into a single unit which is a novel approach. This concept has several advantages like a monitoring system having only a few sensors is less complicated, easier to install and maintain and has a lower cost compared with a system having separate sensors and monitoring units for each monitoring function. Moreover, maintaining or increasing a power networks' reliability in a cost-effective way is also an important aspect for network owners.

Ferrite materials have high permeability, high resistivity and low eddy current losses which make it ideal for applications where high frequency currents are measured. This research work focuses on the development of ferrite based inductive sensors for continuous on-line PD and PQ monitoring at MV side. The effect of winding configurations and air gaps on the amplitude response, transfer impedance, saturation current and relative errors is analyzed under laboratory conditions. At the end, the performance of the developed sensors is compared with commercially available HFCT sensor, the Rogowski coil and power quality current sensors.

2 HIGH FREQUENCY CURRENT TRANSFORMER (HFCT) SENSORS

High frequency current transformers are sensors with ferromagnetic cores. Due to the high sensitivity and high self-inductance, the output signals are proportional to the current at fairly low frequencies [6]. The basic principle of the current transformer is to produce an alternating current in its secondary winding which is proportional to the alternating current flowing through its primary winding. HFCT sensors consist of a wound toroidal ferromagnetic core unlike the Rogowski coil which has an air core but both detect PD pulses through the magnetic field. HFCT sensors have good frequency bandwidth and sensitivity but they may suffer from saturation because of the magnetic core if they are installed around the phase conductor with high phase current. On the contrary, the Rogowski coil does not saturate because of an air core but their sensitivity is poor when compared with HFCT sensor. The Rogowski coil also needs a digital integrator to obtain the primary current waveform which makes it cumbersome for permanent installation.

An effective PD sensor should be compact and easy to install, sensitive to tens of picocoulombs (pC) of PD level and have a high saturation current. The sensor is characterized by a suitable frequency response for measuring fast PD pulses, passband transfer impedance which is the ratio between the secondary voltage and the primary current and the saturation current in order to measure the PD pulses without experiencing saturation. The higher transfer impedance ensures better sensitivity but it is a trade-off between frequency range, the saturation current and transfer impedance of the sensor which will be explained later in detail.

2.1 SENSORS CONSTRUCTION

Two different ferrite materials were used to develop sensors at the Tampere University of Technology (TUT) for PD measurement as well as PQ measurement at frequency range below 2.5 kHz at the MV side. Novel sensors were constructed using toroidal cores. These sensors are compared with a commercial HFCT sensor and the Rogowski coil (developed at TUT earlier [4]) for PD measurements. In addition, they are compared with the commercial power quality current sensors for PQ measurements. Different winding configurations, i.e., 4, 9 and 20 turns were wound on each core using enameled copper wire of diameter 0.19 mm. The windings are spread evenly over the core area as this helps to reduce the leakage inductances. Experiments are also performed using split ferrite cores with air gaps which lean the B-H loop, making it possible to use the core at higher magnetic field level. It is desirable to delay this saturation for measuring PD signals if a high current is flowing through the conductor. All the sensors were terminated with 50 ohm during the measurements.

2.2 COMPARISON OF DIFFERENT SENSORS

One method of comparing different ferrite core sensors is to measure the frequency response (transmission coefficient) of each sensor. Thus, amplitude ratio measurements were performed using Agilent 4395A Network Analyzer combined with an S-parameter test set. S-parameter test set provides the capability to measure reflection and transmission characteristics of two-port devices in either direction with a single connection. A full 2-port calibration was performed before the measurements in order to correct the systematic errors [4]. After calibration, the S_{21}-parameter i.e. forward

transmission coefficient from 10 kHz to 100 MHz of each sensor was measured. The signal output of the network analyzer, port 1, was passed through the sensor and terminated with 50 ohm. Sensor output was connected using a coaxial cable to the network analyzer port 2. The S_{21}-parameter describes how well an input signal is transferred via sensor to its output. Thus, it corresponds to the frequency response of the measured sensor [7]. It is important to analyse the performance of each sensor over wide frequency ranges which helps selecting the best possible option for PD and PQ measurements.

3 EXPERIMENTS AND ANALYSIS

For the sake of simplicity designed sensors are named M1 (core 1) and M2 (core 2). Experiments are performed for closed core and split core with different air gaps to study the performance of each sensor with respect to the frequency response, passband transfer impedance and saturation current. In addition, relative amplitude error and phase angle error are also calculated to study the potential of the developed sensors to be used for PQ measurements.

3.1 SOLID FERRITE CORE SENSOR

Figure 1 depicts the frequency responses i.e. amplitude ratios as the function of the frequency of solid core sensor M1 and M2 with different winding configurations wounded evenly around the core. It is clearly visible that the frequency responses of both sensors with 4 turns winding configuration are not flat over higher frequencies as with 9 and 20 turns but their sensitivity is still better than other winding configurations. With 20 turns winding configuration, the frequency responses of both sensors have similar flat response over a wide frequency range until their sensitivity starts to increase 3 dB to 5 dB, respectively then drops and finally resonance frequencies are reached. In comparison, the frequency responses of sensor M1 and M2 with 9 turns winding configurations have flat response over a much wider bandwidth until they reach resonance frequencies. In addition, they exhibit good overall sensitivity as well as low resonance peaks when compared with other winding configurations. It can also be stated from the amplitude ratio curves that the resonance peak of all sensors regardless of their winding configurations, appears in the frequency range 75 – 90 MHz which already gives quite good frequency range in the higher end to measure PD signals. It can be concluded from the amplitude ratio curves that the sensitivity of the sensors decreases with the increasing number of winding turns. The observation about decreasing sensitivity with the increasing number of turns is also in accordance with the studies done earlier about ferrites [8].
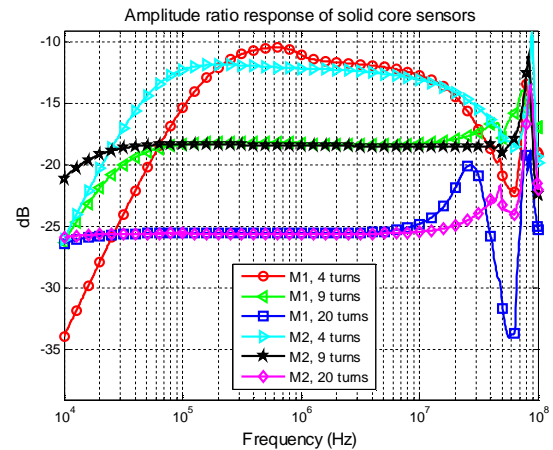

Figure 1. Amplitude ratio response of sensor M1 and M2 with different winding configurations.

A good sensor should have high enough sensitivity and flat frequency response over a wide usable bandwidth. Sensor M1 with 9 turns winding configuration seems to be the best choice among the core materials as well as the number of turns. It exhibits high enough sensitivity, flat amplitude ratio response between 30 kHz (-3dB cut off) to 45 MHz (-3 dB cut off) as well as low resonance peak which makes it an excellent choice for PD monitoring.

3.2 SPLIT FERRITE CORE SENSOR

Solid ferrite core sensors have shown good frequency response which gives quite good range to monitor PD signals. The problem with solid core sensors is that they require power to be disconnected before installation. Another problem is that they cannot bear high currents because of the core material saturation. Split core sensor solves this issue but it affects the frequency response of the sensor and can be less accurate than a solid core sensor. One source of inaccuracy mainly comes from the imperfect contacts between the two halves of the core material. Furthermore, the distribution of the secondary windings is not evenly spaced around the whole magnetic core but around two halves. Two halves should have quite flat contact surfaces and sufficient amount of pressure should be applied to keep them intact. Another advantage of the split core sensors is that they can be retrofitted into a live cable without disturbing the power delivery, which makes them a unique choice for on-line PD measurements.

Investigations are done to study the effect of split ferrite cores by increasing the size of air gaps. Since sensor M1 and 9 turns winding configuration are proved to be the best so it will be used to carry out the rest of the measurements. Figure 2 depicts the comparison of the amplitude ratio responses of the sensor M1 with closed and split cores with three different air gaps.
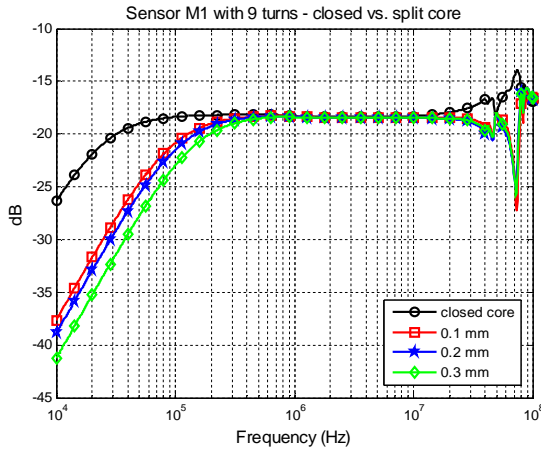
Figure 2. Amplitude ratio response of sensor M1 - closed core and split core with different air gaps.

It is quite visible from the amplitude ratio curves that air gaps affect the frequency response of the sensor. The lower -3dB cut-off frequency which was 30 kHz in case of closed core sensor increases to around 85–130 kHz but the amplitude ratio response is still quite flat over the frequency range of interest with varying air gaps of 0.1 mm to 0.3 mm. To summarize, the working frequency range of sensor M1 with respect to different air gaps (as set by the lower and upper -3dB cut-off frequency) is between 85 kHz to 45 MHz which is quite promising range to detect PD signals.

3.3 COMPARISON OF FREQUENCY RESPONSES

In this section, the performance (in terms of sensitivity and amplitude ratio response) of sensor M1 (core 1) and M2 (core 2) is compared with the commercial HFCT and the Rogowski coil. Split core sensors (M1 and M2) with 9 turns winding configurations and 0.3 mm air gap are used to make the comparison. The commercial HFCT sensor has an air gap of 0.25 mm, whereas the Rogowski coil has an air core.

With reference to Figure 3, sensor M1 has good sensitivity, lower -3 dB cut-off frequency (130 kHz) and flat amplitude ratio response which extends up to 45 MHz. On the other hand, sensor M2 has a flat amplitude ratio response but the lower -3dB cut-off frequency is around 230 kHz which is quite high in comparison with M1. The commercial HFCT has the lowest -3 dB cut-off frequency (70 kHz) but the amplitude response is flat only up to 15 MHz. Moreover, the sensitivity is considerably lower when compared with sensor M1 and M2 in the passband region. In comparison, the Rogowski sensor has the lowest overall sensitivity and unstable amplitude response at higher frequencies. The resonance peak of the Rogowski sensor also appears in the PD frequency range which may affect the measurement. Resonance peaks appearing further from the band pass which is the case with developed sensors and the commercial HFCT sensor are easier to handle using low-pass filtering.
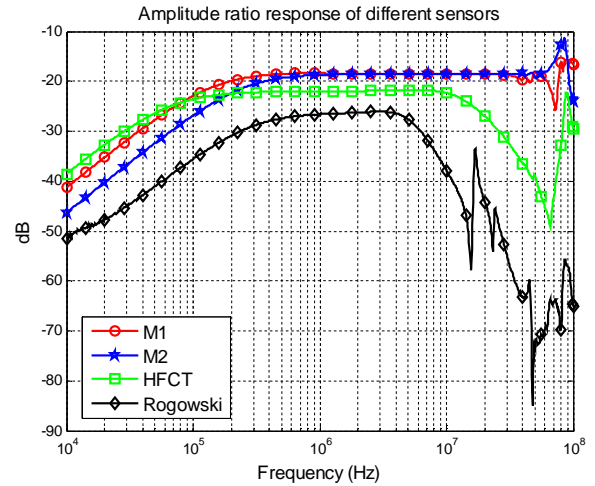

Figure 3. Comparison among the amplitude ratio responses of developed sensors, commercial HFCT and the Rogowski coil.

3.4 HIGH FREQUENCY TRANSFER IMPEDANCE

The length of the air gap is the key parameter in the sensor design because it directly affects the sensitivity and the lower cut-off frequency of the sensors as demonstrated in Section 3.2. This section will explain how different air gaps affect the sensitivity of the sensors. Sensors are characterized by transfer impedance (Z_T) which is the ratio of the voltage across the secondary winding terminated at 50 ohm (V_S) to the current of the primary winding (I_P).

$$Z_T = \frac{V_S}{I_P} \qquad (1)$$

Passband transfer impedances of the sensors were measured to study the effect of air gaps on their sensitivity. Additionally, a comparison with a commercial HFCT and the Rogowski coil is made to demonstrate their sensitivity. Both designed sensors use 9 turns winding configuration, 0 mm refers to the split core without spacer. Transfer impedance test was setup using a signal generator and an oscilloscope as shown in Figure 4. A sine wave with 1 MHz characteristic frequency was generated using a signal generator and passed though the sensors using the BNC connector and terminated with 50 ohm. Oscilloscope is used to measure the output of the sensors.
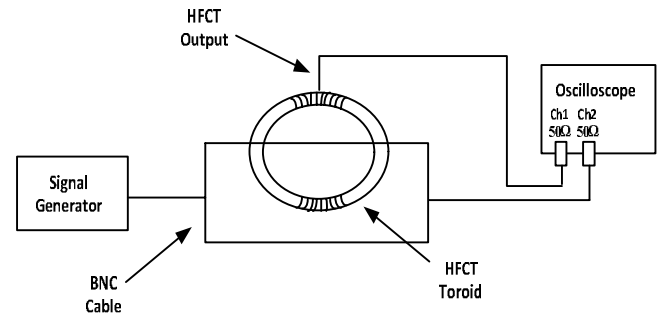

Figure 4. Transfer impedance test setup.

