Partial Discharge Propagation and Sensing in Overhead Power Distribution Lines

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledge.

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Kheng Jern KHOR

26/03/2010
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Summary of Research

Partial discharge phenomenon have been widely researched and commonly accepted as precursors to potential distribution line failures. The work in this thesis focuses on developing a low cost and market competitive online partial discharge monitoring system for distribution lines.

The work carried out in the early stages examines the sources of partial discharges such as damaged insulators and damaged conductors. Online and offline methods were evaluated for their suitability in detecting faults in distribution lines. Common online fault detection methods such as leakage current monitoring, acoustic detection, electromagnetic radiation sensing and infra-red imaging will be presented in the literature review.

To further understand the characteristics of the partial discharge signals, a test was carried out on an artificially polluted insulator covered in kaolin. The 22kV ceramic insulator was artificially polluted to produce partial discharge signals for data collection and further observation. Capacitive voltage dividers were used to step down the line voltage for safe monitoring on the oscilloscope throughout the entire test.

With a better understanding of the partial discharge signal, the information is then used in a computer simulation. The two simulation packages used for simulations are MATLAB and ATPDraw. As MATLAB was easier to control and allows consideration for skin effect, the final data presented was simulated using the MATLAB package.

The next stage of this thesis looks into the design of sensors capable of detecting partial discharge signals. The two sensors designed are the PCB Rogowski Coil and the capacitive coupler. Both sensors are able to detect high frequency signal but the capacitive coupler proved to be more reliable and provides more clearance from the line that is being monitored.

The final part of the thesis provides a glimpse of the proposed fault detection system. The sensors are placed on two points on the line and the data is fed into a data logging device. With the advances with the GPS system, the localization of the fault can be found easily.
Chapter 1: Introduction

1.1 Power Transmission, Distribution Systems & Overhead Power Line.

Commercial electrical power has started since the 1880s. Since then, the systems used for delivering power have gotten bigger and interconnected. When it started, the common practice consisted of individual generators connected to properly matched loads. An example is the world’s first power station, the Pearl Street power station designed by Thomas Edison which went into operation in 1882 in New York City. Its main purpose was to serve the factories, residences and street lighting.

The trend since the 1900s was to interconnect isolated systems with each other. Doing this has helped expand the coverage area and thus increasing the number of customers. Other technical advantages from having interconnected systems are improvement in load factor, enhancement of reliability by pooling generating reserves and economic purposes by being less expensive to build and operate one large generator instead of several small generators.

In a power distribution grid as shown in Figure 1, the source starts from the power plant which generates 3-phase AC power. Once the power has been generated, the power is then connected to the power transmission system by connecting the power from the generator to a transmission substation at the plant. A step-up transformer is then used to step up the voltage and connected to the transmission line. The reason for stepping up the voltage is to reduce the transmission line losses over long distances by having a higher voltage and minimal current. Common transmission line voltages are usually 110kV and above. For the power carried by the transmission line to be useful for consumers and safely distributed around residential areas, the voltage has to be stepped down at the end of the transmission line in a power substation with a step down transformer. Once the voltage has been stepped down, the distribution part consists of a bus bar which is used to split the distribution power into multiple paths.

In Australia and most part of the world, the distribution networks mainly consist of overhead systems. Overhead lines usually span hundreds of kilometer long and are supported by poles approximately every hundred meters apart depending on the type of conductors used as some are thicker and heavier thus requiring more support. All
poles are buried in the ground at the base and the height of the poles needs to be high enough for traffic to go by without obstruction. These poles are mainly erected using timber poles as they are cost efficient. With the occurrence of poles catching fires, some utility companies have been using concrete or steel to prevent the issue while at the same time driving up the cost of setting up a new distribution network. To ensure the conducting cables are safely separated from the poles, insulators are used. Insulators are made with materials with high dielectric strength such as ceramic or polymer. As for the conducting cables, bare aluminium or aluminium alloy cables are used. This is due to the lighter mass that aluminium has compared to other conducting materials and cheap as it is widely available as a raw material found around the world.

![Figure 1 Electricity Grid System used in North America](image)

**1.2 Failures on Overhead Distribution Line**

Distribution line feeders have long been part of the power grid system. Here in Australia, some insulators on wooden poles for feeder lines have been installed since the 1970s are still in service. As everything will experience wear and tear, many of these insulators would have experienced structural damage or covered in pollution over the years. When an insulator is compromised, its dielectric properties will be affected and the common problem occurring will be a small leakage current bypassing the insulator. If this goes undetected for a long time, the current will build
up and cause pole fire. This will then affect the entire section of the distribution branch and unnecessary blackout for the consumers.

In Australia especially in Victoria, bush fires are a main concern during the hot summer months as the trees and plants dries up in the bush area. Sparks or arching phenomenon from power lines may cause a fire to start if coming in contact with the easily flammable dried vegetation. In the recent 2009 Black Saturday Fires, 173 fatalities were recorded [1]. Although there were other factors causing the fires, some of them were thought to be cause by power lines. If proven to be true, the power companies will be heavily penalizes as lives are put at risk. When lives are at stake, it is important to find potential faults as early as possible before it causes an avoidable fire.

Overhead lines using timber poles and bare aluminium conductors are commonly used in the distribution phase of a power grid here in Australia. An ideal scenario is that the conductors carry the 50Hz signal and the specific voltage for the particular feeder-line. At any given time when a measurement is done on a distribution line, there will always be unwanted interference such as lightning surges [2], RF noise in the background coming from sources such as radio broadcasting stations and switching transients in the power network [3]. Apart from the unwanted noise, faults within the system such as cracked insulators or insulators which are highly polluted will produce partial discharge signals that could be observed in the distribution line [4].

1.2.1 Insulation Failure

The insulator is a vital part of a power pole as it separates the bare conductor and the supporting pole to prevent live current from being grounded through the pole. After being put in service for more than a few decades, wear and tear of the insulator will start to affect the performance of the dielectric strength of the insulator. For ceramic insulators, cracks and structural damage will begin to appear as the insulator approach the end of its service life [5]. For polymer insulators, exposure to UV radiation will cause the insulator to age and become brittle and break [6]. When this happens, partial discharge will occur where the current from the conductor will temporarily bridge the insulator to the supporting structure pole. If the supporting pole
is made of timber, a pole fire may start when the current generates enough heat to start smoldering the wood [7].

Partial discharge according to International Electrotechnical Commission’s “IEC 60270 High-voltage test techniques – Partial discharge measurement” [8] is a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor.

i. Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally, such discharges appear as pulses having a duration of much less than 1µs. More continuous forms can, however, occur, such as the so-called pulse-less discharges in gaseous dielectric. Partial discharges are often accompanied by emission of sound, light, heat, and chemical reactions

ii. “Corona” is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation.

1.2.2 Surface Pollution

Surface pollution is another problem faced by insulators, when an insulator is commissioned in a highly polluted area such as industrial zones or the coastline where there are plenty of salt spray, layers of pollution will settle on the insulator surface over time. When this happens, the pollution layer which may consist of conductive elements will bridge the current from the conductors to the power pole through the pollution layer. On a dry day, surface pollution may not be an apparent problem, but when it drizzles or when a thick fog rolls in, the moist surface of the insulator with added pollution may start acting like a conductor [9]. This is when corona discharge is known to happen.

Corona discharge is an electrical discharge brought on by the ionization of electrons surrounding the conductor. This happens when the strength of the electric field exceeds a certain value but conditions are not capable of causing a complete electrical breakdown [10].
1.2.3 Broken Conductor

Broken conductors are also known to produce partial discharge and corona discharges. When a conductor bunch has a broken strand, the protruding strand will cause partial discharges when the line is energized with high voltage. Broken strands may be caused by conductor fretting or burning, conductor spatter due to molten aluminium arising from arcs generated when the conductors clash [11].

1.3 Condition Monitoring Techniques for Overhead Distribution Line

Condition monitoring for overhead distribution line can be divided into two main techniques which are online and offline methods. Online methods are monitoring systems that are able to monitor the line while it is energized without disrupting the power supply it is carrying. As for offline methods, it requires the section of the distribution line under test to be disconnected from the entire power distribution network.

There are four well established online monitoring methods which are used by utility companies to monitor their assets. They are leakage current monitoring systems [12], infrared thermal imaging [13], electromagnetic radiation monitoring method [14] and acoustic detection [15]. As there isn’t a flawless method, the online monitoring systems have its advantages and disadvantages. The main advantage is that field testing or continuous monitoring systems can be carried out without disrupting the power supply to customers. The disadvantage is that it is expensive to carry out such tests. Some of the online methods require expensive equipments and requires a technician to visit each distribution pole for the observation to be carried out.

For offline testing, two common methods practiced by the utility company is called the Hipot testing [16] and the Very Low Frequency (VLF) test method [17, 18]. Both these methods are considered as destructive methods as when the tests are carried out, an overvoltage is applied to the line for a short time and it will accelerate the damage of the weak part of the insulation [19]. The advantage of this method is that it is reliable and accurate in identifying the problem points. The disadvantage is that the distribution line has to be offline for the test to be carried out.
Current detection systems are still expensive to implement and power failures caused by pole fire are still occurring. Hence the need for a reliable design and cost effective sensor for detecting partial discharge is still yet to be realized. Through this thesis, a novel design for a partial discharge sensor will be designed and explored for implementation on power distribution lines to detect partial discharge signals.

1.4 Objectives and Scope of Work

The main objectives of this research project are to investigate the propagation characteristic of partial discharge on overhead distribution line and to develop a low-cost sensing method to detect the partial discharge on overhead lines. This proposed power line sensing system allows power utilities to monitor their asset remotely and continuously. Partial discharge signal produced by faulty insulator and overhead conductors are usually pre-cursor to major line failures such as pole fires and line collapses.

The research project is carried out in three stages. The initial stage of the project involves the study of propagation characteristic of partial discharge over a long distance using MATLAB simulation software. A single-phase distribution line of 100km was simulated. An experimental work in the lab was also carried out at the same time to identify the frequency range of the partial discharge signals produced from polluted insulators. The second stage of the project involves the development of a low-cost sensor that could extract partial discharge signals from power lines. For the third stage, the sensors are tested in the lab to verify its ability to monitor high frequency signals produced by partial discharges.

This thesis is organized into 6 chapters. The first chapter provides an introduction to the power line systems and the problems it faces. Chapter two will cover the literature review of current technology that has been used by researchers and utility companies to detect partial discharge. The third chapter will move on to look at the characteristics of partial discharge and how it propagates along a long distribution line. Chapter four will then deal with the proposed development and design of novel sensors to detect partial discharge signals. Chapter five will then present the results from testing the sensors on it capability to detect partial discharge signals. Finally chapter six will be the conclusion and discussion of this work and how these sensors are capable on reducing pole fires on distribution lines.
Electrical discharge signals are found in the transmission and distribution networks and they are usually early signs of failure. Therefore, continuous condition monitoring of the equipment in the networks is essential in detecting the discharge before it develops into complete breakdown of insulation and causes unexpected power failure. There are four major components of the distribution networks that are known to produce electrical discharge such as partial discharge and corona discharge. The four components which are of concern to researchers are the power transformers [20], cables [21], gas-insulated switchgear [22] and insulators [23].

There are also many types of condition monitoring system for power transmission and distribution networks. Some of the condition monitoring systems requires section of the network under test to be isolated from the rest of the grid before testing can be performed. This is called the offline condition monitoring system and they are used regularly to perform condition assessment on equipment such as power transformer and underground cable. With the recent development in sensing technology, there are now many condition monitoring systems that are able to continuously monitor for faults while the system is online and energized. Once the monitoring system is installed, information such as the partial discharge activity and the location of the fault will be detected and transmitted to the network operator.

2.1 Online Condition Monitoring Methods

The online condition monitoring method refers to the methods used in measuring partial discharge while the system under test is energized and the test does not influence the operation of the system. Being able to monitor the network in the online mode saves the trouble of having to shut down a particular section of the distribution line under test. This will also avoid the issue of overloading other parts of the power network to compensate for the section under test. The following sub sections will delve into various types of online partial discharge monitoring methods for overhead distribution network.
2.1.1. Leakage Current Monitoring System

Porcelain and silicon rubber insulators are widely used as insulators on distribution line poles. However, the performance of these insulators will be degraded when they are exposed to heavy surface pollution and moist conditions [24]. The leakage current measurement system is a system that is installed to monitor the leakage current flowing from the high voltage conductor to ground via the surface of the insulator. The leakage current level is used as an indicator to the level of pollution and degradation to an insulator.

