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To cite this article: S Akhmal *et al* 2022 *J. Phys.: Conf. Ser.* **2312** 012038

Development of Detachable Rogowski Coil Current Sensor using PCB for High Voltage Cable Partial Discharge Measurement

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Abstract. Insulation failure in High Voltage (HV) cables is evaluated using a variety of monitoring techniques. Previous silicon technologies were outperformed by wide-bandgap semiconductor power devices with faster switching speeds. Their precise current management or current protection measures must be upgraded. As a result, their precise current control or protection measures have become more sophisticated. The traditional Rogowski Coil (RC) with the magnetic core, on the other hand, has low measurement accuracy, a short measuring range, and is difficult to fabricate. This paper presents and discusses the development of a Rogowski Coil using a detachable Printed Circuit Board (PCB) as a current sensor for Partial Discharge (PD) measurement. Furthermore, the development of this innovative current sensor concentrated on the detachable PCB Rogowski Coil's capability to measure as a high-voltage (HV) current sensor and its sensitivity in fault diagnosis, over-voltage current sensing, and high-impulse current sensing on HV cables. The experimental design, techniques, and measurement parameters used in models were discussed. Finally, a brief analysis of the detachable PCB RC current sensor such as sensitivity, maximum voltage and current detection is presented. This paper can also be used as a guideline for other researchers to develop an advanced RC current sensor using PCB as a HV current sensor in the future. The measurement results of the detachable PCB RC current sensor such as the sensitivity and current detection signal can also be used as a guideline by another researcher. As a result, the goal of this project is to measure PD on HV cables using an RC current sensor by utilising PCB technology.

Keywords : Rogowski Coil, Printed Circuit Board, Partial Discharge, High Voltage

1. Introduction

Rogowski coils were introduced for the first time in 1912, and they were used to detect magnetic fields. Because the output voltage and power of the coils were limited at the time, they were unable to be used for current measurement purposes. Rogowski coils are more suitable for such applications today, thanks to the availability of microprocessor-based protection and measurement devices. [1] [2]. Typical protection designs require substantial wiring to connect a variety of protective and measuring equipment. These conventional designs are rigid as they require changes in load and power system configuration. Additionally, complicated testing and maintenance processes are required on a periodic basis. The complexity of the conventional design sometimes results in a relay malfunction. The effects of external magnetic fields and current transformer (CT) saturation also pose a problem for measurements. So, the innovative Rogowski coil design is significant for making an advanced protection system. A well-designed RC current sensor on the PCB can help reduce the chances of irregularities and short circuits. PCB have become increasingly important as technology advances at a rapid pace. They are found in virtually every electronic device, circuit boards and almost all electronic products. PCBs also play a role in noise reduction. [3]With the right components positioned on the board, it can reduce the inductance that can be created between the via holes. The PCB Rogowski current sensor is capable of withstanding high-voltage power. Many advantages can be gained by using PCB RC current sensors, including the following: no damage from a large load, the ability to measure a wide range of currents from a few milliamperes to megaamperes without saturating due to the non-magnetic core, a compact and light-weight design, a wide bandwidth between 0.1 Hz and 1 GHz, low cost, safety due to the absence of a direct connection to the main circuit, and excellent transient response[4].

2. Rogowski Coil Current Sensor Measurement

Current sensors, such as the RCs are used to measure alternating current (AC) or high-frequency (HF) current pulses in electrical circuits. RC current sensor consisted mainly of a radial coil of wire with the lead from one end going back through the coil's centre to the other end, bringing both terminals to the coil's same end. This technique is occasionally referred to as a Rogowski counter-wound [5]. Other methods employ a full toroid geometry, which has the advantage of preventing waves fluctuations in the coil from being excited by the central excitation. The entire assembly is then enclosed around the straight conductor that will be used to measure the current. The winding density, diameter, and rigidity of the coil are critical for maintaining resistance to electric fields and has low sensitivity to the measured conductor's position [6]. Due to the fact that the field created in the coil is approximately equal to the rate of change of current with in straight conductor, the output of the RC is typically connected to an integrator circuit to generate a current-proportional output signal[7]. This is frequently accomplished using single-chip signal processors equipped with integrated analogue to digital converters. Moreover, it can be made self-contained without the use of an external circuit by connecting a low inductance resistor through parallel with the output. Also, this approach strengthens the sensing circuit's protection to noise. The coil of Rogowski is usually connected to a filter and an integrator in order to function properly. A common method of accomplishing this is to use single-chip signal processors that are equipped with integrated analogue to digital converters. A low-inductance resistor connected in parallel with the output can also be used to make the circuit self-contained and eliminate the need for an external circuit. By using this approach, the sensing circuit's protection to noise is improved.
Figure **1** shows a conventional Rogowski Coil connected with a filter or integrator with a conductor induced inside the windings.