Table 1 shows the transfer impedance against different air gaps using 1 MHz characteristic frequency. It should be noted that the Rogowski coil has an air core and commercial HFCT

has an air gap of approximately 0.25 mm. Both are shown on the right most column of the table.

Table 1. A comparison of transfer impedance

Sensor	Air Gap (on one side of the core)			
	Closed	0 mm	0.2 mm	0.3 mm
M1	6.20 Ω	6.05 Ω	5.95 Ω	5.90 Ω
M2	6.02 Ω	5.93 Ω	5.80 Ω	5.72 Ω
HFCT	-	-	-	3.45 Ω
Rogowski	-	-	-	1.45 Ω

The results suggest that the sensitivity of the developed sensors reduces as the air gap increases. This is mainly because of the imperfect contacts between the two halves of the core material. In comparison, the developed sensors and the commercial HFCT sensor have much higher transfer impedance than the Rogowski coil. However, the sensitivity of the developed sensors is much better than the commercial HFCT sensor. To summarize, it can be stated that the smaller the air gaps the higher the sensitivity and the lower the lower cut-off frequency.

3.5 HIGH CURRENT SATURATION TEST

Another purpose of inserting air gaps is to reduce the saturation of the magnetic materials which is the state when an increased current cannot further increase the magnetization of the material. The air gap tunes the permeability of the core so that the saturation takes place for a higher current [9]. Higher current saturation is desirable if measurement is done with the real conductor. High current flowing through the conductor may saturate the magnetic core which cannot measure the PD signals properly. A high current test was set up using a variable autotransformer to increase the 50 Hz current. The overall test setup is shown in Figure 5.
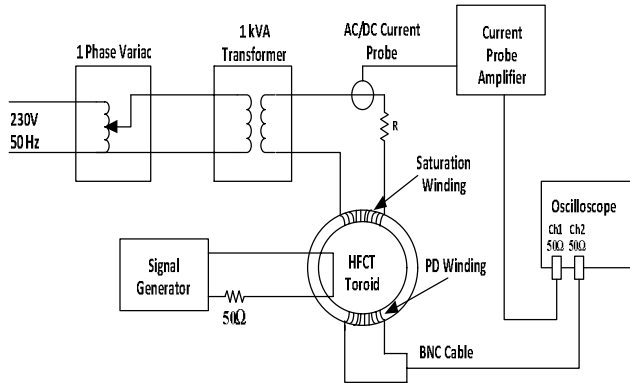

Figure 5. Saturation current test setup.

Table 2 shows the saturation current recorded for the developed sensors, the commercial HFCT and the Rogowski coil. Both developed sensors use 9 turns winding configuration and different air gaps. The Rogowski coil has an air core so it does not saturate and the commercial HFCT has an air gap of approximately 0.25 mm. The saturation current for the commercial HFCT sensor is shown on the right most column of the table. It is clearly visible from the

table that increasing the air gap increases the saturation current of the developed sensors. The saturation current of sensor M1 (core 1) and M2 (core 2) with 0.3 mm air gap is higher than the commercial HFCT sensor. It can be concluded that the developed sensors have high saturation current as well as a wider frequency bandwidth compared with the commercial HFCT sensor. More detailed analysis on other ferrite cores and the effect of 50 Hz saturation waveform on the developed sensors is demonstrated in [10].

In conclusion split core sensor M1 (core 1) with 9 turns and 0.3 mm air gap seems to be the best candidate for PD measurements because of its higher transfer impedance and saturation performance as well as flat amplitude ratio response between 130 kHz and 45 MHz. To verify the effectivity of sensor M1, laboratory measurements were carried out using a PD calibrator and real PD data captured by measuring a 20 kV feeder on-site at a substation. Both time-domain and frequency-domain analysis have demonstrated the good capability of sensor M1 for detecting PD signals [11].

Table 2. A comparison of saturation test.

Sensor	Air Gap (on one side of the core)			
	Closed	0 mm	0.2 mm	0.3 mm
M1	10.0A	12.5A	68.0A	100.0A
M2	3.0A	13.5A	55.4A	67.3A
HFCT	-	-	-	64A
Rogowski	-	-	-	-

4 MV POWER QUALITY MEASUREMENT

The sensor design has been optimized so that it allows the measurement of both high frequency currents and power frequency current on the MV side as well. Power frequency current measurement enables power quality measurement at frequency range below 2.5 kHz at the MV side and it is also useful in estimating the thermal loading of the transformer and/or incoming cable. This information can be utilized in interpreting the PD measurement results since partial discharges are often temperature dependent. The following section presents thorough measurements to determine the final accuracy of the developed sensors for MV power quality measurements.

4.1 AMPLITUDE RESPONSE

The HFCT sensors developed at TUT have strongly frequency dependent amplitude responses at frequencies outside their band pass (flat curve). Below the pass band the sensitivity decreases approximately 20dB/decade as illustrated in Figure 6. Thus, at low frequencies the frequency response is similar to a Rogowski sensor without integration. By integrating the output voltage waveform of the sensor according to equation (2), it is possible to extract the 50 Hz and harmonic current information from the PD signal.

$$i(t) = i(0) - \frac{1}{M} \int_0^t u(t)dt \qquad (2)$$

where u(t) is the output of the sensor, M is the mutual coupling between the primary conductor and the sensor

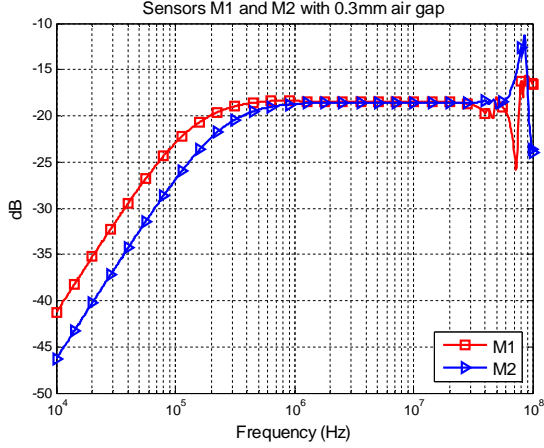winding and i(t) is the current in the primary conductor [12].

Figure 6. Amplitude ratio response of sensors M1 and M2 at frequency range 10 kHz…100 MHz.

4.2 EXPERIMENTAL SETUP

The performance of the inductive sensors developed at TUT was studied at frequency range 50…2500 Hz by laboratory measurements. The measurement setup consists of an arbitrary waveform generator, a current amplifier, a 4-channel digital storage oscilloscope with 8 bit A/D converter and a reference shunt box as shown in Figure 7. The reference shunt box has different resistors to monitor different levels of current. The shunt box was used as a reference sensor since it provides accurate current measurement with zero phase error.

As demonstrated earlier the split core sensors with 0.3 mm air gap are more suitable for PD measurements due to the high saturation current along with a wider frequency bandwidth. As a result, split core sensors with 9 turns winding configuration and 0.3 mm air gap were used in this experiment to study the performance of the inductive sensors for low frequency measurements.
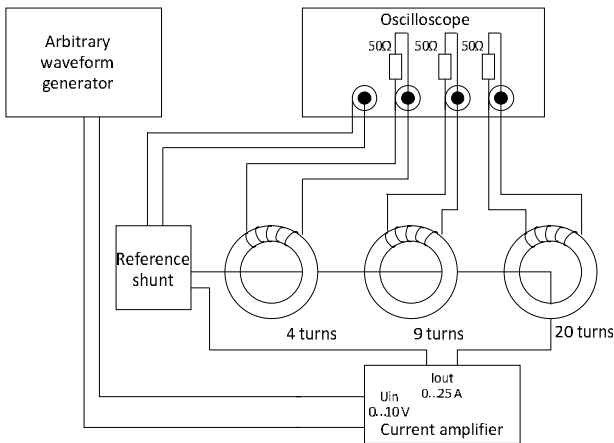

Figure 7. Test setup for developed sensors at 50…2500 Hz.

4.3 RESULTS AND ANALYSIS

Figure 8 illustrates the output of 0.2 A 50 Hz current measured by reference shunt and sensor M1 with 9 turns

winding configuration and 0.3 mm air gap. Reference shunt measurement produces quite clean 50 Hz output, whereas the output voltage of the sensor is dominated by high frequency disturbances caused by the current amplifier's pulse width modulation and it is difficult to see the 50 Hz component.

As stated earlier in Section 4.1 the output of the developed sensor at low frequencies is similar to the Rogowski coil output which is proportional to the rate of change of the primary current. Consequently, integration can be performed to restore the 50 Hz current and harmonics by using an analog circuit or digitally by using a signal processing algorithm. Since an analog integrator is vulnerable to zero-drift of the operational amplifier and other non-ideal factors, it may not be possible to restore the measurement current truly in practice. However, a digital signal processing approach provides better stability and repeatability [13].
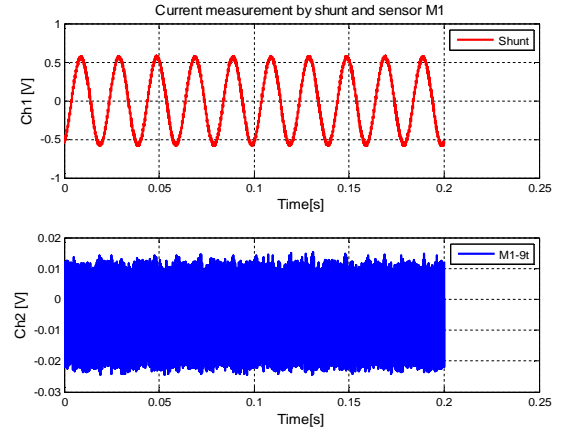

Figure 8. 50 Hz current of 0.2 A measured by the reference shunt and sensor M1.

Figure 9 depicts the output of sensor M1 after numerical integration. It is clearly visible that the high frequency disturbances become negligible and the 50 Hz signal revealed by M1 is almost identical with the reference shunt measurement.
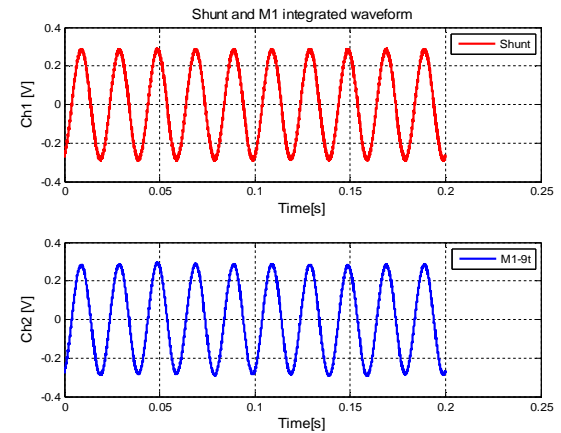

Figure 9. 50 Hz current of 0.2 A after numerical integration.

5 RELATIVE AMPLITUDE AND PHASE ERRORS

The relative amplitude error and phase angle error of the developed sensors compared with the reference shunt were studied at frequency range 50…2500 Hz against primary currents of 0.2…10 A. All current values were tested against each frequency for both sensors to study the degree of accuracy of both sensors to measure the primary current. As depicted in Figure 10 even at a low primary current of 0.2 A sensor M1 has an error of less than 3 % compared to shunt for all frequencies and the error tends to be lower with increasing current for all frequencies. In contrast, sensor M2 performs worse with an error of approximately 12 % to 15 % at 0.2 A current for all frequencies. The reason for high amplitude error is the high lower -3 dB cut-off frequency of M2 compared with M1 which affects the sensitivity of the sensor at lower currents. However, the amplitude error decreases with increasing current for all frequencies which is already quite good at 5 A.
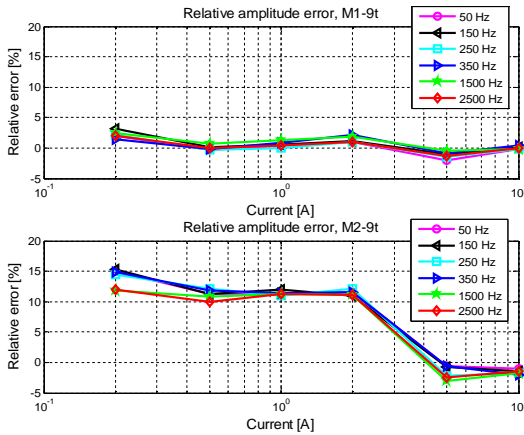

Figure 10. Relative amplitude error of sensors M1 and M2 with 9 turns winding configuration and 0.3 mm air gap.

