COMPARISON OF CONVENTIONAL SENSOR WITH SINGLE MODE OPTICAL FIBER SENSOR FOR MONITORING OF PARTIAL DISCHARGE IN OIL INSULATION

ALAA RAZZAQ KHALLAWI

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical - Power)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JUNE 2014

This project is dedicated to my family for their endless support and encouragement.

ACKNOWLEDGEMENT

First and foremost, I would like to express heartfelt gratitude to my supervisor **Assoc. Prof. Mohd Muhridza Yaacob** for his constant support during my study at UTM. He inspired me greatly to work in this project. His willingness to motivate me contributed tremendously to our project. I have learned a lot from him and I am fortunate to have him as my mentor and supervisor

Besides, I would like to thank the authority of Universiti Teknologi Malaysia (UTM) for providing me with a good environment and facilities such as Institute of High Voltage and High Current (IVAT) to complete this project with software which I need during process.

ABSTRACT

High-voltage transformer is the most critical and expensive component in a power system network in order to ensure the stability of the system. Partial discharge (PD) is small electrical sparks present in an insulator as result of the electrical breakdown of a gas (for example air) contained within a void or in a highly non-uniform electric field. Partial discharge (PD) phenomenon is one of the reasons that happen in high voltage appliances and lead to failure of power transformer, leading to expensive repair and power outage. An acoustic emission (AE) phenomenon also happens near the discharge zone that is used to detect (PD).Partial discharge detection is a technique widely used for high voltage equipment insulation condition monitoring and assessment. Many researchers have used acoustic emissions (AE) at the vicinity of the discharge zones to detect PD. This project compares the sensitivity of single mode fiber optical sensor with capacitive sensor. The fiber optical sensor (FOS) and capacitive sensor were immersed in an oil tank fitted with two steel electrodes which were connected to different values of high voltage source. The data obtained by both sensors were then analyzed in time and frequency domain, and compared by peak analysis that suggest that single mode optical fiber was able to act as acoustic sensor with large wide band of signals. These experimental results are interesting which also suggest that both sensors have peculiar characteristics for the detection of AE and could be used as per the PD detection requirements.

ABSTRAK

Pengubah voltan tinggi adalah komponen yang paling kritikal dan mahal dalam rangkaian sistem kuasa bagi memastikan kestabilan sistem. Pelepasan separa (PD) adalah percikan api kecil elektrik hadir dalam penebat akibat kerosakan elektrik gas (sebagai contoh udara) yang terkandung dalam kekosongan atau dalam medan elektrik sangat tidak seragam. Pelepasan separa (PD) fenomena adalah salah satu daripada sebab-sebab yang berlaku dalam peralatan voltan tinggi dan membawa kepada kegagalan kuasa pengubah , yang membawa kepada pembaikan mahal dan gangguan kuasa . Akustik pelepasan (AE) fenomena juga berlaku berhampiran zon pelepasan yang digunakan untuk mengesan (PD) . Pengesanan pelepasan separa adalah satu teknik yang digunakan secara meluas untuk voltan tinggi penebat peralatan pemantauan keadaan dan penilaian. Ramai penyelidik telah menggunakan pelepasan akustik (AE) di sekitar zon pelepasan untuk mengesan PD. Projek ini membandingkan sensitiviti serat mod tunggal sensor optik dengan sensor kapasitif. Serat optik sensor (FOS) dan sensor kapasitif telah direndam di dalam tangki minyak yang dipasang dengan dua elektrod keluli yang telah disambungkan ke nilai yang berbeza daripada sumber voltan tinggi. Data yang diperolehi oleh kedua-dua sensor kemudiannya dianalisis dalam domain masa dan frekuensi , dan dibandingkan dengan analisis puncak yang mencadangkan bahawa mod tunggal gentian optik mampu untuk bertindak sebagai sensor akustik dengan band besar luas isyarat. Keputusan ini eksperimen adalah menarik yang juga mencadangkan bahawa kedua-dua sensor mempunyai ciri-ciri khusus untuk mengesan AE dan boleh digunakan sebagai satu keperluan pengesanan PD.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PD	-	Partial discharge
μm	-	Micro meter
μS	-	Micro second
AC	-	Alternative voltage
AE	-	Acoustic emissions
CH	-	Channel
Cm	-	Centimeter
DC	-	Direct current
DGA	-	Dissolve gas analysis
DWT	-	Discreet wavelet transform
EHV	-	Extra high-voltage
EMI	-	Electro-magnetic interference
F	-	Frequency
FFT	-	Fast Fourier transform
FOS	-	Fiber optical sensors
GHz	-	Giga hertz
GI	-	Gra
GIS	-	Gas insulated switcher
H	-	Hue
He-Ne	-	helium–neon laser
HF	-	High frequency
HPLC	-	High performance liquid chromatography
HV	-	High Voltage
HVNS	-	High voltage network system
IEC	-	International Electrotechnical Commission
kHz	-	Kilo hertz