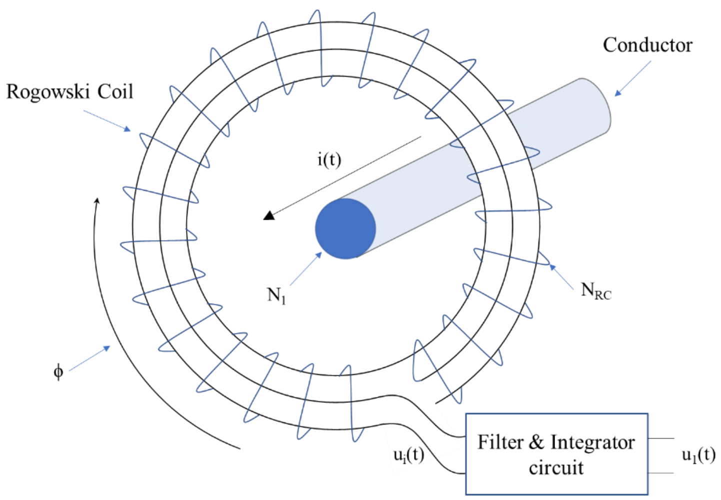

Figure 1. Rogowski Coil with filter and integrator circuit.

As illustrated in
Figure **1**, a measurement current i(t) induces an alternating current magnetic flux, which in turn induces a voltage in an RC's sensing winding. Equation (1) defines the voltage that is induced in the coil [5]:

$$u_i(t) = N_{RC}\frac{d\phi(t)}{dt}\cdot\frac{N_{RC}N_1}{R_m}\cdot\frac{di(t)}{dt} = M\frac{di(t)}{dt} \tag{1}$$

Where N_{RC} is the number of turns in the RC winding, N_I is the number of turns in the current *i(t),* R_m is the reluctance of the toroid with N_{RC} winding, and M is the mutual inductance between N_{RC} and N_I. When measuring high currents, one conductor ($N_I=1$) is naturally used.

Integrating the induced voltage according to equation (2) yields the time course of the measured current *i(t)* :

$$i(t) = \frac{1}{M}\int_0^t u_i(t)dt = \frac{k_I}{M}u_1(t) \tag{2}$$

where u_i(t) is the integrator that determines the output voltage, and k_I is the integrator constant. When measuring high current, harmonic waveforms, *I(ωt),* exist and the induced voltage can be expressed as in equation (3):

$$u_i = j\omega MI \tag{3}$$

Where $\omega = 2\pi f$ denotes the angular frequency of the current being measured in relation to the frequency, f. When measuring mains current with an RC and an integrator, the total system constant is given by equation (4):

$$k_s = \frac{U_1}{I} \tag{4}$$

where U_1 and I are the root-mean-square/effective values of the voltage on the output of the integrator and the current passing through the central conductor. It is the purpose of this paper to explore the practise of 50 turns primary windings on the printed circuit board in the calibration of RC current sensor at high currents measurement.

3. Detachable Rogowski Coil Printed Circuit Board (PCB)

The Easy Exploratory Data Analysis (EDA) PCB software is used to design the PCB RC current sensor. The high precision detachable PCB RC current sensor design presented here is comprised of a printed circuit board with a multilayer design. Figure 2 and Figure 3 shows an encapsulated circular shape with two detachable pins on the PCB RC current sensor for easier installation. The detachable PCB RC current sensor is equipped with one imprinted coil winding in each direction (clockwise and counter-clockwise). The top and bottom sides of the PCB are imprinted to establish a coil around the board's centre. Conductive-plated via holes connect the conductive imprints on the upper and lower sides of the PCB. Precision is achieved through a computer-controlled manufacturing process that ensures the coils have an accurate geometry. The detachable PCB RC current sensor designs make use of multi-layer PCBs, which results in increased accuracy and manufacturing efficiency. Detachable PCB RC current sensor can be designed in a variety of shapes to suit the application and in split-core configurations to allow for installation without disconnecting the primary. In order to make it easier to set up the HV cables during measurements, the PCB has a detachable design. The connection between the PCB RC current sensor and the oscilloscope is made using a Sub Miniature version A (SMA) connector.