Figure 11 shows the phase angle error of both sensors M1 and M2 as a function of current for each frequency. With a low 0.2 A primary current at 50 Hz, the error for both sensors M1 and M2 compared to shunt is about 0.3 degrees and 0.45 degrees, respectively. Moreover, the phase angle error of M1 and M2 is less than 0.7 degrees and 0.6 degrees, respectively for all current values at frequencies up to 350 Hz (7th harmonics). For higher frequencies, phase angle error for both sensors increases further with increasing current. Higher phase angle errors are primarily caused by oscillatory field fluctuations due to the mechanical resonances of the coils at high currents. However, the overall phase angle error is less than 2.5 degrees and 3.5 degrees for M1 and M2, respectively.
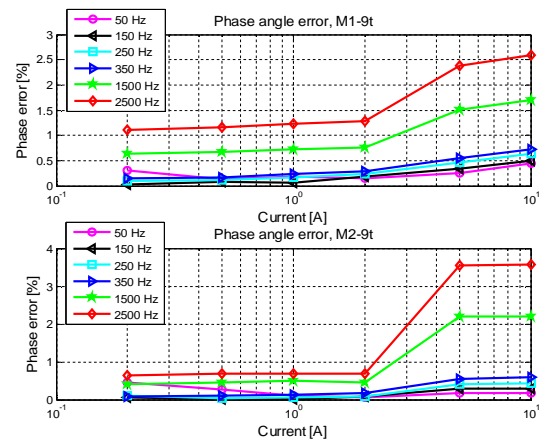

Figure 11. Phase angle error of sensors M1 and M2 with 9 turns winding configuration and 0.3 mm air gap.

As the results indicate, both the amplitude and phase angle error seem very promising for monitoring purposes compared with commercially available power quality current sensors such as, Fluke (i1000s), LEM Flex (RR3020/RR3030) and Dranetz (TR2501A). Fluke has the phase shift errors of more than 3 degrees and amplitude error of 3 % in the range 48 Hz to 65 Hz [14]. LEM has phase angle error of ±1 degrees (45 to 65 Hz) [15]. Dranetz has phase angle error of 1.5 degrees (40 Hz to 5 kHz) and amplitude error of 2 % in the range 1 A…5 A [16]. It can be concluded that the accuracy of the developed sensors is quite adequate for indicative power quality measurements even at low currents 0.2 A…1 A. Phase angle error of sensor M1 is less than 0.7 degrees for all current values at frequencies up to 350 Hz. Amplitude error is 3 % at primary current 0.2 A for all frequencies but the error decreases even further with increasing current. Hence under laboratory conditions, split core sensor M1 seems to be the best choice also for PQ measurements.

6 CONCLUSION

Ferrite cores offer a cost-effective and accurate solution for developing inductive sensors which cover a wider frequency bandwidth. Two different core materials were studied and the series of measurements were performed to choose the best sensor which can be used for both PD and PQ measurements. Closed core sensors provide a flat amplitude ratio response and higher transfer impedance but poor saturation performance. On the contrary, split core sensors provide high saturation performance on account of frequency bandwidth and transfer impedance. In comparison with the commercial HFCT and the Rogowski coil, both split core sensors M1 and M2 with 9 turns winding configuration and 0.3 mm air gap have a wider frequency bandwidth and higher transfer impedance. In addition, the saturation performance of both sensors is also better than the commercial HFCT.

Consequently, the split core sensor M1 with 9 turns winding configuration and 0.3 mm air gap seems to be the best candidate for PD measurements. It has the highest transfer impedance and saturation current as shown in Table

1 and Table 2, respectively. In addition, it has a flat amplitude ratio response over a much wider frequency bandwidth. Moreover, it has shown an adequate performance for PQ measurements compared with sensor M2 and commercial power quality current sensors in terms of relative amplitude error and phase angle error. The phase angle error is less than 0.7 degrees at primary current 0.2 A…10 A at frequency range 50 Hz…350 Hz which is quite good in comparison with the commercial PQ current sensors where the range varies from 1 degree to 3 degrees. The overall relative amplitude error is less than 3 % at primary current 0.2 A…10 A at frequency range 50 Hz…2500 Hz which provides nearly the same or better accuracy than commercial power quality current sensors.

PD measurement is one of the most versatile methods for assessing the condition of high voltage insulations and predicting potential component failures. Hence, the novel split core sensor M1 presented in this paper can be used to monitor PD signals on MV cable carrying current up to 100 A without saturation over the frequency range between 130 kHz and 45 MHz. It also enables the simultaneous recording of 50 Hz and harmonic currents at the medium voltage side of the transformer which is a novel approach. This can be used e.g. for estimating the thermal loading and hot-spot temperature of the transformer. Monitoring 50 Hz and harmonic currents on the medium voltage side also helps in pinpointing the causes of potential power quality problems.

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Publication IV

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A Versatile Solution for Continuous On-line PD Monitoring

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Abstract— **Smart Grid concept substantially increases the power measurement need in the future for efficient and guaranteed power delivery. The medium voltage (MV) cable is an important asset of a distribution network and it must guarantee a stable operation of the supply. With the increasing age of the underground MV cables in power grids, the accident and failure arising from insulation degradation is becoming one of the main challenges against power system reliability. It is also essential economically to extend the life span of the medium voltage cable. Continuous on-line partial discharge (PD) monitoring is an excellent way to determine the overall health of the MV components and to detect incipient faults in underground cables. However, continuous on-line PD monitoring is not widely used primarily because no adequate cost-effective solution is available for permanent installation. This paper presents the development of a versatile solution for continuous on-line PD monitoring of MV cables at secondary substation. The laboratory tests and data analysis exhibit the capability of the proposed system to detect PD signals successfully.**

Index Terms— **amplifier, condition monitoring, data acquisition unit, filter, FPGA, high frequency current transformer, partial discharges, smart grid.**

I. INTRODUCTION

As underground cabling of medium voltage network is increasing in rural areas, at the same time, they are aging in cities. It may be difficult to maintain the power supply specifically in rural areas via alternative network configurations during the fault location and repair. The repair times of faults in underground cables are much longer than in overhead lines and therefore, incipient faults must be detected before they cause an interruption. To minimize outages and interruptions to supply, utilities must be able to monitor and locate faults more quickly and develop condition monitoring in a more preventive direction. Condition monitoring therefore, plays a vital role in attempting to locate the cable that implores the most urgent reliability concerns. The best way to detect incipient faults in underground cable networks is continuous on-line PD monitoring.

The term "partial discharge" is defined by IEC 60270 (Partial Discharge Measurements) as a "localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor". Generally, such discharges appear as sharp pulses having time duration of less than 1 μs [1]. Partial discharge activity occurs at defects, such as air-filled cavities within the insulation material when the electrical field strength exceeds the breakdown strength of the insulation material. PD may deteriorate the electrical strength of insulating material which ultimately leads to the complete breakdown of the cable. On-line PD detection is an important monitoring tool to avoid catastrophic failures of power networks and high voltage equipment.

On-line PD measurements for condition monitoring has not been economically possible in medium voltage networks because of the high cost of the equipment and resources needed [2]. While mobile solutions, such as oscilloscope [3] and spectrum analyzer are available but they are not practical for continuous on-site measurement and permanent installation due to the data storage limitation and the heavy cost of the equipment. Moreover, post-processing on measurement data is also necessary to draw the meaningful results. Additional research on the development of on-line PD monitoring systems has been done [4, 5] but none of them offer multi-channel monitoring solution which is required for PD detection and localization. There are commercially available PD monitors from several manufacturers for underground cables but those capable of continuous on-line monitoring are still relatively expensive for permanent installation. For example, a smart cable guard device for on-line monitoring and localization of PD's and faults in MV cables is presented in [6]. The development and deployment of portable on-line partial discharge monitoring device for condition monitoring of MV cables and switchgear is proposed in [7]. A new joint embedding a sensor for monitoring the level of PD is discussed in [8]. A new technique based on automated on-line PD mapping is introduced in [9]. Most commercial PD monitoring solutions require a large expenditure for permanent installation. For example, a typical cost of the commercial monitor is €30,000 [7]. Thus, a utility with extensive network coverage requires a huge investment. Therefore, implementation of condition

monitoring method at minimal cost is an important concern for utilities.

This paper presents the design and development of a cost-effective solution for continuous on-line PD monitoring which can be installed permanently at secondary substation. The monitoring system consists of cost-effective and robust high frequency current transformer (HFCT) sensor, filter & amplifier unit and data processing unit. Authors have developed ferrite based low-cost inductive sensors, filter & amplifier unit and FPGA based processing unit for data analysis. A comparison between the monitoring system and an 8-bit oscilloscope in terms of resolution and signal-to-noise ratio (SNR) is also made to show the better sensitivity of the monitoring system. The study also includes laboratory measurements using PD calibrator data and real PD data collected from 20 kV line to demonstrate the capability of the monitoring system to be used efficiently and permanently in the field for detecting PD signals.

II. MONITORING SYSTEM

Real-time systems measuring and recording high frequency phenomena require high sampling frequency and much more data processing capability to capture and process the PD signals. Finding the location of the PD source is difficult in on-line measurement because of the high amount of disturbances especially for longer cables where discharge pulses don't reflect properly. The use of multiple sensors will greatly improve the reliability and sensitivity in the detection of the PD pulses and reflections. By measuring all three phases, it is possible to determine in which phase the PD source is located. Another measurement is required to capture 50 Hz mains voltage for synchronization. Hence, a minimum of 4 channels is required for PD detection and localization. The proposed system is based on 8 channels and hence, the monitoring is done at secondary substation so it gives an added advantage to use other channels for monitoring power quality at LV side as well. Fig. 1 shows the placement of the sensors on MV cable in secondary substation.
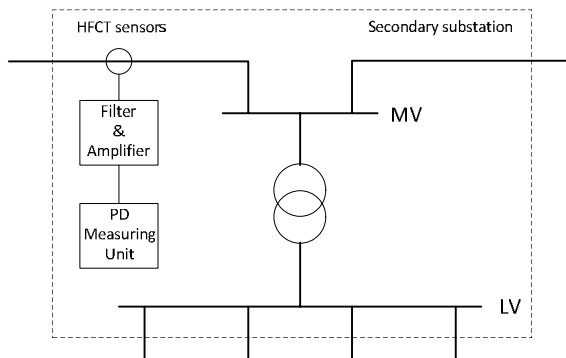

Figure 1. Installation of sensors on MV cable at secondary substation.

The hardware architecture of the versatile monitoring system is shown in Fig. 2. Essential parts of the on-line monitoring system are the inductive sensors which measure the magnetic field inductively and provide galvanic isolation. Ferrite based HFCTs developed by authors are used to measure the PD signals. Filter & amplifier unit also developed

by authors is used to filter out low and high frequencies and amplify the signal of interest to find possible partial discharge pulses. Most important parameters like aliasing, power frequency fundamental wave and harmonic waves should be attenuated so that they do not appear after sampling.

A high dynamic range and bandwidth is required to correctly record the shape of the PD pulse. If the sampling frequency is twice the bandwidth of the system which fulfills the Nyquist criterion, the peak value of the PD pulse cannot be captured correctly since there are too few samples compared to the length of the pulse. Thus, an 8 channel, 12-bits, 65 MHz ADC with serialized low voltage differential signaling (LVDS) interface is used as a front end for the monitoring system. LVDS is a common standard for high speed data converter. Most multichannel high speed ADCs have gone to serial output like LVDS to save pin count and package size.

The high speed mezzanine card (HSMC) or HSMC-ADC-Bridge passive interconnect board by Texas Instrument enables the output of high speed LVDS ADCs to be directly connected to a standard HSMC interconnect header, a typical input on latest FGPA EVMs. This enable high speed data converter EVMs to directly interface to FPGAs for prototyping purpose, saving the time and the cost of producing a custom board.

FPGA is a promising choice due to high flexibility and reusability, moderate costs and easy upgrading due to the use of abstract hardware description language (HDL). Unlike processors, FPGAs are truly parallel in nature so different processing operations do not have to share the same resources. The Altera development kit is used as a design platform which is built around Altera Cyclone V System-on-Chip (SoC) FPGA. In addition, an on-board high speed mezzanine connector (HSMC) with high speed transceiver allows an easy way to interface LVDS based ADCs.
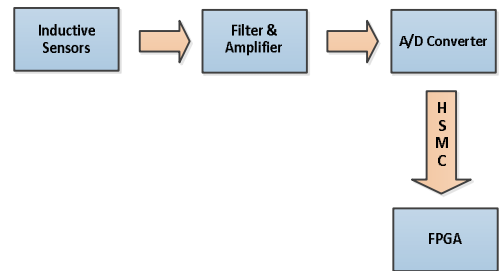

Figure 2. Hardware architecture of the monitoring system.