kV	-	kilo volt
LC	-	Leakage current
LED	-	Light emit diode
M	-	Meter
MHz	-	Mega hertz
mm	-	Millimeter
MMF	-	Multimode fiber
mW	-	milli watt
Nm	-	Nanometer
Pc	-	Pico Column
PZT	-	Piezoelectric
RIV	-	Radio interference voltage
rms	-	root mean square
SI	-	Step index
SNR	-	Signal to noise ratio
UHF	-	Ultra high frequency
UT	-	Ultrasound transducer
V	-	Voltage
VHF	-	Very high frequency

LIST OF SYMBOLS

λ	-	Wavelength
$P(\lambda)$	-	Spectral power distribution of optical signal
$R(\lambda)$	-	Output response of optical signal
SF6	-	Sulfur hexafluoride
C a	-	Capacitance of the test object which is not affected by any PD
C b	-	Stray capacitance of the PD source
C c	-	Internal capacitance of PD source
∂n	-	Change in refractive index
Pe	-	Effective photoelastic constant
P	-	Applied pressure
E	-	Young's Modulus
I	-	Interaction length
Φ	-	Phase change

CHAPTER 1

INTRODUCTION

1.1 Introduction

An important tool for improving the reliability of high voltage (HV) insulation systems are partial discharge (PD) measurements. The interpretation of such measurements aims at extracting from the measured data information about insulation defects which then are used for estimating the risk of insulation failure of the equipment. Modeling of PD activity gives an insight of this activity and can provide important information for insulation diagnosis.

Partial discharge (PD) has attracted much attention due to the high financial outlay needed to repair the damage it causes. A high voltage network system (HVNS) has a number of heavy transformer installations which continuously work to distribute electricity to substations. Stability of any power system network determines the life time of the high voltage equipment installed in the network. The expensive components of the high voltage equipment are the power transformers which are expensive and can incur high repair costs. Each fault on a single unit of the heavy transformer installations has a huge financial impact on the maintenance cost of the installations. Hence, continuous operational monitoring is very important. Failures due to PD cause deterioration of the high voltage transformer performance and result in breakdown, fires and damage to the system. PD detection technique is widely used for high voltage equipment protection, insulation condition monitoring and general high voltage network assessment. Hence, a good understanding of PD mechanisms, its characteristics and development processes are important. Insulation of the high voltage transformer has a high risk for dielectric stability when PD occurs. Therefore, continuous measurement and monitoring of PD is important so that preventive actions can be taken to avoid equipment damage. Presently, modern testing procedures are available to monitor high voltage insulation in the high voltage transformer. There is now a new trend to monitor high voltage insulation using sensitive predictive diagnostic tools. PD results in many different physical phenomena such as electromagnetic emission (in the form of radio wave, light or heat), acoustic emission (in the audible and ultra-sonic ranges), ozone formation and nitrous oxide gas discharges [1]. For this reason, it has been used as a tool to predict and detect possible insulation failure of the system. The frequency and intensity of PD are the main quality criteria to estimate the life span of the high voltage transformer.

1.2 Research Background

PD are small electrical sparks present in an insulator as result of the electrical breakdown of a gas (for example air) contained within a void or in a highly non-uniform electric field. The sudden release of energy caused when a PD occurs produces a number of effects like chemical and structural changes in the materials. The measurement level indicates the quantity and magnitude of partial discharge. Popular methods of PD detection in high-voltage power equipment utilize electrical, chemical, acoustic and optical measurements [2].

The accuracy of the acoustic PD location approach depends upon being able to detect the PD pressure wave, and to separate the resulting signals from background noise. These problems can be avoided using optical-fiber sensors that can be placed inside the transformer tank without affecting the insulation integrity.

