UNIVERSITÀ DEGLI STUDI DI PADOVA

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COMPUTERISED MEASUREMENTS AND CONDITION MONITORING FOR POLYMERIC INSULATORS AT A LARGE OUTDOOR TEST STATION

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Abstract

In the present work, a measuring system able to detect a small current magnitude and partial discharges activities on polymeric insulators has been studied. Starting from a state of the art of the nowadays steady technologies of insulators design, the study has been moved to the relevant problems caused by aging effects. Hence, considering the issues that could involve outdoor insulators, an important electrical parameter has been taken into account: the leakage current. To detect this kind of current, many transducers have been analysed.

From the theory, the work has moved to an experimental test in the high voltage laboratory of Cardiff University. A characterization of the transducers has been carried out and two of them have been tested to detect the leakage current in a textured polymeric insulator. All the measurement system from the generator to the low-pass filter, the step-up transformer, the voltage divider and the textured polymeric insulator has been analysed to be sure that the whole system can correctly work. The two insulator tests, the dry and the wet pollution test, have been carried out and the results compared and so, analysed with Matlab. The aim was to study the transducer reliabilities.

Finally, simple systems for the remote access of data have been studied and a little experimental test has been carried out.

Sommario

Il lavoro è stato sviluppato con l'obbiettivo di effettuare delle misure su correnti di lieve entità e per il rilevamento di scariche parziali sugli isolatori. Lo studio ha dapprima coinvolto l'apprendimento teorico dello stato dell'arte delle ormai consolidate tecnologie per le strutture degli isolatori. Quindi, sono state prese in considerazione le problematiche dovute alla presenza di condizioni ambientali sfavorevoli. Lo studio è poi proseguito con la valutazione del parametro elettrico utile a identificare lo stato di salute degli isolatori: la corrente di dispersione, per la quale sono stati approfonditi diversi trasduttori.

Il lavoro, inizialmente analizzato in un contesto teorico, è stato poi applicato in un test sperimentale nel laboratorio di alte tensioni dell'Università di Cardiff. È stata effettuata un'analisi di caratterizzazione dei trasduttori, dei quali due ne sono stati utilizzati in seguito per l'analisi della corrente di dispersione su un particolare isolatore polimerico. L'intero sistema di misurazione a partire dal generatore, dal filtro passa-basso, dal trasformatore elevatore, dal divisore di tensione fino all'isolatore polimerico è stato analizzato per avere a disposizione un sistema di misura al quanto più accurato. Sono stati effettuati due test: uno considerando l'isolatore asciutto e l'altro bagnando le superfici dell'isolatore per emulare una condizione ambientale sfavorevole. I risultati sono quindi stati elaborati con il software Matlab. Lo scopo è stato quello di studiare l'affidabilità dei trasduttori impiegati.

Per concludere, sono stati analizzati vari sistemi per l'accesso da remoto dei risultati ottenuti e un piccolo esperimento a riguardo è stato effettuato.

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Introduction

Insulators are essential structures that isolate the high voltage potential to the ground. They have various outdoor applications, from high voltage substations to the overhead lines. As a matter of fact, they can be vulnerable to weather conditions. The formation of a pollution layer together with fog, light rain or high humidity can create a conductive film on the insulator surfaces that leads the leakage current to flow. For that reason, this current can be a great electrical parameter to be analysed and so, to make decisions about the condition monitoring of insulators working in a particular place service.

The main objective of this work is to study the behaviour of this current and create a measurement system in the laboratory of Cardiff University that can detect it. Moreover, the system may be used for an outdoor test station where insulators can be stressed with true weather conditions. With this purpose, the current sensing can be a great challenge due the magnitude of this signal. Many decisions need to be made about the transducers to use and the data acquisition system to implement in the measurement setup. Moreover, before starting any tests, there is a need to characterize the signals sensors. They must be accurate and able to perform reliable measurements. When the whole system is analysed, the transducers can be used to detect the leakage current in a composite test insulator. This kind of insulator differs from the others because it has different behaviours due the material they are made with. Hence, the other challenge consists of compared the results that come from the transducers and make considerations for their reliability. The leakage current waveform may have unexpected events that sensors and data acquisition devices must detect.

Finally, when all these data are collected, it could be useful to have them in another part of the world. So, it can be possible to make decision and monitor the results without long travels.

Chapter 1

Insulators for outdoor environments

In this first chapter, general information about insulators will be provided. A state of the art of the nowadays technologies will be presented. Then some issues correlated with the aging of the insulator materials exposed to weather will be explained. Finally, the test station "Deeside Centre for Innovation" owned by National Grid will be described and some techniques for insulators monitoring will be discussed in order to have general information about the condition monitoring.

1.1 Design of insulators

In every electricity sector, insulation plays a key role to prevent faults and for a safety reason. In the overhead power lines (OHL) and substation applications, insulators suspend the high voltage conductors avoiding the contact between high potential and the ground. This means an intense mechanical stress due to tensile and compressive strength. Furthermore, environmental and electrical factors may affect insulators behaviour as well. These issues are straight correlated with the insulator materials and designs. About that and according to their shapes, insulators could be divided into two macro groups: discs and cylinders [1]. The first group includes the most common "cap and pin" configuration. The others comprise "long-rod", "post" and "barrel" design. The material they are made of can vary from porcelain, glass and polymers as silicon rubber. All these materials have their advantages and disadvantages like the easy wettable, brittle and the heaviness in the case of porcelain and glass. Instead, composite insulators made of polymeric rubber are light, non-brittle and they preserve a great hydrophobicity for a long time. Therefore, the importance of insulators consists in their reliability during the years of service. Several factors, as the manufacturing, the misapplication, the contamination in the material and some mechanicals, electrical and environmental pollution issues may affect the insulation behaviour, causing failures and severe problems for the system reliability.

Hydrophobicity and hydrophilicity are important factors for insulators. They involve adhesive and cohesive forces between a liquid and a solid, causing liquid drops to spread across the surface or to ball up and avoid contact with the surface. In the case of hydrophobic materials, many water drops can be seen on the surface because they are easy to form. For the hydrophilic case, insulator sheds can be entirely covered by a thin layer of water. The standard IEC 6203 [2] explains different methods to measure the hydrophobic and so, the hydrophilic characteristic of an insulator material. A good consideration of the so call wettability[1], can be valid measuring the contact angle θ of a water drop presents on a surface.

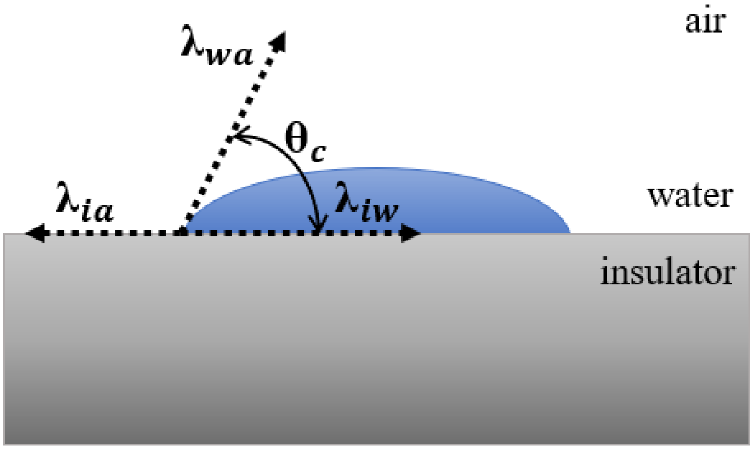


Figure 1.1. *Interfacial tensions distribution on a surface.*

It can be determined by the balance between adhesive and cohesive forces.

The contact angle θ_c depends on three coefficients of interfacial tension λ, as it can be seen in the Young-Dupre equation[2]:

$$cos\theta_c = \frac{\lambda_{ia} - \lambda_{iw}}{\lambda_{wa}} \tag{1.1}$$

[1] Considered as the capability of water to spread over a large area of the surface.

[2] Young-Dupre equation is valid for an ideal solid surface, that is flat, rigid, and chemically homogeneous.

Where w is referred to water, i to insulator and a to air. The differences between the two physical behaviours, hydrophobicity and hydrophilicity, are correlated with the magnitude of the free surface energy. Materials with a high surface energy can be easily wetted, so the contact angle can be considered less than 90°. This is the case of hydrophilic materials. On the contrary, if there is a low surface energy, the contact angle could be greater than 90°, so the water droplets can easily slip along the surface. In this case, the insulation can be considered hydrophobic. Regarding the wet pollution, the angle can vary a lot, and a more hydrophilic behaviour arise even in the polymerics materials, naturally more hydrophobic than porcelain and glass. For a clean surface, θ can be considered about 30° for ceramic and 100° for silicon rubber. When the surface gets polluted, the contact angle becomes zero.
In addition, important considerations might be done considering the mechanical properties of materials. Tensile and compressive strength need to be considered to make good application decisions. As described in [1] , mechanical properties of different materials used for insulator dielectric housing are explained in Table 1.1.

Table 1.1. *Stress solicitation for different materials.*

	Units	**Porcelain**	**Glass**	**Polymer[3]**	**RBGF[4]**
Tensile strength	MPa	*30-100*	*100-120*	*20-35*	*1300-1600*
Compressive strength	MPa	*240-820*	*210-300*	*80-170*	*700-750*

It is clear the major resistance to a compressive state for porcelain, glass and polymer, instead of RBGF with a more tensile strength. These differences allow a variety of applications, from OHLs to bushings where many forms have been designed to be able to stress materials in a good way.

[3] silicone and carbon based.
[4] resin-bonded glass fibre used for the core of a polymeric insulator.

1.1.1 Cap and pin

This configuration is the most popular, thanks to its simplicity of being adapted at different voltage levels. It can be seen in the high voltage overhead lines, supporting the conductors and avoiding the contact between them and the tower.

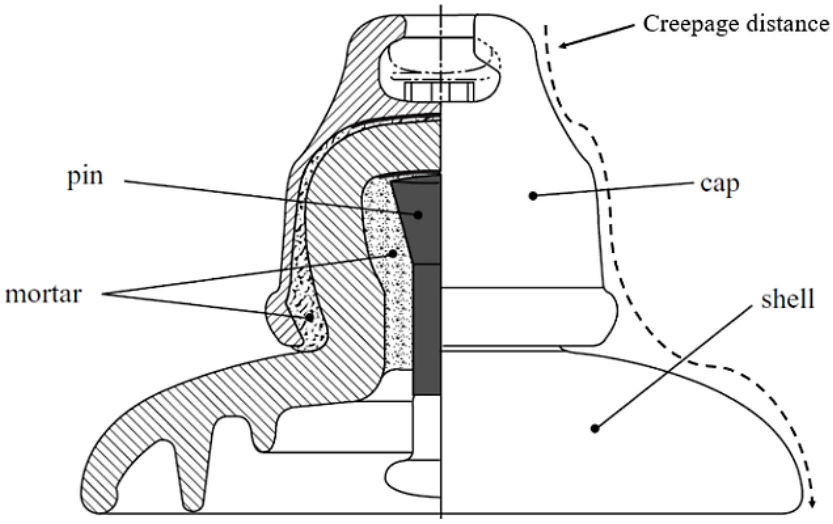


Figure 1.2. *"Cap and Pin" structure* [1].

It is made up of large flat shells or more aerodynamic ones, depending on the weather condition they need to work[5]. The materials can be porcelain or glass. Beneath the cap, pin is inserted into a mortar, a conductive material made with special cements[6] or metal alloys. The caps and the pins are such to allow their interlocking. Thus, many caps and pins could be connected like a chain to create the isolator length needed. The total surface of the chain, from the high potential to the ground, creates a path called "creepage distance". It is so important for the leakage current evaluation because, depending on the pollution intensity, a wet conductive path could be formed across it. Furthermore, many disadvantages correlated with the mechanical structure need to be considered for this type of insulators. These considerations are important because each failure mode has specific consequences from the single unit to all the chain, causing

[5] For example, in foggy regions humidity can affect insulators behaviour. Hence, the shape is made with different layouts compared to others employed in deserts or coastal regions.
[6] Such as Portland cement or Fondu cement.

severe problems for the reliability of the system. In some cases, the creepage distance could decrease, letting the increasing of the leakage current magnitude.

The first issue that may occur, could be the pin corrosion. It takes place in extreme polluted regions, and it can cause the radial cracking of the dielectric, in porcelain or glass, of the insulator. The corrosion attacks the part of the pin connected into the mortar, close to the air surface. As it can be seen in Figure 1.3, it can cause an uncontrollable tensile hoop stress along the radial length of the porcelain due to the mortar growth, causing the cracking. To reduce the corrosion, sacrificial zinc sleeves can be placed close the pin**.**

Figure 1.3. *Effects of radial cracking in a porcelain insulator* [3].

Another failure event involved could be the internal puncture. This phenomenon is mainly related to the quality of the materials and the manufacturing processes employed in the porcelain. It's rare in the case of toughening glass.

Figure 1.4. *Internal punctures causing head cracking in porcelain insulators* [3].

Figure 1.5. *De-Capping of porcelain insulators* [3].

Sometimes tiny cracks can grow over the time under multiple stresses generated by service conditions, and they may result in a severe consequence as the head cracking. Head cracks develop along the cap porcelain and when this event occurs the pin may slip out from the cap in a phenomenon called "De-capping".

Despite all these disadvantages, the cap and pin configuration has been the most common insulators to suspend the high voltage overhead lines. With its structure, porcelain and glass can be subjected to a tensile stress without negatively impact in their natural characteristic, more suitable for a compressive strength. Moreover, this configuration has got a longer creepage distance than other configurations.[7] This is useful because the leakage current path can be favourably higher.

1.1.2 Long-rod

Looking different from the cap and pin configuration, the longrod structures present less metal along the axial length, so they are not as vulnerable as cap and pin to corrosion. In addition, this structure allows porcelain to work in a compressive state whenever any corrosion products or cement growth arise.

[7] Considering the axial length per unit.

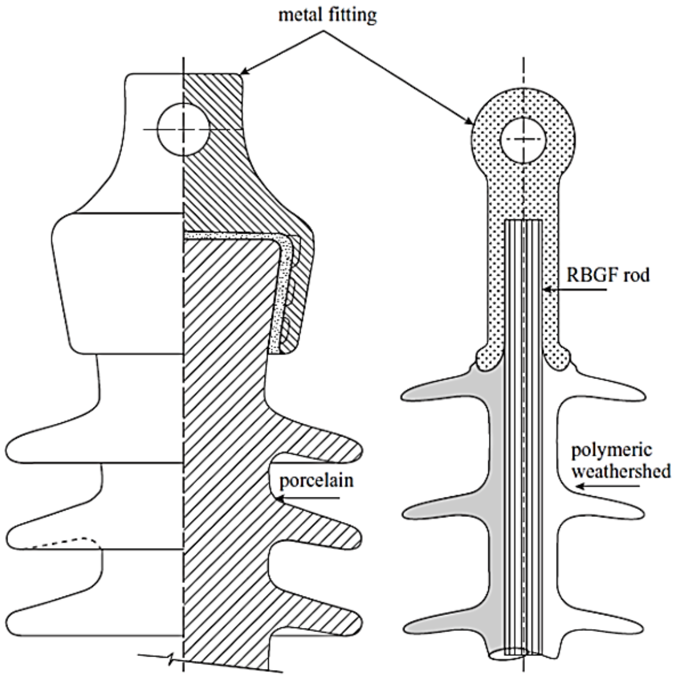


Figure 1.6. *Longrod structures with different housing materials* [1].

These typologies of insulators can be made by a unique piece of porcelain or with an insulation core covered by polymeric housing. These ones can be considered as composite insulators. The core rod could be in Resin-Bonded Glass-Fibre (RBGF), a good material that support high tensile strength. At the top and the bottom, there are metal fittings that allow the connections to the structure.

Wheathersheds could vary from short to long alternatively. This fact prevents the connection between two adjacent sheds when rainwater falls.

Some disadvantages are also presented in this configuration.

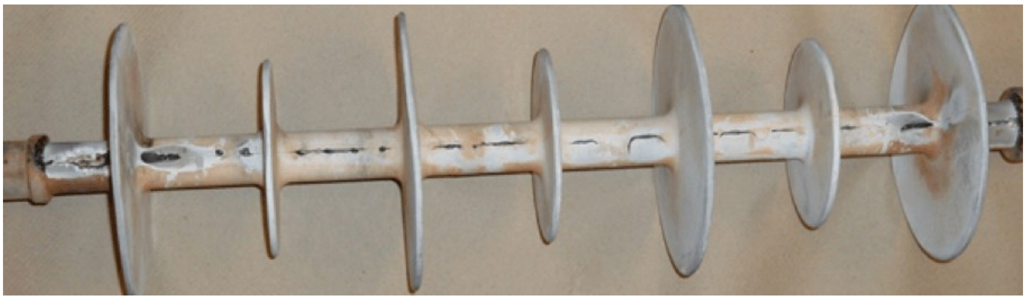


Figure 1.7. *Effects of a "Flashunder" in a composite insulator made with polymeric material* [3].

Composite insulators are not subject to puncture because the high potential is isolated from the ground by a rod. Nevertheless, sometimes punctures can afflict the housing. If it occurs, the phenomenon can evolve in a severe way and the core no longer supports the increasing electrical stress. Hence, the rod can be carbonized along its entire length. This event is also called "Flashunder" [3].

1.1.3 Post

This family includes insulators both for outdoor and indoor environments. The material used can be porcelain or polymers with, obviously, different characteristics. As it can be seen for the cap and pin configuration, also in these insulators made with porcelain, there can be issues with the material aging like the radial cracking.