Over the past decades, leakage current monitoring system is regarded as one of the most reliable method to assess the performance of the voltage insulators. Many developments are reported in the literature focusing in areas such as sensor design and noise filtering and signal processing.

Apart from trying to monitor leakage current, it is critical that prevention methods are put in place to prevent the leakage current problem from the start. Currently, many studies are carried out to provide better understanding of the relationship between the characteristics of the leakage current and the dielectric performance using advance microprocessor based data logging systems. Kim et al. [25] and Gorur [26] studied the relationship between saline fog density and the amount of leakage current by using a 8-bit A/D microprocessor. Another example of using advanced microprocessor for condition monitoring was developed by Vlastos [27], an A/D converter with a frequency range of up to 1KHz was used to record the leakage current and corona discharge.

As leakage current is a well established distribution line occurrence, the IEC Standard 601109 [28] was compiled. The standard contains details on the standard evaluation tests that can be carried out on insulators. Vosloo et al. [29] carried out an investigation on the suitability of the standard in the diverse environment of South Africa and found that the IEC standard is not sufficient. To solve the problem, a purpose built Koeberg insulator pollution test station (KIPTS) was used to carry out testing with more advance data logging systems.

Excessive leakage current could lead to flashover on an insulator or in some instances, the excessive current flowing to ground heats up the metal insertion on a wooden pole and eventually causes smoldering and pole-top fire [12]. As shown by
Wong [30], the amount of leakage current may vary from the age of the wooden pole, atmospheric conditions and the presence of king bolts used in the wooden structure.

Leakage current is always present before a flashover takes place across a polluted insulator. According to Chen, et al.[31], leakage current above 4.4mA poses a danger to the equipment and structure. By identifying the maximum permitted current flowing through the insulator, catastrophic events such as flashover and pole-top fires can be avoided.

2.1.2. Infrared Thermal-Imaging Method

Another common method used by the network operators in condition monitoring of high voltage insulators along distribution line is the use of infrared or thermal cameras. The infrared thermal camera is very effective in picking up defects such as cracks and burned spots on insulators. Damage to the insulators will cause electrical discharge which causes heat to build up on the surface of the insulators. On the other hand, corroded splices or broken conductor strands will produce excessive heat due to high resistance in the connection point, which is generally known as the “hotspots” [32]. In a typical transmission or distribution line, a splice, which is the joint between two conductors or cables, would have 30% to 80% lower resistance than the conductor. However, once the splice is damaged, resistance will increase. If the resistance exceeds 1.2 times more than the conductor, excessive heating will occur [33].

To carry out the inspection for hotspots along the distribution line, experienced maintenance crew has the option of monitoring the line on foot, from a vehicle or a helicopter. One of the advantages of using a thermal imaging camera for line inspection is that investigations can be carried out from a safe distance and does not require any physical contact with the energized line. Another advantage is that it provides quick comparison between three phase power lines because if one of the phases experiences excessive heating, it would be easily distinguished from the other two phases [34].

The infrared thermal imaging method has proven to be effective in finding defects on distribution network. However, it also has several disadvantages. The main problem of using thermal imaging for detecting hotspots on power lines is that it is
easily affected by weather conditions. Studies have shown that wind speed of 10km/h is able to significantly reduce the actual temperature. Apart from heat dissipating through wind, ambient temperature and humidity also affects the accuracy of monitoring [13]. Thermal camera also has a fixed working range, if the distance of the object under test is beyond a range specified by the equipment manufacturer; it will not have a high enough resolution to get an accurate temperature reading. Electrical loading at the time of the inspection is also a problem as the load on the conductors fluctuates throughout the day. The load strongly depends on consumer usage and a fault may not be obvious when it is carrying low current loads during off-peak hours [33].

Lawry, et al. [35], presented a possible solution by introducing conductor replica method where a non-energized replica conductor is place by the transmission line where the exact temperature is taken for both conductors and a comparison is made to avoid disparity coming from weather conditions. Alternatively Snell, et al., suggested the need for better training of inspection personnel to be able to interpret the data collected more accurately. Matos et al. [36], presented a system where the thermal reading of the line is recorded at the same time with laser measurement to monitor clearance between the line and surrounding environment along with a GPS logging system to provide the maintenance crew with a more accurate location. With the results gathered, the condition is then broken into 3 levels to fix the problems depending on its severity.

2.1.3. Electromagnetic Radiation Monitoring Method

When a partial discharge takes place, an electromagnetic radiation is produced by the partial discharge event. Condition monitoring methods based on the electromagnetic radiation were developed for power transformers, gas insulated switchgear and overhead line insulators. Judd et al. [37], used UHF sensors attached to the oil-filled transformer tank to monitor for partial discharges with an accuracy of up to 20m away with reflections taken into consideration. Another area of development is the gas insulated switchgears (GIS). Kaneko et al. [38], diagnosed a GIS from outside using the horn antenna, bi-conical log-periodic antenna, loop antenna and dipole antenna with a conclusion that a dipole antenna have the best sensitivity. The other area of concern which is also the main focus of this research
project is the distribution line insulators. Wong [39] showed that a bi-conical antenna placed up to 4 meters away from the insulator can successfully detect electromagnetic radiations produced by the insulation defects in the very-high-frequency (VHF) range.

Research for detecting electromagnetic waves produced by partial discharges have been widely studied and they are known to exist in the range of VHF (30MHz-300MHz) for distribution line [40] and UHF (300MHz-3GHz) for transformers and GIS [41]. To detect these electromagnetic waves, common methods usually comprise of antennas tuned to a particular frequency. Others novel methods used comprises of capacitive sensors and custom built equipment but such as in the case of Giriantari’s [42] computer discharge analyzer with the ability of monitoring the severity of the pollution on the insulator surface.

The advantages of using antennas and electromagnetic sensors for detecting electromagnetic waves is that power transmission and distribution line can be monitored while it is energized as no direct contact with the high voltage equipment is required. Other advantages can be shown in Moore’s work where multiple antenna setups can provide a 3-dimension localization of the fault up to 15m away using portable equipment [14].

Electromagnetic radiation is not a perfect detection method but it is constantly improving to achieve better reliability and accuracy. One of the main concerns with the electromagnetic radiation method is that the radio broadcast in most countries falls within the working range of partial discharge detectors and can be easily picked up by the sensors. To overcome this problem, Yan et al. [43], attempted to use advanced signal processing techniques such as Fast Fourier Transform (FFT) together with Discrete Wavelet Transform (DWT) to reduce electromagnetic interference from the surrounding environments. Kawada et al. [44], has applied the spatial phase difference method to isolate background noise from partial discharge signals in electrical apparatus. Another limitation working with electromagnetic signals is that as the frequency increases, the propagated signal will attenuate at a higher rate. In the case of Tian et al. [45], he used VHF capacitive couplers to detect faults in cable insulation but found that it is only suitable for detecting faults in short cable sections with an accuracy of 1.5m.
2.1.4. Acoustic Detection

Another popular online partial discharge method is the acoustic detection method. Instead of relying on the electrical signal detection used by antennas and other monitoring systems, acoustic detection sensors pick up acoustic waves that are immune to electromagnetic interference. Acoustic waves produced by partial discharge is commonly observed in the range of audible frequency up to 1 MHz [15].

Acoustic sensors usually come in the form of microphone or acoustic sensors that capture acoustic waves. Three commonly used microphone sensors that are used to detect acoustic waves in air or gases are, condenser microphone, electret microphone and dynamic microphone. The condenser microphone has good sensitivity in detecting signal up to 150 kHz. The main drawback of the condenser microphone is that it requires a separate polarizing power supply and is generally very expensive. As for the electret microphone, it is less expensive than the condenser microphone but slow polarization of the electret which can result in decreased sensitivity. To detect lower frequency signals, a common dynamic microphone used for normal audible waves could be used. All mentioned microphones become more directivity sensitive as the frequency increases and parabolic reflectors can be used to increase directivity at higher frequencies.

Detecting acoustic waves in solids are usually achieved by using accelerometers and acoustic emission sensors. Accelerometers are designed to achieve flat frequency response and it is able to detect frequency to about 50 kHz. Most accelerometers are built using piezoelectric crystal and are usually secured to a surface using adhesive. Acoustic emission sensors are custom made for various frequencies ranging from 30 kHz to 1 MHz. These sensors are resonant sensors built using piezoelectric crystals. The efficiency of the sensors depends on the acoustic impedance matching to the system under measurement.

The acoustic detection method is suitable for detecting partial discharge for the following applications:

i. Outdoor Insulation

Outdoor insulation refers to the insulators used in power line that has been damaged structurally or having its surface covered by layers of pollution leading to partial
discharge. This detection method has long been in practice since 1970 and made popular by researchers such as R. T. Harrold [46-48]. Most partial discharge produced by outdoor insulator are audible noise but difficult to locate instantly. Using a microphone and parabolic reflector, sensitivity of picking up the acoustical noise of the partial discharge and the source of the noise can be improved tremendously.

ii. Gas-Insulated Switchgear (GIS)

Partial discharge occurring inside of a GIS can be detected but limited only to a certain frequency range only. This is because SF₆ has a higher absorption rate than other gases and thus reduces the higher frequency component of partial discharge. Hence an optimum sensor bandwidth is 10 kHz to 80 kHz [49]. To detect the partial discharge, sensors are usually attached to the metal enclosure and to locate the point of source, the sensors are then moved to check every enclosure section and locate the source of partial discharge if there is any. Partial discharge detection in a GIS can get complicated because the acoustic waves are trapped inside the enclosure causing reflections and echoes trapped within the enclosure.

iii. Transformers

New transformers are routinely tested at the manufacturing plants regularly to identify if there are any discharges produced before being put in service. This can be easily done by mounting the sensors on the external enclosure of the transformer. As transformers are known to produce core noise in the 50 kHz - 60 kHz range, sensors are hence required to have a resonance of less than 50 kHz or more than 60 kHz. For online transformer monitoring, simultaneous recording of electric and acoustic signals has been suggested to prevent false alarms from acoustic signals during rain and electrical signals can be affected by corona discharge [20].

iv. Cables

For detection in cables, this method is able to detect partial discharge signals but its capability is very limited. As cables have insulation layers, the partial discharge signal is heavily attenuated during propagation by the absorption of shielding of the cables. To be able to successfully detect any partial discharge signal, the sensor has to be in direct contact with the cable to have a high enough sensitivity. Because of the lack of sensitivity, acoustic detection is usually used simultaneously with electrical detection methods [50].
2.2 Offline Testing

Offline tests are carried out on a predetermined schedule after a system has been in commission for a specific amount of time. This kind of test usually picks up the types of failure which are not usually found through continuous online monitoring. Online monitoring usually picks up slow degradation of the insulators that will cause a failure over a period of time. Offline testing picks up the kind of failures that can breakdown entirely over a very short period of time. One example for offline testing is the Hipot test where voltage twice the system is energized through the cable for a short duration and it should reveal any part of the system which will break down during a surge [51].

Alternatively, other offline methods for servicing old insulators to prevent surface discharges are to manually clean them. Some power companies are known to have them manually washed after a set amount of time after being in service. This is done as some areas facing high levels of pollution will have thick layers of dust and other contaminants that build up on the surface of the insulator. This will cause surface discharge to happen and may lead to a pole fire. If the insulator is washed, it will have its original insulating capabilities again [52, 53].

2.2.1. Very Low Frequency Partial Discharge Detection Method

As described by Steennis et al.[54], the VLF partial discharge detection method uses a 0.1 Hz signal to test long and branched medium-voltage cables. The presented method is able to pin-point the location or locations with significant partial discharge with the accuracy of about 1% of the cable length. To carry out the test, the cable is disconnected from the grid and subjected to a test voltage with a 0.1 Hz frequency. A sensor usually comprising of a capacitive divider is then used to detect the reflected signal. If there is a fault, a high frequency signal will be found on the reflected signal in the range of 1-10 MHz. This test is suitable for diagnosing cables up to 4km, alternatively if 2 sensors are used at both ends of the cable the range can be doubled up to a 8 km range as the partial discharge signal on only required to travel one way and is not required to be reflected. During the test, if partial discharge occurs shortly before breakdown, then such defects cannot be easily found through continuous online monitoring but only through this test where a high-voltage, low-frequency power is used to energize the offline cables for a short duration.
2.2.2. Hipot Test

A common test carried out to identify possible failures is called a Hipot test. Hipot is the short term for high potential. This test is also commonly used to test the safety of high voltage instruments, cables and transformers to verify its electrical insulation level.