III. HIGH FREQUENDCY CURRENT TRANSFORMER (HFCT) DESIGN

High frequency current transformers are sensors with ferromagnetic cores so they have high sensitivity and high self-inductance and as a result, the output signals are proportional to the current at fairly low frequencies [10]. Ferrite materials have high permeability, high resistivity and low eddy current losses which make it favorable for high frequency currents applications. Four different ferrite materials were used to develop HFCT sensors at Tampere University of Technology (TUT) and compared with

commercial HFCT and a Rogowski coil with analogue integrator developed earlier at TUT. Novel HFCTs were constructed using toroidal ferrite cores. Different winding configurations, such as four, nine and twenty turns using enameled wire of diameter 0.19 mm were wound on each ferrite core. The windings were spread evenly around the core because this geometry helps reducing the leakage current. Experiments were performed using solid ferrite cores as well as split ferrite cores with different air gaps size to study the performance of each material. A detailed discussion about the design and construction of HFCTs, measurements to characterize and compare different HFCT construction and the effect of core material, winding configuration and air gaps size on the amplitude response, transfer impedance and saturation characteristics can be found in [11]. Following section briefly explains only about the ferrite material M1 which is the best among other ferrite cores.

Fig. 3 shows the amplitude responses of closed core sensor M1 with different winding configurations. Amplitude response of sensor M1 with 4 and 6 turns winding configurations are not flat over higher frequencies as with other configurations but their sensitivity is still better. Amplitude response with 14 and 20 turns winding configuration have bit similar flat response over wide frequency range until their sensitivity start to increase 3 dB to 4 dB, respectively then drops and finally resonance frequencies are reached. In comparison, 9 turns winding configuration has flat amplitude response over wide frequency range. Moreover they also exhibit good overall sensitivity and low resonance peaks. It can be concluded from the curves that the sensitivity and the lower cut-off frequency decreases with increasing number of turns. A good sensor should have high enough sensitivity and flat frequency response over wide usable bandwidth. Hence, sensor M1 with 9 turns winding configuration seems to be the best choice.
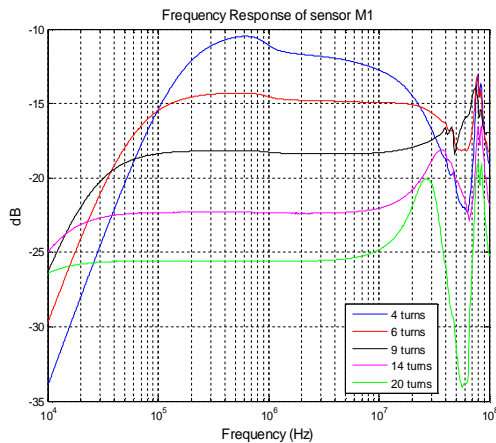

Figure 3.   Amplitude response of sensor M1 with different winding configurations.

The problem with the closed core HFCTs is the core material saturation. Another problem is that they require outage before routing the cable to be measured through the solid core. Split core HFCTs solves these issues on account of transfer impedance and frequency response but it does improve the saturation property. Air gaps tune the permeability of the ferrite core so that saturation takes place for a higher current [12]. Hence, it's a trade-off among frequency response, transfer impedance and saturation current.

In Fig. 4, the performance of all designed sensors (M1…M4) is compared with the commercial HFCT and the Rogowski coil. The commercial HFCT has an air gap of 0.25 mm, whereas the Rogowski has an air core. All developed sensors have split core with 9 turns and 0.3 mm air gap. With reference to Fig. 4, amplitude response of sensor M1 extends up to 45 MHz when compared to developed sensors, commercial HFCT and the Rogowski coil. The commercial HFCT has the lowest -3 dB cut-off frequency and the amplitude response is flat only up to 15 MHz. Moreover, its sensitivity is considerably lower than sensor M1 and M2 in the frequency range 90 kHz to 15 MHz. In comparison, the Rogowski has the lowest overall sensitivity and unstable amplitude response at higher frequencies. According to the detailed experiments and analysis performed in [11], it can be stated that sensor M1 is the best candidate because of its flat frequency response between 130 kHz to 45 MHz, transfer impedance which is 1.7 times more sensitive than the commercial HFCT and high saturation current of 100 A.
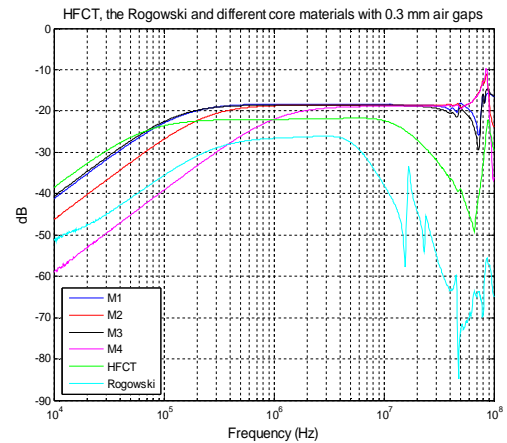

Figure 4.   Comparison of the amplitude response among different sensors.

IV.   FILTER & AMPLIFIER DESIGN

This section explains about the design and development of filter & amplifier unit. Simplified block diagram of the design which has low-pass filter, two separate high-pass filters and an amplifier is depicted in Fig. 5. The low-pass limit is 1 MHz, whereas high-pass limits are 10 kHz and 200 kHz, respectively. This gives a pretty good range to detect PD signals. The main component of the device is operational amplifier (op-amps) made by Texas Instruments. Switching between two filters is done by two jumpers. Sallen-Key topology is one of the two popular active filter structures. It is simple to design and requires only few components with reasonable values. The other topology is Multiple Feedback. Sallen-Key topology was used to design both low-pass and high-pass filters.
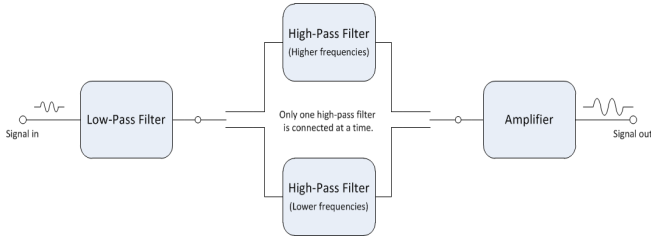
Figure 5.   Block diagram of filter & amplifier unit.

Frequency response of the filter was analyzed using network analyzer Agilent 4395A. An external voltage source was powering the op-amps directly in order to avoid DC voltage at the port of the analyzer. The S21-parameter is measured to characterize the performance of the filter over wide frequency range. Fig. 6 shows the frequency response of the filter & amplifier unit with lower high-pass limit and higher amplification in the passband region. It can be seen that the frequency response is quite smooth in the frequency range between 10 kHz to 1 MHz and an amplification of 17 dB is achieved.
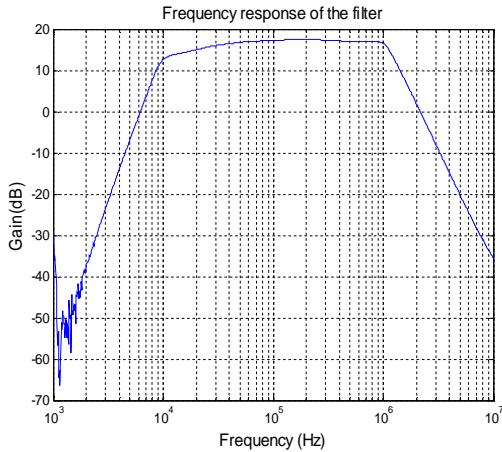

Figure 6.   Frequency response with lower high-pass limit and high gain.

Another important point was to find out how actual PD signal looks like after passing through the device. PD calibrator pulse of 1000 pC is fed through the sensor to the filter input via coaxial cable and the response is measured with the oscilloscope. Fig. 7 presents the input PD pulse and output pulses with lower and higher high-pass cut-off frequencies. It can be observed that the difference in shapes of the frequency responses does not change the shape of the PD pulse significantly. In addition, increasing the lower cut-off frequency increases the oscillation of the PD pulse. Thus, lower cut-off frequency range is better for detecting PD pulses.

One main reason to build this device separately from the measuring unit is the fact that the signal could be filtered and amplified in an early stage close to the sensors so that noises coupled to the sensor cables do not decrease the SNR too much. This unit is light and will fit anywhere but it is recommended to position it as near the PD sensor as possible. Finally, the filter & amplifier unit is assembled inside a

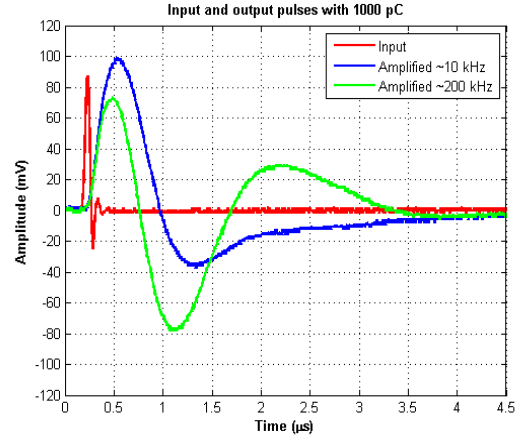painted aluminum case shown in Fig. 9. Two SMA connectors for input and output are also visible.

Figure 7.   PD pulse before and after filtering and amplifying.

V.   FPGA-LVDS INTERFACE

The preferred output for most high speed ADCs especially multichannel ADCs operating at tens of megahertz to hundreds of megahertz is serialized LVDS. The differential signaling protocol of LVDS pair offers common-mode noise rejection and enables higher data transmission. A typical serialized LVDS interface for one channel ADC operating on a sampling clock frequency (f_s) is shown in Fig. 8. ADC data are output serially from D0 to DN-1 at every sampling clock cycle. N is the number of bits. The output data rate is f_s x N. A bit clock (LCLK) is operating at a frequency of (f_s x N/2) because it latches the serial data on positive and negative edges of the bit clock. It is also referred as double data rate bit clock. A frame clock (ADCLK) is used with a frequency of f_s to correctly output the parallel data after de-serialization.
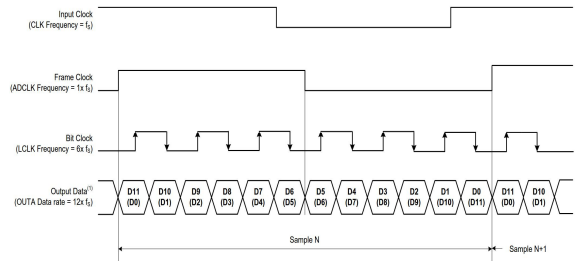

Figure 8.   A typical serialized LVDS interface [13].

Most FPGAs have a double data rate (DDR) flip-flop and register as part of the logic library which can be used to capture data from a serial LVDS interface. The simplest scheme to capture serial LVDS data consists of a DDR logic block followed by a serial-to-parallel shift register [13]. The length of the shift register chain for rising and falling edge data must be at least (N/2) flip-flops. The DDR block captures the ADC data at both edges of the bit clock and outputs two data streams, one at the rising edge and other at the falling edge of the bit clock. The rising and falling edge data are then applied to the respective shift registers. Each channel has two

shift registers. At every rising edge of the frame clock, the parallel data from both shift register chains are latched. Next is data generation block to re-arrange the 12-bits data in the correct order.

VI. PROTOTYPE OF THE MONITORING SYSTEM

The complete chain of the monitoring system is portrayed in Fig. 9. An 8 channel, 12-bits, 65 MHz ADC is interfaced with high speed FPGA via HSMC connector. HFCT sensor M1 can be seen in the chain on the left side with the cable under test to measure the PD signal inductively via the filter & amplifier unit powered by a 10 V battery. The ADC board is powered via banana connectors using a single 5-V power supply which by default uses a power management solution to supply the ADC the analog and digital power supplies. A 100 MHz synthesized arbitrary waveform generator is used to clock the ADC.
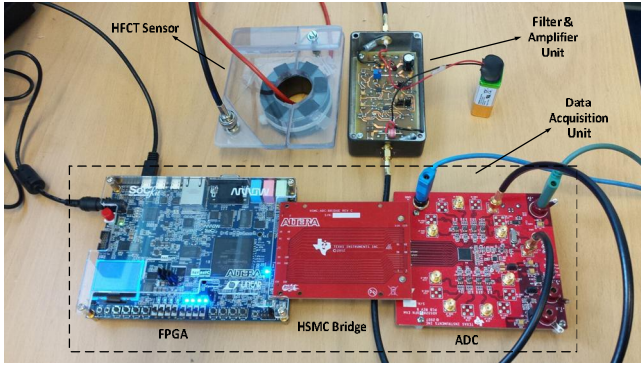

Figure 9. Prototype of the monitoring system.

VII. RESOLUTION AND SIGNAL-TO-NOISE RATIO OF THE MONITORING SYSTEM

The dynamic range requirement for PD signals is quite high because the variation in pulse magnitude is large and it is necessary to be able to measure correctly both high amplitude pulses originating from discharges close to the sensor and reflections or discharges travelling far from the sensor. Many general purpose measuring system for example, digital storage oscilloscope use 8-bits ADC which is insufficient to record the correct shape of the PD pulse. Fig. 10 shows the comparison of the PD calibrator pulse of 10 000 pC captured by monitoring system and an 8-bit oscilloscope. It can be noticed from the figure that the pulse measured by monitoring system is quite smooth compared to oscilloscope because 12-bits has 4096 quantization levels (Q levels), whereas 8-bits has only 256 Q levels.