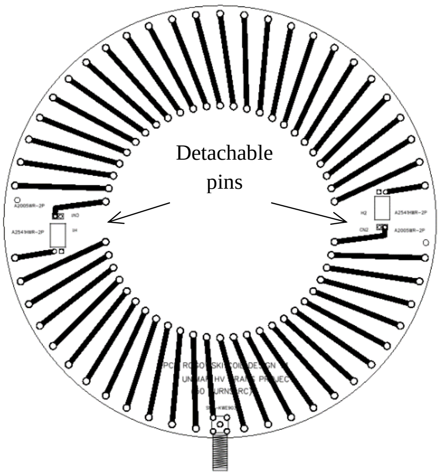

Figure 2. PCB RC current sensor in 2D view

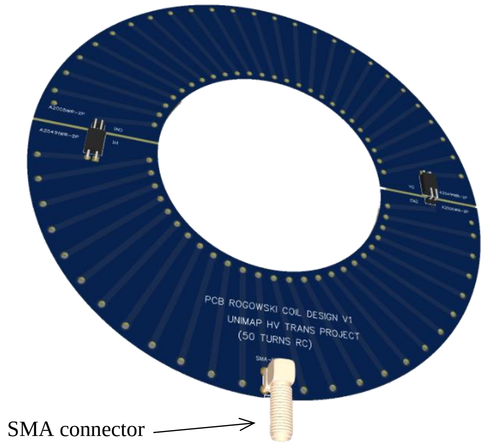

Figure 3. PCB RC current sensor in 3D view with the detachable pins

4. Limitations on PD measurement

Typically, RC is designed for high frequencies of tens to hundreds of MHz [8]. However in this experiment, the measurement performed the conventional method based on the standard IEC 60270, which measures PD pulses in a frequency range below 1 MHz. The standard approach is used to ensure the quality of HV electrical systems. This system is appropriate for laboratory measurements but not for online measurements due to the high noise circumstances for the standard measuring frequencies (<1 MHz). Other methods with greater frequency ranges and bandwidths than the IEC 60270 standard are employed to achieve adequate sensitivity in on-line measurements as well as to analyse collected signals in detail [9] . The PCB RC is built to support a bandwidth of 500 kHz to 50 MHz for this experiment, and the time domain results will be presented in this work as an early detection of the presence of PD in this experiment. It will be measured using the designed filter that will be developed later on to obtain the frequency domain result.

5. Experimental setup for mesurement testing

Figure 4 and Figure 5 depicts the experimental setup for the testing of Partial Discharge (PD) measurement. Parameters for PCB RC current sensors must be calculated and set before the experiment is conducted. HV pulses are injected from the Impulse High Voltage Sources using a High Voltage Construction Kit HAEFELY HV test set. HV pulses are supplied through the HV cable ranging from 1kV-10kV.Two current sensors are used in this experiment. The measurement devices are High Frequency Current Transformers (HFCT), and the second device is a PCB RC current sensor. This is done in order to compare the results of two devices. PCB RC current sensor is connected around the conductor in the circuit and it must be grounded. The connection between the PCB RC current sensor and the oscilloscope is made using a Sub Miniature version A (SMA) connector. The output of the RC is obtained by connecting the SMA coil terminal using a low-capacitance Active Differential Probe (ADP) to the LeCroy Wavesurfer 24Xs oscilloscope. Due to the air core, the sensitivity of the PCB RC current sensor is low, and care must be taken to guarantee the reliability of the measured signal. Because ADP decouples the RC from ground, it greatly reduces loop currents and common voltages at the terminals[8]. Primary current pulses are measured using HFCT as a reference. The primary windings of the HFCT enable it to be used as an accurate reference device for high frequency current waveform measurements. Tests are carried out by observing the RC output waveforms and the oscillation frequency. Two sets of measurements are planned to develop to determine the functionality of the detachable PCB RC current sensor.