This intrusive configuration is particularly useful in substations environments where there is a high level of outside interference [3].

Since the 1960s, which saw the development of laser technology and optical fibers, much work has been done to investigate the possibilities of detecting a variety of physical quantities using optical means. Acoustic sensing has been one of the first successful applications of fiber-optic sensors, and the literature on optical-fiber interferometry for acoustic and ultrasonic sensing is extensive. Underwater acoustic sensing has been studied since the end of the 1970s and many configurations were proposed to optimize system performance [4].

Acoustic detection with fiber 0ptic based sensors is possible if an acoustic wave is able to transfer energy to a fiber, the first successful application of optical-fiber sensors to PD detection was reported in 1996 by Zargari and Blackburn. They developed an intrinsic fiber sensor based on a Michelson interferometric configuration.

In 1998, the same authors worked out another non-intrusive fiber-optic sensor for PD detection that is mounted externally on brushing of a current transformer [5].

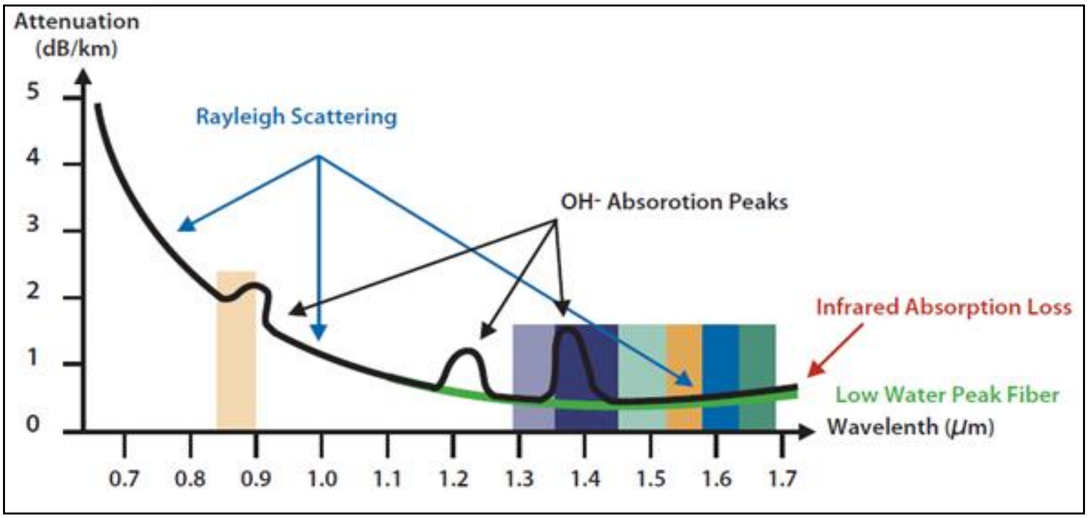

Figure 1.1 Fiber attenuation as function of wave length

Optical fibers detection has several advantages such as: small size and weight, enormous potential bandwidth, immunity to interference and crosstalk, electrical isolation, signal security, low transmission loss [5, 6].

The economic development and social welfare of any modern society depends upon the availability of a cheap and reliable supply of electrical energy. The system of electrical energy consist of three parts: generation, transmission and distribution .these parts are connected together synchronously and any part consist of high voltage equipment such as transformer, circuit breaker, bus bar, isolator, and others. Actually any high voltage equipment contained insulation; the principle media of insulation are gases, vacuum, solid and liquid [7].

Partial discharges (PD) are a cause and a symptom of the degradation of the insulation system and its activity monitoring is used as a tool for insulation condition assessment. PD is small electrical sparks present in an insulator as result of the electrical breakdown of a gas (for example air) contained within a void or in a highly non-uniform electric field. The sudden release of energy caused when a PD occurs produces a number of effects like chemical and structural changes in the materials [8].

The measurement level indicates the quantity and magnitude of partial discharge. There are popular methods of PD detection in high-voltage power equipment utilizes electrical, chemical, acoustic and optical measurements. Measurement of an electrical quantity is convenient and can give precise recording of PD variations in the laboratory. However, it can give an inaccurate recording for conditions at on-site [9-10].