In normal working conditions, electrical devices and power distribution systems produce a minimal amount of leakage current caused by the voltage and internal capacitance. Occasionally due to unexpected surges in the system or design flaw, the insulation can breakdown causing more than usual leakage current to flow. In small devices a person may get a shock but in power systems, it may cause serious burns or death to anyone coming in contact with it. As previously mentioned, wooden poles exposed to excessive current can cause heat built up and eventually lead to smoldering and fire in the right conditions.

The Hipot test also known as the dielectric withstand test is performed to determine whether the insulation level of a product or system is enough to protect anyone that comes in contact will not get an electrical shock. The test is carried out by applying a high voltage between two selected points on the distribution lines or a device’s carrying conductors and its metallic chassis. The current found flowing through the insulation is known as leakage current and this is the main concern on the personnel doing the test. The idea behind the test is that if an unexpected surge comes through the system the insulation is capable of withstanding it without breaking down. Hence the test is usually carried out by applying twice the rated voltage for one minute between all conductors and ground. If the dielectric does not break down and the leakage current does not fluctuate, it will be deemed safe for service. This dielectric withstand test is usually carried out before it is put into service and also used to do routine test to ensure the systems are still capable handling its rated voltage [55].

There are two other types of Hipot tests. One of them is the dielectric breakdown test where the test voltage is increased until the dielectric reach a point of failure where a certain amount of current starts flowing through. This type of test is considered a destructive test as the dielectric is damaged or destroyed as an outcome. By doing this the designers is able to study and predict the dielectrics characteristics and breakdown voltage. The other test is called the insulation
resistance test. This test is done to provide a quantifiable resistance value of a product's insulation level. The test voltage is applied in the same way as a standard Hipot test, but is specified in direct current (DC). The voltage and measured current value are used to calculate the resistance of the insulation.

2.3 **Partial Discharge Sensors**

Partial discharge sensors are usually part of the detection systems using the electrical method for monitoring partial discharge over a period of time. Such sensors are either connected with a direct physical connection or placed in very close proximity of the system under test.

These sensors usually use either capacitive or inductive coupling to capture the signals from the system under test. Capacitive coupling generally picks up all the signals in the frequency range emitted from the system. Whereas, inductive coupling can be used to limit the frequency range detectable by the sensor to only observe the frequency range of interest. It is also common knowledge that capacitive coupling is preferred for high frequency detection and inductive coupling is preferred for detecting lower frequency components as the high inductance is able to filter out higher frequencies. Apart from coupling effect, capacitive divider is also a reliable method of monitoring a particular system by stepping down the voltage flowing through the cable under test.

2.3.1. **Capacitive Coupling**

Capacitive sensor utilizes the capacitive coupling effect of capacitance between two circuit points within an electrical network to transfer of energy. The coupling effect is normally achieved by placing the capacitor in series with the signal to be coupled. Every coupling capacitor and its circuits input electrical impedance forms a high-pass filter. Each additional filter will result in a -3dB frequency filter increment. So to have a low frequency response, the capacitors needs to have a high enough capacitance rating.

For the purpose of detecting partial discharge while a system is online, the conventional set up is done by placing the coupling capacitor in parallel with the test subject. Examples of capacitive coupling methods practiced are, capacitive sensors that are attached around the cable under test [45] and the method that will be
explored later in this thesis is the capacitive plates that are placed close to the cable to pick up the partial discharge signals [56].

Capacitive divider on the other hand, uses a direct connection with the system under test as shown in Figure 2. It works like a common voltage divider but it has the advantage of limiting current through the amount of capacitance found in the type of capacitor used as opposed to using a resistive or an inductive divider. Using the following equation:

\[ V_{out} = V_{in} \times \frac{C_1}{C_1 + C_2} \]  

(1)

\( V_{out} \) can be calculated to ensure the voltage to be monitored is stepped down adequately to be safely connected to an oscilloscope or other monitoring devices without causing any damage.

![Capacitive Divider Diagram](image)

**Figure 2 Capacitive Divider**

### 2.3.2. Inductive Coupling

Inductive coupling is the transfer of energy from one circuit to another by the mutual inductance between the two circuits. This occurs when two conductors are configured in such a way that a change in current flow through one wire will induce a voltage across the ends of the other wire. The two mentioned conductors may either be contained in a single unit of a transformer in terms of primary and secondary winding or totally separated as a transmitter and receiver of an antenna system.
Inductive coupling may either be intentional or unintentional. Inductive coupling favors picking up low frequency energy sources whereas high frequency energy sources usually use capacitive coupling. Although inductive coupling is a method on how some sensors work, it may also end up being an unintentional effect between conductors commonly referred to as cross-talk and is a type of communication interference.

A common inductive coupling method used to measure partial discharge pulses is done in the form of a high frequency current transformer (HFCT) because they provide galvanic isolation and have high bandwidths capable of measuring frequencies up to the tens of MHz range. The drawbacks of using HFCT are that they are very expensive because they are based on ferromagnetic materials that need to have hysteresis to be as low as possible and they may saturate when exposed to high currents [57].

Due to the drawbacks of the high frequency current transformer, Argueso et al. explored the possibility of using a self-integrating Rogowski coil to measure partial discharges. Advantages found in the Rogowski coil is that it is non-saturating when exposed to high currents as it has an air-core, has a linear response, cheap to produce and low inductance which is suitable for measuring high frequencies [58]. This is unfortunately not a perfect sensor as without the ferromagnetic core, it has a low sensitivity and require an amplifier if the signal is too small but suitable for high voltage systems as it only pick up a small fraction of the high voltage signal and able to be displayed on the monitoring device without overloading it.

The principal of how a Rogowski coil works is based upon two Maxwell equations which are Ampere and Faraday’s Law. According to the laws, the current flowing through the main conductor creates a magnetic field in a circular shape. As partial discharge pulses travel along the main conductor, a change can be observed in the main conductor as the magnetic field will be affected accordingly to the high frequency pulses travelling along the main conductor. The voltage observed in Equation 2 will be proportional to the derivative of the current in the wire, so it needs to be integrated to obtain the signal corresponding to the partial discharge. The parameter $M$ is the mutual inductance between the Rogowski coil turns and the main conductor while $i$ is the primary current flowing through the main conductor.
\[ V_{\text{coil}} = M \frac{di}{dt} \] (2)

Rogowski coils are widely used in power applications especially in the protection and measurement systems for measuring transients, current flow and fault testing. Some researchers such as L. Kojovic have successfully developed Rogowski coils on printed circuit boards (PCB). The reason behind it is that they are cheap and easy to produce while providing a compact and high precision design [59]. Thus later in this thesis, further justification of using a PCB based Rogowski coil will be considered and test result will be presented and discussed more comprehensively.
Chapter 3: Partial Discharge Sensing and Propagation on Overhead line

This chapter investigates the characteristics of partial discharge and how it interacts with the distribution line over long distances. The first section of this chapter will consider the partial discharge characteristics by monitoring an artificially polluted insulator in the high voltage laboratory. This section will investigate into the methods used to produce the partial discharge signals and the methods used to detect the partial discharge signals. The purpose of this section is to identify the characteristics of partial discharge produced by polluted insulators. With this information, sensors could be designed to have better frequency response when sensing for partial discharge. Apart from that, the data could then be entered into computer simulation models to study the interaction of partial discharge signals with long distribution lines. The second section will look into how partial discharge signals travels over long distances. As an actual line cannot be easily accessible, this section will investigate the propagation properties of a partial discharge signal using ATP and Matlab computer simulation models.

3.1 Experimental Setup

The entire experimental test presented in this chapter was carried out in RMIT’s High Voltage Laboratory. Figure 3 shows the schematic of the test set up. The overview of the system starts off with the high voltage source supplied by a 100kV single phase power transformer. In this test, the test voltage of 22kV is selected. The voltage can be controlled using a variac located outside the Faraday cage. The output of the transformer is connected to a 4 meter long overhead line bare conductor sitting on a surface polluted insulator.

At the end of the line, a capacitive divider is used to measure the voltage level. The signal from the capacitive divider is then connected to an oscilloscope to monitor the signals picked up from the system. The information is then saved into a data file in Microsoft Excel format for further signal processing and analysis.
3.1.1 Equipment used

a) Test Transformer

The partial discharge free transformer used in the test setup is shown in Figure 4. The transformer is a Ferranti 10KVA, 220/100,000V single phase transformer. A partial discharge free transformer is required for this test as any unwanted corona or partial discharge signals that may interfere with the results during testing.
b) Conductor

There are a few types of bare overhead aluminium conductors permitted that are commonly used in power transmission and distribution networks in Australia. These conductors are well documented in the AS 1531-1991 [60]. The Australian Standard 1531 has divided all of the aluminium conductors into 3 categories. The first type is the pure aluminium conductor labeled with the code AAC/1350 and the other two types of conductors are aluminium alloys carrying the code AAAC/1120 and AAAC/6201. The standard covers the load each category of conductor is able to sustain, required cross-sectional area, resistance per km at 20°C and other physical capabilities required when installing a new line.

In most parts of Victoria in Australia, the bare overhead conductors are widely used to supply the electricity to the customers with the exception of built up city areas where underground cables are preferred. The conductors used in this study were originally donated by Powercor Australia and the images of the conductors are shown in Figure 5. The aluminium conductors are given the code name Neptune by AS 1531. It consists of 19 strands of aluminium wire with a 3.25mm diameter each weaved together to make the main conductor. The cable falls under the category of AAC/1350 which means that it is made of pure aluminium. Another property of the cable is that it has 0.183\(\Omega\) DC resistance per kilometer at 20°C.
c) Insulator and Test Configuration

The most important part of the test configuration is the insulator used. When insulators fail they are caused by structural damage or surface pollution. This can be observed by the occurrence of partial discharge signals from the source of fault. If not detected early, it will lead to the insulator failing and potentially leading to pole top fire. Thus early detection is important to keep distribution lines from failing.

Figure 6 shows the test configuration in the laboratory and the polluted insulator as the source of partial discharge when the transformer is energized. To detect the partial discharge, voltage dividers are used to monitor the system. Two types of voltage divider were used concurrently. The capacitive voltage divider was chosen over the resistive voltage divider as it is more sensitive to high frequencies.

The setup done is meant to resemble a working distribution line and at the same time connected to a compromised insulator that is causing partial discharge signals. In the test, the cable is 4 meters long due to space confinement in the laboratory. A longer cable would have been more helpful to understand the speed of the high frequency signal when travelling along the bare conductor. As for the source of partial discharge, the insulator is polluted with kaolin. When exposed to kaolin, surface discharge begins to happen as the insulator is no longer working within its specific ratings. Once the configuration is energized, partial discharge signals can be observed as the conductor and the ground plane is not insulated by the insulator anymore.
d) Capacitive Voltage Divider and Oscilloscope

Voltage dividers are used for monitoring the line as they are able to reduce the actual distribution line voltage to a safe level for monitoring on the oscilloscope. In this set up, the high voltage discharge-free capacitor, C1 is rated at 100pF. The capacitor box, C2 shown in Figure 7 is placed outside the Faraday cage and has a capacitance of 892nF. Referring to Equation 1, the ratio between the transformer and the capacitive voltage divider is 1:8921. As the test is carried out at 22kV, the voltage monitored at the capacitive voltage divider is expected to be only 2.466V.

The oscilloscope used for this test is a Tektronix TDS 5104 Digital Phosphor Oscilloscope. It has the capability of capturing signals up to 1GHz and a sampling rate of 5GS/s. With 4 input channels, simultaneous monitoring was carried out on the capacitive voltage divider, resistive voltage divider and bi-conical antenna. The purpose of this is to compare the sensitivity of each individual monitoring device.
3.1.2 Insulator Sample

A 5 tiered high voltage ceramic pin insulator with a 22kV rating shown in Figure 8 is used in this study. The sample was obtained from Powercor and commonly found on distribution lines in Victoria. As partial discharge signals are widely known as precursors to future breakdown of the dielectric, the results collected will be useful in identifying the characteristics of the partial discharges travelling along the distribution lines. The test carried out only monitors a single phase line. Distribution lines are usually 3-phase systems carrying 3 conductors on each pole.