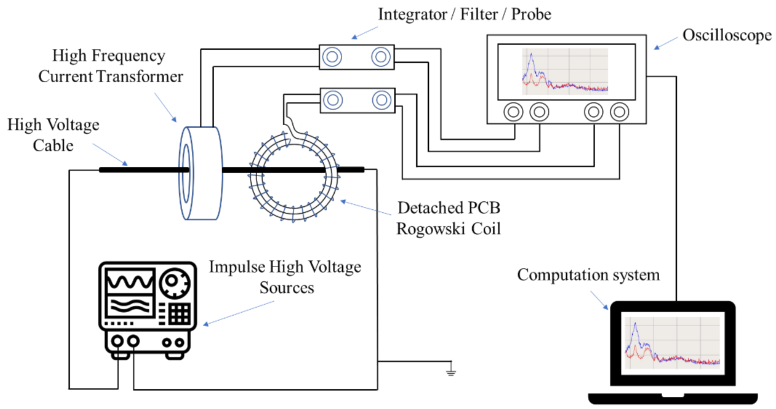

Figure 4. Experimental Setup for Partial Discharge Measurement

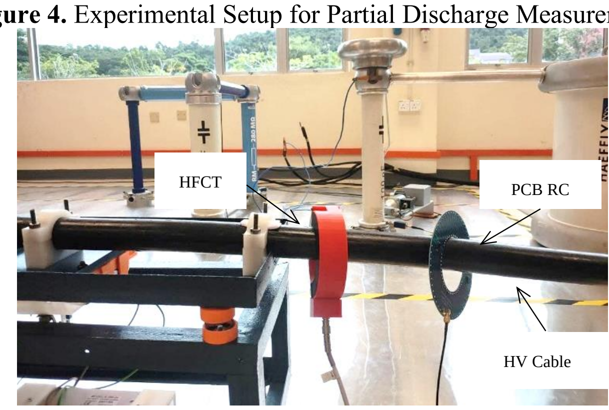

Figure 5. Measurement testing setup in High Voltage Lab UniMAP, Perlis.

6. Data acquisition of PD measurement

The sensitivity and bandwidth of the PCB RC current sensor prototype have been evaluated in the laboratory in order to compare the performance of the two sensors. It has been successfully demonstrated that the PCB RC current sensor prototype can induce current propagation of HV pulse produce by Impulse HV source along a high-voltage cable. Despite the fact that the system was subjected to a range of impulses ranging from 1KV to 10KV, this report will present a concise result with only two data measurements that demonstrate that the PCB RC current sensor is capable of sensing the PD pulse. The first data set will be tested on a 3KV measurement, and the second data set will be tested on a 4KV measurement. HFCT and PCB RC current sensor measurement output captured in the time domain within a very short period of millisecond is represented by the Figure 6 below.

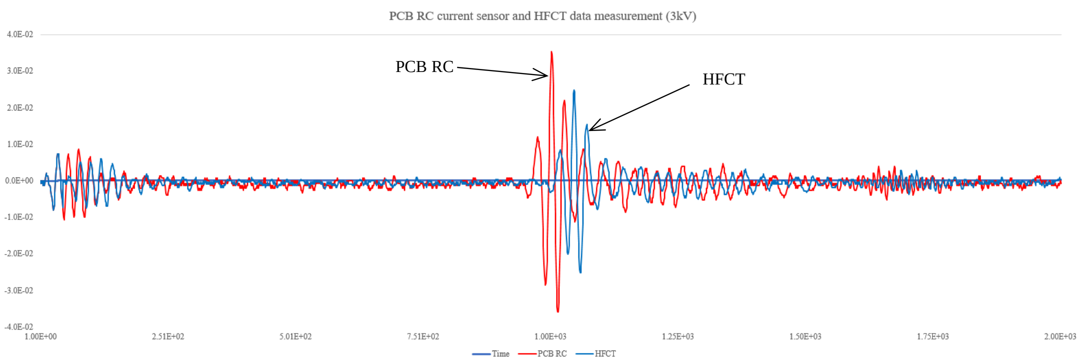

Figure 6. PCB RC current sensor and HFCT data measurement for 3KV testing

Based on the results represented in **Table 1**, the higher positive amplitude of the PD signals measured by the PCB RC current sensors when compared to the HFCT sensor demonstrates the greater sensitivity of the PCB RC current sensors by 30.02%. In terms of voltage sensing, the PCB RC current sensor provides higher sensitivity because of PCB eliminates the probability of the error. A PCB RC produces less electronic noise than a HFCT. The noise can have a significant impact on the overall performance of the circuit. In addition, the graph reveals that the PCB RC current sensor provides a faster response time when compared to the HFCT response time.