Two electrical quantity measurement methods are available. They are the Ultra High Frequency (UHF) method and Pulse Capacitive Coupler method. The UHF method is based on the measurement of electrical resonance at the frequency range of up to 1.5 GHz due to PD excitation. This method is capable of detecting as well as locating a PD source. UHF method has inherent advantages such as low noise levels due to shielding effect of the transformer and very low signal attenuation. This method has immunity against external noise as the UHF sensor is connected inside the transformer. The connection between UHF sensor and power transformer is non-electrical and hence there is reliability and safety against any induced current at the power secondary. The Pulse Capacitive Coupler method collects and measures the PD induced current at the detection coil which has a connection loop through some impedance to the earth line [11-12].

Partial discharge (PD) phenomenon is one of the reasons that happen in high voltage appliances and lead to failure of power transformer, leading to expensive repair and power outage. An acoustic emission (AE) phenomenon also happens near the discharge zone that can be used to detect PD. The sensors are dipped in the oil tank fitted with two steel electrodes which are connected to high voltage source [13-14]. The experimental data of sensors and high voltage discharge parameters are recorded by the recording source. The main problem of high-voltage power equipment is degradation of isolation [15- 16]. The main reason of degradation is partial discharge (PD) phenomena [17]. The PD is hidden activity of small electrical spark present in insulation as a result electrical breakdown occurs in the cable or equipment. The PD phenomenon occurs when the electric field exceed local ionization threshold of dielectric insulation [18]. In the PD phenomenon energy is emitted in the form of electromagnetic emission, radio waves, light and heat and also as acoustic emissions (AE) in the audible and ultrasonic ranges. The ultrasonic pressure waves can be used to detect the intensity and location of PD signal. The frequency band of discharge in oil has wideband range (10-500 kHz) [19-20] PD signals have been detected and located using piezoelectric (PZT) ultrasound sensor for typical frequency about 150 kHz mounted on tank wall. The main problem of PZT sensor, it suffers from degeneration of signal-to-noise ratio due to environmental noises such as electromagnetic interference. Another problem related with externally mounted PZT sensor is multi-path signal, due to the ultrasound signal transport from the source to the sensor along different speed and different path, this mean low level of precision is achieved. Therefore, the sensor must be located inside tank of transformer, close to PD source to overcome to this problem [21, 22].

This sensor which is electrically non-conductive, chemically inert, passive and small in size is the best choice for the detection of PD phenomenon. The optical fiber sensor (OFS) has been used which has some advantages like it has a simple structure, low power consumption, small size, light weight, immunity to electromagnetic interference noises, high sensitivity, corrosion resistance, low prices and large wideband. These advantages make OFS perfect candidate for acoustic detection. The use of interferometric OFS inside transformer can give very high level of sensitivity that can be achieved due to PD phenomenon [23,24]. Recently single-mode OFS has been used based on interferometric measurement of AE inside transformer [25, 26]. The single-mode optical fiber sensor has high sensitivity by using long fiber in sensing arm, but the frequency response is a drawback in this case.

The chemical measurement techniques for detecting PD in high voltage transformer is based on the collection and some chemical measurement of oil and gas samples released during the PD process. Two chemical measurement techniques are used at the present moment. They are the High Performance Liquid Chromatography method (HPLC) and the Dissolved Gas Analysis method (DGA). HPLC analyses PD expelled byproducts such as degraded forms of glucose induced by degradation of insulation. While DGA analyses the accumulated volume of gas produced by the PD. For chemical measurement techniques, sufficient expelled byproducts or gas has to be collected before analysis can begin. Hence there is some time delay between collection and analysis. Chemical measurement techniques are therefore not suitable for real time monitoring. Chemical as well as electrical approaches are incapable of locating the exact position of PD sources [27].

Partial discharge (PD) is a phenomenon which occurs in high voltage equipment and is responsible for many power transformer failures. The complete calibration has been done to evaluate the sensors. The characteristics of acoustic sensor multimode fiber optical sensor (FOS) have been successfully explored. The FOS was placed in oil tank in which optical breakdown was produced by neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (1064 nm) device. The optical signal of light source was linked by photo detector which was also connected with multimode fiber (MMF) by means of fiber optical adapter. The data obtained by FOS sensor was then analyzed in time and frequency domain. The experimental results show that FOS has peculiar characteristics for the detection of acoustic emission (AE) and could be used as alternative detection devices. The partial discharge measurement is a very well known possibility to assess the quality of an insulation system of high voltage devices, because the life of high voltage equipment depends on the present of partial discharge. The aim is the detection of a beginning destruction in the electrical insulation as a result of electrical stress. the characteristics of (PD) using single mode optical fiber sensor in mineral oil explored and monitor the condition of high voltage equipment insulation, and make comparison with the electrical detection method, then analyzed in time and frequency domain.