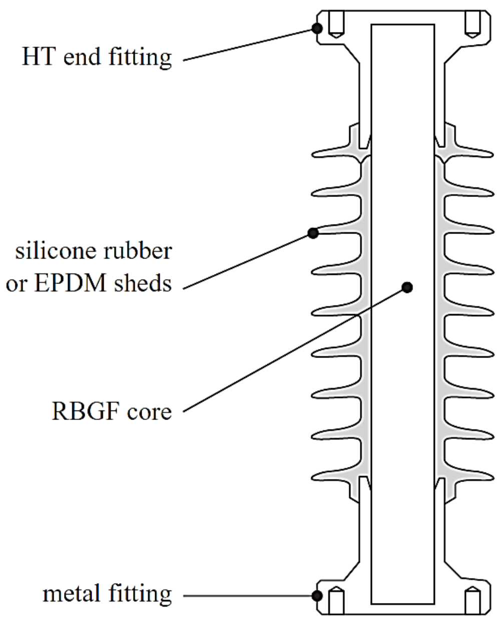


Figure 1.8. *Post insulator structure* [1].

In Figure 1.8 a polymeric post insulator is represented. On the top and on the bottom, two metal fittings could be used to fix other insulators to create a high column. The sheds could be made with silicone rubber or ethylene-propylene rubbers (EPDM) and the core can be made with resin-bonded glass fibre (RBGF). Many applications include a fibre optic cable inside the core, to provide the capability for a communication channel where different signals as voltage, temperature or current can pass in an easy way.

1.1.4 Barrel

The latest typology insulator described is the barrel structure.
These hollow insulators have a variety of applications from outdoors to indoors. They can be used for weather housing of bushing, cables terminal isolation, circuit breaker interrupter heads and wherever a conductor need to pass safely through a conductive barrier such as the case of transformers or circuit breakers.

Figure 1.9. *Barrel insulators used to isolate GILs at the Advanced High Voltage Engineering Research Centre situated in Cardiff University.*

The insulators could be filled with pressurized gases, oil or they can be left empty inside. The materials used for the structures can vary from porcelain to annealed glass and toughened glass, but even polymers can be used for the housings. The core could be a glass fibre tube.
An example is visible in the laboratory of Cardiff University, where huge bushings are used for GILs to isolate the high voltage electrodes.

1.2 The equivalent electric circuit

Moving to a more electrical design, insulators could be represented as the equivalent circuit in Figure 1.10.

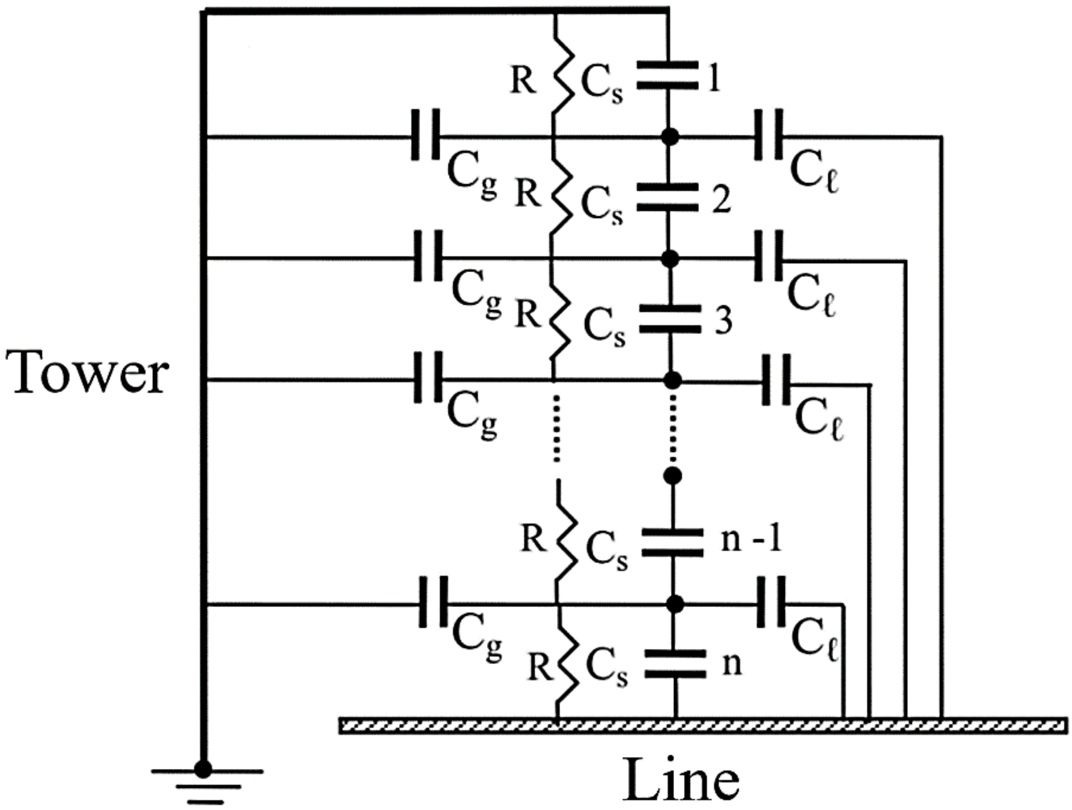


Figure 1.10. *Equivalent electric circuit for an overhead line insulator.*

Each shed can be considered as the plates of a capacitor, where porcelain, glass or polymers are the dielectrics. Along the capacitance series, parasitic elements are considered: C_g and C_l. C_g is the capacitance between the insulator and the ground, instead C_l is the parasitic element between the high potential line. Along the chain of n capacitances, also conductance elements need to be considered for a more complete equivalent circuit. This information is important especially for outdoor insulators in polluted environment. As a matter of fact, considering the natural capacitive behaviour of the insulator chain, a resistive one may arise due to a conductive layer. This means two different behaviours of parasitic current could be detected: the capacitive one and the resistive[8]. Moreover, due to parasitic elements, the voltage across the insulator is not equally distributed. This fact is represented in Figure 1.11, where the percentage trend of the voltage across a cap and pin insulator is represented.

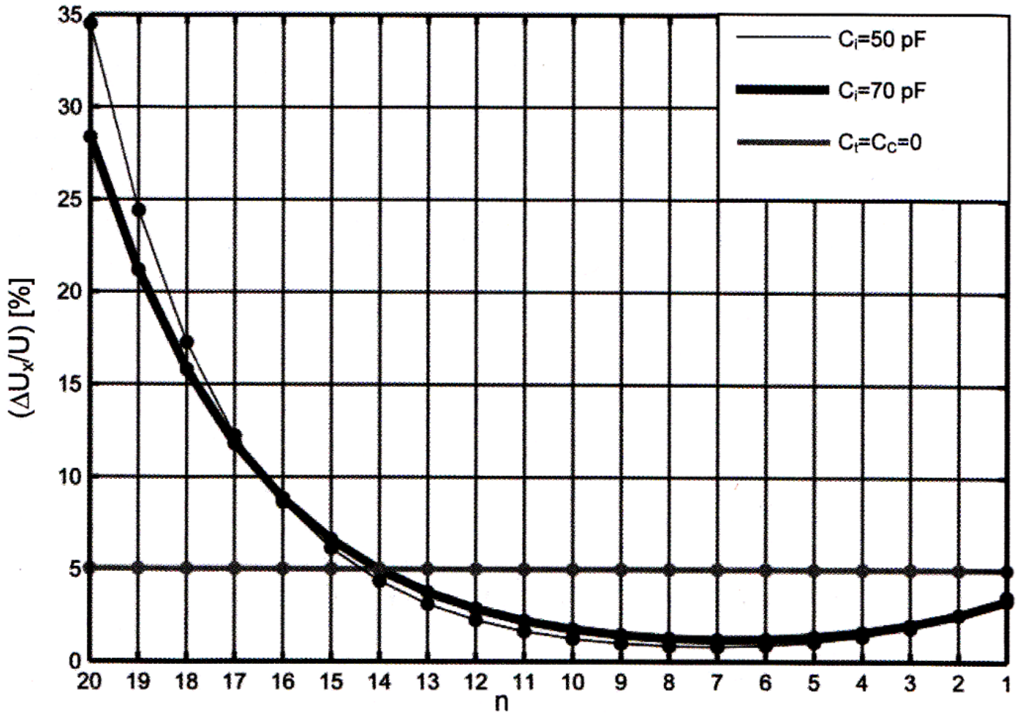


Figure 1.11. *Voltage distribution along 20 elements of a cap and pin insulator for two different values of dielectric capacitance and in the case of zero parasitic elements* [4].

Along the abscissa there are the n sheds of the chain, while in the ordinate axis there is the voltage applied respect the total potential. Two different values of insulator chain capacitance C_i are used, 50 pF and 70 pF, considering also stray elements. The other trend with $C_t = C_c = 0$ represents the case of zero parasitic capacitance. It's evident how those parasitic elements influence the voltage distribution along the insulator and how, in the first two cases, the first dielectric plates are very stressed close to the high potential line.

In [4], analytics formula regarding the voltage distribution are explained. It can be proved that the percentage voltage compared to the total voltage applied along the chain is:

[8] This leakage current will be explained in a better way on the next paragraph.

$$\frac{\Delta U_x}{U} = \frac{1}{C_g + C_l}\frac{C_g}{sinh(rnh)} * \left[sinh\big(r(x+h)\big) - sinh(rx)\right] - \frac{C_l}{sinh(rnh)} * \left[sinh\big(r(rh-x-h)\big) - sinh(nh-x)\right]$$

(1.2)

For instance, as in Figure 1.11, avoiding the presence of parasitic elements $C_t = C_c = 0$ and considering $n = 20$ capacitances, the total voltage along each capacitance could be equally subdivided:

$$\frac{\Delta U_x}{U}[\%] = \frac{1}{20} * 100 = 5\%$$

(1.3)

Hence, each capacitance can be equally stressed at the same time.
In a more realistic case, the voltage could be not equally distributed. Indeed, the capacitance close to the high voltage potential could have 20-30 % of the voltage applied, while the element near the ground could have only 1-2 % of it. To solve this problem, each insulator chain can be equipped with a guard ring near the conductor. The advantage consists in a more uniform potential across all the first capacitances and a possible way for a flashover if it will occur. Consequently, the insulator stress can be more equally distributed to all the chain.

1.3 Leakage current evaluation

As it has been explained before, an insulator could be represented as a long chain of capacitance and resistance in parallel. Hence, there might be a capacitive and a resistive current behaviour. This current is called leakage current. It flows across the body of the insulator elements from high potential to the ground. The main characteristic is correlated with the grade of pollution on the insulator surfaces, but it depends also on the geometry and the material they are made of. As a matter of fact, hydrophobic and hydrophilic characteristics are involved.
To analyse the leakage current behaviour, a step back is necessary. How in the first paragraph it's been explained, insulators could work in an outdoor environment for all their life. This means they are the target for all whether conditions. For instance, in

industrial areas there could be a large concentration of chemicals in the air, so insulator can be covered by them. A similar situation can occur in coastal region, where there could be a great amount of saltiness. Also, dust, night dew and light rain could be a problem. With light rain, the little drops could cover the insulator discs, mix with polluted particles and a conductive film might be formed. On the contrary, places with heavy rain could wash the discs avoiding that phenomenon but this is not always the best case because the little waterfall should not touch the high voltage and the ground at the same time, otherwise a flashover may occur. When the insulator is wetted and covered by a little layer of pollutants, its behaviour may change. The capacitive current behaviour is reduced due to the coexistence of partially conductive, wet and dry regions on the surface. So, a more resistive current could cross the surface. As a matter of fact, due to a more dissipation of energy, certain zones on the insulator could dry out. Consequently, there is no way for that current to drain along the insulators and in these parts called "dry-bands" a more intensive electric field is formed. For that reason, arc discharges may occur, causing a non-negligible current peak up to few amperes. That may cause mechanicals problems for the insulators components, a lot of power dissipation and the measurement system safety may be affected.
After the formation of dry bands and in the case of dry-band discharges, the most serious problem are the flashovers. This complete discharge involves all the insulator chain because it is a full line discharge from line-to-ground, and it releases a huge amount of energy.
So, to resume, this phenomenon can be summarized with these different stages [5]:

1. Depositing of pollutants on the insulator surface
2. Mixing between pollutants and rainwater droplets, creating a liquid film on the surface
3. Flowing of leakage current
4. Formation of dry bands on the surface due to the joule effect
5. Partial discharges
6. Occurrence of flashovers

Providing more information about the leakage current theory, according to [6], in firstapproximation the magnitude of that current can be characterized analytically by this formula:

$$I_{leakage} = \frac{U}{R_m} = \frac{U\pi\gamma_m D}{l} = E\pi\gamma_m D \tag{1.4}$$

Where U is the transmission line voltage while Rm represents the surface resistance due to contaminants. Rm can be subdivided by D, the insulator diameter, l the creepage distance and γ_m the conductivity of the pollutants. U divided by l can be considered as E, the electric field intensity through the creepage distance.

As a matter of fact, the intensity of the $I_{leakage}$ is proportional to the electric field, to the insulator diameter and the conductivity of the contaminants. In other term, it can be considered also inversely proportional to the resistance of the moisture. Hence, if there is a great amount of conductive waterdrops that cover the insulator surface in a particular whether condition, the γ_m coefficient increases or rather the R_m value decreases. This means that the amplitude of the leakage current could increase. Similar considerations can be applied with the electric field, that is why a low E it's better. If E raises, due to dry band formations for example, the leakage current could rise dangerously.

Another meaningful consideration can be done considering the amount of power dissipation caused by the leakage current. Considering the Ohm's law in the microscopic form, significant information could be taken [5].

$$E = \rho \cdot J \tag{1.5}$$

$$J = \sigma \cdot E \tag{1.6}$$

The leakage current intensity can be written as the conductivity multiplied by the electric field. The joule dissipation is considered as:

$$P = E \cdot J = E^2 \cdot \sigma = J^2 \cdot \rho \tag{1.7}$$

Hence, the power dissipation is proportional with the conductance of the pollution layer, and it can increase quadratically with the electric field intensity. This leads the formation of many dry bands in the insulator surface and so, the power dissipation could be very high.

The RMS value of the surface leakage current could be approximately considered between 100µA and 100mA. If some partial discharge occurs, its value can grow a lot. So, considering the whole transmission system, the power dissipation along all the insulators could be huge. For example, considering the relation between the power and the current intensity, it's obvious that the summation of the entire amount of power dissipations for each insulator in a system could be significant for the transmission operator.

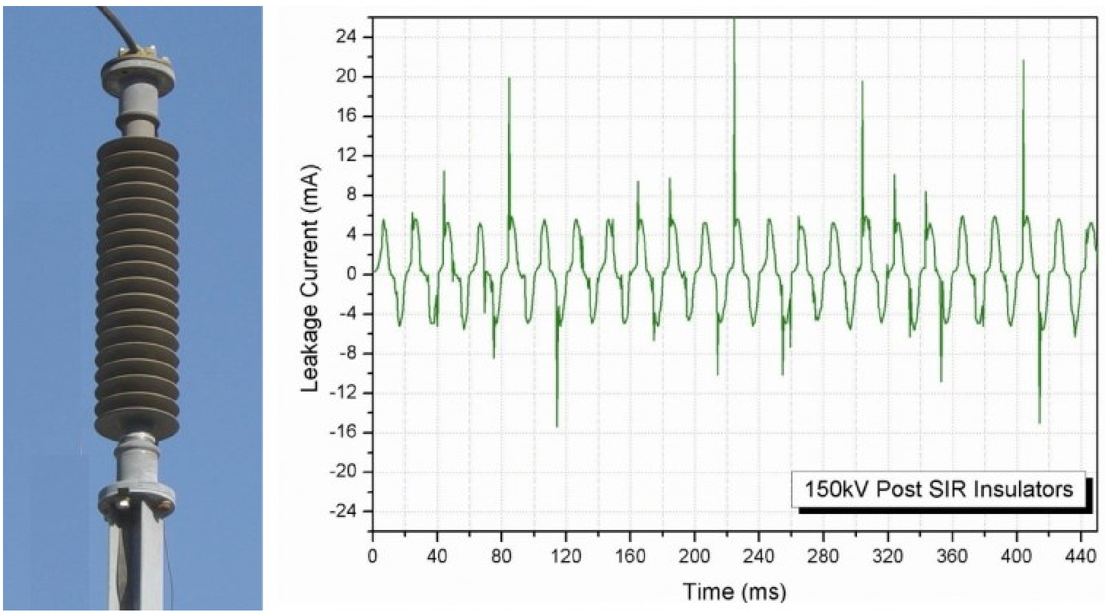


Figure 1.12. *Example of leakage current waveform in a post silicon rubber insulator during period of rains* [7].

The leakage current trend can be mainly considered resistive because its behaviour is correlated with some form of pollution on the insulator. In fact, if there is a conductive layer on the surface, the behaviour becomes strongly resistive, and some current spikes can be visible as in Figure 1.12. In that case, analysed by the experimental process in [7], the effects of light rain with pollution moisture on insulators are clear. A significant deformation of the sinusoidal wave is evident, and the peaks can be up to 24mA. These spikes caused by the dry band formations, can lead the insulator material to lose its hydrophobicity, causing an entire degradation of the structure.

