ROGOWSKI COIL SENSOR FOR PARTIAL DISCHARGE DETECTION

PUOVIN MURUGAIAH

UNIVERSITI SAINS MALAYSIA

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ROGOWSKI COIL SENSOR FOR PARTIAL DISCHARGE DETECTION

by

PUOVIN MURUGAIAH

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RC	Rogowski Coil
CCC	Current-carrying conductor
PD	Partial Discharge
CT	Current Transformer

ABSTRAK

Istilah nyahcaj merujuk kepada ancaman yang boleh menyebabkan kelesuan pada penebatnya di zon medan elektrik yang sangat tinggi. Oleh itu, untuk mengelakkan kelesuan berlaku, pemerhatian yang kerap dilakukan dengan menggunakan kaedah pengesanan yang tepat. Pengukuran nyahcaj jenis ini adalah penting kerana kewujudannya berkaitan dengan penuaan penebat dalam peralatan elektrik. Pengukuran PD biasanya digunakan untuk menilai kualiti penebat peralatan voltan tinggi. Terdapat banyak alat pengesan PD yang ada di pasaran, dan pengesan menggunakan banyak teknik yang berbeza dalam mengukur PD. Makalah ini membentangkan sistem pengesanan PD peranti mudah alih dan kos rendah dengan penggunaan gegelung Rogowski (RC). Kekerapan frekuensi tinggi kerana PD dikesan oleh RC. RC dibangunkan untuk julat frekuensi tinggi dari satu MHz sehingga pesanan seratus MHz. Analisis eksperimen dilakukan untuk menilai prestasi gegelung Rogowski dan kesan litar yang dirancang pada bentuk gelombang RC untuk pengesanan PD. Eksperimen diatur dalam makmal voltan tinggi. Ujian dijalankan mengenai keadaan pengukuran seperti sistem pengukur PD dalam talian. Isyarat PD yang dijana oleh penjana pulse dilalukan melalui pusat RC di mana keluarannya telah disambungkan ke litar yang dirancang. Pengukuran dibuat dengan menggunakan osiloskop untuk mendapatkan bentuk gelombang yang dihasil. Reka bentuk litar dilakukan untuk meningkatkan output RC untuk sistem pengesanan yang lebih baik serta mendapatkan isyarat yang mereplikasi isyarat PD sebenar. Daripada eksperimen ini disiasat bahawa kaedah pengesanan RC ini berfungsi secara linear dan dengan kepekaan tinggi ke input terendah (5pC).

ABSTRACT

The term partial discharge refers to the partial breakdown of insulation that develops in zones of highly concentrated electric fields. So, to prevent the breakdown occurs frequent observations must be done by utilising precise detection methods. The measurement of this kind of discharges is of importance because its existence is related to the aging of insulation in electric equipment. Partial discharge (PD) test is normally used to evaluate the insulation quality of high-voltage equipment. There are many PD detectors available in the market, and the detectors employ many techniques in measuring the PD. This paper presents a simplified and low cost device PD detection system with the use of the Rogowski coil (RC). The high frequency pulses due to the PD are detected by the RC. RC is developed for high frequency range from one MHz up to order of hundred MHz's. An experimental analysis is performed to evaluate Rogowski coil performance and the effect of designed circuit on output waveform of RC sensor for PD detection. The experimental set-up is arranged in high voltage laboratory. The tests are carried out concerning measurement conditions such as on-line PD measuring systems. Input PD signal generated by pulse generator is passed through the centre of RC where the output of it is already connected to the designed circuit. The measurement is made by using oscilloscope to capture the output waveform. The circuit design is done to improve the RC output for better detection system as well as to obtain the signal that is replicates the input PD signal. From the experiment it is investigated that this RC detection method works linearly and with high sensitivity to the lowest input (5pC).

CHAPTER 1

INTRODUCTION

1.1 Backgroud

The usage of high voltage equipment determines the stability of any power system network [1]. This has become a major concern to a handful of distribution companies since the requirements of power supply networks and optimization of network assets has increased significantly. It is to be noted that, failures of equipment are commonly related to the activity of partial discharge (PD). [2]

PD are localized electric discharges in a partial region of a liquid or solid electrical insulation system under high- voltage field pressure which deteriorates the system performance and can lead to breakdowns, fires or irreparable damage to the system [3]. PD is a small start of flash that happens inside the insulation of electrical equipment. There are currently three types of PD that are commonly known today which are corona discharge, surface discharge and internal discharge [3]. Each PD event generates low amplitude pulses of extremely short duration. These pulses can be observed as voltage and current pulses, superimposed on the mains voltage and current. Due to the very short rise time, the spectrum of such transients can reach well into the radio frequency region.