Acoustic method detects and locates the position of PD by studying the amplitude attenuation or phase delay of the acoustic waves propagated from the PD. This mechanical wave (acoustic wave) is caused by the mechanical energy explosion due to the vaporization of material inside the transformer tank creating a form of pressure field. Acoustic wave in the transformer oil can be detected using acoustic sensors (Piezoelectric Transducers PZT). When PZT is mounted outside, on the transformer wall, it will capture interferences from the very noisy environment and this can make PZT sensors, usefulness limited. The PZT sensor can be placed inside the oil tank of the transformer to reduce noise and attenuation of signal [28-29].

Location of PD can be estimated by measuring the time of arrival of acoustic wave and position information is ascertained by using sensors at multiple locations. This makes acoustic emission sensing a more preferable measuring tool in real time. Measurement using the acoustic approach has an additional advantage of possessing better noise immunity for online real time applications. Acoustic method experiences difficulty in locating the exact origin of PD due to interference and degradation of signals from environmental noise. Here, sensitivity is certainly compromised [30].

Optical method that uses optical fiber sensor which is small in size, highly sensitive and light weight, and possesses high frequency response and significant immunity against electromagnetic interference, can measure a wide range of chemical and physical parameters at ease. Apart from PD detection and assessment, optical fiber acoustic sensors have been used successfully in applications such as underwater hydrophones, construction non-destructive diagnosis, and material property analysis traffic monitoring and vehicle detection. Functionally, optical detection technique is based on fiber optic intrinsic interferometers such as Michelson interferometers [31].

The Michelson interferometers, Mach–Zehnder interferometers sensors suffer from fringe fading problems due to random polarization rotation Fabry–Perot interferometric sensors are compact in size compared to Michelson and Mach–Zehnder fiber sensors, and therefore achieve virtually single-point measurement. Due to measurements sensitivity, optical method has restricted use for PD detection [32-33].

In this project will study, the characteristics of (PD) using single mode optical fiber sensor in mineral oil explored and monitor the condition of high voltage equipment insulation, and make comparison with the electrical detection method (capacitive sensor), were then analyzed in time and frequency domain.

1.3 Effect of Partial Discharge

Monitoring of PD activities is used as precautionary measures to ensure that high voltage equipment insulation is not exposed to any unnecessary hazards. Online monitoring techniques provide quick information which can be used in a decision to take remedial action before severe fault in the high voltage power transformer can occur.

A good understanding of the mechanisms, characteristics and the development processes of PD is essential for designers and power systems installation maintenance engineer of HVNS. Fast and accurate information are important to save and protect the HVNS from secondary losses. In general, the cause of any failure in a HVNS is due to the decrease and instability of insulation dielectric strength from the cumulative effects of the thermal, electrical and mechanical stresses [34]. In most cases, the deterioration in dielectric strength is caused by PD. Some basic characteristics of PD calibrators have been explored by Mole in 1970. Till 1980's, commercially available PD detectors were working in the measuring frequency band below 1 MHz the first commercially available wide-band PD detector was developed by Dr. Lemke that works on measuring principle based on an active (electronic) integration of the wide-band pre-amplified PD pulses. Upper cut-off frequency of the wide-band pre-amplifier (10 MHz) allows the detection and location of the PD events [12].

1.4 Partial Discharge Measurement Difficulties

Partial discharge measurement by electrical method is not easy. The discharges take place in the form of pulses and the discharge quantity is low. Measurement of these pulses is also difficult due to electric noise originating from adjoining circuits or from the test set-up itself.