1.4 The Deeside Centre for Innovation test station and the condition monitoring

The important consequences caused by the formation of a conductive layer on the surface of insulators and so, an increasing of discharge activities that may affect the insulators behaviour and characteristics need to be monitored. The leakage current is considered a great electrical parameter that can give a lot of information with its monitoring. In particular, the most important factors are the RMS magnitude and the number and the amplitude of current spikes. All these parameters can be correlated with other kind of measurements as the humidity, pressure, daw point, temperature and the wind speed. Considering all these parameters, with the helping of a weather station to take environmental measurements, several information can be made. For instance, comparing humidity, wind speed, temperature and a leakage current measurement, if there are a lot of discharge activities, the phenomenon can be correlated to an increasing of the humidity in the air with high wind speed for example. Or in the case of a slow increasing of the leakage current magnitude along years of services can be correlated to the aging of the insulator material. Hence, the importance to have different kind of measurements results in more considerations to solve the problem, correlating the issues with the causes. Taking all these measurements and giving them to a computer, there could be the possibility to implement the machine learning. With the implement of this technology, computers could “learn” from the computational mathematical data and the laboratory ones. Hence, they could be able to predict the magnitude of leakage current considering all the measurements setup of a test station and finally, with a comparison with the real ones, give in output some indicators. With these, operators can easily see the dielectric health state and make decisions like the purpose to washing or not the insulators. This approach is presented in [8] with a short presentation of the implementation of a smart solution in the insulator condition monitoring.

All these measurement setups are normally settled in a test station. This is the case of the new Deeside Centre for Innovation owned by the National Grid Electricity Transmission company. This test station born along the river Dee in the north Wales and it was a 400 kV substation. Instead of being demolished, National Grid restored it with the objective to create a 19 acres tests area. During years it has been modified and finally it comprises a substation, an overhead line test area, workshops, storage spaces and offices [9].

Figure 1.13. *Deeside Centre for Innovation test station along the river Dee in north Wales* [9].

There, assets can be tested replicating a live network, so under real life conditions, 24 hours a day, seven days a week. The facility provides a controlled test environment to collects valuable monitoring data to access life performance of a tested asset. Moreover, it allows simultaneous testing of multiple assets with voltages up to 600 kV and current up to 2000 A. The OHLs area comprises a 200m span between to lattice towers where conductors and insulators can be monitored considering real whether conditions. There is a weather station able to detect environmental parameters and thermal cameras to detect any activities on insulators. There can be tested also transformers, gas insulated switchgears and lines.

Hence, this centre can be considered as an enormous outdoor test station, where the condition monitoring of insulators can be made in live conditions and several data can be collected. A good challenge can be the availability of that data from another place far from the test centre. But this problem will be discussed in the last chapter.

Chapter 2

Transducers and signal processing

Considering the importance of measuring the leakage current along the sheds on insulators, in this chapter some techniques and technologies about how to measure it will be described. Some current transducers and data acquisition systems (DAQs) will be considered and the theory about the operations of a digitized measuring system will be discussed.

2.1 The computerised measurement systems

Building a computerised data acquisition system is not as simple as it can seem. Several things need to be considered to create a reliable, accurate and easy-to-use measurement setup. Every equipment has got its accuracy, its error and some phenomena could not be easily measured because of their dynamisms[9]. It can also give in output a great amount of data that need to be easily interpretated.

The first necessary step to build a measuring system involve the understanding of the theory that govern the phenomena that could be seen. As discussed in the previous chapter, the measuring of leakage current in insulators can give a lot of information about their performance, especially for insulator used in outdoor environments. Hence, the best way to have this information is directly measuring that current. There are many methods to measure its low magnitude and to give measurements in output that can be reliable, but many considerations need to be considered. In high voltage environments there is a lot of electrical noise, especially in substations and along the overhead lines, where the measurements take place, so the meter system must consider this inconvenience. Furthermore, there are also important safety requirements, as the possible isolation of the measurement system from the high potential to create a safe

[9] For instance, create a computational model that directly predict the insulator aging through the only measure of pollution is a big challenge due to the dynamism of the sources [8].

measurement setup for the operators and the meter devices. For example, there are some current transducers that can easily isolate the source from the measuring setup.
When all the theory knowledges are clear, the measurement system goes straight the digitization of the analogue signal taken by the sensors and finally the data acquired could be analysed with software on computers. These processes are represented in Figure 2.1.

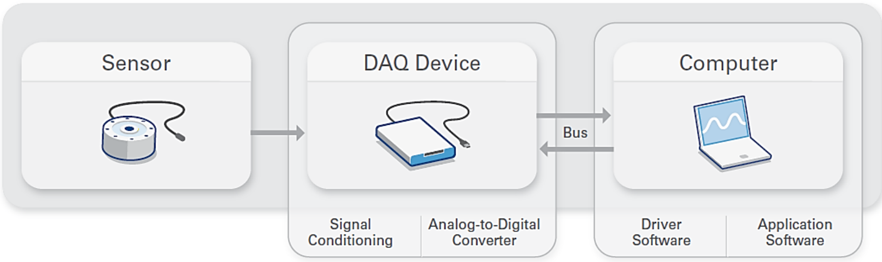


Figure 2.1. *Data acquisition system process* [10].

This measurement setup is called data acquisition system or DAQ system, abbreviated. Digitization is the process of converting an electrical signal from a sensor into a digital signal that a computer can read. Hence, the first step to digitize an analogue signal is the choosing of the right sensors.
These transducers convert a physical phenomenon into a measurable electric signal. There are several sensors in the market, each able to detect a particular signal. For instance, thermocouples, RTDs[10] or thermistors can be used to measure temperatures. Each one has its application. But, interested in detecting currents, many sensors from current transformers to Rogowski coils can be considered. Other techniques include the measure through a shunt resistor, the magnetic field or with the fibre optics sensors. They can be used separately or at the same time. If two sensors are kept working together, a bigger number of considerations of the phenomenon measured could be taken.
The next block is the DAQ device. It is considered as the interface between a computer and the sensors. Its function consists in translating the incoming analogue signals in such a way that a computer can interpret them. A data acquisition device mainly

[10] RTDs means Resistance Temperature Detector.

consists in two parts: the conditioning circuitry and the analogue to digital converter. Starting from the conditioning circuitry, its importance derives from the adjustment of signals before being processed by the analogue to digital converter. Some signals need to be filtered to have a clean output with no noise. Others need an isolation process, or they need to be amplificated. Some signal could be very low and the analogue to digital device could not be able to elaborate it. So, sometimes an amplification process is needed. All these kinds of pre-processing processes are essential before the conversion to digital signals by the ADC[11].

The analogue to digital converter is the main part of a computerized measurement system. It allows the fundamental conversion of information that come from an analogue signal to a digital one, in order to be read by computers. There are different architectures of conversion as the Successive-Approximation Register (SAR), the Delta-Sigma (ΔΣ) and the Pipeline [10]. Each one has its advantages and disadvantages, so the choice is conditioned by the final application.

The final step consists of the sending of all the digital information to a software installed on a PC, where they can be easily interpreted and elaborated. One of the main PC software that manage this exchange of data is LabVIEW made by National Instruments. LabVIEW is a graphical programming environment use to develop automated research, validation, and production test systems[11]. It allows the real time monitoring through a direct access to all the DAQ hardware made by NI or third-party devices and it lets the recording of all data obtained during a test. It is easy to use because it does not need rows of code to work but it has a graphical programming approach. In other term, the operator has got different kind of blocks, each one with is function, and the programming approach consist of connecting all of that. Moreover, there is a visual representation of the hardware that permit the managed by an easy click from the computer. Hence, all the data that come from an ADC can be visualized and saved with a digital automatized approach. It is good instead of using a digital oscilloscope where pictures or data of a signal can be acquired, in the most of cases, with a button for an instant event and not for hours, days or weeks respect an automatized hardware can do.

[11] ADC is the abbreviation of analogue to digital converter.

2.2 Current transducers

These kinds of measurements involved many techniques and technologies, depending on which current is needed to be measured. From now onwards, interested in measuring the low magnitude of leakage current across insulators, some methods will be discussed taking this objective into account.

The selection of current transducers depends on many factors as the magnitude or range of current that can be detected, the accuracy, the bandwidth, the isolation or the cost. Moreover, the output value could be directly read on a display by the instrument or converted to a digital form and acquired by a DAQ device, as seen in §2.1.

Hence, the first parameter that needs to be considered is the magnitude of current, that in case of leakage current it is in the order of µA or mA. It is a very low current, but since some discharge activities must be considered, it could arise up to amperes in the unfortunate case. To be able to measure this low magnitude, transducers need to have a high sensitivity in order to capture the minimum magnitude of input signal required to produce a specified output signal with specific characteristics. It is quite close to the meaning of resolution, which is the smallest change in the underlying physical quantity that produces a response in the measurement. About the meaning of accuracy, it needs to be high for this kind of measurements. It can be explained as the proximity of measurements results to the true value. A sort of relative error between the measure taken by the transducer and the effective real value. But the mainly parameter that must be considered for this kind of measurements is the bandwidth. It could be considered as the capability of the transducer to take a signal and transmit it in a determinate range of frequency without losing information. In a more accurate definition, National Instruments relates the meaning of it as: “Bandwidth describes the difference between limiting frequencies within which the input signal can pass through the system with minimal amplitude loss — from the input at the tip of the probe or test fixture to the output data. The limiting frequencies that determine the bandwidth include both a high and a low frequency that are specified as the frequency (in Hz) at which a sinusoidal input signal is attenuated to 70.7% of its original amplitude. This point is known as the -3 dB point [12]”. Hence, this parameter is very important for the current transducers because they are the first sensors close to the physical phenomenon that is needed to be measured in all its range of frequency. Especially for the condition monitoring of insulator, the sensors must be able to detect the partial discharges that occur at a high range of frequency, in the order of kilohertz up to megahertz. It is usual to adopt various types of transducers, each one with its own range of frequencies. With this method, the sensors can detect information in a wide bandwidth and so, many phenomena can be seen.

The other characteristics for sensors include the isolation and the cost. The first is an important parameter that takes the operator and the meter equipment safety into account. Considering some technologies as the current transformers and Rogowski coils, they are good to isolate the source from the measurement systems because they work with a magnetic field. This can result in a more safety environment if some overvoltage phenomena appear, instead of the measurements across a shunt resistor. In other words, these sensors can be considered as indirect methods to take a signal, instead a direct method as the shunt resistor where the circuit needs to be modified. About cost, it is easy to consider that the best buy is related to what I need to measure, how accurate must be the signal, which bandwidth or sensitivity is needed. Hence, considering all these factors, a compromise could be taken.

Considering all these essential characteristics for measuring the leakage current, the next step is to choose the best transducer that can detect it with a higher accurate measure.

2.2.1 Shunt resistance

Thanks to its lower price, reliability and due to its simple principle, the shunt resistor is the most common approach to sense currents. It is based on the Ohm’s law, which considers that the voltage drop across a resistor is proportional to the current going through it.

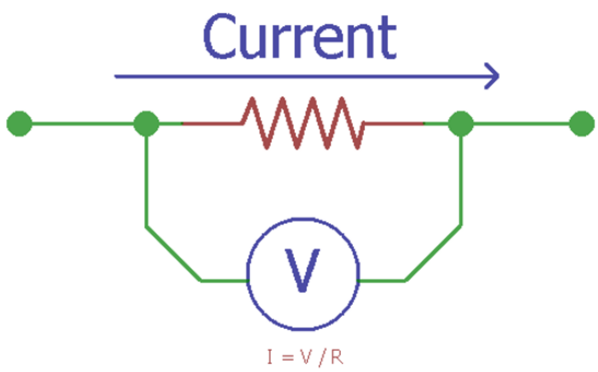


Figure 2.2. *Representation of a current measurement across a resistor considering the Ohm's law.*

The method is valid both for AC and DC currents, but it has some disadvantages. First, despite its high accuracy to detect fast rise-time transient and high amplitude, the shunt resistor suffers of parasitic elements when it works with high frequencies. The parasitic inductances present in it affects high precision current measurements [13]. Moreover, the power dissipation could be very high, considering that it is proportional to the square of the current that pass through the resistance. Hence, the temperature could grow, and the resistance can change its behaviour due to the thermal drift. Thus, this method could not be practical for measuring high current magnitudes, but it could be a right choose for measuring the leakage current, especially to compare its measurements with other kind of transducers to have a wide range of frequencies.

2.2.2 Rogowski coil

These transducers have got a different principle respect the shunt resistors. The main function of the Rogowski coil is the sensing of the magnetic field produced by the current through a conductor [14]. Hence, it is obvious that it works only with AC currents. It consists of an air cored coil placed round the conductor in a toroidal form so that the alternating magnetic field produced by the current induces a voltage in the coil. This latter one is considered as a mutual inductance coupled to the conductor being measured and the voltage output is proportional to the rate of change of current. In the final way, this voltage is integrated electronically by a device to provide a voltage waveform that reproduces proportionally the current.

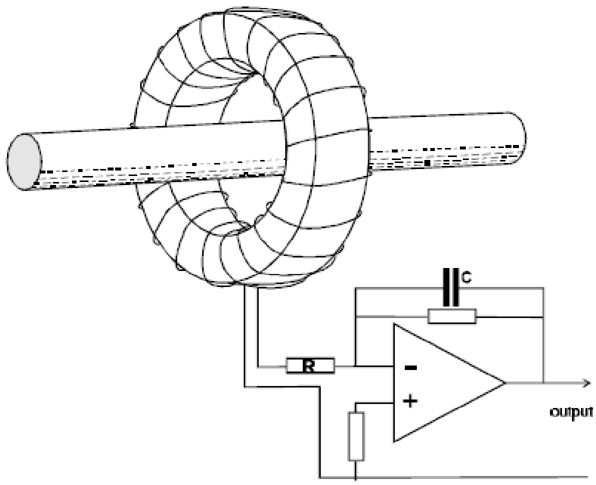


Figure 2.3. *Rogowski coil and its integrator circuit* [15].

The Rogowski coil principle could be analytically expressed starting from the Ampere's law [16]:

$$\oint_{l} \vec{H}\ dl = i \tag{2.1}$$

This formula represents that the circular integral (along the length of the coil) of the magnetic field for an infinitesimal length *dl* is equal to the current flowing through the conductor.

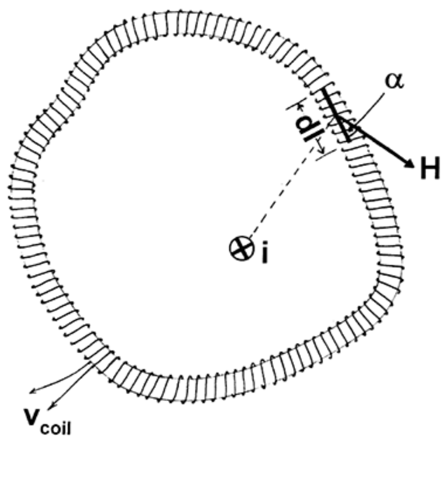


Figure 2.4. *Flexible coil for useful analytical consideration* [16].

Hence,

$$\oint_l H\, cos\alpha\, dl \;=\; i \tag{2.2}$$

The Figure 2.4 illustrates a coil with *n* turns per length unit and, considering the section A, the variation of the flux is given by:

$$d\Phi = \mu_0 H \cdot An \cdot cos\alpha\, dl \tag{2.3}$$

Where integrating:

$$\Phi = \int d\Phi = \mu_0 An \cdot \int H\; cos\alpha\, dl \;=\; \mu_0 nAi \tag{2.4}$$

Considering the Faraday-Lenz law, the voltage in the coil is given by the time flux variation:

$$v_{coil} = -\frac{d\Phi}{dt} = -\mu_0 An \frac{di}{dt} \tag{2.5}$$

Hence, taking the mutual coefficient M from the coil and the conductor into account, the output signal is:

$$v_{coil} = -M \frac{di}{dt} \tag{2.6}$$

Finally, the integrator in Figure 2.3 integrates the voltage to obtain the exact current waveform. The output could be visualised in any form of electronic devices as oscilloscopes, voltmeter or DAQ devices. This transducer could have a flexible former. It helps to take measurements thanks the major adaptability instead of rigid coils. But the main advantage come from the absence of a ferro-magnetic core as conventional current transformers have. With this configuration, Rogowski coils are not subject to magnetic saturation of the core that limit the range of current they can measure. So, they are linear, and the mutual inductance does not depend on the current through the conductor. Moreover, these sensors are great to isolate the source from the acquisition system, instead of shunt resistor. They can be considered as indirect method to take measurements.

Furthermore, they are suitable to measure a wide range of currents and the sensitivity depends on the integrator by the formula [15]:

$$\frac{V_{out}}{I} = \frac{M}{CR}\ [V/A] \tag{2.7}$$

Where C and R can be varied during the calibration of the integrator, depending which sensitivity is needed.

The great disadvantage is the high frequency limit they can work with. Typically, they can work well up the range between 20 kHz and 1 MHz. These limits are determined by the self-resonance of the coil with parasitic elements.

Finally, the integrator need power to work correctly, so this could be a disadvantage for remote and long-term measurements.

2.2.3 Current transformer

These types of transducers are similar to the Rogowski coils principle, but they differ for certain aspects. On the contrary, CTs[12] are not air-core based but their one is made by ferro-magnetic materials. This could be a great disadvantage because that kind of core are subjected to saturation in the presence of DC components or very high AC currents and so, the measurements could not be accurate. Moreover, once the core is magnetized it will contain hysteresis and the accuracy will degrade unless it is demagnetized again. A process of demagnetization of the ferro-magnetic core is called degaussing and it will be explained in the next paragraph with a simple implementation of a CT for low currents.

[12] Abbreviations of Current Transformer.

The principle of a current transformer is simple. It is the same theory of a standard transformer where a current flowing in the primary circuit creates a magnetic field that magnetized the ferro-magnetic core and a voltage in the secondary circuit can be induced.