This is the reason partial discharge detection is used as a part of energy system to monitor the high voltage equipment's health condition so that it is not exposed to any unnecessary hazards [1]. A sensor for detecting and accurately quantifying the pulses is required to have a wide operating bandwidth and high sensitivity. Table 1.1 shows some of the requirements of an ideal high frequency pulse current measuring sensors [2].

Table 1.1: Requirements of ideal high frequency pulse current measuring sensors

FEATURES	PARAMETERS
Physical	• Cost effective • Light weight • Flexibility of installation.
Measurement	• Suitable for online non-intrusive measurements, • Safety of the sensor and measuring system.
Operational	• Higher sensitivity • wide bandwidth • linearity of operation

In the event where PD takes place, the risk of insulation system dielectric instability is high. Hence, the measurement and monitoring of PD is very much significant [4]. The IEC standard 60270 is commonly used as a benchmark during the detection of PD current and charge by commercially available instruments [5]. There are various types of sensors to detect PD pulse such as antenna, acoustic sensor, chemical sensor and Current Transformer (CT). However, The Rogowski coil (RC) has been considered to be one of the most favourable sensors with respect to the above requirements [2]. The RC is defined as a transducer which is able to detect PD current signal. The RC is used in order to measure the PD currents which has high frequency signal.In addition, and the RC is a favorable sensor due to its lightweight, fast response and low cost equipment for PD detection. For applications such as PD detection and measurement, the design of the coil is focused on high frequencies up to tens to hundreds of MHz. The geometrical parameters of the RC will very much affect the features mentioned above [2].

In this research, the developed RC detects the PD pulses generated by pulse generator. To achieve the features above, geometrical and electrical parameters are specified. Experimental test is done to investigate the effect of high pass filter and amplifier circuit with three types of modification on output waveform of RC. The final output waveform is analyzed and the result obtained are briefly discussed in this paper. It is essential that a power system designer and a power system installation maintenance engineer to have a good understanding with regards to PD mechanisms, characteristics and its development processes.

1.2 Problem Statement

Presence of PD need to be prevented to avoid electrical equipment from getting damaged. To detect the presence of PD a suitable RC sensor is needed. Besides, parameters of the RC sensor is important to detect high frequency PD signals. A proper RC sensor able to provide more reliable and accurate measurement results. The RC produces output which has very low amplitude voltage pulses.

At this moment, the experiment conducted in the high voltage laboratory USM to diagnose the PD in insulation oil is using the impedance matching circuit (IMC). The PD measurement using IMC should have the reference device to ensure that the measurement is accurate. Thus the RC is determined as one of the detecting device to be the reference of the PD detection.

1.3 Objective

The objective of this research are as follow:

1. To detect partial discharge pulse.
2. To develop Rogowski Coil for partial discharge measurement.
3. To amplify the PD signal detected by RC.

1.4 Scope of Work

The scope of this research is to develop a Rogowski Coil that can detect Partial Discharge signals with high frequency. Besides, the recommendations to specify the parameters of the coil that can affect the sensitivity and performance. Design amplifier circuit to improve the detected signal by RC. Three different types of amplifier circuit is designed to see the effect of amplification on RC measurement. Do analysis on obtained signal and data to find out the sensitivity and the linearity of this RC sensor.

1.5 Thesis Outline

The thesis is classified into 5 chapters, the outline of the thesis can composed as follow;

Chapter 2 summarizes literature review of PD measurement device. The PD detection methods and disadvantages are described. The definition, design and working principle are discussed.

Chapter 3 describes the methodology used to conduct the project. This chapter explains the project flow and the test method to determine PD. This chapter describes how the RC is constructed and how the amplifier circuit is designed.

Chapter 4 presents the actual PD signal and RC measurement signals for different PD magnitude. Analysis is made in this chapter to find out the linearity and sensitivity of this detection sensor. A brief discussion is made on the RC measurements.

Chapter 5 concludes the thesis work and the recommendation for future work addressed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter review on the PD detection methods. The review includes the definition, the geometrical parameters and electrical equivalent circuit of RC. This chapter ends with the summary literature review.

2.2 Partial Discharge

The failures caused due to electrical insulation are one of the reasons of unexpected disruption in power systems and associated electrical machines and power cables. In general, the power generation, transmission and distribution are stated to be the most expensive electrical assets in high voltage power systems, which are subjected to numerous electrical, thermal, environmental and mechanical stresses [8].