Another important factor to be considered while designing the monitoring system is signal-to-noise ratio which limits the smallest measurement that can be taken with certainty since any measured amplitude less than the noise floor will be considered as noise. A comparison between an 8-bit oscilloscope and monitoring system is also made to show the sensitivity of both systems. A PD calibrator pulse of 10 000 pC is measured using both systems to calculate the SNR. PD is a sharp pulse having time duration of less than 1 µs, therefore a small portion of the data which has PD pulse and

the same portion of the noise is used to compute the SNR. The SNR is calculated using the following equation.

$$SNR(dB) = 20\log 10(Signal\ Vrms/Noise\ Vrms) \qquad (1)$$

The monitoring system has SNR of 38 dB, whereas oscilloscope has SNR of 12 dB. Thus, the monitoring system reduces the quantization noise up to 26 dB compared to the oscilloscope which clearly expresses the better sensitivity of the monitoring system.
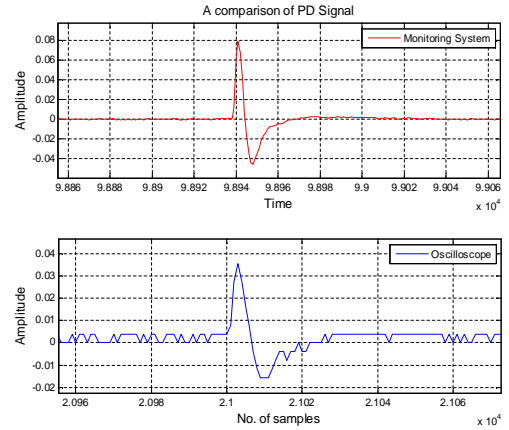

Figure 10. PD pulse captured by monitoring system and oscilloscope.

VIII. LABORATORY TEST AND ANALYSIS

To verify the effectivity of the monitoring system, laboratory measurements are carried out using the real PD data captured from on-site measurement. The order of the monitoring system is as follows: HFCT sensor, filter & amplifier unit, LVDS ADC and high speed FPGA. The block diagram of the laboratory system setup is shown in Fig. 11. ADC is powered by a 5 V supply and a clock generator is used to clock the ADC.
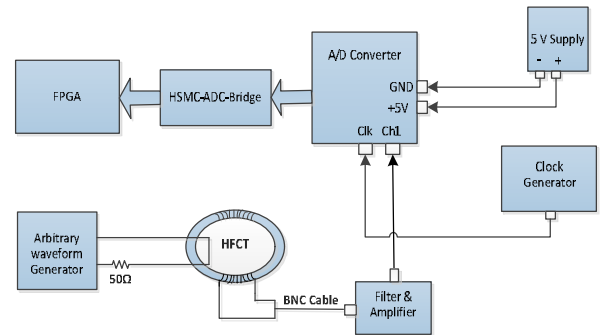
Figure 11. Laboratory setup of the monitoring system.

A real PD data captured earlier by measuring a 20 kV line is injected through the cable using 100MS/s arbitrary waveform generator and terminated at 50 ohms. The HFCT sensor M1 is placed around the cable to measure the signal inductively. The filter & amplifier unit is used before the actual sampling to reduce the quantity of noise and to amplify the signal of interest. In the end, ADC is digitizing the input signal for further processing. The real PD data sensed directly

by HFCT sensor M1 and captured by the monitoring system and the oscilloscope is shown in Fig. 12. The monitoring system has captured all PD pulses quite accurately.

Figure 12. Real PD signal captured by monitoring system and oscilloscope.
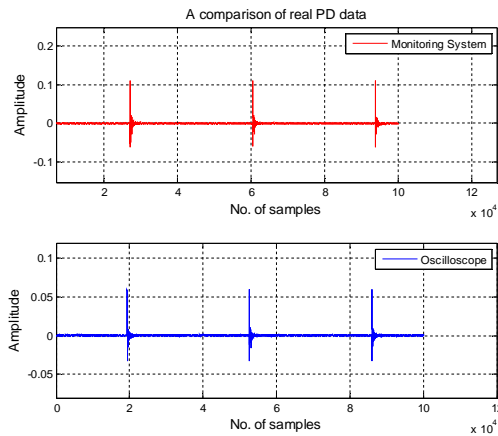
Frequency-domain analysis is another important criterion in PD signal analysis which features frequency distribution of the PD pulses. A comparison of the frequency spectrum of the signal measured by both systems is shown in Fig. 13. It is noticeable that spectrum of both systems are quite alike. Monitoring system has captured high frequency components extending up to 1 MHz which is the higher cut-off (low-pass) frequency of the filter and it already gives quite good frequency range for detecting PD signals.
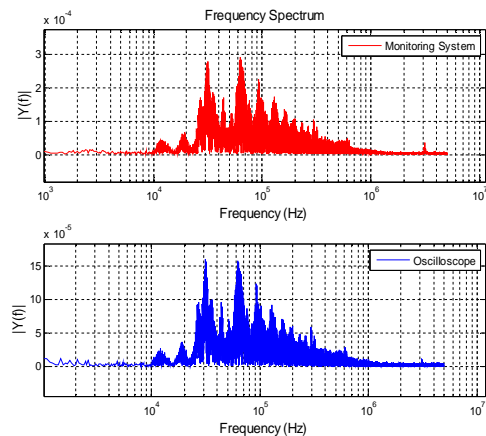

Figure 13. Frequency spectrum of the real PD signal measured by both systems.

IX. CONCLUSION

To meet the demand of continuous on-line PD monitoring, this paper puts forward a versatile and cost-effective solution which can be installed permanently to monitor MV cables at secondary substation. The cost of the system including HFCT sensors, filter & amplifier unit and data processing unit is quite low compared to the commercial monitoring systems available in the market.

Through measurements it is verified that the monitoring system has better SNR compared to an 8-bit oscilloscope. Laboratory measurements using time-domain and frequency-domain analysis have demonstrated that the monitoring system has captured PD calibrator pulse as well as real PD pulses quite accurately. Hence, the monitoring system can be installed permanently at secondary substation to monitor MV cables carrying current up to 100A over the frequency range of 130 kHz to 45 MHz.

In future smart grids, condition monitoring plays an increasingly important role in order to minimize unplanned outages and avoid major repair costs. The proposed system has 8 channels which extend the possibility of developing the system further in future to add power quality monitoring at LV side. The monitoring system can easily be used as a research platform to develop new applications and analysis methods for condition monitoring to be used at secondary substation.

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Publication V

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A Novel Concept of Secondary Substation Monitoring: Possibilities and Challenges

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Abstract—**Smart Grid concept substantially increases the measurement need in the future for efficient and flexible power delivery. Distribution network monitoring has been traditionally focused on primary substation (i.e., high voltage/medium voltage), whereas least attention has been given to secondary substation (i.e., medium voltage/low voltage). Distribution network operators are facing considerable network investments in the near future due to the renewal of aging cable networks in cities and renewal or replacement of overhead lines by underground cables in rural areas. To focus on the network renewals at the correct places to decrease the occurrence and duration of unplanned power interruptions and to maintain good power quality despite the proliferation of e.g. distributed generation and electronic loads, the need for proactive network monitoring is ever increasing. Secondary substation is an ideal location for data acquisition because both MV and LV network can be monitored. This paper proposes a novel cost-effective secondary substation monitoring concept for smart grids which can be installed permanently at secondary substation for partial discharge (PD) monitoring, power quality (PQ) monitoring and disturbance recording. No sensors having expensive high voltage insulations are needed, which makes the solution cost-effective and reliable.**

Index Terms—**secondary substation; proactive network monitoring; partial discharge; power quality; disturbance recording; harmonics; inductive sensor; ADC; FPGA**

I. INTRODUCTION

In distribution networks, measurement data from primary substation (typically 110 / 20kV) is already available. Due to the introduction of AMR meters, data will also be available from each low voltage customer. However, secondary substations (20 / 0.4 kV) seldom have any remotely readable measurement systems. As underground cables in cities are aging and cabling of medium voltage networks is also increasing in rural areas, condition monitoring is becoming an important measure in preventing unplanned and long lasting outages. Secondary substation measurements would be extremely useful both in MV and LV network fault location and in giving early warnings of incipient faults.

On-line partial discharge monitoring of secondary substation is an excellent way to determine the overall health of MV components and detect developing faults in underground cables. The penetration of photovoltaic (PV) inverters [1] and distributed energy resources (DERs) [2] in general along with electrical vehicle (EV) chargers, heat pumps and other devices with power electronic network interface increases the challenges related to voltage and harmonic levels in LV networks. In addition, demand for the high quality power and strict compliance requirement from regulatory authorities increases the need for a multifunction secondary substation monitor such as the one presented in this paper. It is an essential part of developing the future distribution network automation.

Traditionally, distribution automation outside primary substation has been mainly applied for different kind of fault management applications. In case of overhead line networks this is natural because the fault caused e.g. by storms is quite common and there has been a need for fast fault isolation and restoration. In addition to fault management, there is a need and possibilities for new applications, such as power quality monitoring [3,4] and condition monitoring [5]. The commercial applications currently available for secondary substation monitoring are limited to frequency range below 2 kHz and the condition monitoring information obtainable is usually relatively simple alarms (door open, vibration, flood). Continuous on-line PD monitoring of secondary substations has not been economically possible because of the high costs of the equipment and resources needed [6].

This paper describes the development of a novel monitoring concept for secondary substation which includes low-cost inductive sensors and resistive dividers and a versatile multichannel data acquisition unit. In addition, it also describes what monitoring functions can be incorporated into the novel monitoring device and how data can be utilized to analyze the electrical network during normal operation and different disturbance events.

II. State of the Art in Distribution Network Monitoring

There are already some commercially available secondary substation monitoring/control units and systems [3,4] which are capable of monitoring some or all of the quantities listed below:

- voltage levels (10 minute average)
- voltage sags and swells
- phase currents
- hourly averages of active power
- hourly averages of reactive power
- total harmonic distortion (2…15 harmonic)
- disturbance recording
- temperature (e.g. transformer)

Usually, these monitoring units are measuring the voltages and currents at the secondary side of the transformer due to the high cost and space requirements of MV instrument transformers. Due to the relatively low sampling rate (some kHz) of the available monitoring devices, they are not capable of measuring partial discharges, rapid voltage changes, transients or other higher frequency problems, which could be useful in case of studying, for example, customer complaints or claims. Additionally, or as the main functionality, currently available secondary substation monitors may have remotely readable/controllable I/O:s for various alarms (door, vibration, flood, transformer proximity) and controls (e.g. remote control of disconnector) [5].

Smart meters are becoming more common at the customer end of distribution networks. In Finland, they were installed at practically all customers by the end of 2013, which considerably improves the possibilities of monitoring and estimating the network state (e.g. hourly active power). Many of the meters also provide some kind of information on simple power quality quantities such as voltage levels. There is, however, a large variation in the implementation of these functionalities and the measuring and recording principles. Usually, it is possible to get only 10 minute average values of the voltages (often as a statistical distribution, not a time series) and 1 hour values of the active power. Also reactive power is measured by the meters, but usually it is read to the central system only from meters located at large customers. Measurement data with a higher time resolution and more extensive set of monitored quantities from locations along the MV feeders would give a much better understanding of the network status.

Fault location, isolation and supply restoration is currently based mainly on information available from the protective relays located at primary substations. Some companies may have remotely readable secondary substation monitors mentioned earlier in this chapter, which may be used in fault location, but this is quite rare.

Partial discharge monitoring is one of the most versatile methods of monitoring the condition of high voltage insulations. There are commercially available devices from several manufacturers for PD monitoring of underground cables for instance, but those capable of continuous on-line

monitoring are still relatively expensive and as such, more suited for primary substation monitoring [7,8,9]. Periodic on-line monitoring, on the other hand, often fails to detect rapidly developing faults. Currently, there are no low cost devices suitable for continuous on-line PD monitoring of secondary substations.

III. Secondary Substation Monitoring Functions

The secondary substation monitoring concept proposed in this paper combines measuring functions for PQ, PD and disturbance recording/fault location into a single unit. The concept has several advantages compared to a separate PD and PQ/disturbance recording systems. A monitoring system having only a few sensors and one measuring unit is less complicated, easier to install and maintain and has lower hardware costs compared to a system having separate sensors and units for each monitoring function. Also electromagnetic compatibility aspects related to cabling, shielding and power supplies are easier to manage in a single device which helps in achieving a good sensitivity for PD monitoring.

Table 1 shows a list of the MV and LV quantities monitored by the novel secondary substation monitor. The functions marked with (x) may or may not be implemented depending on the characteristics of the sensors used and whether they enable the measurement of the related frequency range. I_L, U_L, I_0 and I_n refer to MV phase currents, LV phase voltages, MV zero sequence (residual) current and LV neutral current, respectively.