1.5 Problem Statement

Electrical insulation is an important component in high voltage power equipment. After many years in-service, deterioration of the insulation system is inevitable due to the cumulative effect of mechanical, thermal and electrical stresses. The level of partial discharge (PD) activity is one of the leading indicators that may be used to assess the plant insulation quality. Furthermore, if the location of the PD source can be identified, the fault can be quickly rectified and the time lost due to outage is minimal. With HV oil-filled power transformers, a commonly-used on-line diagnostic method to detect and locate the discharge site is through the use of acoustic sensors. They can be easily attached externally to the transformer tank wall to pick up the ultrasonic signals associated with the electrical discharges. Location is possible by triangulation based on measurement of the propagation times at several different sensor positions [35-36].

Advances in optical fiber technology have opened up many new areas of applications beyond its traditional ground in telecommunications. One important field is the use of optical fibers as sensors which enable much more accurate measurement than conventional instrumentation. Furthermore, optical fiber sensors are well suited for use in hostile environments, often encountered in HV power engineering [37].

At present, they have been used successfully by some electrical utilities to measure the temperature inside transformer windings. It is not surprising that such technology may be extended to monitor other parameters which are critical in the maintenance of power transformers. Besides the advantage of immunity to electrical interference, the presence of optical fiber sensors inside the transformer does not affect its insulation integrity. We used single mode optical fiber to detect partial discharge signal in mineral oil transformer because it has several advantages such as: small size and weight, enormous potential bandwidth, immunity to interference and crosstalk, electrical isolation, signal security, low transmission loss.[38].

1.6 Research Objectives

This study would focus on the following objectives:

- To conduct an experiment for the detection of PD using single mode optical fiber sensors under high voltage insulation oil conditions.
- To characterize the Partial discharges through waveform shape analysis.
- To Comparison of optical and conventional electrical sensors for partial discharge signal monitoring in oil insulation.

1.7 Scope of Research

The scope of this work is described below:

- In this work a single mode optical fiber sensor would be used to detect PD signal in mineral oil transformer because it has the advantages such as: small size and weight, enormous potential bandwidth, immunity to interference and crosstalk, electrical isolation, signal security, low transmission loss.
- This study would confind in the high voltage range upto 1-50 kV applied to the electrode of the discharge reactor. This study would confined in the comparison of two sensors; optical fiber sensor and conventional sensor(capacitive sensor).

1.8 Significance of the Study

As mentioned above, the convention techniques of detection for partial discharges are expensive and have drawbacks in accuracy. The optical fiber sensor technique can also be used as an inexpensive alternative for the detection of PD in heavy transformers to monitor the efficiency and working of the transformer. The optical fiber sensor technique is inexpensive and more reliable than conventioonal sensors and provide safty due to total isolation from the line high voltage.

1.9 Thesis Organization

The project consists of five chapters, organized as following:

- Chapter one in this research presents an overview as a whole. The background, problem statement, objectives and scope have been described.
- In chapter two literature review of arc discharge have been described.
- In chapter three, the experimental set-ups and procedures employed and the equipment in this study are described.
- In chapter four present the result and discussion of experimental work.
- Finally, chapter five will contains the conclusion of the main finding of this work.

REFERENCES

[1] Tenbohlen S., Denissov D., Hoek S. M., and Ring Z. Partial Discharge Measurement in the Ultra High Frequency (UHF) Range. *Dielectr. Electr. Insul. IEEE Trans.* 2008. vol. 15, no. 6, pp. 1544–1552.

[2] Hawley R. and Jiniswale S., *Measuring Partial Discharges,*. London: R. Hawley and S. Jiniswale. (1964). Measuring Partial Discharges,. London., 1964.

[3] Yaacob MM and Alsaedi, MA, Partial Discharge in HV Equipment Using Acoustic and Optical Method,Advanced Materials Research, Vol. 845, 283-286(Scopus).

[4] Yaacob MM and Alsaedi, MA, In situ Detection of Partial Discharge Using Leakage Current, Fiber Optic Sensor and Piezoelectric Sensor Techniques, Advanced Materials Research Vol. 845, 277-282 (Scopus)

[5] Yu B, Kim D.W, Deng J, Xioa H and Wang A. Fiber Fabry-Perot sensors for dection of partial discharges in power transformers, *'Applied Opt.*, vol. 42, no. 16, pp. 3241–3250, 2003.

[6] Yaacob MM, Alsaedi, MA, and Iqbal S.M.Z. A Study of The Sensitivity of Multimode Optical Fiber Acoustic Sensors and Piezoelectric Film Sensors for Acoustic Emission Monitoring of Partial Discharge in Oil Insulation, Optical Review Springer, manuscript no : OR12071R (Springer, 2013)(IF=0.75)(in-press).