The PD issues are a common cause leading to power system failure. PD can be stated as an electrical discharge or pulse generated in a dielectric solid surface or liquid insulation system. PD occurs when insulation containing defects or voids is subject to high voltages. If left untreated PD can degrade insulation until insulation failure occurs.

2.3 Partial Discharge Detection

PD detection system is a system that can detect and display PD signals for better reliability. This system can work in many ways with various types of detection methods. The PD emitted energy as electromagnetic emission, acoustic emission and ozone and nitrous oxide gases. PD signals can be detected by using these emitted energies [9].

The first stage is the pre-breakdown operation, starting with slow damage of the insulation followed by further insulation degradation with time. Second one is a post-breakdown condition when the complete failure of the insulation occurs, and the component is damaged beyond recovery. If an upcoming fault can be detected during the pre-breakdown operation, the faulty component could be repaired in advance, which would lead to significantly shorter power outage duration due to the faulty component.

Currently, there are two types of measurement techniques carried out to test if there are any faults along the CC line. They are on-line and off-line measurements. With the on-line measurement, the power line continues working as normal and no disruption of service is required. The methods currently available are using very high frequency (VHF) antennas, infrared sensors, acoustic, radiometric, capacitive coupling and Rogowski coil [10].

2.3.1 Acoustic Detection

The non-electric type measurement like acoustic emission method is often concerning localization of the PD origin. Acoustic detection, concentrates on the capturing and recording of an acoustic signal produced by a PD. The acoustic emission Methods can be very effectively used for the online PD Detection, since this method is immune to Electromagnetic noise, which can greatly reduce the sensitivity of electrical methods, especially when, applied under field conditions [11].

2.3.2 Radiometric Detection

Radio frequency detection of PD is a long-established principle, being described in the international standard for PD measurement. In its simplest form, a directional radio receiver can be used to determine the general location of an electrical discharge within a high voltage equipment’s. As the ability to perform RF measurements became more readily available, studies of these measurements for PD applications were carried out. Radiometric detection method basically can be related to electric detection method. The electrical pulses take place in the nanosecond order. Besides that, it has a frequency component that can be measured over 1 MHz [12].

2.3.3 Electrical Detection

The electrical detection methods are very sensitive to the Electro-magnetic interference, also such interference signals may be controllable in a Laboratory. There are many types of current detecting hardware has been proposed for transient current measurements in Electrical field [13]. The Rogowski coil has been proposed to be a standout among the most suitable sensor which fulfils most of the requirements. Rogowski coil was named after Walter Rogowski.

Rogowski coils be made up of helical coil of wire with the lead from one end returning through the centre of the coil to the other end, so that both terminals are at the same end of the coil and the two ends are usually connected to a cable. It is usually designed in shape of a donut or toroid. Circular, oval and rectangular are the most familiar core cross sections. These electrical devices are unique in that their coil turns are wound around a non-magnetic air core, rather than an iron core [2].

In this research, the design of a Rogowski coil to measure very low currents, but with a very high frequency, such as partial discharges, is exposed. The Rogowski coil used as a PD transducer is very advantageous because it is inexpensive and easy to use. Besides, it provides the needed bandwidth for this application [15]. D. Ward and J. Exton [16] showed that Rogowski coils have better performance in a vast majority applications; lightning test, partial discharge monitoring and sudden short circuit test, as compared to the other current measuring devices. Kojovic [17] proposed a new configuration of Rogowski coil based on printed circuit board (PCB) being useful in transient current measurement. In this paper, the number of PCB coils was increased without decreasing its bandwidth to improve the amplitude of the coil's output signal. Figure 2.1 shows typical RC sensor with various diameter size.

Figure 2.1: RC with various diameters

Table 2.1: Advantages and Disadvantages of RC

ADVANTAGE	**DISADVANTAEGE**
• Flexible core coils • Non-intrusive to the live conductor • Easy temperature compensation • No risk of secondary winding opening • Excellent linearity (have no magnetic materials to saturate)	• The output of the coil must be passed through an integrator circuit to obtain the current waveform. • Rogowski coil does not have a response down to DC

Table 2.1 shows the advantages and disadvantages of the RC sensor. Because of these disadvantages as in Table 2.1, Rogowski Coil are essentially utilized when ease-of-establishment is a high priority. Traditional or split- centre current transformers are utilized when precision, noise immunity and currents during power quality events are a high priority.