TABLE I. List of Monitored Quantities at LV and MV Side of Secondary Substation

Quantity	Frequency range		Monitoring function		Channels used		
MV-side	HF	LF	Primary	Secondary	PD	PQ	DR
I_{L1}	x	x	PD detection and location	LF: 50 Hz current, current harmonics, transformer loading, cable loading	x	x	x
I_{L2}	x	x			x	x	x
I_{L3}	x	x			x	x	x
I_0		x	MV fault location				x
LV side							
U_{L1}	(x)	x	LV Voltage quality, harmonics, disturbance recording	50 Hz voltage reference for PD measurements, HF: PLC/HF interference, transients, MV phase-to-phase voltage estimation, detection of broken MV phase conductor, LV faulty phase detection, fault type assesment	x	x	x
U_{L2}	(x)	x			(x)	x	x
U_{L3}	(x)	x			(x)	x	x
I_n		x	LV earth fault location estimation	Neutral conductor loading, neutral conductor fault		(x)	x

HF: frequency range at least 10 kHz…2 MHz

LF: frequency range at least 50 Hz…2.5 kHz

(x): optional (needed for some additional/secondary function in PQ analysis)

x: essential

The preferred sensor locations for the secondary substation monitor are presented in Fig. 1. The high frequency current transformer (HFCT) sensor used for partial discharge and MV PQ measurement can be installed either at the cables (or

bushings) connecting the MV busbar to the transformer or to the incoming cables of the secondary substation. The former installation location is useful for monitoring the loading and estimating the hot-spot temperature of the transformer, the latter is optional for monitoring the loading of the incoming cable and estimating its temperature and temperature variations. Depending on the other measurements in the network (e.g. other secondary substations) it may be possible to estimate other quantities mathematically based on sensors only in one of these locations.
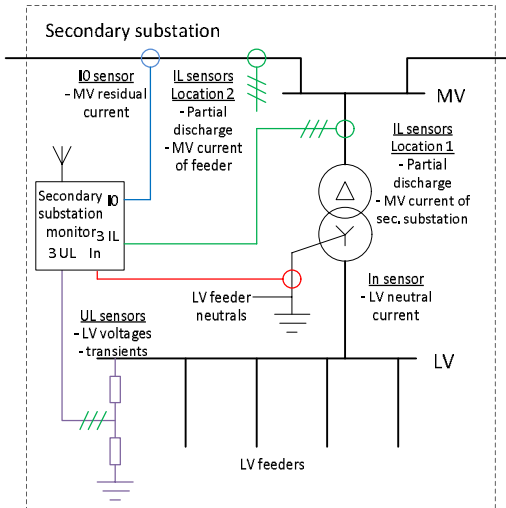

Fig. 1. Proposed MV and LV sensor locations for the novel secondary substation monitor.

A. Partial discharge measurement

In underground cable networks, PD measurement is a useful tool in detecting incipient faults on cable terminations and joints. It may also reveal aging and defects caused by mechanical or thermal stresses on the cable itself. Due to the practical reasons and cost of the continuous on-line PD monitoring systems, conventionally they have been installed at primary substations [10]. However, there are several reasons favoring the installation of PD monitoring at secondary substations, such as lower disturbance level and better possibilities for automatic PD location (fewer feeders). Additionally, due to the communication infrastructure needed for smart grid remote control functionalities at secondary substations and the decreasing prices of measurement technology, installation of PD monitoring equipment at secondary substations is becoming an economically feasible alternative. In the secondary substation monitor, partial discharge measurement is planned to be implemented using HFCT sensors developed by the authors [19] in locations indicated earlier in Fig. 1.

On-site measurements [11] at secondary substations have indicated that PD measurement with sensors installed at the earth strap of the cable termination is more susceptible to interference signals and cross coupling of signals between phases. The preferred installation location at the phase conductor also allows the measurement of primary 50 Hz current and harmonic currents to estimate the thermal loading of the transformer or incoming cable. If installation to the

phase conductor is not feasible due to the secondary substation construction, the sensors may be installed at the earth strap, but the PD data analysis becomes more complicated due to additional interference and at the same time, the possibility for MV current and power quality monitoring is lost.

B. Power Quality Measurements

Power quality measurement is becoming more important due to changing loads and the proliferation of distributed energy resources. Power quality monitoring on secondary substations would allow better estimation of the hosting capacity of the network considering DERs [12] and potential power quality problems could be predicted and managed before they cause customer complaints or other problems. Information about the voltage levels and PQ at the secondary substations would also be useful in exceptional network operating conditions.

Power quality measurement is planned to be implemented primarily at the low voltage side of the secondary substation using resistive dividers at all three phases. This sensor implementation places the emphasis on the traditional voltage quality phenomena at frequency range below 2.5 kHz defined in [13] but also makes it possible to measure high frequency (HF) transients and disturbances up to a few MHz if the disturbance voltages are high enough to be detected by the A/D converter (ADC). The voltage signal of at least one phase is used to synchronize the PD data with the MV phase voltages.

Neutral conductor current (I_n) measurement can be used to monitor the loading of the neutral conductor, which is important especially if the load current includes a considerable amount of triplen harmonics. Triplen harmonics sum up from all three phases in phase to the neutral conductor and thus, may cause overloading of the neutral conductor and junctions. Neutral current measurement can be used also for triggering disturbance recording and detecting loose contacts in neutral conductor or verifying neutral conductor faults together with phase voltage measurements. Neutral conductor faults may cause serious over voltages and electrical shock risk at customers.

The HFCT sensors used mainly for PD measurements also allow load current and PQ measurements at the MV side at frequency range below 2.5 kHz as described later in chapter IV. Monitoring the load currents, peak demand and harmonics on secondary substations are useful for planning future network investments and e.g. transformer maintenance. Especially, on feeders with industrial customers or high penetration of DER information about the harmonic current injection at secondary substations would be useful in locating potential causes of power quality problems, assessing the transformer loading and aging [2,14] and the compliance with recommendations given e.g. in IEEE 519 or IEC 61000-3-6 [15,16].

C. Disturbance Recordings

Disturbance recording is planned to be implemented both at the low voltage and medium voltage sides of the secondary substation. The disturbance recording can be triggered based

on the following momentary value or rms criteria or both:
- · I_0 above a predefined upper limit
- · I_n above a predefined upper limit
- · $U_{L1}...U_{L3}$ above a predefined upper limit or rms below a predefined lower limit

As one of the triggering conditions is fulfilled, a predefined number of cycles of the waveform data before and after the triggering moment will be recorded from each of the 8 channels for analysis.

Based on the LV phase-to-neutral voltages, it is possible to estimate MV phase-to-phase voltages. These can be used, for example, to detect a broken MV conductor which may present a life hazard especially on covered conductor and bare overhead lines if it remains undetected. In such a fault, two of the MV phase-to-phase voltages decrease to approximately half of the nominal value and one remains at the nominal value.

The MV residual current I_0 criterion is used to capture waveforms related to earth fault events in the MV network. An earth fault in a medium voltage feeder causes the residual current to increase in the feeder upstream from the fault and based on the data captured at the secondary substations at a high sampling rate, it is possible to locate between which secondary substations the fault has occurred. The principle is similar to the fault passage indicators reported e.g. in [3,17]. This helps in decreasing the duration of interruptions by enabling quicker fault location, isolation and supply restoration.

The LV neutral current I_n criterion is used to capture low voltage network earth faults. Based on the neutral conductor current and phase-to-neutral voltage recordings and network information it may be possible to estimate the fault location and to detect the faulty phase(s).

IV.   SENSOR SOLUTIONS

The secondary substation monitor has a total of eight channels i.e., four on the MV network side and four on the LV network side. The sensors used to measure these quantities have a considerable effect on the cost, accuracy and reliability of the system.

A.   Partial discharge and MV currents

HFCT sensors developed earlier by the authors were selected for the MV current measurement mainly due to their high sensitivity (transfer impedance) in the PD frequency range, flat amplitude response and high saturation current as well as robust construction [18]. One HFCT sensor in each phase is used to measure partial discharges occurring at the secondary substation and on the feeder connected to it. Power frequency current measurement enables power quality monitoring at the MV side and it is also useful in estimating the thermal loading of the transformer and/or the incoming cable. This information can be utilized in interpreting the PD measurement results, since partial discharges are often temperature dependent.

The HFCT sensors developed at TUT [18] have strongly frequency dependent amplitude response at frequencies outside their passbands. Below the passband the sensitivity decreases approximately 20dB/decade as illustrated in Fig. 2.
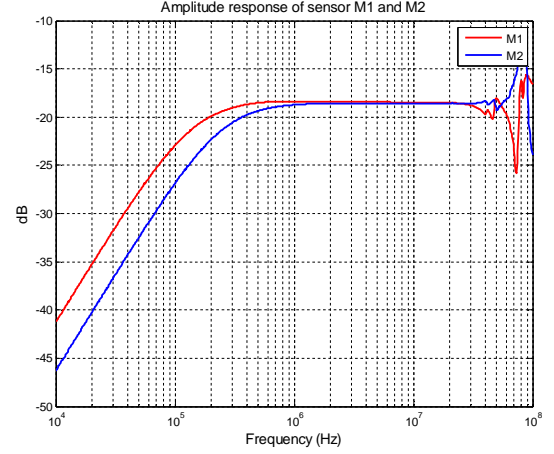

Fig. 2. Amplitude response of sensors M1 an M2 developed at TUT at frequency range 10 kHz…100MHz.

Thus, at low frequencies the frequency response of the HFCT sensor is similar to a Rogowski sensor. By integrating the output voltage waveform of the sensor according to equation (1), it is possible to extract the 50 Hz and harmonic current information from the PD signal.

$$i(t) = i(0) - \frac{1}{M} \int_0^t u(t)dt \qquad (1)$$

where u(t) is the output of the sensor, M is the mutual coupling between the primary conductor and the sensor winding and i(t) is the current in the primary conductor [20].

The HFCT sensor design has been optimized so that in addition to PD measurement, it allows power quality measurement at frequency range below 2.5 kHz at the MV side which is a novel approach compared to standard sensor solutions. Fig. 3 illustrates the output of 0.2A 50 Hz current measured by reference shunt and sensor M1 with 9 turns winding configuration. It is clearly visible that even a low primary current of 0.2A at 50 Hz revealed by sensor M1 after numerical integration is identical to the shunt measurement.

The sensor has shown adequate performance for PQ measurements compared to commercial power quality monitors in terms of relative amplitude error and phase angle error. The phase angle error is less than 0.7 degrees at primary current 0.2 A…10A at frequency range 50 Hz…350 Hz (7th harmonics) which is quite good compared to commercial PQ monitors where the range varies 1 degree to 3 degrees. The overall relative amplitude error is less than 3 % at primary current 0.2 A…10 A at frequency range 50 Hz…2500 Hz (50th harmonics) which provides nearly the same or better accuracy than commercial power quality monitors. Detailed analysis about the potential of the HFCT sensor dealing with PQ measurements can be found in [19].
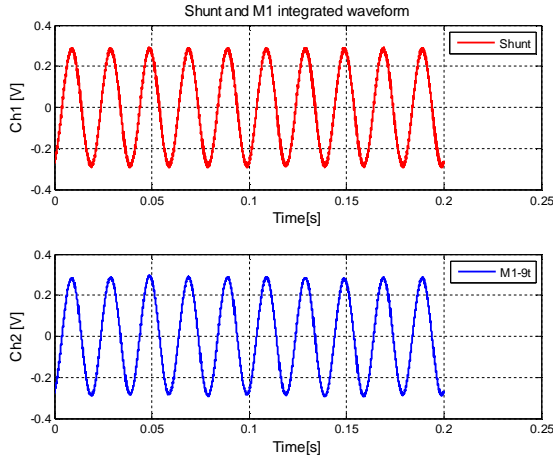
Fig. 3. 50 Hz current measured by shunt and sensor M1.

B. MV residual current and LV neutral current

The residual current I_0 measurement at the MV side will be implemented using a cable type current transformer. Theoretically, it would be possible to calculate the residual current also based on the MV phase currents, but since the same sensors are used for partial discharge measurement and the signal scaling to ADC is made primarily based on the PD signal level, the result would be less accurate than the one obtained with a separate 50 Hz cable type current transformer. I_0 will be used for disturbance recording and MV network fault location as described earlier in chapter III.

The neutral current measurement I_n at the low voltage side of the secondary substation will be implemented using a LV current transformer at the neutral conductor between the transformer and LV switchgear.

V. MONITORING SYSTEM ARCHITECTURE

Real-time system measuring and recording high frequency phenomena requires high sampling frequency and data processing capacity. FPGA is a promising choice due to low-cost, high speed and great performance. The novel idea of combining different monitoring functions into a single unit is driven by previous research done by authors dealing with PLC and PD monitoring systems, respectively [21,22].

Fig. 4 depicts the general architecture of the novel secondary substation monitor. A front end of the system should have a wide frequency bandwidth and high enough dynamic range to handle both PD and PQ data. An 8-channel, 12-bits 65 MHz ADC with a serialized LVDS interface has been used for the measurement unit. Multichannel ADC enables various measurements at LV and MV side of the transformer.

Voltage measurements and current measurements are implemented using resistive divider and HFCT sensors at LV and MV side of the transformer, respectively. A filter & amplifier unit is used to attenuate unwanted signals and amplify signals of interest.

Signal processing block processes the sampled data to extract the information related to the PD and PQ phenomena and disturbances in the network. PD can be monitored using trend analysis or frequency spectrum analysis. PD occurs over the course of time so continuous monitoring of PD activity over long periods and the analysis of trend is desirable. In order to monitor power quality, it is essential to measure RMS voltage and current, frequency, harmonic distortion and waveform. Disturbance recording module can be triggered by RMS over or under voltage or high LV side current (I_n) or MV side current(I_0).