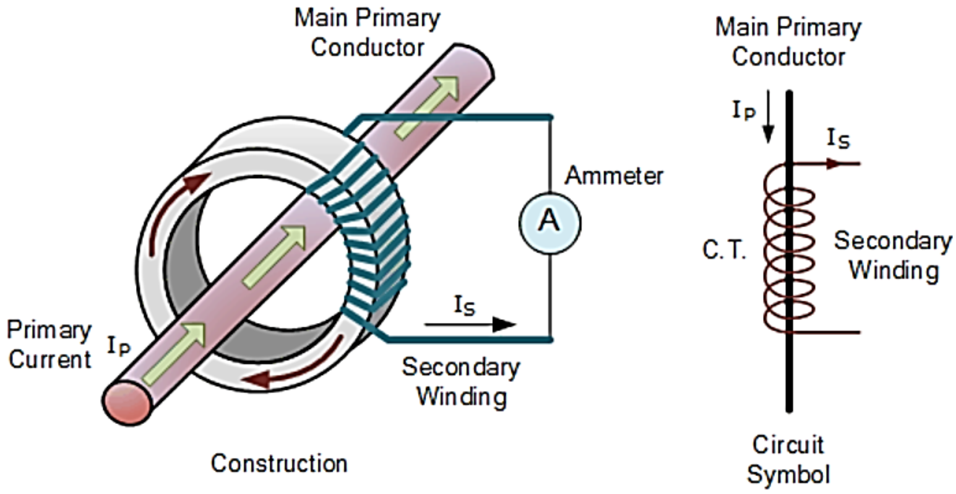


Figure 2.5. *Current transformer principle.*

Basically, the primary circuit is composed of the conductor where the main current I_p passes through. Hence, the CT is put around the conductor where the magnetic field from the primary induces an electromotive force on the secondary winding where the current I_s can now circulate. The secondary of the current transformer is made up of many turns of fine wire having a small cross-sectional area.

Analytically, the principle could be sum up with this simple proportion:

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{2.8}$$

Hence, changing the number of turns of wire N_2 in the secondary circuit, it is possible to have different ratio between the currents. It is notable that if N_2 is high, consequently the ratio between the currents is high, so from the current point of view the transducer could be considered as a step-down transformer.

Different from the Rogowski coils, CTs are self-powered, so they can be considered passive elements. Moreover, it is impossible to have a flexible type of them because of the ferro-magnetic core.

About the core demagnetization referred to the main problem of the core saturation due DC components in CTs, the degaussing method can be described as a procedure able to delete or reduce the residual magnetisms presents in a ferro-magnetic coil. Due to hysteresis effect, each time a CT is powered and then turned off, a little amount of magnetic field could be remained, especially for heavy currents with DC components. Hence, as described in [17], one method used for demagnetizing the CT is to apply a suitable variable alternating voltage to the CT's secondary winding, with an initial magnitude sufficient to force its flux density above its saturation point, and then decrease the applied voltage slowly and continuously to zero. With this method the residual field memorised in the core can be erased. Another method consists in varying the secondary loop resistance gradually from low to high to low at a consistent rate. The amount of variable secondary loop resistance will be determined by what resistance is required to drive the CT beyond the knee of its B-H excitation curve and demagnetize its core. This is typically a resistance that will cause a 65% to 75% reduction in secondary loop current [17].

2.2.3.1 Characterization of a simple current transformer for low currents

To better understand the demagnetization phenomenon and how a current transformer works, a little experimental test has been done in the Advanced High Voltage Engineering Research Centre of Cardiff University.

For the measurement setup, a simple workbench was prepared. It consisted of a sine square oscillator with variable voltage amplitudes (they could be varied from 0 to 12 V peak-to-peak), a bank of variable resistors, a multimeter to make comparison of current measurements, and an oscilloscope. The CT tested was the current transducer CTSR series manufactured by LEM company [18].

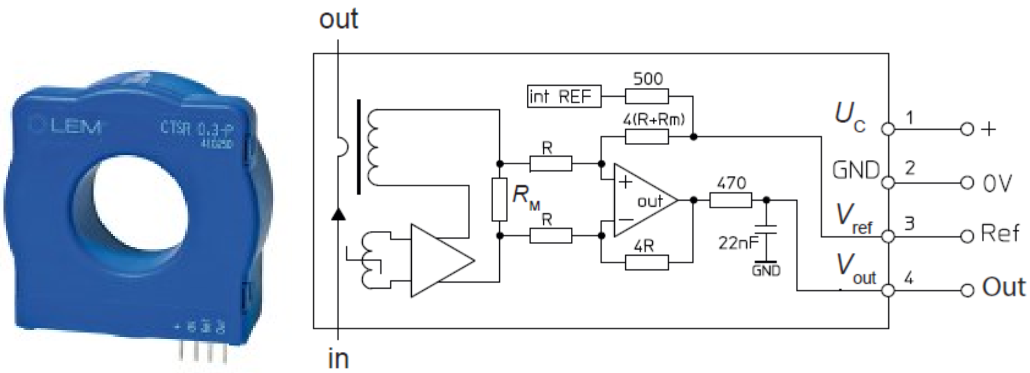


Figure 2.6. *Current Transducer CTSR series 0.3-P and its equivalent electric circuit.*

Table 2.1. *CT 0.3-P parameters.*

Parameter	Symbol	Unit	Min	Typ	Max
Primary nominal residual rms current	I_{PRN}	mA		300	
Primary residual current, measuring range	I_{PRM}	mA	-500		500
Supply voltage	U_C	V	4.75	5	5.25
External reference voltage	V_{REF}	V	2.3		4
Output rms noise voltage	V_{no}	mV		4	
Frequency bandwidth	BW	kHz		3.5	
Accuracy	X	%			1.9
Theoretical sensitivity	G_{th}	V/A		4	

The CT comprised an electronic circuit inside the case, so it needed to be powered. The energy was provided using a simple battery working at 5 V made by RS company. The electric circuit were energized at different voltage levels, so the current took by the multimeter in series with the variable resistances was compared with the output signal from the current transformer. In the light of the facts, the characterization provided these values.

Table 2.2. *Comparison between the current value output from the CT and the multimeter (Sensitivity of CT: 4 V/A).*

V_{source} [CH1]	CT LEM [CH2]	I_{CT}	$I_{multimeter}$
V *[RMS]*	*mV* *[RMS]*	*mA* *[RMS]*	*mA* *[RMS]*
2.31	4.84	1.21	1.02
2.38	87.50	21.88	21.03
2.83	56.00	14.00	13.15
3.34	124.00	31.00	29.50
4.37	20.23	5.06	4.99

In first approximation, it can be visible how closes are the current measurements. The error between the two devices is low, so there was a good response from the CT at low magnitude of current, as it was expected from the datasheet [18].

In addition, before the analysis, a degaussing procedure has been carried out. Degaussing is the process of decreasing or eliminating a remanent magnetic field [19].

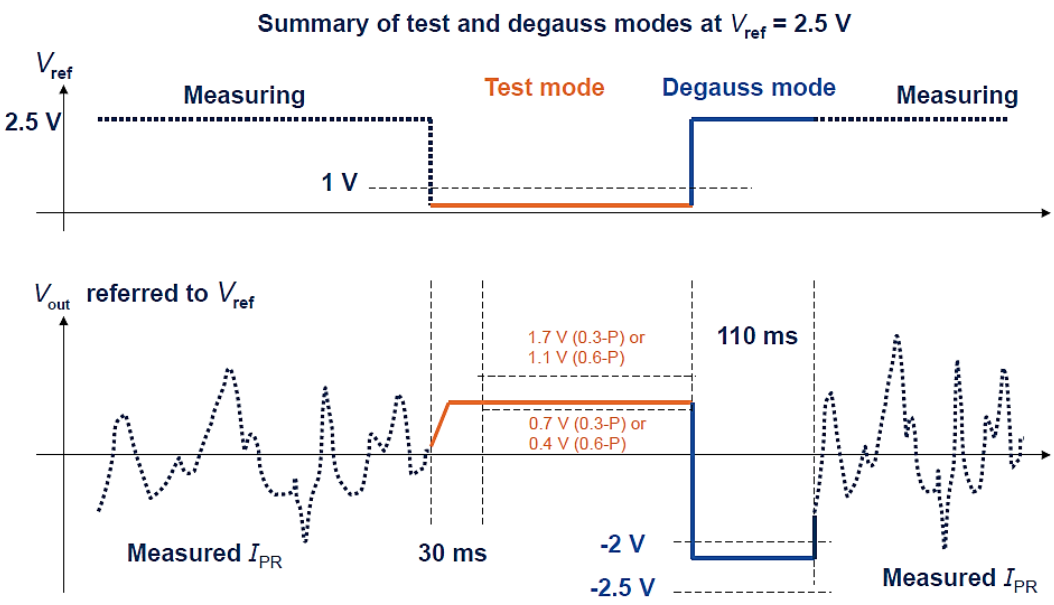


Figure 2.7. *Degaussing procedure for the CTSR series 0.3-P* [20].

A referred voltage of 2.585 V was applied to the 3-Ref pin. From the figure above, it's evident that when the pin V_{ref} is released from the low-level voltage defined in the test mode, there is a rising edge on V_{ref} which generate an automatic degauss. It lasts typically 110 ms and then the measured current could be captured with a better accuracy.

2.3 DAQ measurement devices

As mentioned in §2.1, DAQ is the process of measuring an electrical or physical phenomenon, such as voltage, current, temperature, pressure, or sound. A DAQ system consists of sensors, DAQ measurement hardware, and a computer with programmable software.

About the measurement hardware, it could be difficult to find the right choice, considering the wide number of devices present. National Instruments, a big company leader in the DAQ devices production, suggests answering five questions for choosing the right system [21]:

1. What types of signals do I need to measure or generate?
2. Do I need signal conditioning?
3. How fast do I need to acquire or generate samples of the signal?
4. What is the smallest change in the signal that I need to detect?
5. How much measurement error does my application allow?

Hence, without entering details of how to detect signals, the first answer considers the various functions of DAQ devices. If they can measure analog signals with analog inputs or to generate analog signals with analog outputs. Or they could have digital inputs/outputs that measure and generate digital signals. Another possibility could be the function of counter/timers to count digital events or generate digital pulses/signals. Some devices have only one function, instead others can be considered "multifunction" because they can include all of them. However, the latter may have a fixed channel count. If a more customization is needed, there is another modular platform that can be personalized. It consists of a chassis to control timing and synchronization and different I/O modules. The advantage is the possibility of a complete personalisation, choosing modules that exactly perform in a more accurately way the function needed. Moreover, the number of slots for the chassis can be selected for the use.

Figure 2.8. *National Instruments cDAQ – 9188 with eight modules able to convert analog signals into digital signals.*

In Figure 2.8 an example of a DAQ device made by National Instruments is represented. It belongs to the family of Compact DAQs devices. It is a benchtop strumentations, good for taking various measurements, conditioning and digitizing them. There is the possibility to connect the system to a PC with the Ethernet port, thus it allows the exchanging of data and the monitoring of all the modules connected. The modules can elaborate measurements as voltages, currents, sounds, temperature and a various of analog/digital signals. This justified the completely customization of that DAQ device.

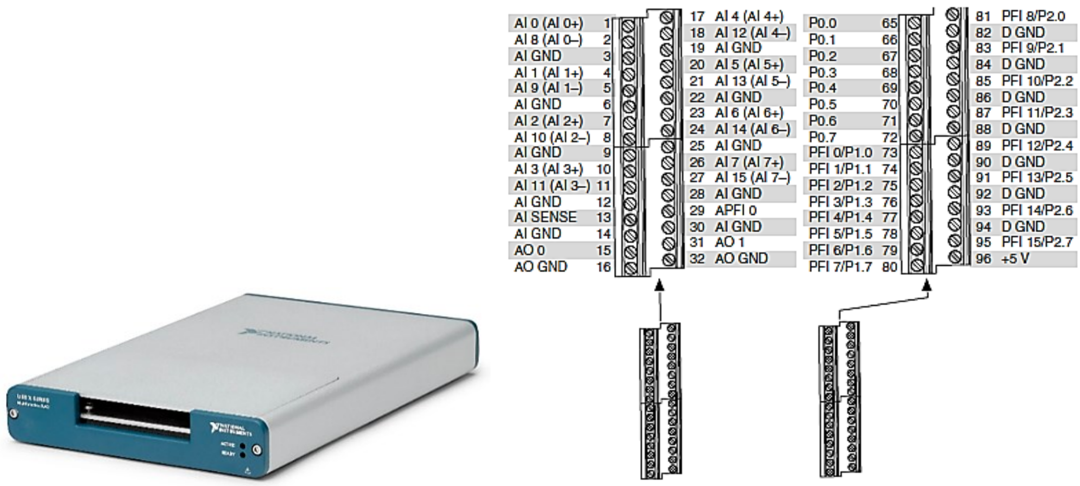


Figure 2.9. *USB-6351 Multifunction I/O device manufactured by National Instruments.*

In Figure 2.9 there is another DAQ device, but instead of the previous one, it has a more compact form and it can be connected to a PC with a USB connection. There is not the possibility to change modules and it has more limitations. Anyway, it could be a good compromise for portability and cost.

The other important question needed to be answered is the possibility of signal conditioning. A typical data acquisition device can measure voltage in the range of +/- 5 V or +/- 10 V. Hence, any time an out-range analog signal needs to be directly measured it must be adapted to the input voltage range. This factor avoids dangerous phenomena that could compromise the system and obviously, the measurements. Generally, for high voltage measurements the previous conditioning includes the isolation and the attenuation. Some of these factors could be included inside the module devices, nevertheless an external signal conditioning is preferable. For example, the conditioning can include a surge arrester to protect the system from overvoltage.

The third question includes the most important specification for a DAQ device: the sampling rate. It can be considered as the speed[13] at which the analog-to-digital converter takes samples from the signals. So, the right choice of the DAQ device depends on the maximum frequency is needed to be taken from the measurements. But to be sure which "speed" is needed, the Nyquist theorem must be considered. It states that a periodic signal must be sampled at more than twice the highest frequency component of the signal [22]. However, it is a good idea to sample at least 10 times the frequency of the interest signals to have a more accurate representation.

[13] Speed considered as S/s (Sample per second).

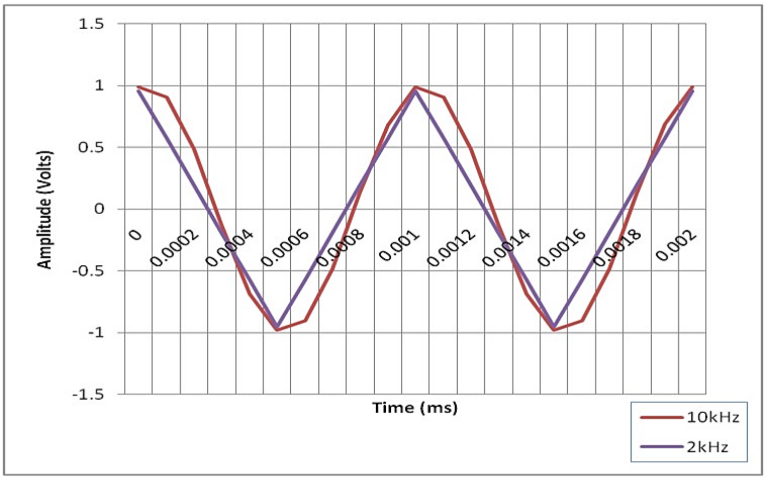


Figure 2.10. *Example of a 1 kHz sine wave sampled at 10 kHz (Red line) and 2 kHz (Purple line)* [21].

About the DAQ device resolution, it can be considered as the smallest detectable variation in the signal. The ADC converts the signal considering various binary levels of voltages. These depend on the bit resolution of the converter. For instance, an 8-bit ADC can represent 2^8 discrete voltage levels and a 16-bit ADC can represent 2^{16} = 65536 discrete levels. This means a more resolution for a waveform representation. Considering the range voltage of +/- 10 V, a 16-bit ADC can detect approximately a 305 µV change.

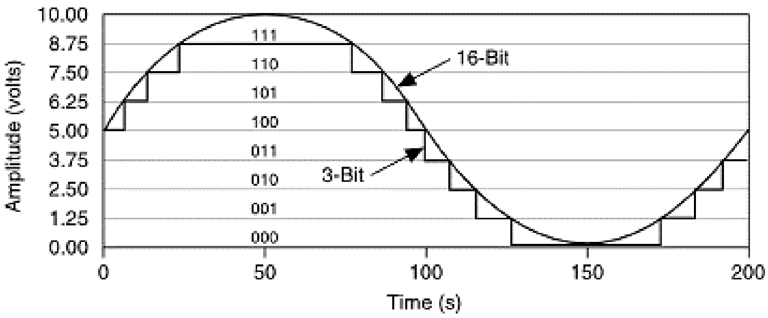


Figure 2.11. *16-bit and 3-bit waveform resolution representation* [21].

Finally, the last specification that need to be considered is the accuracy. It is not different for the same description provided for the current transducers since it is influenced by them. Indeed, accuracy depends not only on the instruments, but also on the signal's noise for example. Hence, some devices provide a self-calibration, isolation, or other circuitry to increase the accuracy.

Chapter 3

Comparative performance of transducers for the leakage current monitoring

A measurements setup has been prepared in the laboratory of the Advanced High Voltage Engineering Research Centre at Cardiff University. The aim of this chapter will be the detecting of the leakage current signal along a textured polymeric insulator with different transducers. Hence, the previous characterization of them will be analysed in order to have a reliable and accurate measurement system.