2.4 WORKING PRINCIPLE OF ROGOWSKI COIL (RC) [8]

The output voltage produced by rogowski coil as in equation 2.1,where A is the area of one of the small loops, N is the number of turns, l is the length of the winding(the circumtance of the ring), $\mu_0 = 4\pi \times 10^{-7}$ V.s/(A.m) is the magnetic constant, R is the major radius of the toroid and r is its minor radius.

$$v(t) = \frac{-AN\mu_0}{l}\frac{dI(t)}{dt},$$ 2.1

- Flux induced

$$\Phi = \int d\Phi = \int \mu_0 ANH\, dl \cos\alpha$$ 2.2

And

$$M = AN\mu_0$$

Where N is the number of turns of the coil. Equation (2.4) shows the importance of the mutual inductance M in current measurement sensitivity. That is as M increases the induced voltage across the coil, Vrc increases.

$$i_{in}(t) = \int H\, dl \cos\alpha$$ 2.3

Where i_{in} is the total electric current bounded by the enclosed path (2.3). H is the magnetic field intensity in Amperes/m, and is related in free space, to the magnetic flux density B (in Tesla).

$$V_{rc}(t) = -M\frac{di_{in}}{dt}$$ 2.4

This formula assumes the turns are evenly spaced and that these turns are small relative to the radius of the coil itself. The output of the Rogowski coil is proportional to the derivative of the wire current. The output is often integrated so the output is proportional to the wire's current:

- Rogowski coil around Conductor

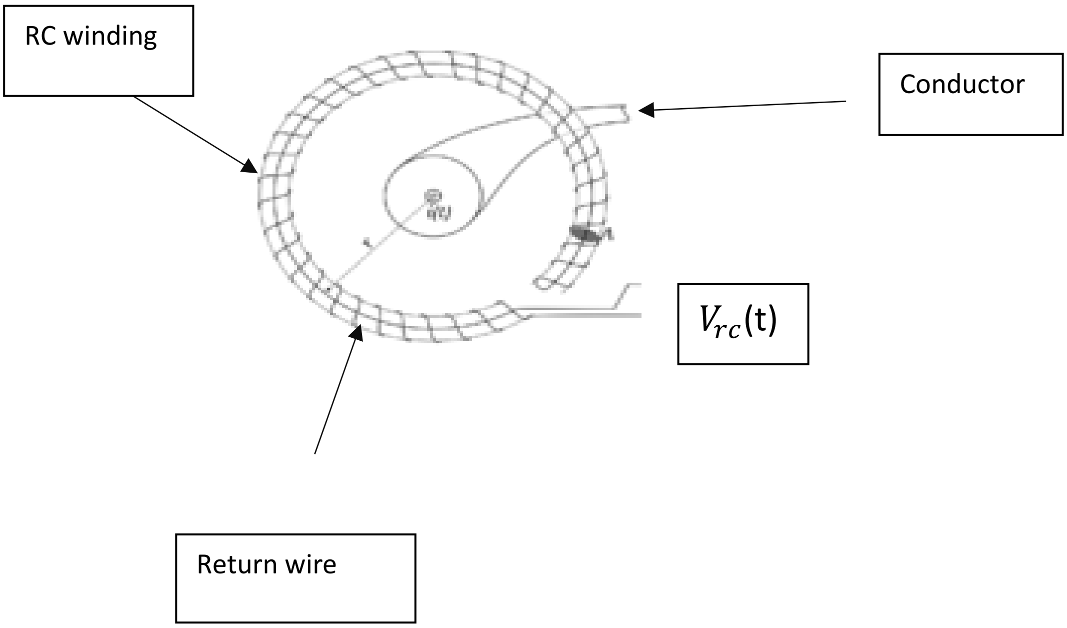

Figure 2.2: RC mounted around conductor [2]

The Figure 2.2 shows RC sensor with the current conductor placed on the centre for detection. The RC winding is a helical coil of wire which wind on the core surface. The return wire is lead from one end returning through the centre of the coil to the other end to complete the loop. The PD detection is applied around conductor without disturbing the flow of the current in conductor. After the detection the RC gives Induced voltage as the output [2].

2.5 Geometrical Parameters of RC

The Figure 2.3 shows all geometrical parameters included in RC development and how the changes in parameters can affect the performance of the RC sensor. Geometrical parameters need to be considered before design a RC. RC can be designed in various types with different sets of parameters and materials. As shown in Table 2.3 Parameters can influence the performance of these Rogowski coil. Selection of parameters according to recommendations will improve the sensitivity and bandwidth of this coil in PD detection [2]. Current range and frequency range up to one to hundreds order of MHz of the signal that need to be measured can be adjusted by changing the parameters of the coil.