A local database will be used to store bulk data, such as PD and disturbance records from each secondary substation monitor. A centralized database will be used to collect preprocessed data from the substation monitors around the network. Communication between the local database and centralized database can be implemented using 3G/4G modem with TCP/IP protocol. It may also be modified to interact with an IEC 61850 based substation automation system.

The centralized database will act as a high level database to monitor the overall health of the network and to analyze phenomena where it is beneficial to have information from various locations in the network, such as fault and partial discharge location.
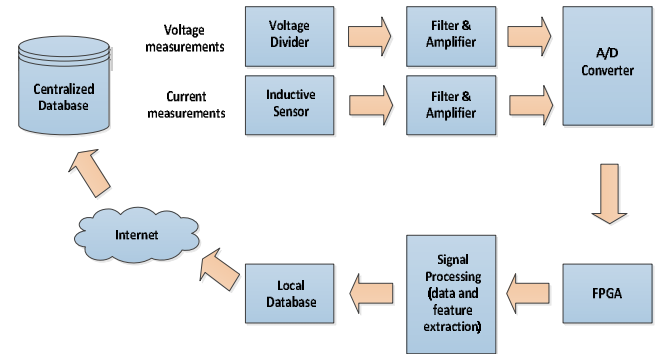

Fig. 4. General architecture of the novel secondary substation monitor.

VI. DESIGN CHALLENGES

This chapter focuses on the design challenges when combining several functionalities in a single unit. The dynamic range requirements are high especially in PQ and PD measurements. A compromise has to be made between the dynamic range of the PD measurement and the accuracy of the power quality measurement, since the same A/D converter is used to measure both phenomena and both the PD and PQ information are extracted from the same sampled signals with different signal processing method.

However, the high sampling rate used due to the needs of PD monitoring can be used to achieve extra bits of resolution for low frequency PQ monitoring also at the MV side current measurements. In PQ measurements relatively low level harmonic components need to be extracted from the voltage or current where the power frequency component is dominating. Dedicated PQ analyzers usually have 16-bit A/D converters but in this case a 12-bit ADC has been selected to

achieve a high enough sampling rate for PD measurements. The lower resolution may be compensated by the high oversampling ratio achievable with the high speed ADC in the frequency range of PQ measurements. For example, a 12-bit ADC already at a sampling rate of 1.28 MHz yields an effective resolution of 16 bits at frequencies below 2.5 kHz [23].

In PQ measurements it is also important to have a high frequency resolution on a relatively narrow frequency band i.e. <3 kHz to determine accurately enough the 50 Hz harmonics. Thus it is practical to down sample the signal to make the PQ data processing more efficient. The original sampling frequency of the secondary substation monitor also has to be adjusted so that it enables accurate calculations of the 50 Hz voltage or current and its harmonic components.

In partial discharge measurements it is usually necessary to use several different amplification steps to scale the incoming signal to the ADC input voltage range according to the partial discharge level. The scaling obviously has an effect on the accuracy of the simultaneous PQ measurement on the MV side, which has to be taken into account. On the other hand, a detected high partial discharge level which is an abnormal situation, naturally moves the focus of monitoring to the PD phenomenon and PQ monitoring becoming a secondary (less accurate) objective is not necessarily a problem.

In PD measurements, the variation in pulse magnitude is large and it is necessary to be able to correctly measure both high amplitude pulses originating from discharges close to the sensor and reflections or discharges travelling far from the sensor. The selected 12-bit A/D converter provides an excellent dynamic range for PD measurements, provided that the low frequency current signals in the PD channel are optimized to an adequately low level according to the expected load currents. In PD analysis it is also important to process a wide frequency band in a shorter time. Thus, the optimization of the frequency domain analysis and filtering algorithms is important.

VII. CONCLUSION

In future smart grids, secondary substation monitoring plays a vital role in improving the power grid reliability and flexibility. Along with the communication infrastructure, it lays the foundation on which various monitoring, control and network automation applications can be built. The secondary substation monitoring concept presented in this paper uses FPGA based-data acquisition & processing unit which uses resistive dividers and high frequency current transformer sensors for measuring different quantities at LV and MV side of the secondary substation.

The proposed secondary substation monitoring concept would fundamentally improve the possibilities of predicting and preventing component failures at secondary substations and connected feeders. Information on the voltage level and quality at secondary substations would be useful in network operation (e.g. to increase the hosting capacity of DG) and network planning.

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Publication VI

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FIELD TESTING OF A WIDEBAND MONITORING CONCEPT AT MV SIDE OF SECONDARY SUBSTATION

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ABSTRACT

Smart grid concept substantially increases the need of monitoring devices in the future for efficient and flexible power delivery. Secondary substation is an ideal location for monitoring both LV and MV networks which can be used to improve the power grid resilience. This paper presents the key features and practical experience gained from the deployment of novel wideband high frequency current transformer (HFCT) sensors for monitoring power quality (PQ) as well as partial discharges (PD) at MV side of the transformer. Additionally, a network simulation is carried out using real-time digital simulator (RTDS) to test the possibility of detecting an earth fault cost-effectively at MV side of secondary substation.

INTRODUCTION

Distribution network operators are facing considerable network investments in the near future due to the renewal of aging cable networks in cities and renewal of existing underground cables or replacement of overhead lines by underground cables in rural areas. The proliferation of e.g. distributed generation and electronic loads poses new challenges to maintaining the power quality in distribution networks. To focus the network renewals at the correct places in order to decrease the occurrence and duration of unplanned power interruptions and to maintain good power quality proactive network monitoring is becoming essential. Secondary substation is an ideal location to gather large amount of data from LV and MV networks. Secondary substation monitoring would be extremely useful both in MV and LV network fault location and damage assessment and in giving early warnings of incipient faults.

This paper studies the potential of the wideband HFCT sensor which can be installed at MV side of the transformer for partial discharge (PD) monitoring, power quality (PQ) monitoring and disturbance recordings/fault location [1]. HFCT sensors lay the foundation of the novel cost-effective secondary substation monitoring concept presented earlier by the authors [2]. No sensors having expensive high voltage insulations are needed, which makes the solution cost-effective and reliable. In addition, a cost effective way of detecting phase-to-earth faults in the MV network using the HFCT sensors is demonstrated using the RTDS (Real-Time Digital Simulator).

MAIN FEATURES OF THE WIDEBAND MONITORING CONCEPT

Main features of the wideband monitoring concept are presented in Table 1. I_L, U_L, I_0 and I_n refer to MV phase currents, LV phase voltages, MV zero sequence (residual) current and LV neutral current, respectively. The architecture of the wideband monitoring system includes HFCT sensors for current measurements at MV side, resistive divider for voltage measurements at LV side and multichannel data acquisition unit for processing of the data as presented in [2]. However, this paper deals only with the MV-side quantities which depends heavily on the performance of the wideband HFCT sensors.

Table 1. List of monitored quantities at MV and LV side of secondary substation

Quantity	Frequency range		Monitoring function		Channels used		
MV-side	HF	LF	Primary	Secondary	PD	PQ	DR
I_{L1}	x	x	PD detection and location	LF: 50 Hz current, current harmonics, transformer loading, cable loading, MV faulty phase detection	x	x	x
I_{L2}	x	x			x	x	x
I_{L3}	x	x			x	x	x
I_0		x	MV fault location				x
LV-side							
U_{L1}	x	x	LV Voltage quality, harmonics, disturbance recording	PD 50 Hz voltage reference, HF: PLC/HF interference, transients, MV phase-to-phase voltages, LV faulty phase detection, fault type assessment	x	x	x
U_{L2}	x	x				x	x
U_{L3}	x	x				x	x
I_n		x	LV earth fault resistance and location estimation	Neutral conductor loading, neutral conductor fault		x	x

HF: frequency range 130 kHz…45 MHz

LF: frequency range 50 Hz…2.5 kHz

EARTH FAULT LOCATION IN MV NETWORK

An earth fault takes place when one or several phases come in contact with the ground. It is quite common in MV distribution networks where about half of the faults are single-phase earth faults [3]. Early detection of these faults are necessary in order to avoid long outage durations. When an earth fault occurs, initial transient always takes place which has higher amplitude than the steady state fault current and a residual current increase is observed. Traditional protection and control IEDs are unable to detect transients due to high sampling frequency requirements [4].

The principle presented in this paper uses RMS-based detection method. It uses HFCT sensors developed by the authors [1] to measure the three phase currents and the residual current (I_0). Such a detection scheme significantly reduces the component costs in the MV network since no voltage measurement is needed.

To describe the detection method, a radial distribution network simulation is performed in the RTDS environment. Figure 1 depicts the single line diagram of the network model used for earth fault detection. The modeled MV network is an isolated neutral network and it consists of four 10 km long underground cable feeders. M2…M4 shows measuring location of three phase currents using HFCT sensors at each secondary substation. M1 is located at MV substation. The fault is assumed to be located near the first secondary substation.
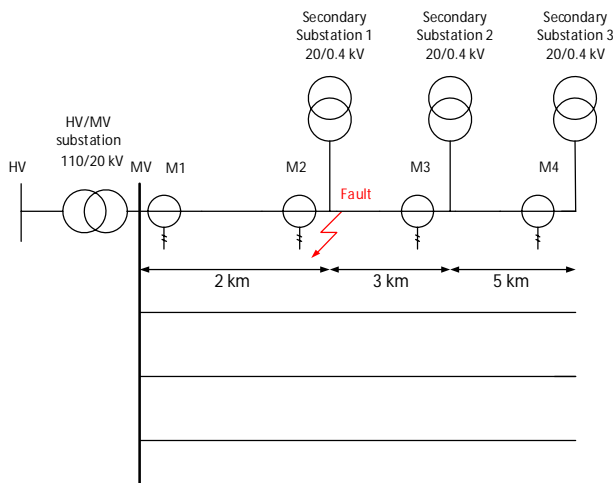

Figure 1. Network model used in RTDS simulation.

Fault is simulated in each phase of the feeder one by one and measured at different locations as indicated by M1...M4. Figure 2 illustrates the case where fault is simulated in phase L1 of the feeder and measured at M1.
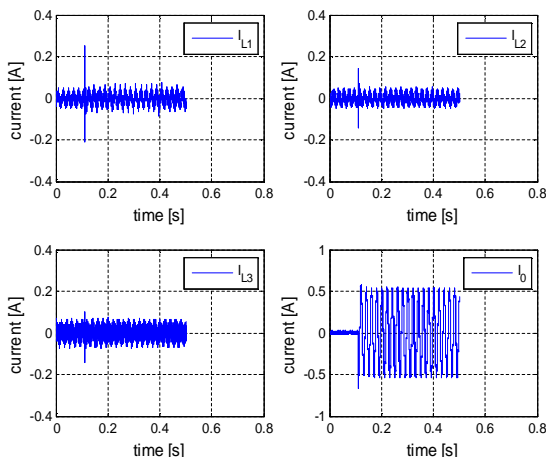

Figure 2. HFCT outputs (phase current derivatives) and residual current measured at M1 in case of fault at L1.

The initial transient phenomenon can be observed in all three phases. During the transient, current flows from one phase to another phase for compensating the change in the network [3]. However, the amplitude of the transient is higher in phase L1 due to the occurrence of the fault in the same phase. Furthermore, residual current (I_0) is increased considerably, which is another indication of the earth fault. High frequency noise observed in the phase current derivatives are mainly due to the power electronics of the amplifier and the fact that the HFCT output is a derivative of the phase current (high frequencies are amplified). Numerical integration of the HFCT outputs reduces the noise.

Figure 3 represents the integrated waveforms of the cases where faults occurred in all three phases and measured at M1. A change in the current amplitude of the faulty phase is clearly visible in all cases. A transient is observed in the healthy phases as well but they are quite stable. Due to the earth fault a part of the feeder current returns to the feeding substation via the earth, other feeders and their capacitances to earth which causes the residual current (I_0) of the feeder to increase.
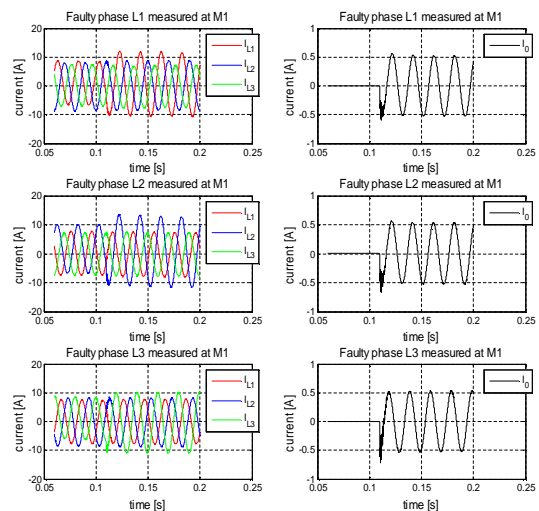

Figure 3. Integrated phase currents and residual currents measured at M1 in case of faults at different phases i.e. L1…L3.

