# WIRELESS ROGOWSKI COIL SENSOR BASED ON PARTIAL DISCHARGE DETECTION SIGNAL FOR ON-LINE CONDITION MONITORING IN THE MEDIUM VOLTAGE POWER CABLES

**MOHAMAD NUR KHAIRUL HAFIZI BIN ROHANI**

**UNIVERSITI MALAYSIA PERLIS**

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by

**MOHAMAD NUR KHAIRUL HAFIZI BIN ROHANI**
**(1440911211)**

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**School of Electrical System Engineering**
**UNIVERSITI MALAYSIA PERLIS**

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| Date of Birth | : | 17 May 1989 |
| Title | : | Wireless Rogowski Coil Sensor Based On Partial Discharge Detection Signal for On-Line Condition Monitoring In the Medium Voltage Power Cables |
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## LIST OF ABBREVIATIONS

| | |
|---|---|
| 3D | 3 Dimension |
| ABS | Acrylonitrile Butadiene Styrene |
| AC | Alternating Current |
| ADC | Analog to Digital Converter |
| CAD | Computer Aided Design |
| CC | Capacitive Coupler |
| DGA | Dissolved Gas Analysis |
| DSI | Discrete Spectral Interference |
| EMI | Electromagnetic Interference |
| EMTP-ATP | Electromagnetic Transient Program-Alternative Transient Program |
| FEM | Finite Element Method |
| FPGA | Field-Programmable Gate Array |
| F-POF | Fluorescent Polymer Optical Fiber |
| GMR | Giant Magneto Resistive |
| HE | Hall Effect |
| HFCT | High Frequency Current Transformer |
| HV | High Voltage |
| IoT | Internet of Thing |
| LCC | Line Communicate Converter |
| MI | Magneto Impedance |
| MV | Medium Voltage |
| PD | Partial Discharge |
| PLA | Polylactic Acid |

| | |
|---|---|
| PMT | Photon Multiplier Tubes |
| PSIM | PowerSim |
| RC | Rogowski Coil |
| RF | Radio Frequency |
| RMS | Root Mean Squares |
| SMD | Surface Mount Device |
| VHDL | Verilog Hardware Description Language |
| XLPE | Cross-Linked Polyethylene |

## LIST OF SYMBOLS

| | |
|---|---|
| $C_{gap}$ | Gap Capacitance |
| $C_l$ | Lumped Capacitance |
| $D_{rc}$ | Diameter Rogowski Coil Sensor |
| $D_{wire}$ | Diameter Wire |
| $L_l$ | Lumped Inductance |
| $M_c$ | Coil Mutual Inductance |
| $R_{in}$ | Inner Radius |
| $R_l$ | Lumped Resistance |
| $R_{out}$ | Outer Radius |
| $V_{out}$ | Output Voltage |
| $V_p$ | Peak Value |
| $V_{pp}$ | Peak to Peak Voltage |
| $V_{rc}$ | Rogowski Coil Output Voltage |
| $Z_{out}$ | Terminating Impedance |
| $f_r$ | Resonant Frequency |
| $t_d$ | Time Different of Arrival Time |
| $\sum\Delta$ | Sigma-Delta |
| $A$ | Area |
| $B$ | Magnetic Density |
| $g$ | Turn to Turn Distance |
| $h$ | Height |
| $l$ | Length of wire |
| $L$ | Total length of the cable |

| | |
|---|---|
| $N$ | Number of Turns |
| λ | Flux Linkage |
| Ω | Resistance (ohm) |
| $X$ | Location of PD pulse |
| $v$ | Propagation velocity |
| $\rho$ | Copper Resistivity |

**Penderia Gegelung Rogowski Tanpa Wayar untuk Pengesanan Isyarat Pelepasan Separa Pada Keadaan Pemantauan Atas Talian Dalam Kabel Voltan Sederhana**