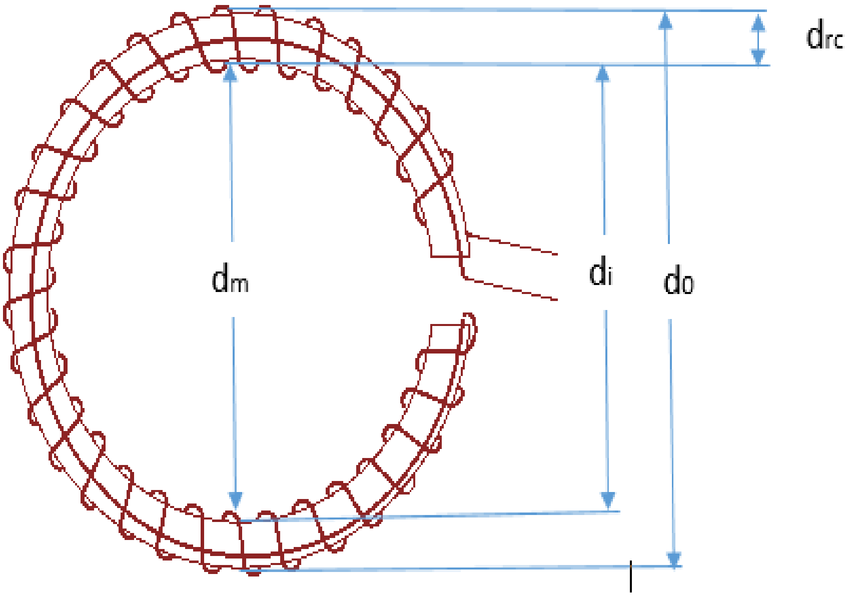

Figure 2.3: Geometrical parameters of RC [2]

Table2.3: Recommendations for RC geometrical parameters

PARAMETERS	RECOMMENDATIONS	
	Changes	**Advantages**
Diameter of coil , dm	• Decreasing	• Improved performance • Sensitivity increase • Bandwidth increase • Lower weight • Smaller size • Easy placement of test line in the center of coil
Diameters of core , drc	• Decreasing	• Easy installation • Easy for bend and to get shaped • Less space required
Number of turns , N	• Less turns	• Improve the bandwidth significantly • Reduce weight
Diameter of wire , dw	• Larger	• Reduce resistance of wire • Good mechanical strength

CHAPTER 3

METHODOLOGY

3.1 Introduction

The chapter discuss about how this research was conducted. The apparatus and devices that used in experimental setup is explained. This chapter proceeds with Section 3.2 which elaborate about the flow of research. In Section 3.3, development of RC is discussed and diagram of the assembled RC is included. It continues with Section 3.4 which contains the geometrical parameters of RC designed in this research. In addition, calculations and formulas are briefed to determine the characteristic of RC corresponding to geometrical parameters used. Lastly, the experimental test setup diagram is presented.

3.2 Flow of Research

The knowledge about RC is important in this research. The main cause of designing the Rogowski Coil is determined. The significant facts that affect the sensitivity, bandwidth and performance of this RC were emphasized and jotted down to improve the understanding of this device. The parameters which include electrical and geometrical of RC were identified and shortlisted for the purchasing purposes. Then, RC is constructed and tested in lab. Experimental test with PD pulse generator carried out. The output waveform and result is than analysed and discussed briefly.