Table 1. Experimental result for PCB RC current sensor and HFCT for 3kV

Type of Sensor	Amplitude (mV)
PCB RC current sensor	35.3
HFCT	24.7

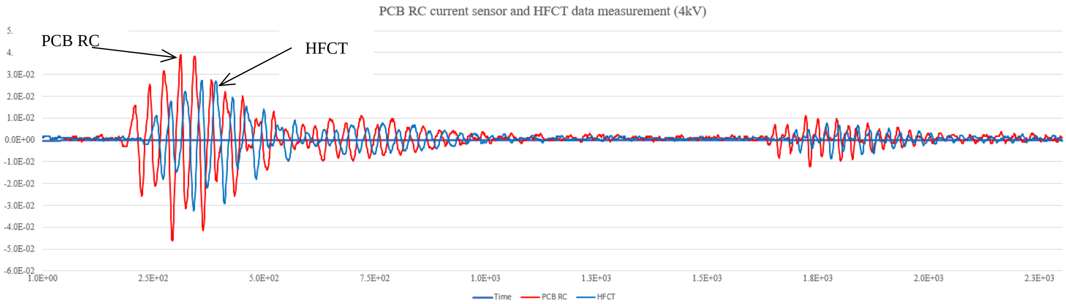

Figure 7. PCB RC current sensor and HFCT data measurement for 4KV testing

Data measured in Figure 7 and Table 2 also shows the same pattern with the previous data measurement. PCB RC current sensor has more sensitivity compared to the HFCT. The increment in the measured signal captured between the PCB RC current sensor and the HFCT on both measured supplies is proportionally increased by 9.4 percent compared to the baseline signal captured. Therefore, the larger the PD pulse source that has been detected, the greater the amount of sensitivity that will be detected. This paper only presents the results of an oscilloscope measurement of sensitivity; many other data points were collected during the measurement process and are not presented here for convenience. Only a few measurements are presented in this paper, but they are sufficient to demonstrate that the development of the PCB RC current sensor may be capable of achieving the same detection as the HFCT.

Table 2. Data measurement for PCB current sensor and HFCT for 4kV testing

Type of Sensor	Amplitude (mV)
PCB RC current sensor	39.0
HFCT	27.3

7. Conclusion

This paper discusses the development of a PCB RC current sensor as well as a method for detecting the breakdown of insulating materials caused by the PD phenomenon. With particular emphasis on the progression from helical to PCB implementation and the applications in power electronics, it is also worth reading. According to the findings of this study, the PCB RC current sensor will continue to be relevant in the future, especially with the development of more power-electronic systems that use wide-bandgap devices. Its functions remain the same: to provide short-circuit protection, condition monitoring, loss computation, and control in an matchless small footprint, which is required for the construction of a compact power-electronic system with high efficiency. But despite this, there are still issues that need to be resolved in terms of structure, anti-interference, core insertion, signal processing and model development. The noises under investigation must be reduced to white and harmonic noises, despite the fact that there is no appropriate range of pulsating interferences, which are significantly more difficult to operate due to their resemblance to the shape and frequency spectra of the PDs, to be investigated. Aside from that, there is a scarcity of automatic adjustment methods that can be used to increase the system's long-term viability while decreasing the reliance on the operator's ability. Exploration to answer these and other unanswered questions must, therefore, continue indefinitely.

8. Acknowledgement

The authors would like to acknowledge the support from the Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis (UniMAP) for the FTKE Research Activities Fund and would like to thank the Ministry of Higher Education (MOHE) Malaysia for the additional monetary support under the Fundamental Research Grant Scheme (FRGS) (Grant No: FRGS/1/2019/TK04/UNIMAP/03/5).

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