## ABSTRAK

Pengukuran pelepasan separa (PD) menyediakan maklumat yang berharga untuk menilai keadaan penebat voltan tinggi (HV) pada sistem kuasa. Dalam kajian ini, penderia gegelung Rogowski (RC) tanpa wayar yang baharu berdasarkan kepada pengesanan PD dalam kabel kuasa voltan sederhana (MV) dibentangkan. Kajian ini dibahagikan kepada tiga bahagian iaitu pembangunan penderia PD, teknik pra-penapisan dan integrasi tanpa wayar. Satu siri siasatan ke atas kepekaan dan jalur lebar untuk empat jenis penderia RC ditunjukkan. Pembangunan prototaip pertama telah dijalankan dengan bantuan perisian SolidWorks 3-dimensi (3D) bantuan komputer reka bentuk (CAD) dan pencetak MakerBot 2X 3D. Selepas itu, penderia dimodelkan dan simulasi menggunakan perisian *Electromagnetic Transient Program-Alternative Transient Program* (EMTP-ATP) berdasarkan parameter yang telah dikenalpasti. Satu teknik pengukuran penamatan tunggal (*single-end)* telah digunakan sebagai sistem pemantauan PD dalam talian pada tiga fasa voltan sederhana *cross-link polyethylene* (XLPE) kabel kuasa bawah tanah dengan keluasan 240 $mm^2$ konduktor tembaga. Untuk mengesahkan keputusan yang dicapai dari simulasi, pengukuran eksperimen telah dijalankan. Eksperimen ini telah diulang bagi setiap reka bentuk penderia RC. Dalam usaha untuk mencapai penderia PD yang terbaik, pilihan yang tepat adalah paling utama. Dalam kes ini, keputusan menunjukkan bahawa bentuk geometri segi empat tepat mempunyai prestasi yang lebih baik merujuk kepada pengesanan isyarat PD. Bentuk segi empat tepat penderia RC telah dipilih untuk dibandingkan dengan penderia konvensional RC yang lain. Teknik pengukuran dua penamatan (*double-end)* telah digunakan di mana dua daripada penderia RC diletakkan pada jarak tertentu untuk menganalisis halaju perambatan dan masa ketibaan isyarat PD ditangkap oleh penderia berdasarkan saiz XPLE kabel kuasa yang berbeza. Analisis ke atas ketepatan teknik lokasi *double-end* dan *multi-end* PD telah dijalankan. Keputusan teknik lokasi *double-end* dan pelbagai penamatan (*multi-end)* PD masing-masing mempunyai 0.138 % dan 0.026 % peratusan ralat. Satu eksperimen telah dijalankan untuk menilai kesan perbezaan penderia RC tidak terlindung, dilindungi dan perintang penamatan, $R_t$. $R_t$ adalah sebahagian daripada parameter yang boleh meningkatkan prestasi penderia RC. Penguat kendalian (*op-amp*) dan penapis *Butterworth* laluan tinggi aktif yang telah direka dengan menggunakan topologi *Sallen-key* yang digunakan untuk menguatkan dan menyekat gangguan isyarat keluaran daripada penderia RC dalam bahagian kedua. Integrasi penderia RC ke dalam sistem komunikasi tanpa wayar telah dibincangkan dalam bahagian akhir. Peranti penukar analog kepada digital (ADC) berkelajuan tinggi diperlukan untuk menyempel isyarat PD. Walau bagaimanapun, ADC konvensional di pasaran adalah lebih mahal untuk kelajuan yang tinggi. Oleh itu, Sigma-Delta (ΣΔ) ADC topologi dibangunkan dalam Altera DE0-Nano. Pengesanan puncak dengan teknik had diperkenalkan dalam bahagian ini. Kemudian, data yang akan dihantar secara tanpa wayar kepada unit pengkalan menggunakan modul frekuensi radio (RF) sebagai *transceiver* dan Altera DE2-115 digunakan sebagai unit pengkalan. Dalam usaha untuk mencapai persampelan digital yang tepat frekuensi tinggi isyarat PD, N-bit resolusi adalah paling utama. Dapatan analisis ini, resolusi 4-bit dipilih dalam kajian ini sebagai penyelesaian yang terbaik untuk ΣΔ ADC untuk persampelan isyarat PD.