To produce partial discharge, a pollution layer was applied according to the IEC 507 standard [61]. The idea is to replicate the conditions faced by the insulators which are exposed to conditions such as salt spray, industrial pollution and dust. When the pollutants cover the surface of the insulator, the dielectric properties of the insulator is compromised and leakage currents starts to form a path across the insulator surface and at the same time partial discharge signals could be observed along the power line [62].

The kaolin pollution mix is achieved by mixing 40g of kaolin with 1000g of distilled water. Once a consistent mixture is obtained, the mixture is then sprayed evenly on the insulator and left to dry until a layer of white powdery surface is found on the entire insulator. In the test, only the dry condition scenario was tested and documented. This is because in a wet testing, water or salt spray will result in a flashover occurring at 15kV and the results were inconclusive.

Figure 8 Kaolin polluted insulator
3.1.3 Results

Figure 9 and Figure 10 are comparisons of an unpolluted and polluted insulator on a 50Hz sine wave. Figure 9 is the screen shot of the oscilloscope displaying the 50Hz signal of an ideal distribution line voltage of $22kV_{RMS}$. This is the expected signal of a fully functional power line where there are no faults hence no surges can be observed. When a fault is introduced, the signal as seen in Figure 10 is observed. The high frequency component found on the 50Hz signal is the partial discharge signals as it only appears when a kaolin polluted insulator is put in place.

Figure 10, shows that all of the partial discharge signals are found in the positive cycle of the 50Hz 22kV power line voltage. Figure 11 is the Excel plot of the positive half of a 50Hz signal. The graph was plot using MS Excel as the screen shot image on the oscilloscope was not very clear. From the average of a few positive half of the 50Hz signal, it was found to have about an average of 63 high frequency pulses.

![Figure 9 Clean 22kV 50Hz power line signal](image-url)
Further inspection of the signal could be seen in Figure 12. It shows the MS Excel plot of a signal zoomed in to fully observe the characteristics of the high frequency component. The sampling rate for data storage of the signal is 800ps per point. The first full cycle of the high frequency signal last for about 48ns which equated to 20.83MHz. Keeping to Nyquist–Shannon sampling theorem, the data collections needs to be done at least half the time of a full cycle which is 24ns per sampling point. As the sampling rate used was 800ps a point which is 30 times more than the required minimum; making the presented data very accurate. As the average peak to peak voltage found is 0.91V, the actual line value would be $5740V_{\text{RMS}}$ by applying the capacitive voltage divider ratio.

Further information observed from this data collection is tabulated in Table 1 and shows that the partial discharge signal usually starts with a falling edge with a fall time of 8ns. After the first full cycle, it takes an average of 642ns of decay time before the signal is no longer found in the 50Hz component. This happens after an average of 14.4 cycles after the first full cycle.
Figure 11 Positive half cycle of 50Hz 22kV signal

Figure 12 Zoomed in view of the high frequency signal found on the 50Hz 22kV signal
Table 1 Data of partial discharge characteristics found

<table>
<thead>
<tr>
<th>Total time</th>
<th>$V_{\text{pk-pk}}$</th>
<th>Rise Time</th>
<th>Decay time</th>
<th>No. Decay Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>576ns</td>
<td>1V</td>
<td>8ns(-)</td>
<td>532ns</td>
<td>12</td>
</tr>
<tr>
<td>624ns</td>
<td>0.96V</td>
<td>8ns(-)</td>
<td>580ns</td>
<td>13</td>
</tr>
<tr>
<td>628ns</td>
<td>0.72V</td>
<td>12ns(-)</td>
<td>584ns</td>
<td>13</td>
</tr>
<tr>
<td>528ns</td>
<td>0.72V</td>
<td>8ns(-)</td>
<td>484ns</td>
<td>11</td>
</tr>
<tr>
<td>785ns</td>
<td>1.32V</td>
<td>9.6ns(-)</td>
<td>745ns</td>
<td>17</td>
</tr>
<tr>
<td>841ns</td>
<td>0.84V</td>
<td>7.2ns(-)</td>
<td>805ns</td>
<td>18</td>
</tr>
<tr>
<td>799ns</td>
<td>0.84V</td>
<td>8.8ns(-)</td>
<td>763ns</td>
<td>17</td>
</tr>
<tr>
<td>Average</td>
<td>683ns</td>
<td>0.9143V</td>
<td>8.8ns(-)</td>
<td>641.8571ns</td>
</tr>
</tbody>
</table>

3.1.4 Discussion

In this section, the outcome of the wet insulator testing is discussed along with how the data collected is used later in the research work and how it may compare to an existing power line.

Figure 13 is the screen shot of the result from wet testing. Wet testing was done by evenly spraying the insulator with water covering its entire surface. The results were inconclusive as there was no high frequency pulses found, instead the 50Hz component get distorted as shown in the picture and is usually followed by a flashover tripping the transformer. In Figure 13, the 3 signals are comparison of a capacitive and resistive voltage divider and the other channel is a filtered input to remove the 50Hz component for easy triggering of the high frequency pulses.

From the data collected and the tabulated results, the results can be used in a simulation model to verify of how far the signal will travel and how the signal will interact with a bare overhead line conductor. As all conductors have resistance and reactance causing the attenuation of signals, it is important to understand how far the signal can travel before it becomes undetectable. It is found in earlier research as discussed in Chapter 2’s literature review, when the frequency increases, its attenuation also increases exponentially. Hence, lower frequencies are preferred for online continuous monitoring as the sensors can be placed further apart.

As the test was conducted within the laboratory environment and done on a short length of cable, it is expected to have some differences in an actual line as there
would be surges from switching, lighting, heavy machinery or factory which may introduce unwanted noise and maybe even perhaps altering the frequency of the partial discharge that is of interest. So filters and amplifiers may be introduced to counteract such problems if they occur when doing the test outside of the high voltage laboratory.

Figure 13 Distortion of 50Hz signal in wet testing

3.2 Partial Discharge Propagation on Overhead Line

This section considers partial discharge propagation in distribution lines to predict how partial discharge signals will interact with distribution line power signals. Due to the fact that unused distribution lines are not easily available for testing purposes, the alternative was to use computer simulations to simulate the attenuation characteristics of a partial discharge signal over different distances. Simulation programs today are reliable in predicting outcomes without actually having to do a test in the field. Using the simulation program, different parameters and possible
noise interference in the real distribution line such as skin effect can be introduced to the simulated model. With these capabilities it will make the simulation result more realistic when compared to a functional distribution line.

Even with all the capabilities of the simulation program, it will never produce a perfect simulation result compared to having a physical testing on a distribution line commissioned by the power companies. As distribution lines are used everywhere, external disturbances or unpredicted noise may introduce outcomes that may not be considered during the computer simulation.

The simulation done in this chapter is a straightforward simulation of a long distribution line. It is powered at one end and terminated on the other without any additional branches. This simulation is done for the sole purpose of considering the attenuation rate over different distances.

For this purpose, two programs were considered for the simulation. The two programs are widely used in the power network simulations and each has its own advantages and distinct additional features. The following section will outline their main capabilities.

### 3.2.1 MATLAB SimPowerSystem vs. ATPDRAW

As mentioned before, ATP and Matlab’s Simulink-SimPowerSystem are similar programs but with slightly different capabilities. The following comparison was compiled by a group of researchers in Budapest University of Technology and Economics to summarize the capabilities of both programs [63].

<table>
<thead>
<tr>
<th>ATP-EMTP</th>
<th>MATLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Sources</strong></td>
<td></td>
</tr>
<tr>
<td>- DC source, current or voltage</td>
<td>- DC voltage source</td>
</tr>
<tr>
<td>- AC source, current or voltage</td>
<td>- AC voltage or current source, External controlled voltage or current source (controlled by an arbitrary signal)</td>
</tr>
<tr>
<td>- Ungrounded AC or DC voltage source</td>
<td>- 3-phase programmable control source (time variation of amplitude, phase and</td>
</tr>
<tr>
<td>- AC source, 3 phase, current or voltage</td>
<td></td>
</tr>
<tr>
<td>- Ramp source, current or voltage</td>
<td></td>
</tr>
<tr>
<td>- Two-slope ramp source, current or voltage</td>
<td></td>
</tr>
<tr>
<td>- Double exponential source</td>
<td></td>
</tr>
<tr>
<td><strong>Heidler, Standler, Cigré type source, current or voltage</strong></td>
<td>frequency by step, ramp or modulation, 2 harmonics in addition</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>TACS controlled source</strong></td>
<td></td>
</tr>
</tbody>
</table>

2. **Switches**

| Single phase time controlled | Single and three-phase logical controlled (opens at next current zero-crossing) |
| Three-phase time controlled | Ideal switch (parallel to an RC snubber circuit) |
| Voltage controlled | |
| TACS (external) controlled | |
| Static (random, based on predefined distribution functions) | |
| Systematic (periodic) | |

3. **Machines**

| Synchronous, 3 phase | Synchronous, 3 phase (Fundamental or standard parameters, former ones in SI or pu) |
| Synchronous with TACS control, 3 phase | Simplified synchronous, |
| Synchronous, set initialisation under ATP, 3 phase | Permanent magnet synchronous, |
| Induction (Asynchronous), set initialisation under ATP, 3 phase | Synchronous machine voltage regulator and exciter |
| Induction (Asynchronous), set initialisation under ATP, 1 phase | Asynchronous |
| DC, set initialisation under ATP | DC |
| | Steam turbine and governor |
| | Hydraulic turbine and governor |

4. **Lines and Cables**

<table>
<thead>
<tr>
<th>Lumped</th>
<th>Lumped</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLC equivalent 1, 2, 3 phase</td>
<td>Π Section line, parameters: Number of Π sections and R, L, C values</td>
</tr>
<tr>
<td>RL coupled non-symmetric 2, 3, 2x3 phase</td>
<td>Distributed (based on Bergeron's method)</td>
</tr>
<tr>
<td>RL coupled, symmetric 3, 2x3 phase</td>
<td>Parameters given by N*N matrices,</td>
</tr>
<tr>
<td><strong>Distributed</strong></td>
<td>Parameters given by sequential components.</td>
</tr>
<tr>
<td>Transposed 1, 2, 3, 6, 2x3, 9 phase</td>
<td></td>
</tr>
<tr>
<td>Untransposed 2, 3 phase</td>
<td></td>
</tr>
<tr>
<td><strong>LCC line/cable</strong></td>
<td></td>
</tr>
<tr>
<td>Defined by the geometrical and material data of the line/cable 1 to 9 phase. Bergeron, Π, J-Marti, Noda and Semlyen type of transmission line models.</td>
<td></td>
</tr>
</tbody>
</table>

5. **Transformers**
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Ideal, 1 phase (only the turn ratio can be given)</td>
<td>- Resistor, time-dependent</td>
<td>- Diode</td>
</tr>
<tr>
<td>- Ideal, 3 phase (only the turn ratio can be given)</td>
<td>- Resistor, current-dependent</td>
<td>- Thyristor (Valve)controlled by TACS</td>
</tr>
<tr>
<td>- Saturable, 1 phase (2 windings)</td>
<td>- Resistor, TACS (external) controlled</td>
<td>- Triac</td>
</tr>
<tr>
<td>- Saturable, 3 phase (2 or 3 windings, the winding connection and phase shift can be chosen)</td>
<td>- Inductor, current dependent</td>
<td>- Diode, Thyristor</td>
</tr>
<tr>
<td>- Saturable, 3 phase, 3-leg core type (Y/Y only) with high homopolar reluctance</td>
<td>- Inductor, current dependent with initial flux</td>
<td>- IGBT</td>
</tr>
<tr>
<td>- BCTRAN</td>
<td>- Hysteresis inductor</td>
<td>- GTO</td>
</tr>
<tr>
<td>- BCTRAN</td>
<td>- Hysteresis inductor with initial flux</td>
<td>- Mosfet</td>
</tr>
<tr>
<td>- BCTRAN</td>
<td>- Metal-oxide surge arrester</td>
<td>- 1, 2 or 3-arm bridge of any of the</td>
</tr>
</tbody>
</table>

Three phase transformers are assembled from single-phase ones.

Parameters can be defined either as R, L, C or as P and Q.

Metal-oxide surge arrester
9. Power Electronics Control Blocks

- Need to be constructed by the user using TACS or MODELS.
- Timer (generates a control signal at specified transition times),
- Synchronised 6 or 12-pulse generator (to fire the 6 or 12 electronics switches of a 6 or 12 pulse converter).