[7] Yaacob MM and Alsaedi, MA, partial discharge signal analysis in insulation oil using optical chromatic technique, Applied machines and materials (Scopus) (in press).

[8] Kreuger, EH. *Discharge Detection in High Voltage Equipment*. London: Temple Press Books, 1964.

[9] CENELEC., High-voltage test techniques,, partial discharge measurements. 2001.

[10] Hettiwatte, S.N., Wang, Z.D., Crossley, P.A., Jarman, P., Edwards, G. and Darwin, A. An electrical PD location method applied to a continuous disc type transformer winding, in *Properties and Applications of Dielectric Materials*, 2003, pp. 471–474.

[11] Huecker T. and Gorablenkow J., UHF Partial Discharge Monitoring and Expert System Diagnosis, *IEEE Trans. Power Deliv.*, vol. 13, no. 4, pp. 1162–1167, 1998.

[12] Judd MD M. S., C.G., Testing UFH partial discharge detection on a laboratory based power transformer, in *proceeding of HIGH VOLTAGE ENGINEERING*, 2005, p. 2005.

[13] Harrold R. T., Acoustical Technology Applications in Electrical Insulation and Dielectrics, *IEEE Trans. Electr. Insul. Vol.*, vol. EI-20, no. 1, pp. 3–19, 1985.

[14] Ma, K. I. J. Zhou C, Interpretation of Wavelet Analysis and its Application in Partial Discharge Detection, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, pp. 446–457, 1992.

[15] Macià-Sanahuja C., Lamela H., and García-Souto J. a., Fiber optic interferometric sensor for acoustic detection of partial discharges, *J. Opt. Technol.*, vol. 74, no. 2, p. 122, Feb. 2007

[16] Judd M. D. and Hunter I. B. B., Partial Discharge Monitoring for Power Transformers Using UHF Sensors Part 2 : Field Experience, vol. 21, no. 3, pp. 5–13, 2005.

[17] Bartnikas, R. Partial Discharges Their Mechanism, Detection and Measurement, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 5, pp. 763–808, 2002.

[18] Karmakar S., Roy N. K., and Kumbhakar P., Partial discharge measurement of transformer with ICT facilities, *2009 Int. Conf. Power Syst.*, pp. 1–5, 2009.

[19] Eleftherion P M., Partial Discharge XXI: Acoustc Emisson-Based PD Source Location In Transformer, *IEEE Electr. Insul. Mag.*, vol. 11, no. 6, pp. 22–26, 1995.

[20] Montanari F., Cavallini G.C.; Puletti A., A new technique to partial discharge testing of HV cable systems, *IEEE Electr. Insul. Mag.*, vol. 22, no. 1, pp. 14–23, 2006.

[21] Boggs, S.; Densley J. N, Fundamentals of partial discharge in the context of field cable testing,‖ IEEE Volume: 16, Issue: 5, Page(s): 13 – 18, 2000, *IEEE Electr. Insul. Mag.*, vol. 16, no. 5, pp. 13–18, 2000.

[22] Meijer A., Smit S., Gulski J.J, Girodet E.; Partial discharge early warning system in gas-insulated switchgear, in *Transmission and Distribution*, 2002, vol. 2, pp. 931 – 936.

[23] Greene JA, Tran T A, Bhatia V, Gunther M F, Wang A. Optical fiber sensing technique for impact detection and location in composites and metal specimens, *IOPscience*, vol. 4, no. 2, pp. 93–99, 1995.

[24] Furstenau N. Schmidt M. Horack H. Goetze W. Schmidt W., Extrinsic Fabry-Perot interferometer vibration and acoustic sensor systems for airport ground traffic monitoring, *IEE Proc -0ptoulectron*, vol. 144, no. 4, pp. 134–144, 1997.

[25] Das S., Studies on Partial Discharge Detection Using Optical Sensors, 2010.

[26] Jones G. R., Intelligent Optical Fiber Based Systems for Monitoring the Condition of Power Equipment, *’The Reliab. Transm. Distrib. Equip.*, no. 406, pp. 73–78, 1995.