Table 2 depicts detailed analysis of the RMS current of all phases before and after the earth fault measured at location M1. The residual current increases whenever there is a fault in any phase of the feeder. Additionally, RMS current of the respective faulty phase is increasing. Based on the RMS current of the individual feeder, faulty phase of the feeder can be easily identified.

Location of the fault can be estimated based on the proposed concept that the wideband monitor should be installed at each secondary substation [2]. As stated earlier, measurements are performed at different locations i.e. M1…M4 in order to detect the earth fault. For

location estimation, let's use the case with fault in phase L1 only and measurement results from all four locations.

Table 2. RMS current measured by HFCT sensors at M1 before and the after the fault

Fault at L1	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.59	5.93	5.17	0.0020
After fault	7.88	6.10	5.20	0.37
Fault at L2	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.37	5.19	5.17	0.0027
After fault	5.42	8.61	5.32	0.37
Fault at L3	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.38	5.92	5.60	0.0015
After fault	5.54	5.99	7.52	0.37

Table 3 shows the RMS current of the MV feeder with fault in the phase L1 only measured at all four locations. It is noticeable that M1 is located upstream from the fault so the change in the faulty phase current I_{L1} and I_0 is clearly visible. Since M2 is located upstream of the fault and very close to the fault location, a higher I_{L1} as well as I_0 can be witnessed. In contrast, measurement from M3 located downstream of the fault does not show significant change in the faulty phase I_{L1}, whereas I_0 has small change. Similarly, measurement from M4 neither exhibits any change in faulty phase I_{L1} nor the residual current I_0. Based on the higher RMS value measured at M2, it can be concluded that the fault is located close to secondary substation 1 upstream of the measurement.

Table 3. Faulty phase L1 currents measured by HFCT sensors before and the after the fault

Location M1	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.59	5.93	5.17	0.0020
After fault	7.88	6.10	5.20	0.37
Location M2	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.61	5.96	5.20	0.0027
After fault	7.91	6.10	5.22	0.40
Location M3	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.42	5.96	5.18	0.0016
After fault	5.24	6.12	5.21	0.10
Location M4	RMS currents [A]			
	I_{L1}	I_{L2}	I_{L3}	I_0
Before fault	5.48	6.02	5.24	0.0013
After fault	5.35	6.14	5.25	0.06

Cost-effective implementation of earth-fault detection is challenging. Due to the wideband nature of the HFCT sensor, earth fault detection is possible based on current measurements through retrofit install.

MV POWER QUALITY MONITORING

The HFCT sensors mainly developed for PD measurements also allow PQ measurement at frequency range below 2.5 kHz at the MV side of the secondary substation. Monitoring the load currents and harmonics on the secondary substations is useful for planning future network investments and e.g. transformer maintenance. Especially, feeders with industrial customers or high penetration of DER can be monitored to extract the information about the harmonic current injection at secondary substation. It would be useful in locating potential causes of power quality problems, assessing the transformer loading and aging [5,6] and the compliance with recommendations given e.g. in IEEE 519 or IEC 61000-3-6 [7,8].

Three HFCT sensors were installed at primary substation around a live 20 kV feeder phase conductors with load current 26 A for PD and PQ measurements. Additionally, a commercial power quality sensor LEM Flex (RR3030) was installed in one of the phases to compare the results. Figure 4 shows time-domain representation of the currents measured at 20 kV feeder by HFCT and the commercial power quality current sensor. Three HFCT sensors were measuring the three consecutive phases of one feeder and LEM was measuring only phase L3. The output of the LEM sensor is clean compared to HFCT outputs because it is already integrated.
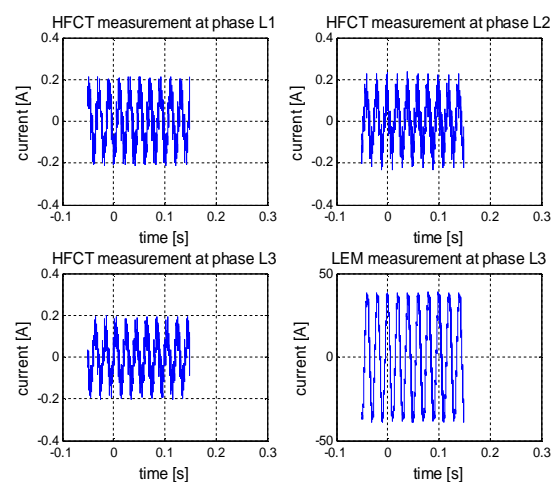

Figure 4. Current measurement at 20 kV feeder using HFCT and LEM current sensors. HFCT waveforms represent the derivatives of the phase currents while LEM waveform is already integrated by the sensor's built in analog integrator.

Let's take a closer look at the output of the HFCT sensor and LEM sensor measured at phase L3 of the feeder. Figure 5 depicts the current measurement of both sensors. HFCT sensor output is also integrated to obtain the actual power frequency current. It is visible that the output produced by HFCT sensor is quite identical to the LEM current sensor output. LEM output is more noise, partly

because of its larger measurement range of up to 300A compared to that of the HFCT (up to 100 A).
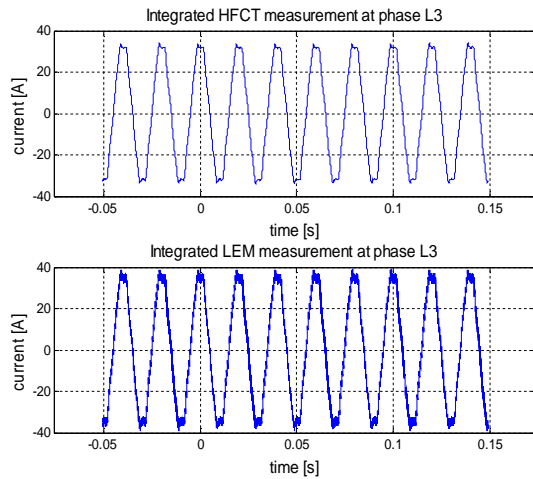

Figure 5. Integrated current waveforms of the HFCT and LEM current sensor measured at phase L3 of the feeder.

In IEC 61000-4-7, 200 ms window is specified for harmonic measurement. Figure 6 represents the frequency-domain analysis of the 200 ms current measured at phase L3 by HFCT and LEM sensor. The fundamental frequency harmonics can be observed in the output of both sensors.
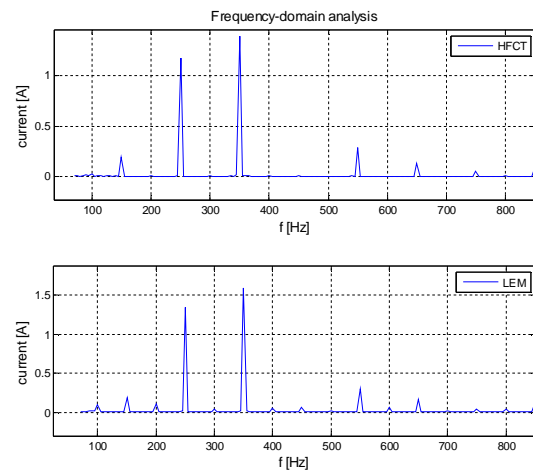

Figure 6. Frequency-domain analysis of the current measured by HFCT and LEM at phase L3 of the feeder.

It can be concluded that the performance of the HFCT sensor is adequate in the field for power quality measurement. It has shown similar results compared with the commercial power quality sensor in terms of the harmonics analysis. Harmonics increase the eddy current losses exponentially causing temperature rise of transformers. Hence, PQ measurements at MV side can help e.g. for estimating thermal loading and hot-spot temperature of the transformer. Moreover, it helps identifying potential power quality problems in the network, which is becoming increasingly important with

the proliferation of distributed generation, electric vehicles and electronic loads.

PARTIAL DISCHARGE MONITORING

Partial discharge measurement is one of the most versatile tools for detecting incipient faults in transformers, switchgear and underground cables, terminations and joints. HFCT sensors were installed around a live 20 kV feeder phase conductors for PD measurements. The amplitude response of the HFCT sensor is optimized so that by a digital high pass filtering the partial discharges and other high frequency phenomena occurring in the MV network can be monitored with high sensitivity simultaneously with the power frequency current measurement. The HFCT sensors exhibit a flat amplitude response at a frequency range of 130 kHz…45 MHz [1] and as such they are excellent for partial discharge monitoring of underground cable networks. Figure 7 presents the high frequency (HF) information extracted from the measurement data presented in Figure 4 using a digital first order Butterworth high-pass filter having a corner frequency of $f_c = 25$ kHz. For the sake of clarity, high frequency information is presented here only for three cycles. Due to the high-pass filtering the 50 Hz and harmonic frequencies are absent in channels L1…L3 and high frequency signals can be easily observed. In this case, only very small partial discharge activity can be observed in phase L3.
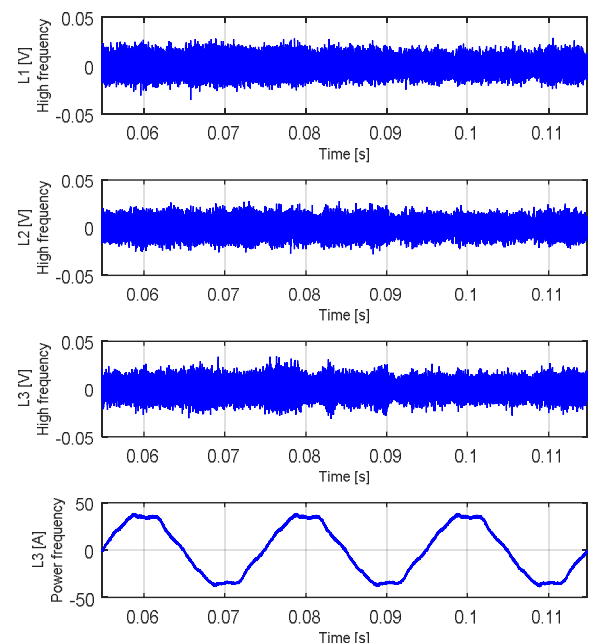

Figure 7. Partial discharge measurement performed at a 20 kV feeder

Figure 8 presents another example of a measurement performed at two 20 kV feeders simultaneously on a 110 / 20 kV primary substation having a double-busbar system. Feeder 1 with a load current of 26 A and feeder 2

with a load current of 80 A were connected to different busbars. In feeder 2, phase L3, high frequency impulses occurring at regular intervals caused by some power electronics device can be observed. The impulses occur at the zero crossings and the commutation notches visible in feeder 2, phase L3, power frequency current waveform presented in the bottom figure. Feeder 1, phases L1 and L3, are almost free of partial discharges and high frequency disturbances.

In conclusion, HFCT sensors have shown promising results in detecting PD and high frequency signals. They can be installed at secondary substation to monitor PD signals on MV cables carrying current up to 100 A over the frequency range of 130 kHz…45 MHz. It also enables the simultaneous recording of the 50 Hz and harmonic current which is a novel approach. The results indicate that using a suitable high-pass filtering partial discharge and high frequency information can be successfully extracted from the raw measurement data containing also power frequency information.
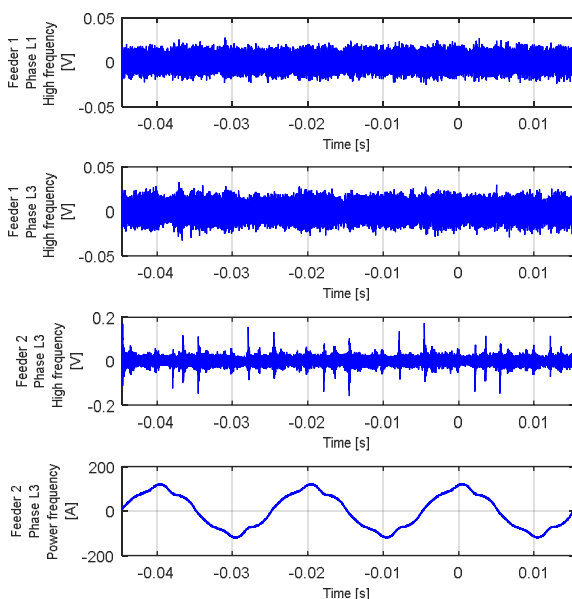

Figure 8. Partial discharge measurement performed at two 20 kV feeders on a 110 / 20 kV primary substation.

CONCLUSION

Cost-effective wideband high frequency current transformer sensors have been introduced for measurement at MV side of secondary substation. HFCT sensors are the foundation of the novel secondary substation monitoring concept since they reduce the cost of measuring at MV side of the network. A successful testing of the sensors in the field has been carried out for measuring MV-side quantities as shown in Table 1. The performance of the wideband HFCT sensor has fulfilled the expectations considering the fact that they can monitor PQ and PD and locate earth faults. Additionally,

field measurements have proved that HFCT sensors do not experience any saturation when the maximum load current was 80 A.

Future work will concentrate on the development of the data acquisition unit to process the data in real-time. The secondary substation monitoring concept would fundamentally improve the possibilities of predicting and preventing component failures at secondary substations and connected feeders. Information on the voltage level and quality at secondary substations would be useful in network operation (e.g. to increase the hosting capacity of DG) and network planning.

ACKNOWLEDGMENT

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