10. Measurement Elements

- Probe TACS
- Ideal voltage and current measurement
- Branch voltage measurement
- Instantaneous power and energy (for most elements)
- Ideal voltage and current measurement
- Impedance measurement
- True RMS meter
- Fourier coefficients
- THD
- Active and Reactive power
- 3 phase sequence analyser
- abc to dq0 transformation and vice versa

11. Signal Processing Units

**TACS sources in the signal processing network:**

- DC
- AC
- Pulse
- Ramp

**Transfer functions:**

- Transfer function (user defined transfer function in the “s” domain, max. 7th order)
- Integral
- Simple derivative
- Filters (first order low/high pass)

**Devices:**

- Frequency sensor
- Relay-operated switch (controlled by an external signal absolute value)
- Level-triggered
- Transport delay (give a limited delay that consists a fix and an input dependent component)
- Point-by-point non-linearity
- Multiple open-close switch (Gives 18

**Some additional sources:**

- Step
- Ramp
- Sine wave
- Random generator (gives uniformly or normally distributed random signal)
- Arbitrary repeating sequence
- Clock
- From file

**Sinks (simulation outputs):**

- Numerical display
- Time scope
- XY scope
- Power spectral density scope (FFT),
- Spectrum analyser (transfer function between two points, with some restrictions)
- To File
- Auto-correlator and cross-correlator

**Continuous:**

- Derivative
- Integrator
- Transfer function (user defined transfer function in the “s” domain)
- Variable delay (apply variable time
- open and close sequences at the times set
- Controlled (resetable) integrator
- Simple derivative
- Input-IF component (Output is one of the three inputs depending on two reference signals)
- Signal selector (Gives one of the inputs or a maximum/minimum value depended on a selector signal value)
- Sample and track (Output follows the sum of the input or samples it or delays it by $\Delta t$)
- Instantaneous minimum/maximum
- Minimum-maximum tracking (Holds the minimum/maximum of the inputs)
- Accumulator and counter (Holds or integrates the sum of the inputs controlled by external signals)
- RMS value of the sum of input signals

**Fortran statements:**

- General (determined by Fortran expression)
- Basic Math operations
- Basic Logical operators

**Discrete:**

- Sample/Hold (Zero/First-order sample and hold function)
- Transfer functions (user defined transfer function in the “z” domain)

**Math, logical, statistical:**

- Wide range of functions (complex, logical, trigonometric, statistical etc.)
- Algebraic Constraint: it solves an equation $f(x) = 0$ where $x$ is the output of this block and it is indirectly connected back to the block's input, which is $f(x)$. This connection realizes the function $f$. In each simulation step an iteration of the output is performed so that the input equals to zero.

**Non-linear:**

- Several types of simple non-linear functions (Relay, Quantiser, Dead zone, Rate limiter, Saturation etc.)
- $n$ dimensions look-up table (user defined value n-tets, e.g. in 2D case a simple function given by pairs of points; linearly interpolated in between)
- Flip-flops (J-K, S-R, D, D Latch, Clock)
- Counters

**Filters (20 types):**

- Analog
- Digital
- Adaptive

12. User Defined

- Components that can be developed by the user programming in MODELS simulation language
- Components that can be developed by the user either in Matlab's programming language or C or Fortran

13. Others

- Transposition (Makes defined transposition between interconnected 3 phase elements)
- User specified (Some possibilities to load the user specified elements from
- Controller blocks: PID, fuzzy, neural networks, etc
- Optimal control toolbox
- DSP blockset
- Fixed point blockset
When the elements found in the table above is used to build a power line network model, a solver is required to compute the data and produce the expected outcome of the network usually in the form of a graph. For ATPDraw that uses the ATP-EMTP solver, it uses a fixed time step trapezoidal rule method for solving differential equations. Whereas, MATLAB’s Simulink-SimPowerSystem offers seven types of fixed step and eight types of variable step solvers with its suitability depending on the complexity of the model it needs to solve.

In short, both program packages are capable of simulating electrical networks of the same class problems. This is due to the ability of user defined elements in both programs. That said, a user would require an in-depth understanding and experience of network modeling and the process can be very time consuming. And the advantage of the ATP-EMTP package is that it is able to simulate the physical process of transmission lines and transformers quickly and easily. Whereas, MATLAB’s package is more flexible in the area of power electronics, signal processing and control.

### 3.2.2 Requirement of The Simulation Model

Partial discharge monitoring requires sensors to be installed and spaced out evenly along the distribution line. To do this, understanding the characteristics of partial discharge signals is important to predict how much attenuation will happen to the signal. It is commonly known that skin effect happens on bare conductors and causes unwanted resistance and signal losses.

In AC circuits, the current density is greater near the outer surface of the conductor. The current tends to crowd towards the outer surface referred to as skin effect. A longitudinal element of the conductor near the center of the axis is
surrounded by more lines of magnetic force than near the rim. This results in an increase in inductance towards the center. The decreased area of conductance causes an apparent increase in resistance. At 60 Hertz, this phenomenon is negligible in copper sizes of #2 AWG (6.54mm) and smaller and aluminum sizes #1/0 AWG (8.25mm) and smaller. As conductor sizes increase, the effect becomes more significant [64].

With the consequence of skin effect, higher frequencies will be affected considerably more if it was travelling along a distribution line where the 50Hz signal would usually be transmitted without any problems. Hence detecting partial discharge in the VHF and UHF range will not be very practical as sensors will be needed every few meters apart. The reason is that skin effect will cause high resistance and losses to the partial discharge signal. This can be further explained by skin depth as the higher the frequency the smaller the skin depth distance measured from the surface of the conductor due to high inductance in the center of the conductor [65].

So to effectively set the distance between sensors, it is important to understand the characteristics of the partial discharge signal travelling along the distribution line conductor. Predicting the attenuation rate of the signal is vital so that the signal does not attenuate beyond recognition. As mentioned, skin effect is the main cause of the attenuation for partial discharge signals. Other attenuation factors may also be caused by signal reflection where if the transmission line is not terminated properly, the signal will be reflected back to the source. And the original signal source may be cancelled out if the reflected signal was in an opposite phase.

### 3.2.3 Capabilities and Limitations

As mentioned before, the purpose of computer modeling and simulation is to identify the characteristics of partial discharge signal. To achieve this, the simulation program is required to deal with very long distribution lines and sample high frequency signals. From the result, it is expected to discover how the high frequency partial discharge signal will behave over the long distances and if it will attenuate beyond detection using sensors.

This section will look into the advantages and problems faced using the two computer simulation package presented earlier in this chapter.
a) MATLAB

For Simulink’s SimPowerSystem, the smallest possible sampling step size is 2ns and abiding in Nyquist law, it is capable of simulating frequencies up to 250MHz. To ensure that the results are accurate, 4ns was chosen to run simulations for the balance of simulation time and accuracy. The only drawback was that the simulation time increases when compared to a bigger simulation step. An example for the time taken to simulate and plot a 30ms graph using a 4ns step takes 6 minutes, whereas using a 10ns step size takes only 3 minutes. Another limitation with the package is that the time scale for the output graph only goes to 100 µs where shorter time periods cannot be observed accurately.

To calculate the skin effect, Simulink has a “RLC Line Parameter Tool” shown in Figure 14 that calculates the resistance, inductance and capacitance of the line. It is done by considering its surrounding objects and clearance from ground. The calculated value of RLC is then entered in the Distributed Parameter Line of the simulation model.

The solver used to simulate the model is a variable step solver called ode23t (mod. stiff/Trapezoidal). It was chosen because it produces more consistent results and variable step was chosen because it solves the model faster and more efficiently.

![RLC Line Parameter Tool](image)

Figure 14 RLC Line Parameter Tool
b) ATPDraw

ATPDraw has an adjustable step size and simulation time increases as the step size becomes smaller and the smallest step size is dependent on the computer’s memory. Skin effect can also be included in the simulation model under the LCC function as shown in Figure 15.

The setback with the LCC function is that an error will occur for the slightest mistake in the configuration. The simulation solver screen will show an error but no information is provided on how the error could be fixed. The fixed time step solver is much slower than the MATLAB’s variable step solver when running simulation using the same step size. ATPDraw is just as capable as MATLAB’s package but not as user friendly.

Figure 15 LCC Function in ATPDraw
### 3.2.4 Simulation Model

Both simulation models from ATPDraw and MATLAB’s Simulink SimPowerSystem will be presented but the ATPDraw’s model does not take skin effect into consideration as the errors that occurred could not be solved. Both models represent a single phase 22kV distribution line with a 4kV high frequency signal added to the system. 4kV is chosen as the partial discharge voltage level because from the results of the previous section indicates that the partial discharge signal averages about 5.7kV using the capacitive divider ratio and 4kV was chosen to be conservative to account for lower amplitude signals. 25MHz frequency is used as the artificially added high frequency signal because from the previous section it was found to be 20.83MHz but further observation showed that it varies between 20-30MHz so 25MHz was chosen as an average value.

#### a) ATPDraw Simulation Model

Figure 16 shows the simulation model for ATPDraw. The distribution line here is represented by the ‘distributed parameter line’ element but does not consider skin effect losses. The input voltage is 22kV at 50Hz and the artificial partial discharge signal is 4 kV at 25 MHz. The power line spans across 35km and ends with a terminating impedance to prevent reflection.

![Figure 16 ATPDraw simulation model layout](image-url)
b) MATLAB’s Simulink Simulation Model

Figure 17 is MATLAB Simulink’s simulation model. It is similar to the ATPDraw model but is able to include skin effect into consideration when using the RLC Parameter Tool for calculating the RLC values to be used in the distributed parameter line element. The input voltage is fixed at 22kV, 50Hz and the artificial partial discharge signal is fixed at 4kV\(_p\). Various values were simulated for the line length, artificial partial discharge frequency and simulation time step. 14 different frequencies from 1MHz to 100MHz were simulated against 3 different distribution line lengths of 1km, 10km and 100km. Another simulation test carried out explored the effects of simulation time step between 2ns-10ns for a 100km line at 1 MHz, 20 MHz, 50 MHz and 100MHz. The results will be presented in the next section.

![Figure 17 MATLAB’s Simulink model layout](image)

3.2.5 Results

a) ATPDraw Simulation Result

From the simulation in Figure 17, two points are monitored at P1 and P2. Figure 18 (b) and Figure 19 (b) are the result of Ohmic loss and time delay resulting from the 35km distribution line. The amount of attenuation suffered by the distribution line signal is a drop of 2.8kV\(_p\) and a 116.6 \(\mu\)s delay.
b) MATLAB’s Simlink Simulation Result

For the simulation in MATLAB, it is assumed that the signal from the source is 22kV, 50Hz as defined in the AC power source element and only the signal at the end of the line is monitored. Figure 20 shows the result ‘Scope 1’ of the Simulink model found in Figure 17. The high frequency pulse is the artificially added signal by the signal generator in the model to replicate a partial discharge found in distribution lines.

Figure 21 highlights the problem faced with the output graph’s time axis as the time scale does not indicate anything below 100µs. As we do not expect the
frequency to change, it is sufficient to just measure the voltage amplitude loss over the various distances simulated. Figure 22 shows 2 pulses generated from the signal generator with minor attenuation over the 1km distribution line.

Figure 20 Simulink’s graph of 22kV 50Hz with a high frequency pulse of 4kV at 25Mhz

Figure 21 Zoomed in graph of Figure 21 and Simulink’s time scale problem
Figure 22 High frequency signal that was artificially added to the distribution line signal.

Table 2 is the summary of the high frequency signal attenuation over different distribution line lengths of 1km, 10km and 100km. Figure 23 then shows the graph plot of how the signal behaves over the particular distance.