3.1 The measurement system setup

With the aims of studying the reliability of a current transformer, a Rogowski coil and a shunt resistor measuring the leakage current across a polymeric insulator, an experimental test has been realized in the high voltage laboratory of Cardiff University. This laboratory is situated in the School of Engineering, and it is considered as a modern research facility with extensive expertise in gaseous and solid insulation systems, overvoltage protection, condition monitoring, earthing and electrical safety. It has been home to the National Grid Centre since 2005 and is internationally recognised for its high voltage engineering research [23].
The laboratory has got different cages, each one qualified with standard procedures. Cage 2 has been used for the entire test and it is qualified with the standard IEC 60270 – "Partial discharge measurement" [24]. Before using the cages, several safety procedures must be done. There are two different keys, one for a general breaker and the other for the cage door. Moreover, a long non-conductive rod for manual use must be inserted in an opposite location out the cage before energising the system in order to block the door. This rod has got a conductive material on the summit, and it is connected to the ground system. Each time a test has done, the operator must take the rod, enter the cage, and touch all the possible conductors that could have residual

charges. Finally, the ground-rod need to be kept in contact with the conductive part for all the time, just to be sure that every possible high potential can goes through the ground and not the body of operator. This procedure must be done each time a test needs to effectuate.

Anyway, considering the IEC standard configuration, several electrical components were present inside and outside the cage.

Figure 3.1. *Foster variac transformer.*

Out of the cage there was a Variac variable transformer. It returned different percentages of input voltage, turning the knob. It was connected to the normal phase-ground voltage at 230 V.

After that, the successive element was the isolation transformer, inside the cage.

Figure 3.2. *Foster isolation transformer 2 kVA, 230/115 V.*

This transformer was important for the cage setup because it avoided the creation of ground-loops. Ground loops could be formed by the difference in the ground potential in all the components inside the cage. Moreover, an electrostatic shield between the primary and secondary windings enhances safety and provides suppression of transients and electrical noise. In addition, it avoided the passing of DC components from the secondary circuit to the primary.

In other words, its mainly function was correlated to the formation of a safe environment for the power source positioned out of the cage.

After the isolation transformer there was the low-pass filter. It consisted of a resistance, an inductance and a capacitance.

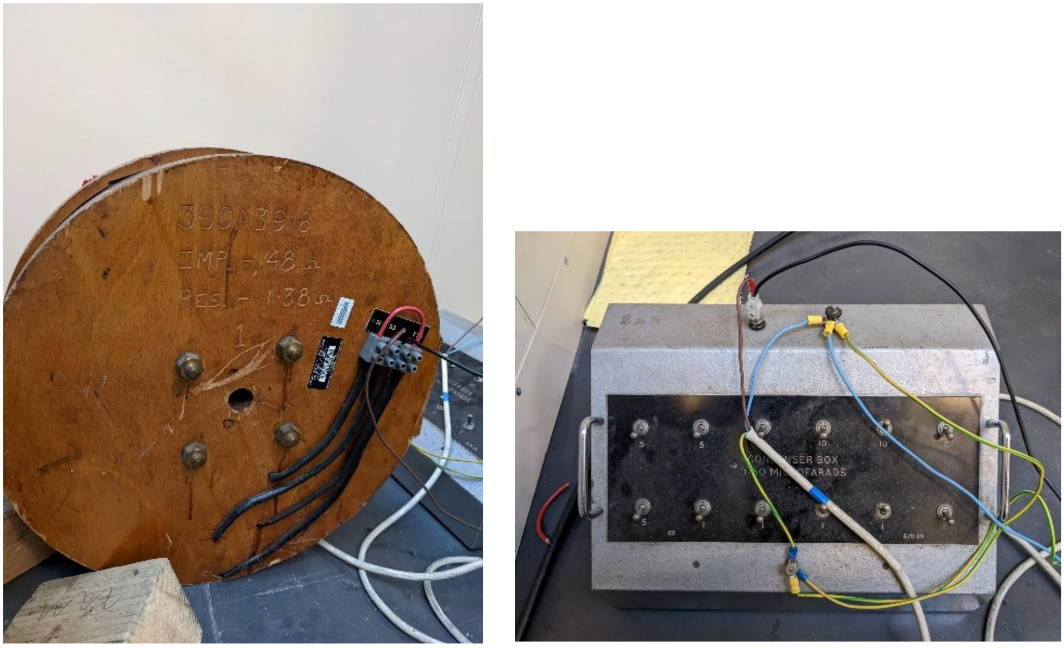


Figure 3.3. *The low-pass filter including an inductance and a resistance in the wood wheel and a capacitance on the right.*

The value of the capacitance filter was 48 μF. For the inductance, in first approximation some cross-measurements with a multimeter have been done to find the exact value and to know exactly how the coils were connected inside the wooden wheel.

Table 3.1. *Coil resistance cross-measurements.*

	S1	**S3**	**F1**	**F3**
S1	X	∞	0.5 [Ω]	∞
S3		X	∞	0.5 [Ω]
F1			X	∞
F3				X

Considering the four output terminals for each side of the coil, the resistance measurements have been done with a multimeter. In Table 3.1, the resistance between each couple of terminals of one side are visible. For the measurements, the contacts resistance $R_{contacts} = 0.15\ \Omega$ between the two terminals of the multimeter has been considered. Hence, from Table 3.1 the possible electric circuit of the coil inside the wooden wheel can be extrapolated.

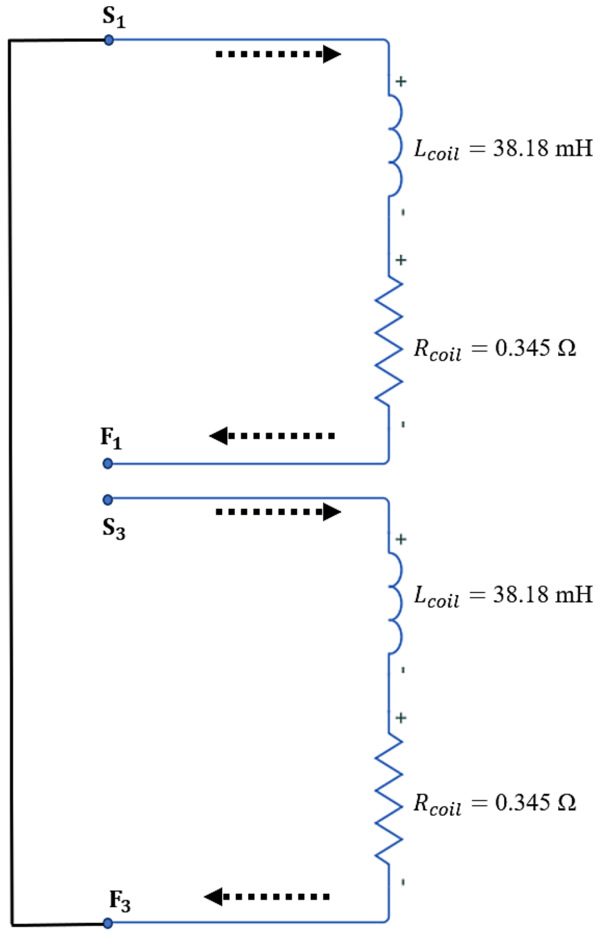


Figure 3.4. *Possible equivalent electric circuit of the coils each side of the wooden wheel.*

Short-circuiting the F_3 and S_1 terminals (as in Figure 3.4) and considering the circuit connection coming from S_1 and going out from F_1, the multimeter measured a resistance value between F_1 and S_3 of $R_{F1-S3} = 0.8\,\Omega$, considering the contact resistance. So, with Table 3.1 and Figure 3.4, it could be possible to deduce that there could be two coils each side of the wooden wheel. Indeed, considering the unclear values written on the wooden surface of $R_{tot} = 1.38\,\Omega$ and an impedance of $Z_{tot} = 48\,\Omega$, it could be possible to effectuate some analytical considerations in first approximation.

$$Z_{coil} = (R_{tot} + j\omega L_{tot}) = \frac{Z_{tot}}{4} \tag{3.1}$$

$$L_{coil} = \sqrt{\frac{(\frac{Z_{tot}}{4})^2 - (\frac{R_{tot}}{4})^2}{(2\pi 50)^2}} = 38.18\, mH$$

(3.2)

$$R_{coil} = \frac{R_{tot}}{4} = 0.345\, \Omega$$

(3.3)

Hence, with the multimeter measurements and considering only one side of the wooden wheel:

$$\frac{R_{tot}}{2} = 0.69\, \Omega$$

(3.4)

$$R_{F1-S3} = 0.8 - R_{contacts} = 0.65\, \Omega \approx 0.69\, \Omega$$

(3.5)

These analytical considerations confirm the specifications written on the wooden surface and the internal connections of the coils. In the light of the facts, the filter value used in the test considered:

$$L_{filter} = 76.36\, mH$$

$$R_{filter} = 0.69\, \Omega$$

Consider these values there was the possibility to define the cut-off frequency.

$$\frac{1}{2\pi\sqrt{LC}} = 83.13\, Hz$$

(3.6)

It was a 2[nd] order filter, so its job was to filter the frequencies above the cut-off frequency. The role of this filter was to create a safety system for the measurements devices from high frequencies signals components as the ones created by the partial discharges. The RLC circuit formed a harmonic oscillator for current and it could resonate when the inductive and capacitive reactance became equal. Moreover, the presence of the resistor made that any oscillation induced in the circuit died away over time. This effect of the resistor is called damping. This presence also reduces the peak resonant frequency somewhat. When the frequencies become higher the capacitive reactance becomes low, so the current signals pass through it and go to the ground system. In the opposite case, when frequencies are lower, the inductive reactance become low and the capacitive reactance arise, so the signal prefers to pass through the inductance and so, it is not filtered.

After the low-pass filter, there was a step-up transformer. It increased the voltage up to 50 kV.

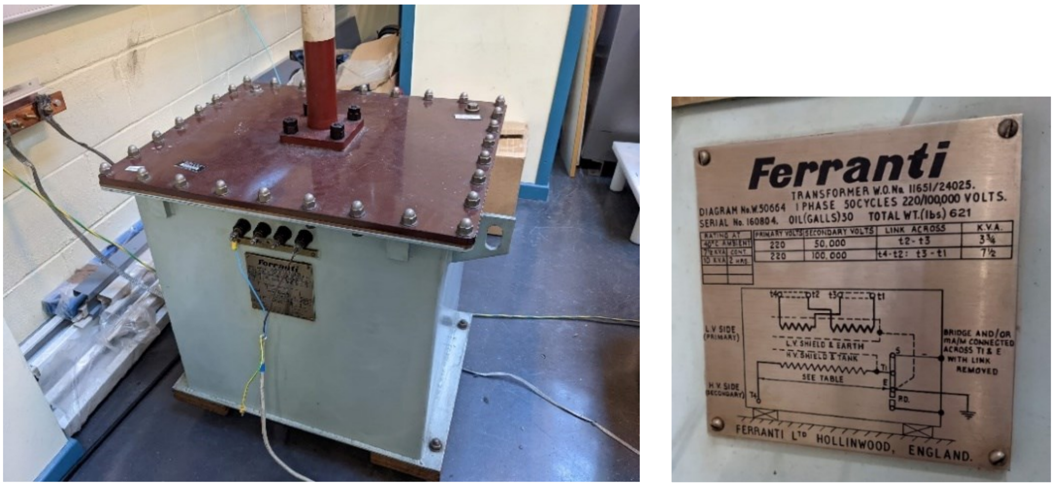


Figure 3.5. *Step-up transformer and its specifications. The link was connected across t2 and t3, so it worked with 50 kV in the secondary.*

Connected to the transformer there was the voltage divider and the tested polymeric insulator. The voltage divider gave the possibility to measure the voltage used in the insulator tests, considering the ratio of 3750:1. So, a coaxial cable transmitted the signal from the divider to the oscilloscope.

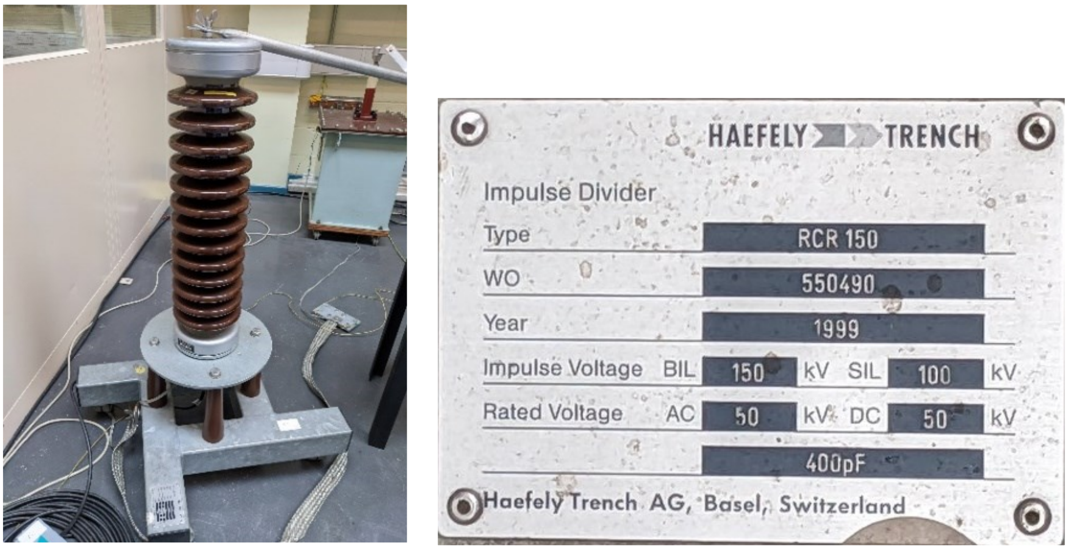


Figure 3.6. *Haefely voltage divider with a ratio of 3750:1.*

Regarding the insulator tested in the cage, a textured polymeric insulator has been used.

Figure 3.7. *Textured silicon rubber insulator.*

This kind of insulators are used in distribution overhead lines up to 132 kV [25]. Their silicon rubber surfaces have been investigated during years because some concerns can arise in their long-term performance in polluted environment. The silicon rubber gives them a high hydrophobicity compared to ceramic or glass. But, in some parts below the sheds, where the self-washing effectuated by the rain is not able to wash the pollution, it can deposit and so it can accumulate. Moreover, since the ceramic and glass can be moulded easily with a more anti-fog design to avoid this problem, the polymeric ones can be not. So, there can be an increasing of the leakage current and arc discharges along this part, due to a higher electric field intensity. For that reason, an in-house textured path for polymeric insulators was made and studied at Cardiff University. The protuberances along the trunk permit an increasing of the creepage distance without increment the length of the entire insulator. The geometry of these textured patterns is visible in Figure 3.8.

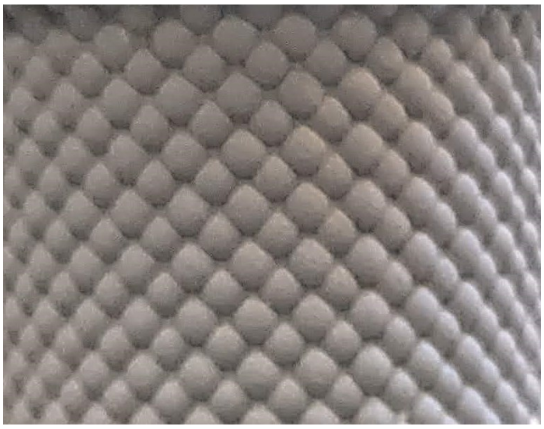


Figure 3.8. *Shank pattern of the textured composite insulator.*

It can be visible the square-intersection bases of the hemispherical protuberances. This leads to a more resistive path for the leakage current and so, its magnitude can decrease. As some leakage current analysis effectuated at Cardiff University told, with this configuration the magnitude of this current is less than a standard configuration [26]. Another advantage that come from these textured surfaces is the difference in the electric field distribution respect a non- textured surface. This fact can lead in a better behaviour of the material along the shank whenever fog deposits on it.

The insulator tested and illustrated in Figure 3.7 has got five sheds with different inclination and surface area. This structure help the self-washing and it allows droplets to slip out from the sheds without creating a connection between two adjacent sheds.

Finally, about the data acquisition devices, a digital oscilloscope[1] has been used for the visualization of the output from the current transducer, the resistive box and the Rogowski coil. Moreover, a USB-6351 Multifunction I/O by National Instruments (see Figure 2.9) has been used coupled with the oscilloscope. Nevertheless, it returned no reliable data because an unexpected noise was injected in the system as it can be seen later.

To summarize, in Figure 3.9 the equivalent circuit of the measurement setup is represented.

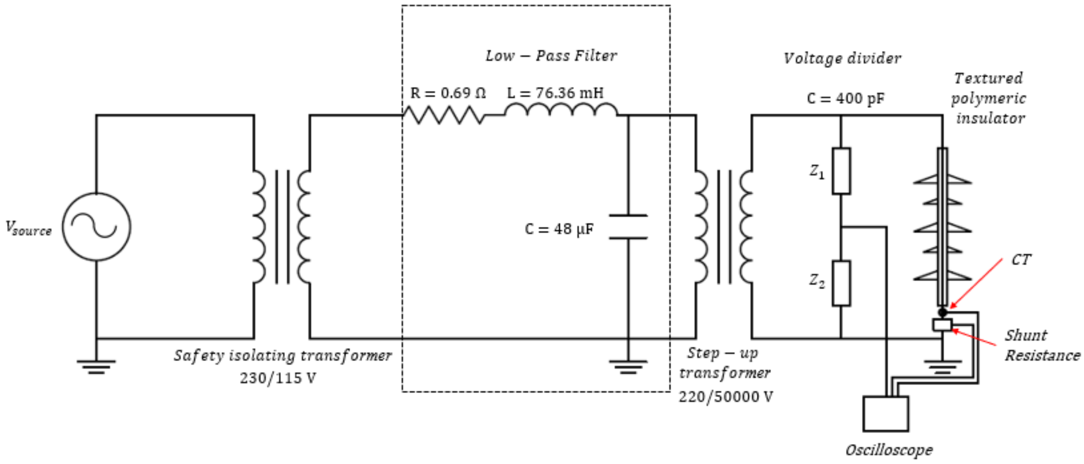


Figure 3.9. *Equivalent electric circuit of the measurement setup for the isolator tests in the laboratory of Cardiff University.*

3.2 Transducer characterizations

Before starting the high voltage test with the silicon rubber insulator, some comparative tests have been done to verify the reliability of three different kind of current transducers used to detect the leakage current. It has been used:

1. A shunt resistance
2. A Rogowski coil
3. A high frequency current transformer

The tests have been carried out at a bench in the laboratory. There was a sine generator, an oscilloscope, a set of resistances used as loads and a multimeter.