**Wireless Rogowski Coil Sensor Based On Partial Discharge Detection Signal for On-Line Condition Monitoring in the Medium Voltage Power Cables**

## ABSTRACT

Partial discharge (PD) measurement provide a valuable information for assessing the insulation health in high voltage (HV) power system. In this research, a novel wireless Rogowski coil (RC) sensor based on PD detection in the medium voltage (MV) power cables is presented. This research is divided into three sections which are RC sensor development, pre-filtering technique and wireless integration. A series of investigations on sensitivity and bandwidth for four types of RC sensors was demonstrated. The prototype development first was carried out with the assistance of SolidWorks 3 dimension (3D) computer aided design (CAD) software and MakerBot 2X 3D printer. Subsequently, the sensors were modeled and simulated using Electromagnetic Transient Program-Alternative Transient Program (EMTP-ATP) software environment based on the lumped parameter identification. A single-end measuring technique was used as an on-line PD monitoring system on the three-phase medium voltage underground cross-link polyethylene (XLPE) insulated power cable with a 240 $mm^2$ nominal area copper conductor. In order to verify the simulation results, an experimental measurement was carried out. This experiment was repeated concurrently for each design of the RC sensors and the precise selection for the best sensor is paramount. In this case, the results indicated that rectangular geometrical shape performed better with regard to the detection of the PD signal. The rectangular shapes of RC sensor has been selected in order to compare with the conventional RC sensor. Double-end technique measurement has been used where two of RC sensor is placed on the certain distance to analyse the propagation velocity and arrival time of PD signal captured by the sensor based on the different size of XPLE power cables. The analysis on accuracy of double-end and multi-end PD location technique have been conducted. The results between double-end and multi-end technique have 0.138 % and 0.026 % percentage error of PD location respectively. An experiment has been conducted in order to evaluate the effect of unshielded, shielded RC sensor and terminating resistance, $R_t$. The $R_t$ is a part of parameter which can improve the performance of RC sensor. An operational amplifier (op-amp) and active Butterworth high-pass filter which has been designed using Sallen-key topology that is used to amplify and suppress the noise of output signal from RC sensor in the second section. The integration of RC sensor into wireless communication system has been discussed in the final section. High speed analog to digital converter (ADC) device is required to sample the PD signal due. However, the conventional ADC in the market is expensive in high speed rate. Thus, Sigma-Delta ($\sum\Delta$) ADC topology is developed in Altera DE0-Nano board. Peak detection with threshold technique is introduced in this section. Then, the data transmitted wirelessly to the server unit using radio frequency (RF) module as a transceiver and Altera DE2-115 board is used as a server unit. In order to achieve the accurate digital sampling of high frequency PD signal, the N-bit resolution is paramount. The finding of this analysis, 4-bit resolution is selected in this research as the best resolution for the $\sum\Delta$ ADC to sampling the PD signal.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Recently, electrical utility companies are enhancing their focus on the modernization of their distribution systems. The upgrading exercise is aimed to improve on reliability, efficiency and safety of the system. The utmost issue when discussing on the issue of reliability is an unscheduled interruption due to faulty electrical equipment. In Peninsular Malaysia, the annually energy demand increased 2.22 % from 112,358 in 2013 to 114,856 GWh in 2014 was recorded (Energy Commission of Malaysia, 2015). However, the disruption from power system fault will lose in a million of Ringgit Malaysia. Based on the percentage of unscheduled interruption recorded by NUR Distribution Sdn. Bhd. as a one of electricity distribution company in Malaysia as shown in Figure 1.1, the faulty equipment contributes the highest percentage which is 51.91 % and followed by overload, 23.08 %, damage by third party and quality of material are 9.62 %. Lastly, natural disasters such as wind, storm, flood, landslide and others are 5.77 %. As the energy supplier, the percentage of the unscheduled interruption should be as low as possible. The earlier interruption detection in the power system via modern technologies is necessary.