Table 2 Frequency vs. Distance

<table>
<thead>
<tr>
<th>F (MHz)</th>
<th>1km Voltage Level (Vp)</th>
<th>10km Voltage Level (Vp)</th>
<th>100km Voltage Level (Vp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3840</td>
<td>3830</td>
<td>3741</td>
</tr>
<tr>
<td>5</td>
<td>3830</td>
<td>3822</td>
<td>3735</td>
</tr>
<tr>
<td>10</td>
<td>3815</td>
<td>3786</td>
<td>3732</td>
</tr>
<tr>
<td>15</td>
<td>3784</td>
<td>3750</td>
<td>3681</td>
</tr>
<tr>
<td>20</td>
<td>3738</td>
<td>3714</td>
<td>3722</td>
</tr>
<tr>
<td>25</td>
<td>3650</td>
<td>3642</td>
<td>3560</td>
</tr>
<tr>
<td>30</td>
<td>3604</td>
<td>3549</td>
<td>3708</td>
</tr>
<tr>
<td>40</td>
<td>3470</td>
<td>3372</td>
<td>3690</td>
</tr>
<tr>
<td>50</td>
<td>3289</td>
<td>2811</td>
<td>3447</td>
</tr>
<tr>
<td>60</td>
<td>3070</td>
<td>2818</td>
<td>3564</td>
</tr>
<tr>
<td>70</td>
<td>2828</td>
<td>2505</td>
<td>3626</td>
</tr>
<tr>
<td>80</td>
<td>2577</td>
<td>2147</td>
<td>3605</td>
</tr>
<tr>
<td>90</td>
<td>2335</td>
<td>1763</td>
<td>3586</td>
</tr>
<tr>
<td>100</td>
<td>2115</td>
<td>1345</td>
<td>3391</td>
</tr>
</tbody>
</table>
Table 3 shows how the simulation step size affects voltage amplitude over various frequencies of 1MHz, 20MHz, 50MHz and 100MHz. Figure 24 then shows the graph plot where it can be seen that higher frequencies simulated by large step sizes does not produce a consistent result.

**Table 3 Simulation Step Size vs. Frequency**

<table>
<thead>
<tr>
<th>Simulation Step Size</th>
<th>1MHz</th>
<th>20MHz</th>
<th>50MHz</th>
<th>100MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10ns</td>
<td>3739</td>
<td>3029</td>
<td>760</td>
<td>3560</td>
</tr>
<tr>
<td>9ns</td>
<td>3740</td>
<td>3169</td>
<td>760</td>
<td>3560</td>
</tr>
<tr>
<td>8ns</td>
<td>3741</td>
<td>3271</td>
<td>1074</td>
<td>3544</td>
</tr>
<tr>
<td>7ns</td>
<td>3741</td>
<td>3720</td>
<td>3471</td>
<td>2200</td>
</tr>
<tr>
<td>6ns</td>
<td>3741</td>
<td>3447</td>
<td>2317</td>
<td>1502</td>
</tr>
<tr>
<td>5ns</td>
<td>3741</td>
<td>3560</td>
<td>2925</td>
<td>2447</td>
</tr>
<tr>
<td>4ns</td>
<td>3741</td>
<td>3722</td>
<td>3476</td>
<td>3392</td>
</tr>
<tr>
<td>3ns</td>
<td>3741.5</td>
<td>3683</td>
<td>3399</td>
<td>2485</td>
</tr>
<tr>
<td>2ns</td>
<td>3742</td>
<td>3728</td>
<td>3560</td>
<td>3391</td>
</tr>
</tbody>
</table>
3.3 Conclusion

Identifying the partial discharge characteristic was successfully carried out and the results were very useful for building the simulation model and defining the parameter for the frequency range to be simulated. In the partial discharge characterization, only the polluted dry kaolin insulator produced partial discharge signals. The frequency of the initial first sine wave varies between 20MHz to 30MHz and the amplitude was found to average around 5.7kV as they vary every time.

As for the simulation, attenuation over long distances was minimal. As it is only a single phase line model and it does not consider signal coupling from other lines. Hence the simulation done is meant to only show how the signal will travel along the conductor without considering its interaction with its external environment if there are any. Further consideration into multiple branches or adding noise to the simulation model would help make it more a realistic. Computer simulation can only do so much and it is a constantly improving method, the most reliable result would be carrying out a test on a functional distribution line but it will be a problem as testing would require the line to be turned off causing power disruption to customers.
Chapter 4: Sensor Design and Development

4.1 Introduction

Partial discharge detection has been recognized as a fault detection method in high voltage transmission and apparatus for a long time. As shown in Chapter 2, there are a lot of established methods available and most of them have their advantages and disadvantages. The goal in this chapter then is to design a sensing method that is solely focused on detecting partial discharges on a distribution line. At the same time, the sensing method needs to be reliable and comparable to current available technology.

A few motivations in the design of this sensor are to reduce the cost of the equipment and mainly on the part that is responsible for capturing the partial discharge signal for recording on a data recording system. As found in Chapter 3, the sensor is required to detect frequencies between 20MHz to 30MHz as that is where the most partial discharge frequencies are found. The design also aims to monitor a distribution line with minimal effort after setting up by monitoring a few kilometers of a distribution line at a time.

The following sections will look into two designs proposed for the use of partial discharge detection. The first one is based on the design of a Rogowski coil and the second is a contactless voltage sensor based on the effects of capacitive coupling.

4.2 Rogowski Coil

Rogowski coil is a type of current transformer and they have long been used as a current metering device or protective relay in high voltage systems [66]. Current transformers are used when the current of the conductor under test is too high for direct monitoring. The current transformer is able to monitor the line without any physical connection and has a step down ratio of the current flow depending on the current transformer’s design.

Rogowski coils are named after its inventor Walter Rogowski in 1912 and is designed by having a coil consisting of a length of wire wrapped around a substrate to form a circle with a hollow center [67]. It is a non-evasive method for monitoring
and measuring alternating current (AC) or high speed current pulses through a conductor. The main advantages is that Rogowski coils uses an air core which leads to low impedance and no danger of saturating the core as compared to conventional iron core current transformers. Other useful features of the Rogowski coil are its linearity which enables a same coil to measure currents from a few mA to a several million amperes and it can be easily calibrated at any current level [68]. With its wide dynamic range, it is very useful in situations where the approximate value of the current to be measured is not known beforehand. As Rogowski coils are better than conventional iron core current transformers, they are widely used in the application of current measurement on high voltage electric railways, power transmission and distribution lines [69]. Dubickas has also shown that Rogowski coils are also capable of detecting high frequencies pulses by having a minimal number of windings to increase the coil’s bandwidth but at the same time it reduces the sensitivity of the coil [70].

As Rogowski coils are able to detect high frequencies, researchers have started to use them in partial discharge detection. According to Robles et al., to increase the bandwidth and allow higher frequency partial discharges to be detected, inductance, resistance and capacitance will have to be kept to a minimum to achieve the required dynamic response [71]. Low impedance will lead to a low sensitivity of the Rogowski coil, so it is important to get a right balance to be able to have a high enough voltage amplitude and wide enough bandwidth for monitoring partial discharge signals [58]. An example shown by Hashmi et al, was that they manage to monitor partial discharge of up to 5MHz effectively in covered conductors of a single phase distribution line [72].

To further improve Rogowski coils (RCs), researchers have started making printed circuit board (PCB) RCs to achieve more consistent windings and dimensions. Traditional RCs are handmade and they vary in density and have poor repeatability in getting consistent results whereas PCBRCs can be mass produced and have a higher rate of repeatability in results along with a predicted life span of 27 years in outdoor conditions [73]. The design proposed by Qing et al. combines a PCBRC with multiple small assistant boards to increase sensitivity and tested them in temperatures of -30°C, 20°C and 90°C together with a conventional RC where the conventional RC had a higher error rate in higher temperatures. Also from the test they found that their design was suitable in measuring transient currents and precise
metering of sine-wave currents of up to 20MHz [74]. Kojovic proposed a design of PCBRC consisting of 2 coils interconnected next to each other and each coil is wound in opposite directions to increase sensitivity and reduce external interference. The coil pair was tested from 1A to 190kA and produced exceptionally good linearity for a voltage vs. current plot [59]. Further test done by Karrer et al. shows that PCBRCs are capable of working in high current environments and in a 500A system produces an error rate of less than 1 percent [75]. More recent work by Kojovic includes an ATP simulation to simulate the response of the PCBRCs for protection system applications using the saturable transformer model [76]. He also presented different PCBRC designs such circular, oval and rectangular shaped coils along with the option of a split core style for installation without the need to disconnect the conductors [77].

4.2.1. Design of Rogowski Coil

The Rogowski coil that is required in this research project is a sensor that will be able to detect partial discharge signals in the frequency range of about 20MHz as presented in the data collection in the previous chapter. Two types of Rogowski coil will be presented in this section, the first one is a handmade coil using copper enamel wire wound around a plastic holder and the second one is a pair of interconnected PCB Rogowski coils. This section will consider the specifications for the coils and sensitivity in detecting high frequency signals and further testing will be carried out for a full system implementation on the next chapter.

In order to design the coil and predict its capabilities, equation 2 is used to find out the output voltage level of the coil. As the mutual inductance $M$ can be defined by the dimensions of the coil, the Rogowski coil was designed to detect voltage levels high enough to be processed by the monitoring device.

Referring to equation 2, mutual inductance $M$ can be further deduced from the coil’s rectangular cross section as shown in equation 3:

$$V_{coil} = M \frac{di}{dt} \quad (2)$$
\[ M = \frac{\mu_0 NW \log{b}}{a} \]  

(3)

\( \mu_0 = \text{The permeability of air which is } 4 \, \square \times 10^{-7} \text{ H/m} \)

\( N = \text{Number of turns in the coil} \)

\( W = \text{Width of the coil} \)

\( a = \text{Inside diameter of the coil} \)

\( b = \text{Outside diameter of the coil} \)

Another consideration that will affect the bandwidth of the coil is the frequency response based on the coil's inductance and capacitance. Where the frequency response can be found using equation 4. By keeping the capacitance and inductance low, higher frequency responses can be achieved.

\[ f_c = \frac{1}{2\pi \sqrt{LC}} \]  

(4)

a) **Handmade Rogowski coil**

Figure 25 shows the hand wound Rogowski coil with a conductor going through the middle and a plastic pipe which is used as insulation to prevent direct contact between the conductor and copper enamel wire. Figure 26 shows the Rogowski coil sealed in epoxy for insulation and weather sealing. Table 4 shows the measured parameters on the handmade Rogowski coil.

**Table 4 Handmade Rogowski Coil Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Diameter, a</td>
<td>50mm</td>
</tr>
<tr>
<td>Outer Diameter, b</td>
<td>30mm</td>
</tr>
<tr>
<td>Width, W</td>
<td>40mm</td>
</tr>
<tr>
<td>Number of Turns, N</td>
<td>12</td>
</tr>
<tr>
<td>Length of Wire</td>
<td>1.5m</td>
</tr>
<tr>
<td>Diameter of Wire</td>
<td>1mm</td>
</tr>
<tr>
<td>Measured Resistance, R</td>
<td>66m(\Omega)</td>
</tr>
<tr>
<td>Measured Capacitance, C</td>
<td>225(\mu)F</td>
</tr>
<tr>
<td>Measured Inductance, L</td>
<td>1.1(\mu)H</td>
</tr>
</tbody>
</table>
Figure 25 Handmade Rogowski coil

Figure 26 Handmade Rogowski coil sealed in epoxy
b) PCB Rogowski coil

Figure 27 shows a single PCB Rogowski coil slotted in the conductor and Figure 28 is the PCB Rogowski coil pair sealed in epoxy with a $1\Omega$ termination resistor. Table 5 shows the measured parameters of the PCB Rogowski coil.

Table 5 PCB Rogowski Coil Specifications

<table>
<thead>
<tr>
<th>PCB Rogowski Coil</th>
<th>Single</th>
<th>Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Diameter, $a$</td>
<td>27mm</td>
<td>27mm</td>
</tr>
<tr>
<td>Outer Diameter, $b$</td>
<td>155mm</td>
<td>155mm</td>
</tr>
<tr>
<td>Width, $W$</td>
<td>2mm</td>
<td>4mm</td>
</tr>
<tr>
<td>Number of Turns, $N$</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Length of Wire</td>
<td>1.744m</td>
<td>3.488</td>
</tr>
<tr>
<td>Diameter of Wire</td>
<td>1mm</td>
<td>1mm</td>
</tr>
<tr>
<td>Measured Resistance, $R$</td>
<td>1.8$\Omega$</td>
<td>3.6$\Omega$</td>
</tr>
<tr>
<td>Measured Capacitance, $C$</td>
<td>250nF</td>
<td>500nF</td>
</tr>
<tr>
<td>Measured Inductance, $L$</td>
<td>0.05$\mu$H</td>
<td>0.1$\mu$H</td>
</tr>
</tbody>
</table>

Figure 27 PCB Rogowski coil
4.3 Capacitive Coupler

This second sensor is an alternative sensor based on capacitance between the distribution line and the metallic PCB plate inside the weather resistant enclosure. This sensor works on the fundamental principal of a mutual capacitance that happens between transmission lines when placed parallel next to each other. All transmission lines have resistance, inductance and capacitance in their natural characteristics. When two lines are placed next to each other, mutual capacitance occurs between the two lines and when a surge occurs in one of the lines, it is then coupled into the other line next to it.