[1] A WaveJet Touch 354 manufactured by Teledyne Lecroy. It is a 500 Mhz bandwidth oscilloscope with a speed sampling of 2GS/s.

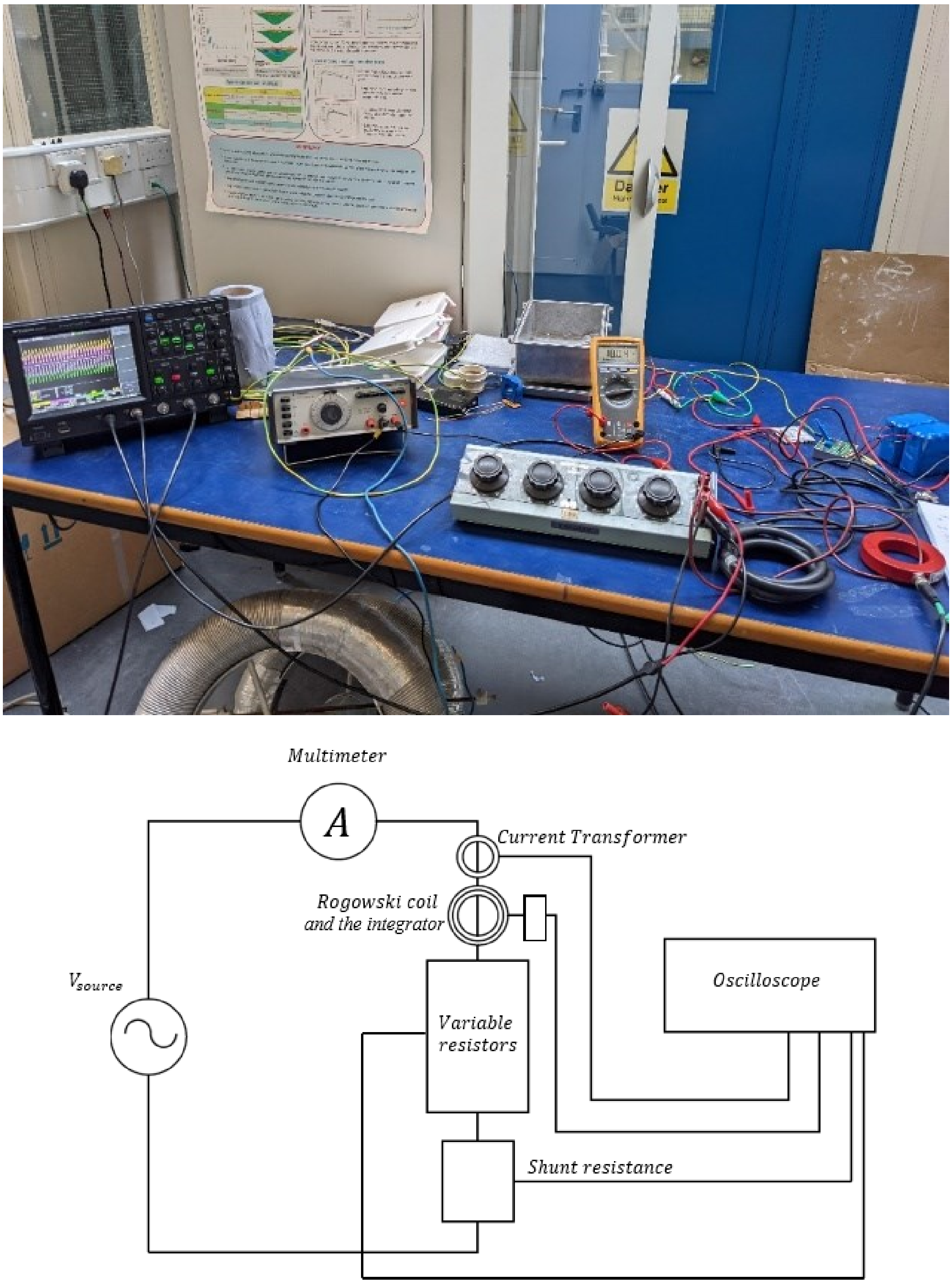


Figure 3.10. *Desk measurement setup for the transducer characterizations and the equivalent circuit.*

The procedure consisted of manage different value of a small current emulating the magnitude of the leakage current (few milliamperes) and test the response of transducers. If they were able to give a reliable output compared to the multimeter they can be considered good. They were not if random values appeared. This procedure has been repeated with the three sensors, starting from the resistive box.

Figure 3.11. *Shunt resistor box used for the test. With two switches, the Rbox had the possibility to change the R value from 91.92 Ohm to 4700 Ohm.*

The shunt resistor was included in a small metal box. Inside it, there was not only the resistors but other electronic components because the box has been used also as a surge arrester. The signal output travelled along a coaxial cable to the Channel 1 of the oscilloscope. To study its response at low magnitude of currents, only two measures have been done. The R value used was $91.92\ \Omega$.

Table 3.2. *Shunt resistance characterization measurement values.*

R_{box} [CH1]	I_{Rshunt}	$I_{multimeter}$
[V] [RMS]	*[mA] [RMS]*	*[mA] [RMS]*
3.07	0.033	0.033
2.30	0.025	0.025

Hence, comparing the currents measured with a multimeter and the currents calculated from the voltage signal in the resistance box, it could be evident that the two currents measured had the same value, so the resistive box gave in output a reliable signal at 50 Hz.

The other tranducer tested was the high frequency current transfomer CT-F5.0-B.

Figure 3.12. *High Frequency Current Transformer CT-F5.0-B.*

Table 3.3. *High Frequency Current Transformer specifications.*

PARAMETERS		
Low frequency cut-off (3dB)	2634.00	Hz
High frequency cut-off (3dB)	431.50	MHz
Sensitivity in 50-ohm-load	2.50	V/A
Sensitivity error	0.05	%

In Table 3.3 the CT specifications are explained. Looking at the frequencies range, it can be notable that its response is between 2.6 kHz and 431.5 MHz. So, it is able to detect accurate amplitude signals in this order of frequencies. This characteristic can be good for the measurement of the leakage current because, toghether with the shunt resistance, a wide range of frequency measurements can be obtained. Hence, arc discharges could be measured in a better way with the CT, whilst the Rbox can be used to see the current waveform, the phase and the magnitude. The sensitivity considered for this CT depended on the impedence where the circuit was closed. Or, taking the oscilloscope into account, the impedence used by it to have the measurements. The oscilloscope used for all the tests was a Teledyne Lecroy – WaveJet Touch 354, 500 Mhz Oscilloscope 2 GS/s. The acquisition input can be configured with two coupling impedances: 1 MΩ or 50 Ω. Hence, for the CT measurements, it was configured with a DC couple at 50 Ω because the sensitivity was given for 50 Ω. On the contrary it could be used 1 MΩ with a CT sensitivity of 5 V/A.

At the light of facts, considering the characterization of this high frequency CT, some measurements have been taken. The voltage source and the resistive load were varied in order to study different responses. Moreover, the analysis has been done with different frequencies to see the behaviour of the current transformer.

Table 3.4. *High Frequency Current Transformer characterization measurement values.*

Freq.	**Load**	V_{source}	V_{source} [CH1]	**CT [CH4]**	$\mathbf{I}_{multimeter}$	$\mathbf{I}_{load}$	$\mathbf{I}_{CT}$
Hz	*Ohm*	*V [pk-pk]*	*V [RMS]*	*mV [RMS]*	*mA [RMS]*	*mA [RMS]*	*mA [RMS]*
50	1000	6	2.28	19.20	2.28	2.28	7.71
506	200	12	3.81	10.40	19.15	19.05	4.18
5.06k	1000	3	1.22	2.70	1.10	1.22	1.08
5.06k	1000	6	2.31	5.14	2.16	2.31	2.06
5.06k	900	12	4.66	10.30	4.40	5.18	4.14
5.06k	200	12	3.81	42.50	18.04	19.05	17.07
50.44k	1000	3	1.22	2.97	1.10	1.22	1.19
506k	200	12	3.81	42.50	18.04	19.05	17.07
519.4k	1000	3	1.21	3.29	1.10	1.21	1.32

In first approximation, it’s evident the good response of the CT at high frequencies. From 5.06 kHz to 519 kHz the current measurements taken by the multimeter, the CT and from the resistive load are very close. On the contrary, with low frequency the RMS response is not good. This last result could be caused by the range of frequencies at where the current transfomer can properly work.

The CT characterization has been done with the Rogowski coil analysis at the same time. The R. coil was a 4 turns flexible coil made by Rocoil. It was connected with its integrator IFW- 2395 powered with a 15 V Lithium battery.

Figure 3.13. *Flexible Rogowski coil made by Rocoil on the left and its integrator IFW -2395 on the right.*

The datasheet was not available, but from the integrator label it was evident that it had two sensitivities: 1 A/V and 10 A/V. Using the 1 A/V the results obtained are represented in Table 3.5. The 4 coils windings were also considered, so the current outputs were divided by 4.

Table 3.5. *Rogowski coil characterization measurement values.*

Freq.	Load	V_{source}	V_{source} [CH1]	Rogowski coil [CH2]	N. turns cond.	$I_{multimeter}$	I_{load}	$I_{R.coil}$
Hz	*Ohm*	*V [pk-pk]*	*V [RMS]*	*mVmin-mVmax [RMS]*		*mA [RMS]*	*mA [RMS]*	*mAmin-mAmax [RMS]*
50.5	1000	6	2.28	2.24 - 7.14	-	2.28	2.28	0.56 - 1.79
506	200	12	3.81	22.90	-	19.15	19.05	5.73
506	200	12	3.81	62.90	3	19.15	19.05	5.24
506	1000	12	4.65	10.00	-	4.69	4.65	2.50
5.06k	1000	3	1.22	3.00 – 14.00	-	1.10	1.22	0.75 - 3.50
5.06k	1000	6	2.31	4.00 – 6.00	-	2.16	2.31	1.00 - 1.50
5.06k	900	12	4.66	9.30 – 11.00	-	4.40	5.18	2.36 - 2.75
5.06k	200	12	3.81	22.90	-	18.04	19.05	5.76
5.06k	200	12	3.81	43.00	2	18.04	19.05	5.38
50.44k	1000	3	1.22	9.27	-	1.10	1.22	2.32
506k	200	12	3.81	62.70	3	18.04	19.05	5.23
519.4k	1000	3	1.21	6.99	-	1.10	1.21	1.75

As the CT case, different frequency responses were analysed. Anyway, the R. coil results were not reliable. Certain times (as in row 1-5-6-7) the output of the integrator was not stable. It inexplicably oscillated from a minimum to a maximum current value. More turns of the conductor were effectuated around the coil (see row 3-9-11) but the signal, compared with the multimeter and the load, was not reliable. Moreover, with this method there was the possibility to create an unwanted inductance, decreasing again the accuracy and the reliability of the measurement system. In the light of the results obtained, the decision of no using the Rogowski coil during the test of the insulator was effectuated. Anyway, the problem was solved later. Putting the Rogowski coil, the integrator and the battery pack inside a metal box, the measurements was more reliable. It could be because annoying electromagnetic field in the environment changed the Rogowski coil behaviour, very sensitive to the magnetic field. For that reason, these kinds of coils are usually covered with an electromagnetic shield, but maybe, in this case it was not properly configured.

In Figure 3.14 there is an example that justified the random trend of the signal that came from the Rogowski coil.

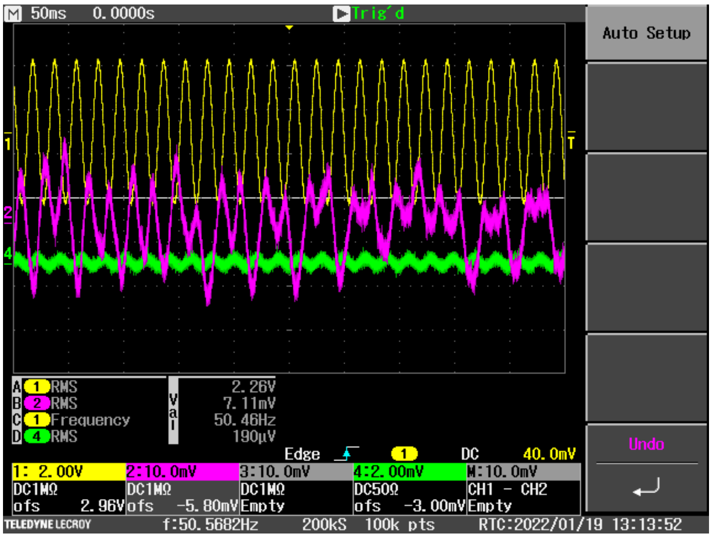
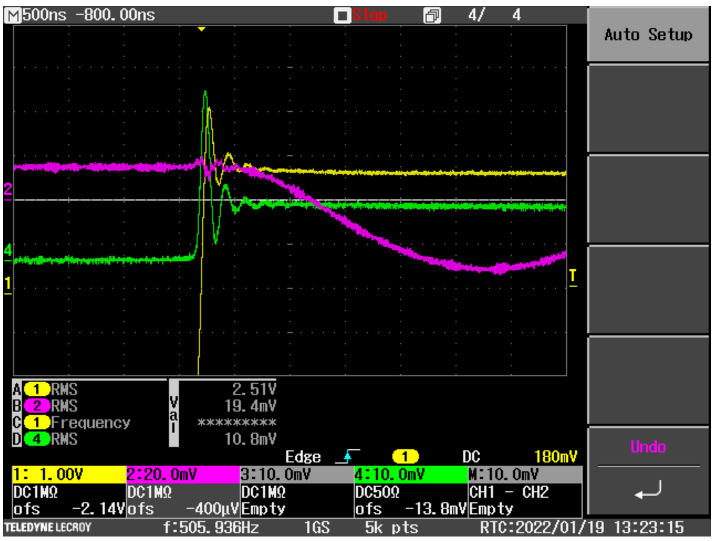


Figure 3.14. *Random R. coil signal (purple line – Channel 2) captured by the oscilloscope at 50 Hz.*

It can be notable the random output signal (purple line) that come from the integrator during the analysis taken in Table 3.5. The sine wave is not visible and the RMS value is totally no-sense. The voltage source (yellow line) is correctly reproduced and the CT signal (green line) have low response due the 50 Hz frequency.

Further analysis has been done to study the step response of the CT and the Rogowski coil.



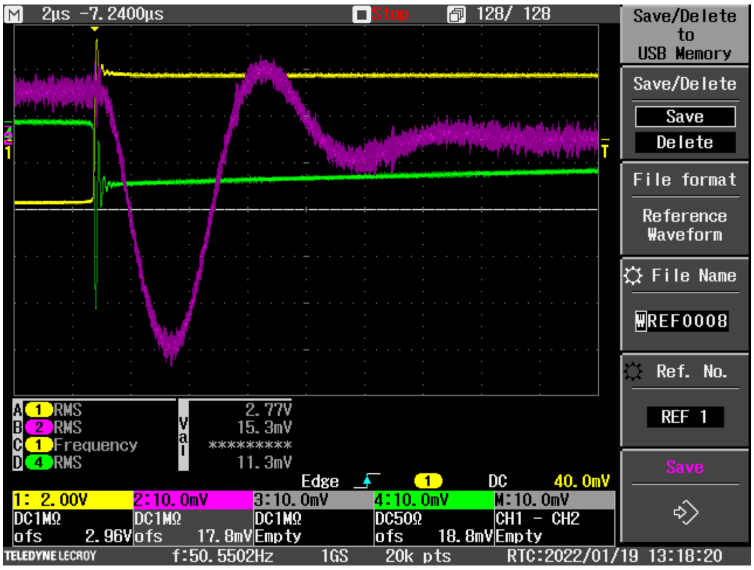


Figure 3.15. *CT (green line) and R. coil (purple line) step response (the yellow line is the voltage source).*

A square wave source was applicated to the circuit and the response of the transducers were different. The CT is really fast and it gives a good output response (green line). Whilst, the Rogowski coil (purple line) has a lower response. Despite Rogowski coils can have good transient response because the presence of a lower mutual inductance due the air core, looking the equation 2.5 and 2.6 in §2.2.2 it is possible to ipotize that the number of winding of the coil can influence the transient response.

3.3 The polymeric insulator tests

After the characterizations, the transducers could be used for the insulator tests. It was decided to not use the Rogowski coil, since its non-reliable results. For the tests, the RMS value of the current measured by CT will not be presented because it didn't give information. The CT can be used to detect the high frequency spikes in the current caused by the arc discharges. The output waveform at 50 Hz of a high frequency current transformer, compared with the resistive waveform output, gives only noise.

Hence, as anticipated, these tests consisted of taking measurements of the leakage current along a polymeric insulator in a dry and wet pollution condition. The objective was to understand the behaviour of the resistive box and the current transformer when arc discharges appeared.