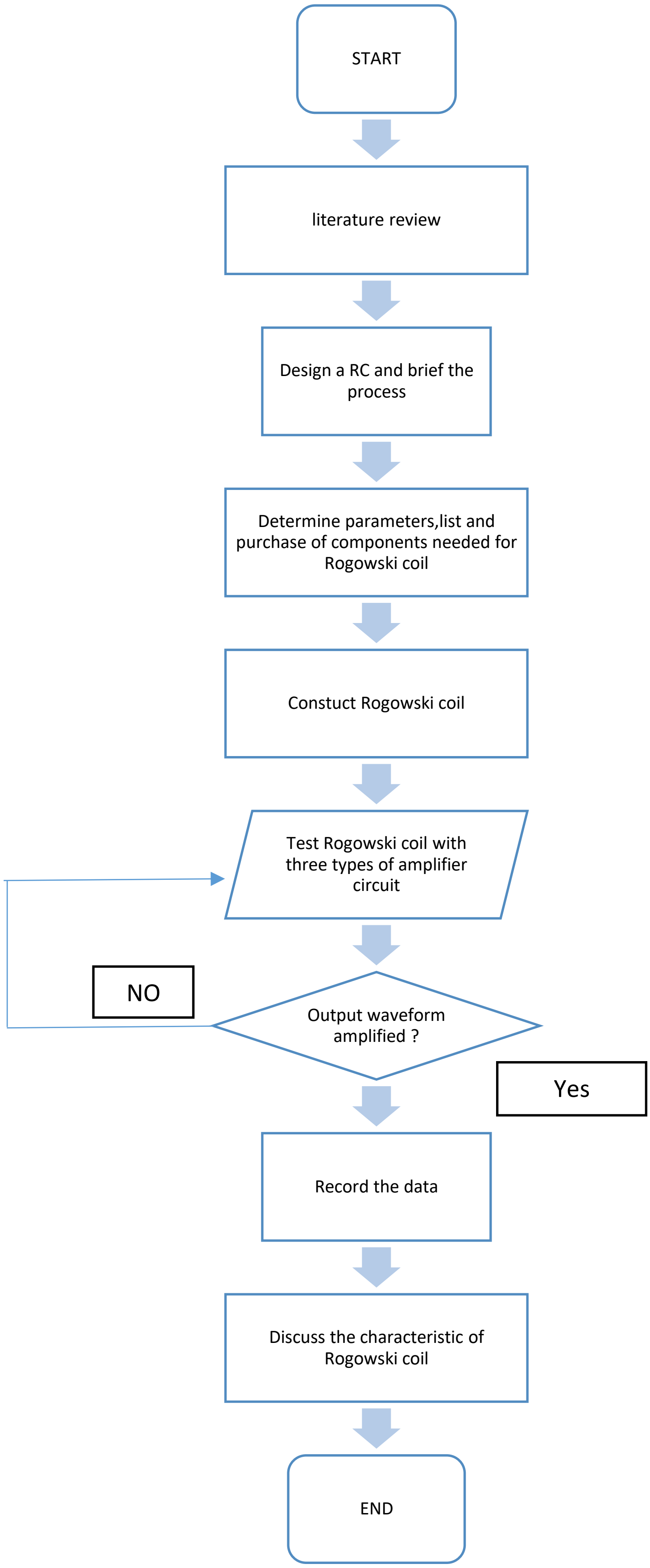

Figure 3.1: Flowchart of research

3.3 Development of Rogowski Coil

Development process of Rogowski Coil needs very clear understanding from other references and journals. Before the development process starts, should have a clear view on definition of Rogowski Coil and the main purpose of Rogowski coil is designed. Figure 3.2 shows the electrical equivalent circuit for RC which consist of Rc, Lc and Cc.

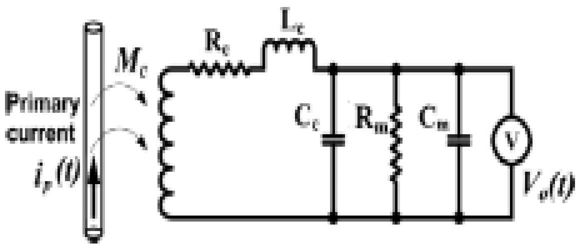

Figure 3.2: Electrical equivalent model for Rogowski coil.

Rogowski coil is mainly an elastic or flexible type sensing equipment in electrical field. Therefore, a flexible type material have to be chosen as core for the Rogowski Coil development. So the designed RC will be easy for handling and easy for installation process. In installation process the Rogowski Coil have to bended into circular shape to be mounted around the current-carrying conductor.

A PVC flexible pipe was chose as the material of non-magnetic core of Rogowski Coil. Advantages of using this mentioned pipe are its flexible, lightweight, elastic and low coast. The parameters of the PVC pipe are suitable for the objective of this research. Furthermore, copper wire is used as the winding wire for the development of RC. The copper wire was chosen because it is a good conductor of current (good conductivity). The diameter of winding wire will effect on the resistivity. According to past research in chapter 2, a proper diameter of copper wire is chose for a low resistivity. The Copper wire is than wind all over the surface of PVC pipe With N number of turns and the return loop of the RC is passed through the centre of the hollow shaped PVC pipe to make both terminals accessible at the same end of RC.

3.4 Geometrical Parameters of Rogowski Coil

The Figure 3.3 shows the constructed RC sensor according to specified parameters as in Table 3.1.The Figure 3.4 shows the end of the return loop which passed through the center of the RC core from the other end. Figure 3.5 shows the RC sensor after the ground wire and the return loop soldered with BNC connector for easier connection method with oscilloscope.