In this research work, the aluminium conductor and the circular PCB capacitive coupling plate works as capacitor. Placed in close proximity, the PCB will be able to pick up the signals from the aluminium conductor through mutual capacitance. With the increment of capacitance, the level of sensitivity of the sensor also increases. To
determine the capacitance between the metallic surfaces the following equation can be used:

\[ C = \varepsilon_0 \varepsilon_r \frac{A}{d} \]  

(5)

**C is the capacitance in Farads**

**A is the area of overlap of the two plates**

**\( \varepsilon_r \) is the relative static permittivity (also known as the dielectric constant) of the material between the metallic surfaces**

**\( \varepsilon_0 \) is the permittivity of free space (\( \varepsilon_0 \approx 8.854 \times 10^{-12} \text{ F/m} \))**

**d is the separation between the plates in meters**

The design of this capacitive coupler sensor is based on Nakamura’s patent of a noncontact voltage sensor housed in a container to prevent corrosion from various weather conditions [56]. Further investigation on the design was carried out by Trinh on the sensitivity of the design from 0.5m to 3m [78].

The design for this research project is shown in Figure 29. The circular PCB plate used is 10cm in diameter and glued to the surface of the plastic enclosure. The enclosure is an 11cmX11cmX11cm cube shaped box. The back plate is made of aluminium and attached to coaxial cable output terminal with a direct connection to the PCB’s copper layer. To ensure the enclosure is water proof, all joints and edges are sealed in epoxy glue. A ten minute submersion test was carried out to ensure there wasn’t any leakage. This was done to ensure no water seepage will happen when installed in outdoor conditions. The sensitivity of the sensor depends on the distance between the PCB plate and the distribution line it is monitoring, a smaller distance produce higher capacitance which in turn increases sensitivity.

Figure 30 is the proposed setup for a 3-phase online distribution line measurement system. The sensors are installed on distribution lines poles with the PCB copper
plate facing the bare aluminium conductors. The sensors are then connected to a data logging device. Sensor systems are then placed every few kilometers apart and with today's global positioning system (GPS), localizing the fault along the distribution line can be done with minimal effort after installing the system.

![Capacitive coupler in enclosure](image1.png)

**Figure 29 Capacitive coupler in enclosure**

![Capacitive coupler sensors on a 3-phase system](image2.png)

**Figure 30 Capacitive coupler sensors on a 3-phase system**
4.4 Sensor Performance

This section presents the result for the sensors sensitivity towards high frequency signals. This is carried out to verify the potential of each sensor being used for partial discharge sensing around the range of 20MHz. All tests are carried out in RMIT’s high voltage lab.

4.4.1. PCB Rogowski Coil High Frequency Test

The PCB Rogowski coil is used as a contactless sensor to monitor the 3m aluminium conductor as shown in Figure 31. The aim is to verify the Rogowski coil capability of sensing high frequency signals produced by a signal generator with frequencies ranging from 1MHz to 30MHz travelling down an actual distribution line conductor.

In the test setup, 3 measuring points are monitored by an oscilloscope. V1 is used to measure the parallel output of the signal generator, V2 is the voltage across the resistor for the voltage detected by the Rogowski coil and V3 is the voltage measured at the end of the conductor. The end of the bare aluminium conductor is then terminated by a 50Ω resistor. The results of the test are presented in Table 6.

![Figure 31 PCB Rogowski coil high frequency sensitivity test](image-url)
<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Input from signal generator (V1)</th>
<th>Voltage at receiving end of cable (V3)</th>
<th>Output voltage measured by Rogowski Coil (V2)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.96 (V_{pp})</td>
<td>1.76 (V_{pp})</td>
<td>4.4 m(V_{pp})</td>
<td>-26.02 -26.49</td>
</tr>
<tr>
<td>2</td>
<td>2.16 (V_{pp})</td>
<td>1.6 (V_{pp})</td>
<td>5.6 m(V_{pp})</td>
<td>-24.56 -25.86</td>
</tr>
<tr>
<td>3</td>
<td>2.28 (V_{pp})</td>
<td>1.4 (V_{pp})</td>
<td>6.8 m(V_{pp})</td>
<td>-23.14 -25.25</td>
</tr>
<tr>
<td>4</td>
<td>2.4 (V_{pp})</td>
<td>1.32 (V_{pp})</td>
<td>6.8 m(V_{pp})</td>
<td>-22.88 -25.48</td>
</tr>
<tr>
<td>5</td>
<td>2.52 (V_{pp})</td>
<td>1.12 (V_{pp})</td>
<td>9.6 m(V_{pp})</td>
<td>-20.67 -24.19</td>
</tr>
<tr>
<td>6</td>
<td>2.56 (V_{pp})</td>
<td>1 (V_{pp})</td>
<td>8.4 m(V_{pp})</td>
<td>-20.76 -24.84</td>
</tr>
<tr>
<td>7</td>
<td>2.64 (V_{pp})</td>
<td>0.88 (V_{pp})</td>
<td>9.2 m(V_{pp})</td>
<td>-19.81 -24.58</td>
</tr>
<tr>
<td>8</td>
<td>2.64 (V_{pp})</td>
<td>0.84 (V_{pp})</td>
<td>9.6 m(V_{pp})</td>
<td>-19.42 -24.39</td>
</tr>
<tr>
<td>9</td>
<td>2.64 (V_{pp})</td>
<td>0.8 (V_{pp})</td>
<td>11.2 m(V_{pp})</td>
<td>-18.54 -23.72</td>
</tr>
<tr>
<td>10</td>
<td>2.64 (V_{pp})</td>
<td>0.56 (V_{pp})</td>
<td>11.6 m(V_{pp})</td>
<td>-16.84 -23.57</td>
</tr>
<tr>
<td>11</td>
<td>2.6 (V_{pp})</td>
<td>0.6 (V_{pp})</td>
<td>11.6 m(V_{pp})</td>
<td>-17.14 -23.5</td>
</tr>
<tr>
<td>12</td>
<td>2.6 (V_{pp})</td>
<td>0.56 (V_{pp})</td>
<td>13.6 m(V_{pp})</td>
<td>-16.15 -22.81</td>
</tr>
<tr>
<td>13</td>
<td>2.6 (V_{pp})</td>
<td>0.6 (V_{pp})</td>
<td>12.8 m(V_{pp})</td>
<td>-16.71 -23.08</td>
</tr>
<tr>
<td>14</td>
<td>2.6 (V_{pp})</td>
<td>0.6 (V_{pp})</td>
<td>13.2 m(V_{pp})</td>
<td>-16.58 -22.94</td>
</tr>
<tr>
<td>15</td>
<td>2.6 (V_{pp})</td>
<td>0.64 (V_{pp})</td>
<td>15.2 m(V_{pp})</td>
<td>-16.24 -22.33</td>
</tr>
<tr>
<td>16</td>
<td>2.52 (V_{pp})</td>
<td>0.64 (V_{pp})</td>
<td>20 m(V_{pp})</td>
<td>-15.05 -21</td>
</tr>
<tr>
<td>17</td>
<td>2.48 (V_{pp})</td>
<td>0.68 (V_{pp})</td>
<td>24 m(V_{pp})</td>
<td>-14.52 -20.14</td>
</tr>
<tr>
<td>18</td>
<td>2.4 (V_{pp})</td>
<td>0.72 (V_{pp})</td>
<td>30 m(V_{pp})</td>
<td>-13.8 -19.03</td>
</tr>
<tr>
<td>19</td>
<td>2.36 (V_{pp})</td>
<td>0.76 (V_{pp})</td>
<td>49.6 m(V_{pp})</td>
<td>-11.85 -16.77</td>
</tr>
<tr>
<td>20</td>
<td>2.32 (V_{pp})</td>
<td>0.64 (V_{pp})</td>
<td>61.6 m(V_{pp})</td>
<td>-10.17 -15.76</td>
</tr>
<tr>
<td>21</td>
<td>2.36 (V_{pp})</td>
<td>0.44 (V_{pp})</td>
<td>69.6 m(V_{pp})</td>
<td>-8.01 -15.3</td>
</tr>
<tr>
<td>22</td>
<td>2.32 (V_{pp})</td>
<td>0.2 (V_{pp})</td>
<td>49.6 m(V_{pp})</td>
<td>-6.66 -16.7</td>
</tr>
<tr>
<td>23</td>
<td>2.28 (V_{pp})</td>
<td>0.28 (V_{pp})</td>
<td>46.4 m(V_{pp})</td>
<td>-7.81 -16.91</td>
</tr>
<tr>
<td>24</td>
<td>2.2 (V_{pp})</td>
<td>0.36 (V_{pp})</td>
<td>58.4 m(V_{pp})</td>
<td>-7.9 -15.76</td>
</tr>
<tr>
<td>25</td>
<td>2.04 (V_{pp})</td>
<td>0.36 (V_{pp})</td>
<td>56.8 m(V_{pp})</td>
<td>-8.02 -15.55</td>
</tr>
<tr>
<td>26</td>
<td>1.88 (V_{pp})</td>
<td>0.52 (V_{pp})</td>
<td>54.4 m(V_{pp})</td>
<td>-9.8 -15.38</td>
</tr>
<tr>
<td>27</td>
<td>1.68 (V_{pp})</td>
<td>0.52 (V_{pp})</td>
<td>50.4 m(V_{pp})</td>
<td>-10.14 -15.23</td>
</tr>
<tr>
<td>28</td>
<td>1.48 (V_{pp})</td>
<td>0.68 (V_{pp})</td>
<td>46.4 m(V_{pp})</td>
<td>-11.66 -15.04</td>
</tr>
<tr>
<td>29</td>
<td>1.32 (V_{pp})</td>
<td>0.72 (V_{pp})</td>
<td>100 m(V_{pp})</td>
<td>-8.57 -11.21</td>
</tr>
<tr>
<td>30</td>
<td>1.4 (V_{pp})</td>
<td>0.44 (V_{pp})</td>
<td>144 m(V_{pp})</td>
<td>-4.85 -9.88</td>
</tr>
</tbody>
</table>
4.4.2. Capacitive Coupler Sensitivity Range Test

This section explores the effects of varying distances of the sensor to the source of high frequency signals to verify the sensitivity levels of the proposed sensor. The test setup for the capacitive coupler is as shown in Figure 32 and Figure 33. The transformer voltage used is $25kV_{RMS}$ and this is then connected to the spark gap. The spark gap is setup in a point-to-plane configuration with a 30mm gap to simulate a partial discharge signal.

In order to identify the sensitivity of the PCB capacitive coupler in the enclosure, the test was carried out with two other sensors. A commercially available bi-conical antenna is used as a reference point and the other sensor used is the PCB capacitive coupler plate without the weather proofing enclosure. All three sensors are placed at the same distance away from the high frequency source for each testing. Measurements were carried out starting from 0.5m away with a 0.5m increment until 3m. Results presented in Table 7 are the average of ten samples for each distance measured on the oscilloscope.

![Figure 32 Top view of the sensor and spark gap setup](image-url)

![Figure 33 Side view of the high frequency signal source to the sensors](image-url)
Table 7 Sensitivity test for varying distances

<table>
<thead>
<tr>
<th>Distance from source</th>
<th>With Enclosure (V_{pp})</th>
<th>Plate (V_{pp})</th>
<th>Antenna(V_{pp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5m</td>
<td>4.624</td>
<td>5.49</td>
<td>6.631</td>
</tr>
<tr>
<td>1m</td>
<td>2.744</td>
<td>3.904</td>
<td>6.36</td>
</tr>
<tr>
<td>1.5m</td>
<td>2.096</td>
<td>2.224</td>
<td>5.588</td>
</tr>
<tr>
<td>2m</td>
<td>2.048</td>
<td>1.84</td>
<td>5.224</td>
</tr>
<tr>
<td>2.5m</td>
<td>2.172</td>
<td>1.94</td>
<td>6.592</td>
</tr>
<tr>
<td>3m</td>
<td>2.18</td>
<td>3.556</td>
<td>6.856</td>
</tr>
</tbody>
</table>

4.4.3. Discussion

Both sensors tested showed potential for use as a partial discharge detector on bare aluminium conductors used in distribution lines. Each sensor has its own advantages and potential problems which will be discussed in this section.