3.3.1 Transducers performance in the "Dry clean" test

Starting with the dry test, the insulator was previously cleaned with alcohol to remove all residual particles from the surfaces and then organised for the test. The measurement setup has been described in §3.1 and here there is a clear representation before the tests. Up the isolator there was a toroidal component utilized to uniform the electric field in pointed areas. This avoided the formation of corona discharges along these parts.

Figure 3.16. *Final measurement setup for the insulator tests.*

For the tests a video camera was utilized. It was a normal commercial camera that make video at a great resolution (1090×1080p) and it was able to detect the discharge activities.

The resistive shunt box was set at 4700 Ω and the system was energized with different percentages of voltage with the Variac.

Table 3.6. *Leakage current measurements for the dry test.*

Variac	V_{source}	V_{source} [CH1]	R. shunt 4700 Ω [CH3]	Shunt Resistance leakage current
%	*kV [RMS]*	*V [RMS]*	*mV [RMS]*	*µA [RMS]*
10	4.58	1.22	23.10	4.91
20	9.49	2.53	47.80	10.17
30	14.36	3.83	72.30	15.38
60	30.68	8.18	154.00	32.77
70	36.08	9.62	180.00	38.30
80	41.25	11.00	206.00	43.83
90	45.38	12.10	228.00	48.51

As it can be notable, the leakage current magnitude (RMS value)[2] measured by the shunt resistance (contained in the Resistance box) is very low, in the order of µA. Different measurements have been taken varying the percentage of voltage source with the Variac, but in any case, no activity referred to arc discharge phenomena was revealed.

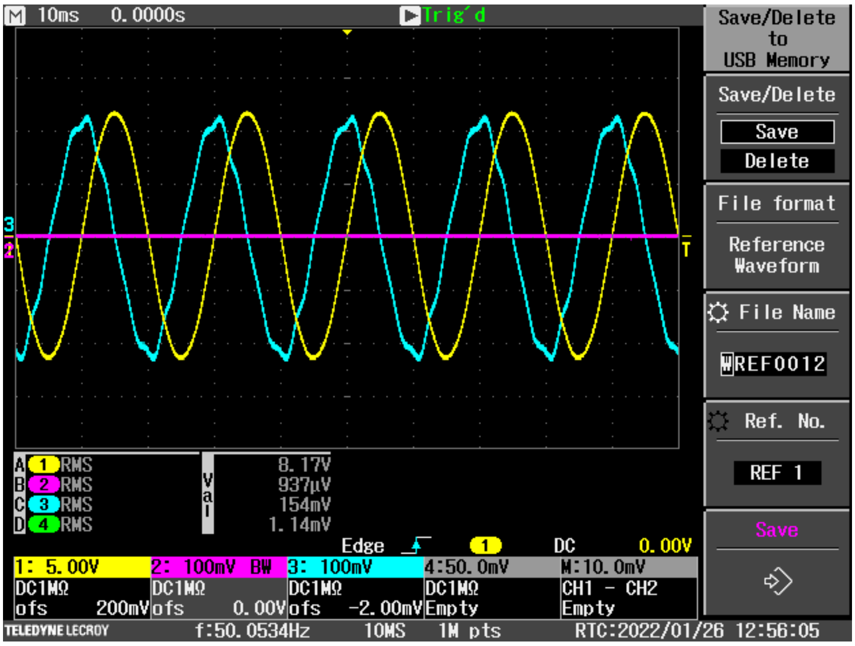


Figure 3.17. *Dry test waveforms. In CH1(yellow line) there is the voltage source, in CH2 (purple line) the CT voltage output and in CH3 (blue line) the R. box voltage output.*

[2] It has been obtained dividing the voltage output magnitude read on the oscilloscope with the 4700 Ω resistance

The signal coming from the R. box (leakage current) is correctly in advance respect the voltage source. This justifies the natural capacitive behaviour of that current in dry conditions where no surface current can flow.

3.3.2 Transducers performance in the "Wet pollution" test

To simulate the wet pollution on the insulator, according with standard procedures[3] the Kaolin[4] chemical solution has been sprayed on all the sheds and trunk surfaces. The objective was to create a wet pollution film along the creepage distance where the leakage current can flow and so, verify the possibility of arc discharge phenomena. Two tests have been done. In the first one, it was not possible to create a liquid film on the surfaces because the polymeric material has a higher hydrophobicity. So, to kill the hydrophobicity a chemical substance called Triton X100 could be used, but instead of it, a shortcut was found. Indeed, in the second test it was sprayed another big quantity of Kaolin on the residual dry solution deposited on the surfaces. This method was able to reduce the hydrophobicity and a wetted film of pollution can be easily formed.

Figure 3.18. *Starting from the left, there is the dry condition. In the centre the first wet pollution deposition and on the right the second spray of kaolin solution.*

[3] IEC 60815 and IEC 60507 include the standard test for insulators in a polluted environment
[4] A clay mineral that creates a conductive solution when diluted in water

The conductivity measured along the shank revealed the creation of a film of liquid on it. On the contrary, the measurements effectuated on the sheds didn't reveal the formation of a good film, in the two wet cases. This phenomenon justified the high hydrophobicity of the silicon rubber material that allow the formation of water droplets that can easily split out along the surface.

For the first wet test, the result was reliable but, since there was not a film on the surfaces, the current behaviour was still so capacitive instead resistive. Nevertheless, the leakage current magnitude increased respect the dry test.

Table 3.7. *Leakage current measurements for the first wet pollution test.*

Variac	V_{source}	V_{source} [CH1]	R. shunt 4700 Ω [CH3]	Shunt Resistance leakage current
%	*kV [RMS]*	*V [RMS]*	*mV [RMS]*	*mA [RMS]*
20	9.11	2.43	90.90	19.34
30	14.29	3.81	157.00	33.40
40	19.73	5.26	221.00	47.02
50	25.16	6.71	291.00	61.92
60	30.53	8.14	363.00	77.23
70	36.00	9.60	574.00	122.10

Since there were not high discharge activities, the CT didn't give responses.

The second wet test gave different results from the first one. Another spraying was added to the surfaces and some arc discharges was observed.

Table 3.8. *Leakage current measurements for the second wet pollution test.*

Variac	V_{source}	V_{source} [CH1]	R. shunt 4700 Ω [CH3]	Shunt Resistance leakage current
%	*kV [RMS]*	*V [RMS]*	*mV [RMS]*	*μA [RMS]*
4.3	2.16	0.58	114.00	24.26
22.3	11.14	2.97	144.10	30.66
29.9	14.94	3.98	342.90	72.96
30.5	15.24	4.06	302.90	64.45
		With 92 Ω R. shunt		
33.9	16.96	4.52	12.030	130.76

The leakage current magnitude increased, especially in the last row, where a 92 Ω shunt resistor has been used. In this case a great discharges activity has been seen on the insulator.

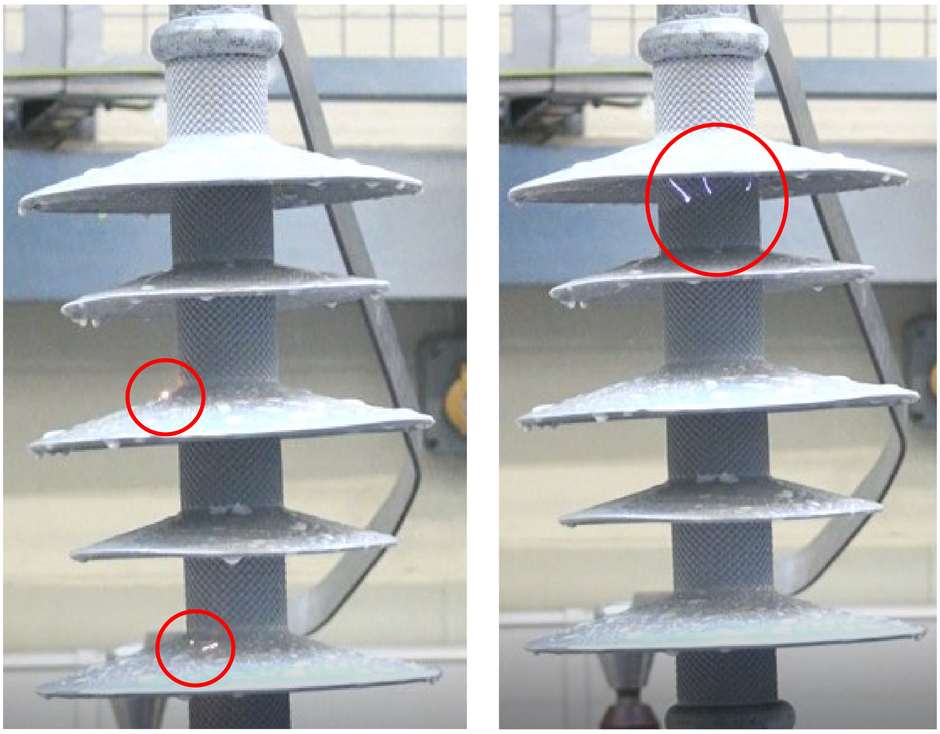


Figure 3.19. *Surface discharge activities along the first shank and on the sheds.*

The arc discharge activities first interested the shed surfaces and then the truck close to the high potential of the insulator.

To recap, the phenomenon happens because there is an increasing in the surface leakage current. This increasing of the magnitude of the current is due the formation of a conductive layer by the deposition of the conductive Kaolin solution. Because there is an increasing in the surface resistive current, there can be a more power dissipation due the joule effects.

$$P = EJ = \frac{J^2}{\sigma} = \frac{I^2}{(\sigma S^2 T^2)} \quad [25] \tag{3.7}$$

Where J is the current intensity, σ the conductivity of the solution, S the perimeter and T the thickness of the polluted solution layer.

Hence, the power dissipation heats the liquid film and between the two droplets there can be an intensification of the electric field. It can be so high that the dielectric (air) may break and a discharge appears. This phenomenon can repeat due to a continuous flowing of the leakage current that creates more dry bands, more discharges that finally could evolve in a flashover. From equation 3.7, it can be notable that the power dissipation depends also on the perimeter S. Hence, that proportion can justify the formation of the arcs in the first shank, which have a smaller perimeter instead of the sheds. Moreover, the distribution of the electric field along all the rod of the insulator needs to be considered. The top part is more stressed respect the bottom part, so there can be more probabilities that arc discharges appear there.

Anyway, that textured polymeric insulator reacted well to these kinds of discharges. The texture creates a surface much more resistant and where the electric field can distribute in a better way respect a non- textured one.

Chapter 4

Data analysis and proposed system for the remote access of results

In the last chapter, the wet pollution test will be commented. The data obtained will be analysed to compare the current transformer signal with the shunt resistance output. Finally, the online data remote access will be discussed in a general way, considering different software and a little experimental test.

4.1 Shunt resistance box and current transformer results

During the dry test there were not arc discharges and so, the high frequency current transformer didn't reveal any activities. The waveform phase of the resistive box output was in advance respect to the voltage source waveform as it can be visible in Figure 3.17 in §3.3.1. This means a capacitive behaviour of the current, so no surface leakage current with a resistive nature was present.

Different was the case of the last heavy wet pollution test, where a lot of arc discharges appeared as demonstrate in Figure 3.19 in §3.3.2. In that test, both the CT and the resistive box detected important discharges peaks in the current waveform.

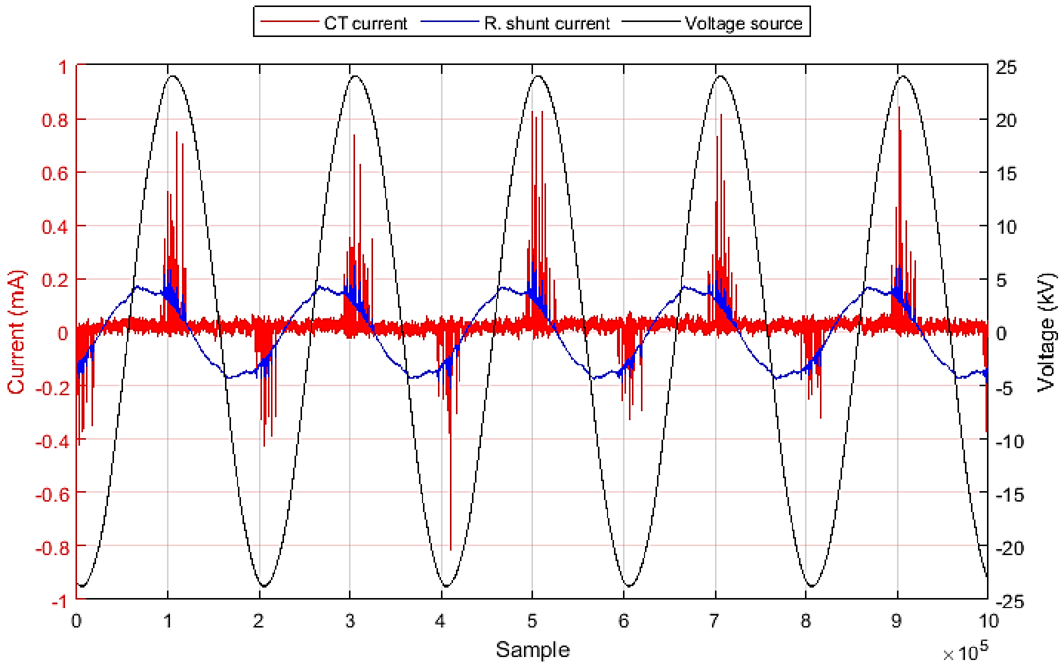


Figure 4.1. *Current waveforms comparison coming from the CT and the Resistive box. They were taken by the oscilloscope digitizer at the maximum sample rate.*

In Figure 4.1 all the signals that came from the transducers and the voltage divider are represented. The oscilloscope was set at the maximum sampling rate, so it can be visible in the x-axis the high number of samples taken in few seconds. In the chart, are also compared the voltage magnitude that arrive approximately to 25 kV during the test, with the current waveforms in order to understand when discharges happened. The activities are present in both positive and negative peaks of the voltage source waveform. Hence, they can be considered surface partial discharges. Maybe, they can be little high frequency sparks between the droplets on the shed surface. The phenomenon could be visible in Figure 3.19.

In this case the current is not completely in phase with the voltage. This means a non-complete resistive behaviour of the current that remain a little bit capacitive also in the wet test.

Considering only one period of the shunt resistance current, with Figure 4.2 further considerations could be made.

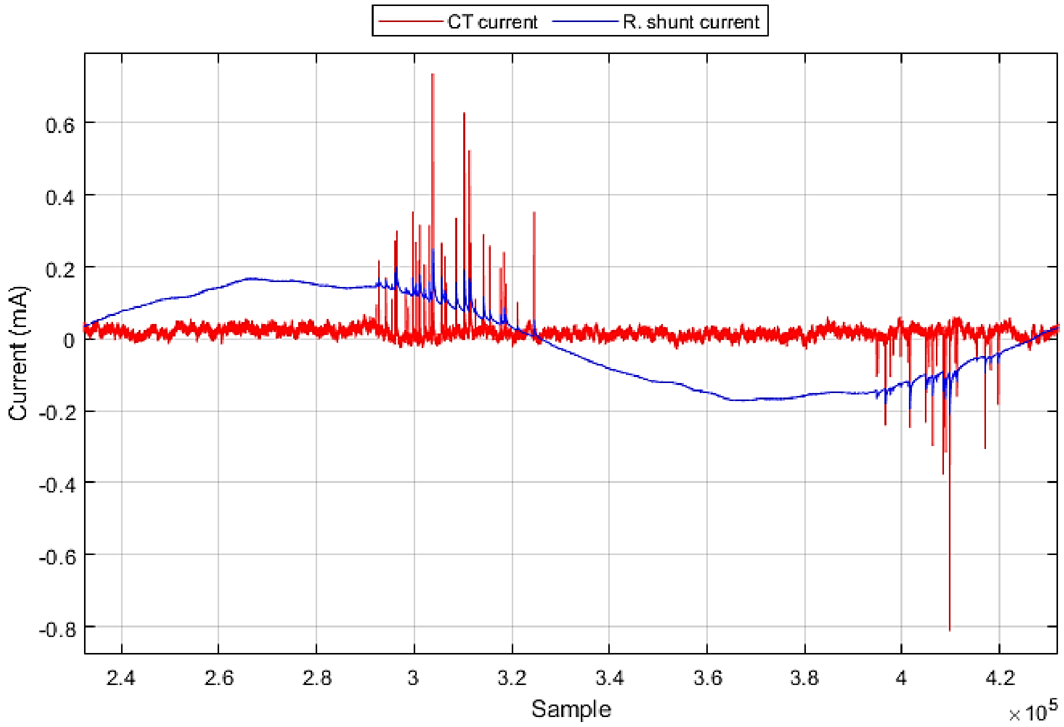


Figure 4.2. *One period representation of the CT and R.box current signals.*

Takin into account the characterization measurements in Chapter 3, the CT reliability has been considered good in its frequency range. In this case, at 50 Hz the interest is only in the detection of high frequency peaks of current. As it can be visible above, the response of the CT respects the peaks detected by the resistive box is good. They captured the same peaks at the same instant.