Figure 3.3: Constructed RC

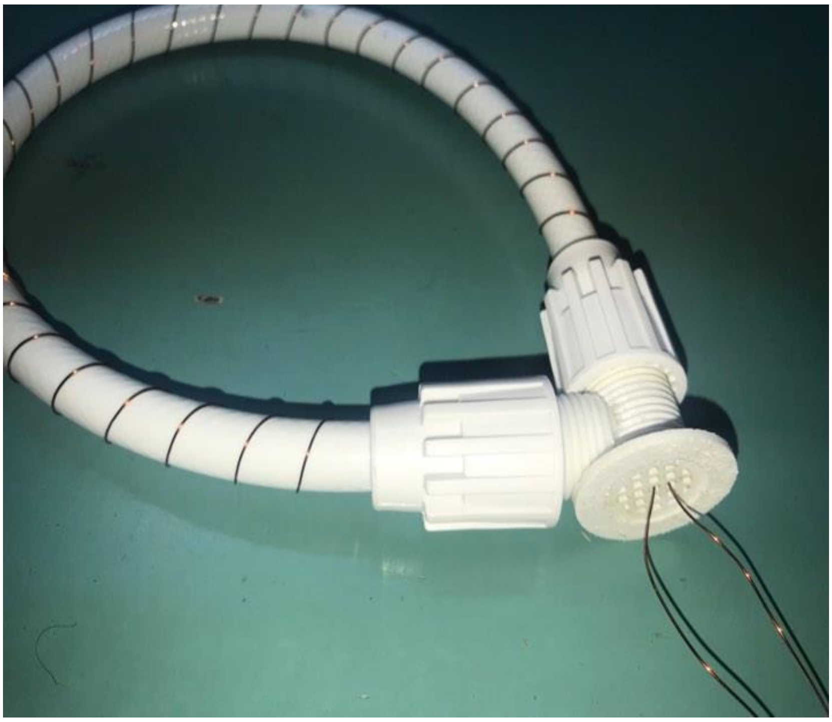

Figure 3.4: Return Conductor

Figure 3.5: BNC connector with RC

Geometrical parameters used for the development of Rogowski coil are listed in Table 3.1. All parameters chose based on recommendations given in [8].This parameter are reported to design a RC with high frequency range of detection from one MHz to order of hundred MHz.

Table 3.1: Geometrical parameters used in this research

PARAMETERS	MEASUREMENTS
Outer diameter of coil , d_o	155 mm
Inner diameter of coil , d_i	125 mm
Mean diameter of coil , d_m	140 mm
Core diameter , d_{rc}	15 mm
Length of coil , l	475 mm
Radius of wire , r	0.5 mm
Number of turns , N	30

3.5 Characteristics Determined by Geometrical Parameters

Calculation was made to determine all the electrical parameters of RC based on the geometrical parameters specified.

3.5.1 Mutual Inductance

Mutual inductance is a decisive parameter for the assessment of a coil's sensitivity. Its value depends on the shape of the cross section of the core used for the coil winding. The most common core cross-sections are circular, oval or rectangular. For different shapes of the coil core cross-section, different expressions are available to determine the mutual inductance. For a circular shaped RC the mathematical formulae is as below [2]:

$$M_c = \frac{\mu_\circ N(\sqrt{R_{out}} - \sqrt{R_{in}})^2}{2} \qquad 3.1$$

Where N = number of turns, permeability constant $\mu_\circ = 4\pi \times 10^{-7} NA^{-2}$, R_{out}=outer diameter and R_{in}=inner diameter

3.5.2 Self – resistance

The coil's self-resistance is due to the resistance of the wire that is used for construct the winding. The copper coil resistance is given by [2]:

$$R_c = \rho \frac{l}{\pi r^2} \qquad 3.2$$

Where copper resistivity, ρ=1.68 × 10^{-8} , l = length of wire, r = radius of winding wire.

3.5.3 Self - inductance

The coil inductance of single circular loop of wire is given by equation (3.3) [2]:

$$L_c = \frac{\mu_\circ N^2 h}{2\pi} \log \frac{R_{out}}{R_{in}} \qquad 3.3$$

h = height of RC

3.5.4 Self – capacitance

The self-capacitance of a Rogowski coil with the construction specified above could be observed as the sum of two capacitance values. The first one is the turn-to-turn capacitance of the coil turns, present for each multi-turn inductor. The second is a specific capacitance that is due to the return wire in the centre of the winding. In the latter case, the capacitance is formed between the turns of the coil and the return winding.