[27] Imad-U-Khan S.; Zhongdong Wang; Cotton, I.; Northcote, Dissolved gas analysis of alternative fluids for power transformers, *IEEE Electr. Insul. Mag.*, vol. 23, no. 5, pp. 5–14, 2007.

[28] Kil,G.-S. Kim, I.-K. Park, D.-W. Choi,S.-Y. and Park C.-Y., Measurements and analysis of the acoustic signals produced by partial discharges in insulation oil, *Curr. Appl. Phys.*, vol. 9, no. 2, pp. 296–300, Mar. 2009.

[29] Pedersen, A.; Crichton, G.C.; McAllister, I.W., The theory and measurement of partial discharge transients, *IEEE Trans.*, vol. 62, no. 3, pp. 487–497, 1991.

[30] Blackbum, T. R. Acoustic detection of partial discharges using non-intrusive optical fiber sensors, in *International Conference on Condition and Breakdown in Solid Dielectrics*, 1998, pp. 8–11.

[31] Lazarevich A. K., Partial Discharge Detection and Localization in High Voltage Transformers Using an Optical Acoustic Sensor, *thesis , Blacksburg, Virginia U.S.A*, 2003.

[32] Chen C. X., Xu Yang G., , Yu Ming, Comparison between optical and electrical methods for partial discharge measurement, *Proc. 6th Int. Conf. Prop. Appl. Dielectr. Mater. (Cat. No.00CH36347)*, vol. 1, pp. 300–303, 2000.

[33] Lamela-Rivera H., Maci -Sanahuja C., and Garc a-Souto,J. a Detection and wavelet analysis of partial discharges using an optical fiber interferometric sensor for high-power transformers, *J. Opt. A Pure Appl. Opt.*, vol. 5, no. 1, pp. 66–72, Jan. 2003.

[34] Dukes,R. B. Sc, D. Ph, E. A. Culpan, and C. Eng, Acoustic emission : its techniques and applications, vol. 131, no. 4, 1984.

[35] Pfeffer T. S. A., S. Coenen, S. Tenbohlen, S. M. Markalous, Onsite experiences with multi- terminal IEC PD measurements and UHF PD measurements, in *ISH*, 2009.

[36] Tian Y., Lewin P. L., Davies A. E. S Sutton. J., and Hathawav G. M., Comparison of On-line Partial Discharge Detection Methods For HV Cable Joints, *Dielectr. Electr. Insul. IEEE Trans.*, vol. 9, no. 4, pp. 604–615, 2002.

[37] Cosgrave J. a., Vourdas a., Jones G. R., Spencer J. W., Murphy M. M., and Wilson a., Acoustic monitoring of partial discharges in gas insulated substations using optical sensors, *IEE Proc. A Sci. Meas. Technol.*, vol. 140, no. 5, p. 369, 1993.

[38] Deng J., Xiao H., Huo W., Luo M., May,R. Wang A., and Liu Y., Optical fiber sensor-based detection of partial discharges in power transformers, vol. 33, pp. 305–311, 2001.

[39] Agoris A. J. L. M., Pantelis D.; Meijer, Sander; Gulski, Edward; Smit, Johan J.; Kanters, On-line partial discharge detection on transformers, in *Electricity Distribution*, 2005, pp. 1–5.

[40] Densley J., Ageing mechanisms and diagnostics for power cables - an overview, *IEEEEl ectrical Insul. Mag.*, vol. 17, no. 1, pp. 14 – 22, 2001.

[41] Wang a, Miller M. S., Plante a J.,. Gunther M. F, Murphy K. a, and. Claus R. O, Split-spectrum intensity-based optical fiber sensors for measurement of microdisplacement, strain, and pressure., *Appl. Opt.*, vol. 35, no. 15, pp. 2595–601, May 1996.

[42] Layton M. R and Bucaro J. a, Optical fiber acoustic sensor utilizing mode-mode interference., *Appl. Opt.*, vol. 18, no. 5, pp. 666–70, Mar. 1979.

[43] Sansonetti J. E, Handbook of Basic Atomic Spectroscopic Data, *J. Phys. Chem. Ref. Data*, vol. 34, no. 4, p. 1559, 2005.

[44] Meijer S., Partial Discharge Diagnosis of High-Voltage Gas-Insulated Systems. Doctoral Thesis, Delft University of Technology,, 2001.