Initial testing of the PCB Rogowski coil showed potential as it picked up about 0.2% of the high frequency signal sent through the bare aluminium conductor in the lab testing. As the Rogowski coil has good linearity, it is expected to output an 8V pulse from a 4kV partial discharge found in the distribution line.

Further testing was carried out by placing the PCB Rogowski coil in the bare aluminium conductor as seen back in Figure 6 with a polluted insulator. Results were inconclusive from the test as the coil started introducing high frequency pulses even without the polluted insulator in place when tested with voltage levels above 7kV. A high voltage insulation tape was introduced for the section monitored by the PCB Rogowski coil but the tape was only able to prevent the high frequency pulses up to 11kV before it appeared again. To prevent damage to the oscilloscope and personal safety, no further testing was done. Another minor problem faced by the PCB Rogowski coil is that it is only possible to install it at the start or terminating end of the line. Splitting the coil for easy installation anywhere along the line was proposed but as isolating the coil from the bare aluminium conductor was a problem, it was not carried out.

With the problem faced by the PCB Rogowski coil, another design was proposed in the form of a capacitive coupler. The capacitive coupler does not require any physical contact with the bare aluminium conductor. It is also less problematic as it presents more installation options as long as the PCB plate is facing the conductor.
From the results, an observation made during measurement is that all sensors measured the high frequency signals in the same phase when it is 2 meters away from the source. Another observation made was that the capacitive coupler plate detected a higher voltage than when it is placed in a sealed weather proofing enclosure. This is believed to be caused by the plastic enclosure acting as a dielectric as it increases the resistance between the capacitive coupler and the high frequency source.

The set back with the capacitive coupler method is that it has not yet been tested on an actual distribution line as it is hard to get the power companies permission to do testing on their live distribution lines. It is also not being able to measure the attenuation rate of partial discharge signals over long distances to have a better understanding of how far apart the sensors need to be installed before the signal is beyond recognition.

With the available equipment in the laboratory, the next chapter will try to provide an overview of the proposed setup of the entire system. This would be done by introducing high frequency signals into a bare aluminium conductor laid out in the laboratory to simulate the effects of attenuation and test the sensitivity of the capacitive coupler.
Chapter 5: System Implementation

Previous chapters have described the characteristics of partial discharge and the types of sensors which are suitable for sensing the high frequency partial discharge signals. The next step in this research work is to setup a system that can be easily installed onto distribution lines to monitor partial discharge signals.

The proposed monitoring system is as shown in Figure 34. It works by having a capacitive coupler monitoring for any transient or discharge signal travelling along the distribution line conductors. From the previous spark gap test, the ideal distance for placing the sensors are 1m to 2m away for a 22kV distribution line. It is also important to ensure the length of the coaxial cable connecting the sensor and the data logger at both end of the system is of the same length to avoid time of arrival errors. The monitored information is then recorded by a data logging system for processing. As Global Positioning Systems (GPS) have advanced tremendously, it has been widely applied in map navigation, geo-tagging of photographs and in this case, locating the source of partial discharge. The set up found in Figure 34 shows a monitoring system for a single phase line. This system can easily accommodate a three phase system by having three sensors as shown in Figure 30.

Power companies in Victoria, Australia have been very careful on providing permission to access to their distribution line for testing. Instead an alternative test was set up in RMIT’s laboratory to verify the basic principles of the proposed system. The aim of the test carried out in the laboratory is to identify the sensitivity of the sensors and how the signal detected by the sensors attenuates over various distances.

Figure 34 Proposed fault detection system
5.1 System Verification

To further understand the proposed detection system, two tests were carried out to ensure the viability of the system to be used as a partial discharge system. The first test is conducted by connecting a recurrent surge generator in the middle of a 20m aluminium conductor line as shown in Figure 35. Two capacitive coupler sensors are used at both ends of the line to monitor the signal from the surge generator. The recurrent surge generator transmits 200V peak pulse lasting for 20 µs as shown in Figure 36. Both ends of the bare aluminium conductor are terminated by a 50Ω resistance bank. To ensure the time delay between sensors and the oscilloscope is standardized, the coaxial cables used are of the same length.

Table 8 shows the results from this test. As expected the data collected from both sensors are almost identical. Figure 37 shows the signal detected on S1 from the various distances and saved in MS Excel. The signal detected at 40cm decreased by more than 50% compared to the signal measured at 20cm. The detected signal from 40cm to 100cm continued to decrease but has more linearity. In terms of ratio between the signal in the conductor and the signal picked up by the sensor ranges 1:2174 for a distance of 20cm and 1:15385 for 100cm.

![Figure 35 Experimental Set-up 1: Single path distribution line setup](image)
Figure 36 Signal from the recurrent surge generator

Table 8 System verification of single path distribution line

<table>
<thead>
<tr>
<th>Distance from Conductor</th>
<th>Amplitude (V&lt;sub&gt;pp&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>20cm</td>
<td>92mV</td>
</tr>
<tr>
<td>40cm</td>
<td>43mV</td>
</tr>
<tr>
<td>60cm</td>
<td>27mV</td>
</tr>
<tr>
<td>80cm</td>
<td>18mV</td>
</tr>
<tr>
<td>100cm</td>
<td>13mV</td>
</tr>
</tbody>
</table>

Figure 37 S1 output at various distance from the conductor
The second test is carried out to further understand the effects of having multiple branches. This is done to make the test resemble an actual distribution line as most distribution lines are built to serve a large area with multiple branches. The second test set up is shown in Figure 38.

The main bare aluminium conductor is 20m long and a 5m long conductor is connected to the middle point of the main conductor to resemble distribution line branch. Sensors are placed at the end of both branches to monitor the 400V peak signal transmitted by the recurrent surge generator. Both the capacitive coupler sensors are placed 20cm away from the conductor in this test. Both branches are terminated by a 50Ω resistance bank. Using identical length coaxial cables, the signal is then sent to the oscilloscope for monitoring and storage. The result from this test is shown in Table 9.
Table 9 System verification for branched distribution line

<table>
<thead>
<tr>
<th>Distance from conductor</th>
<th>Amplitude ($V_{pp}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>20cm</td>
<td>202mV</td>
</tr>
</tbody>
</table>

5.2 Discussion

The capacitive coupler has been tested as how the actual system will be set up on a distribution line; only on a smaller scale. With reference to previous chapters, the partial discharge pulses range around 4kV. As the recurrent surge generator is only capable of producing 400V, it is assumed the voltage level recorded in this test is only ten percent of what is found on an actual distribution line.

Measurements were done from 20cm to 100cm away from the conductor, so the system is definitely sensitive enough to pick up the pulses from a distribution line. The capacitive coupler sensor should be sensitive enough even at further distances due to the higher voltages on an actual distribution line.

From the test carried out, the capacitive couplers are suitable for monitoring online distribution lines. As this is a contactless sensor, it can monitor signal surges along the distribution line without interfering with the power transmission process. The only problem faced is that the signal detected becomes distorted when the distance between the sensor and the conductor increases. This can be observed in the original transmitted signal in Figure 36 and the captured signal from the capacitive coupler in Figure 37.

The aspect of localization of the fault is only briefly discussed here as there are plenty of reliable localization algorithms that have been developed. The latest and most reliable localization method is using the GPS system as shown by Wielen et al. [79] and Boone [80]. Another established method is by artificially injecting a high frequency reference pulse as shown by Wagenaars [81]. Another localization method that had been implemented for a long time is the Time Domain Reflectometry (TDR) as shown by Zhifang [82] and Quak [83]. Markalous et al. [84] further improved the TDR method by applying wavelet to remove noise and by doing this, he managed to produce a more accurate system.
Chapter 6: Conclusion and Discussion

Partial discharge monitoring has become an indispensable part of maintaining and preventing potential failures in distribution lines. The online monitoring methods currently available have been gaining preference over offline methods. The main advantage of an online system is that the line under test can continue to be in-service without disrupting supply to customers. Other advantages of the system include minimum maintenance effort after installation and it is able to monitor the line continuously.

The thesis starts by identifying the problems faced in overhead distribution lines. Some distribution lines in Victoria have been in service for more than 3 decades; wear and tear of the insulators on these lines has led to failures such as pole top fire. Three main causes were identified to cause partial discharge signals in distribution lines. Partial discharge signals are found when the insulator has suffered structural damage or when it has been covered in pollution. Another source of partial discharge is caused by broken conductor strands. By identifying the problems, the foundation is set for this thesis to examine the possibility of detecting these partial discharge signals before they lead to a distribution line failure.

As mention before, online partial discharge detection has an advantage over offline methods. The main online fault detection currently practiced consists of leakage current monitoring system, infrared thermal imaging, electromagnetic radiation monitoring and acoustic detection. Offline methods are less preferred as the line under test is require to be de-energized and causing disruption of service to customers. Apart from that, it is also considered a destructive test as the test carried out will damage and identify the insulators that are nearing the end of their service life. Offline methods that have been practiced are known as the HIPOT test and the Very Low Frequency test. It was also found that a partial discharge sensor that monitors the electrical levels of the partial discharge signal uses either capacitive coupling or inductive coupling. Using this method enables the test to be carried out without having direct contact with the line and thus making it an online contactless system.
To further understand the characteristics of a partial discharge signal, a test was carried out on an artificially polluted insulator covered in kaolin. The insulator used was a fully functional ceramic insulator taken from a 22kV distribution line. After artificially polluting the insulator, it is then used as the source of partial discharge for the test. The observations made from the test showed that the partial discharge frequency from a polluted insulator varies between 20MHz to 30MHz. The test also showed that the partial discharge voltage on a distribution line is about 5.7kV\textit{RMS}.

Throughout the entire test, a capacitive voltage divider was used to step down the line voltage for it to be safely monitored on the oscilloscope.

As access to an actual distribution line was not easily available, the data from polluted insulator is then entered into a computer simulation model to identify how the partial discharge signal behaves over long distances. The two simulation packages used for the simulations are ATPDraw and MATLAB. The computer models were used to simulate a high frequency signal transmitted over long distances along the distribution line. MATLAB was found to be easier to control and allows the simulation of skin effect. It was found that by reducing the simulation step-size produced better accuracy of high frequency signal although it took longer to complete the simulation.

With a better understanding of partial discharge characteristics, sensors are designed for sensing the partial discharge signals. The first sensor is a PCB Rogowski coil that uses inductive coupling to capture the signal from the distribution line. The PCB Rogowski coil was able to pick up high frequency signals of 1MHz to 30MHz transmitted along a distribution line. A problem arises when it is used on an energized line as it produced high frequency pulses itself when exposed to 11kV and above. The other sensor is a capacitive coupler enclosed in a box for weather proofing. As the capacitive coupler does not need to be wrapped around the distribution line, it provides more flexibility during installation. It was then tested for its sensitivity from 0.5m to 3m by using a 25kV, 30mm spark gap as a source of high frequency signals. It managed to pick up the high frequency signals at all the range tested.

The final part of the thesis introduces a fault detection system that uses a cost effective and easy to produce sensor. It works by placing the sensors on different point of the distribution line and the data is fed into a data logging device. If a fault is
observed, one of the localization algorithms mention in the text could be applied to find the source of the partial discharge signal.

6.1 Future Improvements

A partial discharge system for distribution lines was presented in this thesis but all the work and information collected has all been done in the laboratory. A future recommendation would be trying to get a power company who would allow access to actual distribution lines. The signal detected on an actual line may vary from the results found in the laboratory test. External signal interferences may affect the data logging device. To overcome these problems, specifically designed signal filters and amplifiers may solve the expected problems.

At the moment all the results are monitored and recorded on oscilloscopes. To realize a cheap and competitive system, a dedicated data acquisition card would be more cost effective than installing oscilloscopes on every installed sensor system.

As for the PCB Rogowski coil, further improvement maybe achieved by using an epoxy cast with a higher dielectric strength. Doing so will help isolate the coil better from the live line.
List of Reference


Transactions on Dielectrics and Electrical Insulation, vol. 10, pp. 343-353, 2003.


Appendix

Conference Proceedings:

1. Partial Discharge Signal Sensing on Overhead Conductors

2. Partial Discharge Sensing in Overhead Distribution Line