The capacitance value is given by [2]:

$$C_c = \frac{4\pi^2 \varepsilon_\circ (R_{out}+R_{in})}{\log\left(\frac{R_{out}+R_{in}}{R_{out}-R_{in}}\right)} \qquad 3.4$$

Where air permittivity, $\varepsilon_\circ = 8.85 \times 10^{-12}$

3.5.5 Turn-to-Turn Gap

The distance between each turn, g is calculated as [2]:

$$g = \frac{2\pi}{N}\left(\frac{R_{out}+R_{in}}{2}\right) \qquad 3.5$$

3.5.6 Turn-to-Turn Capacitance

Capacitance between gaps of turns is given by [2]:

$$C_{gap} = \frac{\pi \varepsilon_\circ l}{N \log\left(\frac{g}{D_{rc}} + \sqrt{\left(\frac{g}{D_{rc}}\right)^2 - 1}\right)} \qquad 3.6$$

3.6 Circuit Design

This section presents the circuit design of amplifier circuit. All the designed circuit is printed and soldered in PCB. Three types of modification made using this amplifier circuit to see the effect on the output signal of RC. The circuit is designed to improve the produced output waveform from the RC sensor. The first type of circuit is amplifier added with high pass filter and 50 ohm resistor in series. The second type is the amplifier is added with 50 ohm resistor in parallel in the beginning. The third type of circuit is amplifier circuit is modified with 1k ohm resistor at the beginning of the circuit. These all three types of circuit are tested using same range of PD pulse generator input range to see the effect on the output signal of RC.

3.6.1 Metal Casing for the PCB

The designed circuit is printed in the PCB and placed in a metal box with its casing as shown in Figure 3.6.This metal box helps to prevent any external low frequency noises and signal from disturbing the performance of the circuit. So this helps to improve the stability of this RC output. This also provides more reliable PD detection system. Figure 3.7 shows the metal box which already covered with its casing and all the terminals like Vcc, ground, input and output labelled properly.

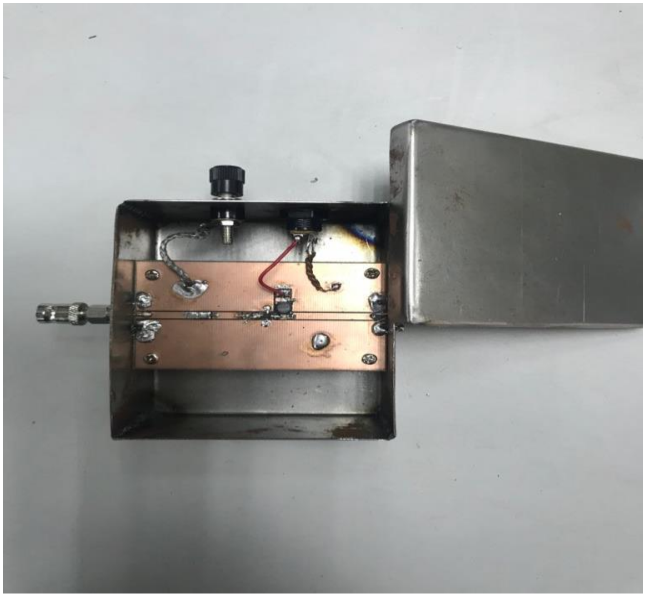

Figure 3.6: PCB placed in the metal box with its casing

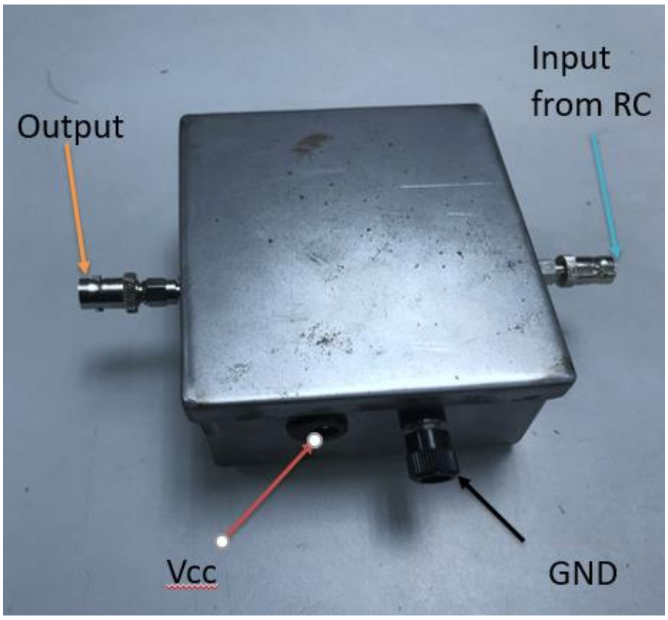

Figure 3.7: Covered metal box with its terminals labelled.