It was reported that insulation failure is mostly caused by electrical equipment's fault (Williams et al., 2002, and Raymond et al., 2015). Part of the statistic is contributed by a breakdown in power cables. Medium voltage (MV) cross-linked polyethylene

(XLPE) underground power cables are widely used in the power distribution, especially in the urban area. Distribution power line using XLPE power cables have become widely used because of their advantages such as lightweight structure, easy to bend, excellent electrical properties, heat resistance, transmission capacity and easy installation (Hu and Duan, 2015).

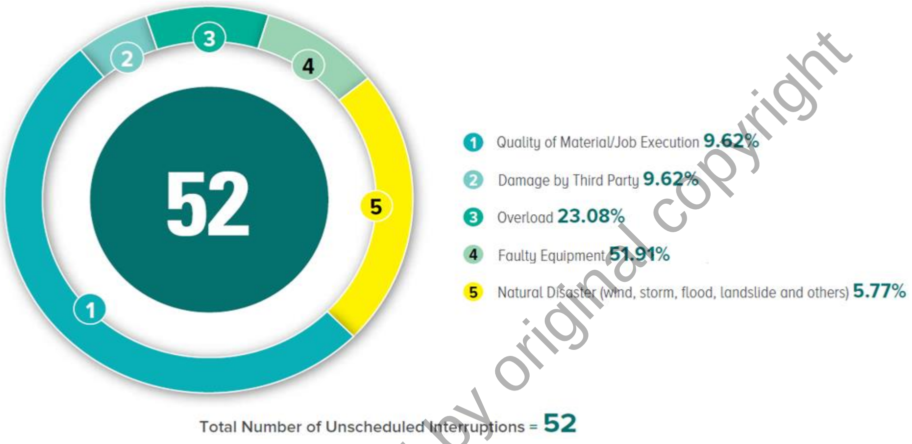


Figure 1.1: Percentage of unscheduled supply interruption by type of interruptions (Energy Commission of Malaysia, 2015).



However, partial discharge (PD) phenomenon may lead towards insulation degradation in high voltage (HV) power cables. PD is a symptom before the fault happened (Sarathi and Raju, 2005, El Mountassir, Stewart, Reid, and McMeekin, 2017, and Ibrahim and Abd-Elhady, 2017). Figure 1.2 shows the scenario of leaning rubber tree on the 33 kV XLPE power cables at Felda Chuping, Perlis, Malaysia. The falling rubber tree on the XLPE power cables may cause PDs activity which can be treated as a gliding discharge due to electric field around the cables is heavily distorted (Hashmi, 2008). PDs are produced in the air gap between the surface of the rubber tree and XLPE cables insulation. This condition may eventually cause to a total failure and in the meantime considerably reduce the life span of the power cable. Therefore, the early stage of fault detection in a power system is required in order to ensure that the MV XLPE power cables are in a good condition. Higher sensitivity and wider bandwidth sensors as an indication of insulation's health are necessary in detecting the PD signal as well.


Figure 1.2: Leaning rubber tree on the 33 kV overhead power cables at Felda Chuping, Perlis, Malaysia.

## 1.2 Research Problem Statement



Currently, the conventional sensors which has low detection in terms of sensitivity and bandwidth is a major concern in early stage of PD monitoring on HV insulation material (Olmos, Primicia, and Marron, 2007). PD sensor for insulation monitoring must be installed in on-line condition on power distribution network (Zhou, Han, and Qing, 2014). Several sensor can be installed during operation such as high frequency current transformer (HFCT) without switch off the power grid and may not risk of failure for the power lines (Sheng, Zhou, Hepburn and Dong, 2015, and Álvarez, Garnacho, Ortego, and