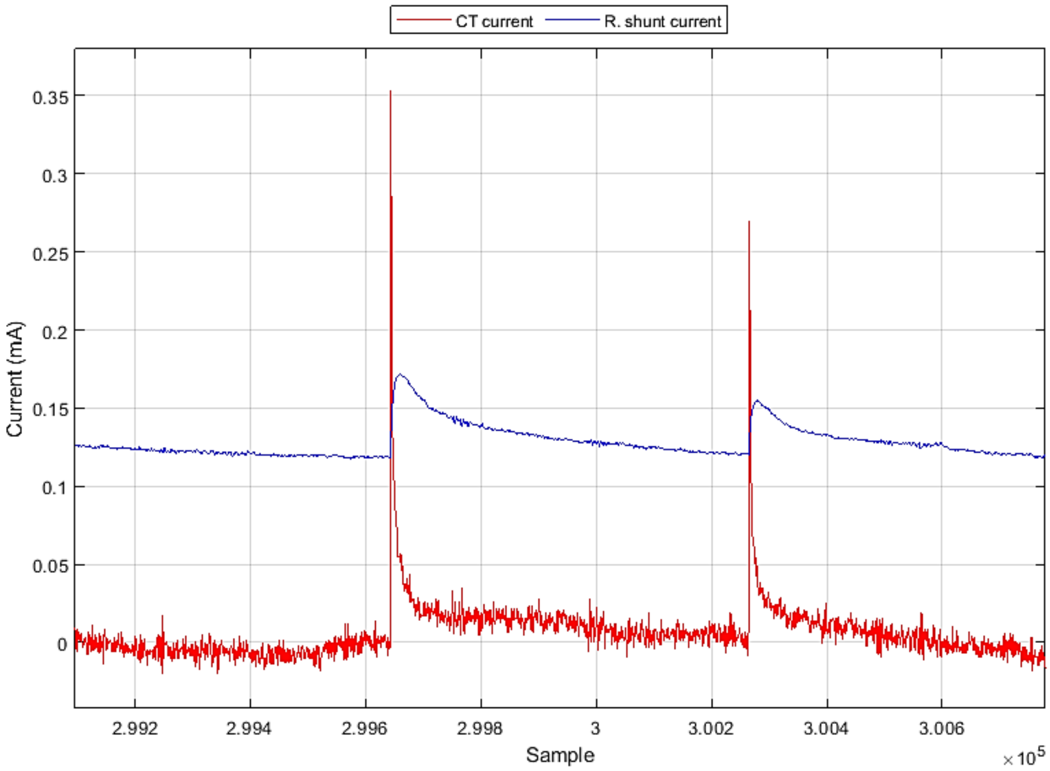


Figure 4.3. *Current peaks amplitude comparison between the CT and the shunt resistance.*

The good response of the CT and the R. box leads to great conclusions for their reliability. It could be visible the fast response in the discharge detection by the CT and the shunt resistance. But the R. box response is a bit slow. As explained in §2.2.1, the shunt resistor could suffer high frequency activities because some parasitic inductance or capacitance can change the performance behaviour [13]. Maybe, in this situation, high frequency peaks lead to increase the impedance due to inductance parasitic element in the resistance, so the magnitude of current could fall due to an increasing of the voltage drop.

Further analysis has been done with the helping of a data acquisition device: the USB-6351 represented in Figure 2.9. Unfortunately, the results were not reliable due to an annoying noise injected by it into the system measurement.

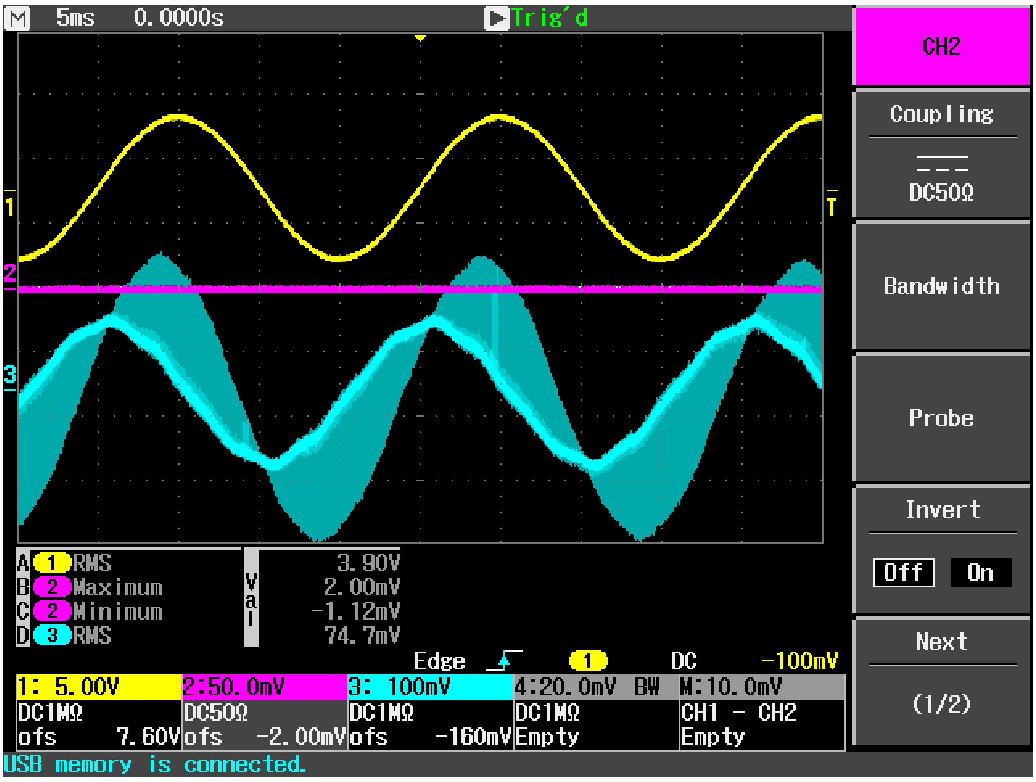


Figure 4.4. *Signals detected by the USB DAQ device connected at the ports of the oscilloscope. The blue line is the distorted signal that come from the shunt resistance. The yellow line represents the voltage source and the purple line is the CT.*

The shunt resistor (blue line) is affected by a tedious effect when the USB DAQ device is connected in parallel with the oscilloscope. The objective was to connect the oscilloscope and the DAQ device together to take large amount of data of the signals and have an instant reliable representation on the oscilloscope. Unfortunately, this was not possible but, some data were taken just to see how accurate the device could detect the discharges.

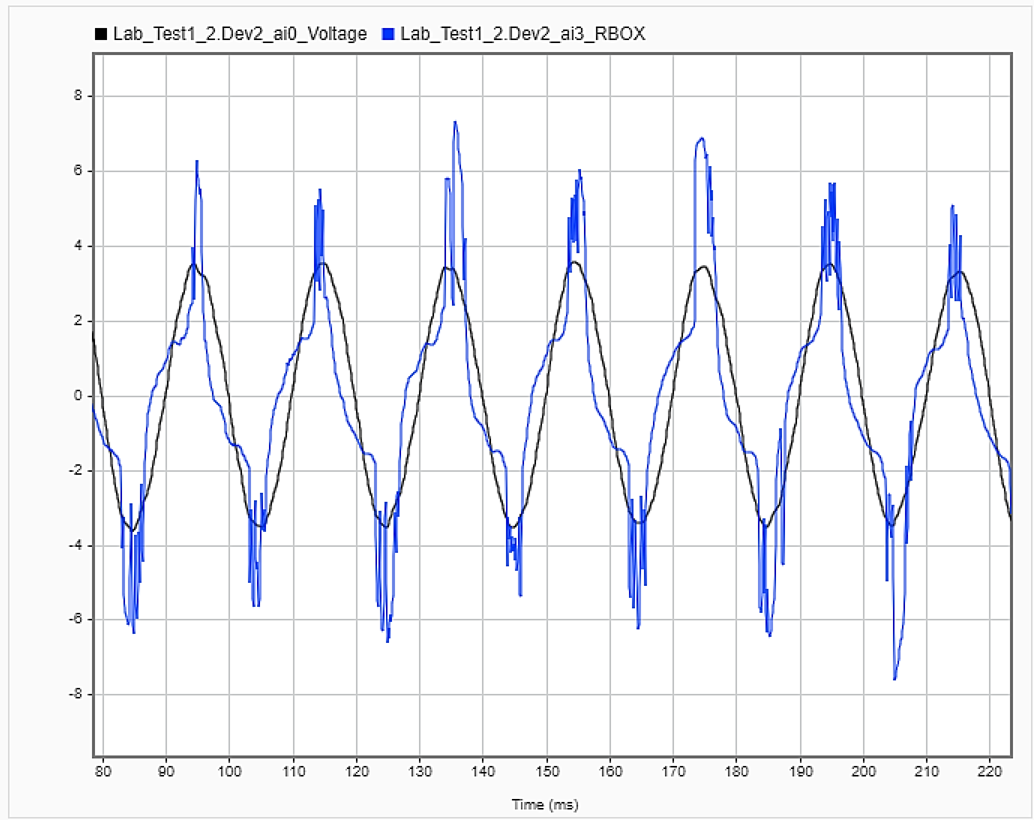


Figure 4.5. *Voltage signals detected by the USB DAQ device. The blue line comes from the shunt resistance, the black line from the voltage source.*

Obviously, the data acquired are not reliable, but the test has been done to study how this device works. The USB- 6351 takes samples at 1.25 MS/s maximum. The rate needs to be divided with the number of channels used. The programme used to acquire data was MathWorks Matlab together with a tool included in it called "Analog Input Recorded". The data was then represented and elaborate with the Matlab tool "Signal Analyzer". In Figure 4.5 the results are represented just to see the waveforms and the discharge activities. Along the y-axis there is the voltage output scale in kV. The shunt resistance voltage was not converted in a current waveform. Anyway, it can be notable the partial discharge activities on both the highest and the lowest peak of the voltage source (black line). The phenomena are very similar to the previous ones, and it can be visible the resistive trend of the R. box voltage waveform (blue line) during the discharges. The data were acquired with low sampling rate due to the enormous amount of data caused by the high resolution of the device. Hence, the results were not as accurate as the signals taken by the oscilloscope with a higher sampling rate.

4.2 Online remote data access

In the last years, internet has been providing numerous services for privates and companies. For instance, cloud systems or cloud computing[5] have opened the door to domestic services with various sensors connected in internet. This wireless technology could be useful when people are out from home. They can have easily access to all the sensors at home and they can menage them wherever they are. Another technology can be the storage of data at home having the remote access everywhere there is an internet connection. Obviously, all these systems need a compromise in term of privacy because there is not the entire control of the transferring of data. Personal information travels along the network and so, they can be vulnerable. This could be a great challenge for the cybersecurity, nowadays. Moreover, another big challenge for the data transferring could be the possibility to save, storage and send huge amount of data. Thinking about a DAQ device, where the analogue-to-digital converter samples at 1.25 MS/s with a 16-bit resolution, it could be possible to extrapolate the exact amount of data:

$$1.25\ \frac{MS}{s} \cdot 16\ \frac{bit}{S} \cdot \frac{1}{8}\frac{byte}{bit} = 2.5\ \frac{MB}{s} \tag{4.1}$$

Hence, it can be possible to understand how big a measurement acquisition can be in term of storage space. Considering a month of data acquisition (30 days), the total amount of data can reach approximately 6.4 TB of data! The possibility to avoid this problem could be an automatized system where data can be saved and deleted with a FIFO technology. Something as the one utilized in security cameras, where the first video recorded is automatically subscribed when the memory occupied reach the maximum.

The problem could grow when the remote access of data is needed. For instance, thinking the possibility to have access of all the data taken by an acquisition system in the Deeside Centre of Innovation in the north of Wales, the amount of data that can be transferred can result in a hard challenge. There can be some solutions hypothesized

[5] Internet technology that provides remotely access services

by me. One of them can be the NAS technology installed in a centre node to give multiple access of all the data saved for everyone around the world that have the credentials. This cannot be considered as an automatized method because it needs operators that take all the data and manually put them inside the NAS storage. Probably, there can be some solution integrating microcontrollers as Arduino or compute module as Raspberry Pi to the systems to automatize the process of saving but recent software technology can reach that.

Anyway, the great solution is a compromise between cost, efficiency, and easy implementation.

4.2.1 Network attached storage (NAS)

Network attached storage (NAS) can be considered as a file-level computer data storage server connected to a computer network providing data access to a heterogeneous group of clients [27]. In other words, it can be considered as a customizable memory storage which can make the data available online to clients. It includes a server, that is the "brain" that control all the storage disks connected to it called "array". Hence, there are some storage disks connected to the server and they are available for everyone in a network. NAS servers are usually used for LAN networks, or Local Area Network. This kind of access is strongly restricted to a local network as the one at private homes or offices. But, in the case of necessity, there is the possibility to have access to a NAS server even if clients are not in a local network area. This technology is the same used by commercial brand like Microsoft, Google, or Dropbox, with their own cloud storage software as Google Drive or Microsoft OneDrive. The advantages to have a private NAS instead of commercial services could be the totally managing of the hard disk memories. The location, where the server is, is known and this can be good for the privacy of personal data. Nevertheless, the cost for a customizable NAS system can be high. This is justified by the costs of all the storage disks that can have a lot of memory (in the order of Terabytes) and in the "brain" of the system, the server. Anyway, an easy solution and cost affordable can be the creation of a NAS using a single-board computer as the Raspberry Pi.

4.2.1.1 In-home NAS system with a Raspberry-Pi module

Raspberry Pi can be considered as a tiny pc module at all effects. Its structure looks like a mini motherboard for computers, and it has a great potential.

Figure 4.6. *Raspberry-Pi Model 4B with ARM Cortex A72 processor.*

This module has got multiple ports including four USB accesses. For that reason, an easy experimental work has been done connecting a pen drive of 8 GB to a USB port and installing a software on the Raspberry mother board. The aim was to create a server with the Raspberry Pi where some storage devices can be installed and made available in a LAN or through internet all around the world. The software is called OpenMediaVault, a network attached storage solution based on Debian Linux. The procedure was easy to do, and finally there was a little NAS system, cost effective, completely customizable, portable and it can give access of data to clients with passwords whenever there is an internet connection.

Figure 4.7. *OpenMediaVault installing process and managing of the USB storage space.*

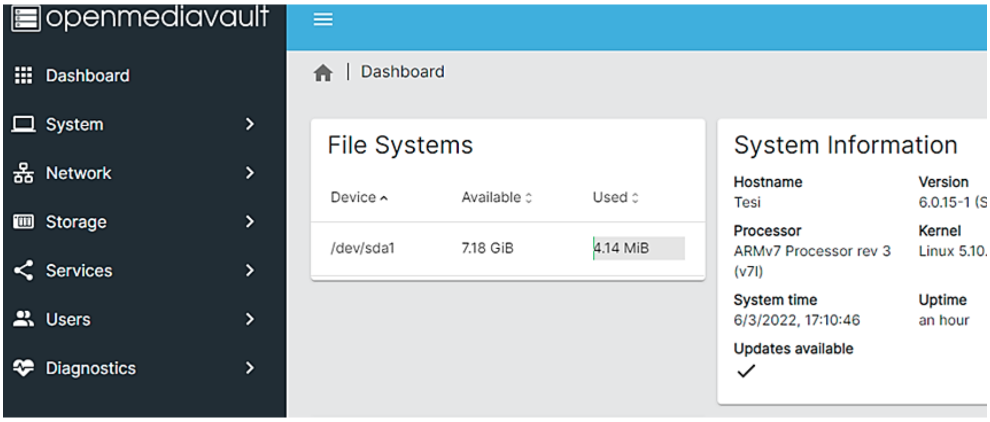


Figure 4.8. *Dashboard of OpenMediaVault with various services available for the storage managing.*

The software looks interesting for the services it provides. There is a totally customizable dashboard where all the hard disk memories connected to Raspberry Pi server can be monitored. There is the possibility to have access to all the information of the server and there is a space where hardware temperatures can be monitored. Moreover, there is the RAID (Redundant Array of Independent Disks) function, which gives the opportunity to create redundancies on the array installed. This helps to create backups of all the data. Obviously, there also the possibility to create groups and users protected by passwords. They can have access to data inside the storages. These functions can be monitored and personalized by the admin who have the entire control of the server. In the services, there is also the possibility to create an easy access to data saved in the hard disks for Windows/Mac users, allowing them the totally implementation in the operative system. Moreover, the files can be read and written on mobile phones. To allow the remote access, there is the function FTP (File Transfer Protocol), which gives the opportunity to have access all around the world where there is an internet connection. This protocol allows only the reading of the files, so there is no possibility to modify folders or data inside the storage. Anyway, this simple system can be a solution to create an easy remote storage data system where users can have access, read files, and make considerations whenever they are. Moreover, is could be a great cost-effective solution, considering the reduced price of the Raspberry Pi instead a commercial server. Obviously, each solution has its advantages and disadvantages, and the best solution come from the necessity. But Raspberry Pi could be a cheaper solution to create a NAS system in a home\office environment or in a place where some tests are conducted and there is a need of having data access from another place.

4.2.2 National Instruments SystemLink software

Another way to get remote data access could be found in SystemLink software. Compared to the previous solution, this system offers a more complete environment which can help to manage test data. SystemLink is a software platform made by National Instruments that includes built-in management tools that help to manage all the test hardware used to take measurements. It includes flexible options for data storage as a wide variety of data analysis and data visualization tools, all easily accessible from the website. So, in other words, SystemLink provides connected intelligence for automated test and automated measurement systems with a central management interface [28]. It works with DAQ devices made by NI or third parts machines[6].

The functions are various, and they mainly include:

- The centralization of a group of systems for remote configuration and monitoring
- The deployment of software with updates to multiple remote systems
- The collection and organisation of test data from automated test systems
- The automation in the transferring of file data from test systems to a central repository

Hence, there is the possibility to create a big automatized system where data taken by DAQ systems, for example in a test station, can be monitored real-time and post-processed with a multitude of software, entirely remote. There is the possibility to control and manage all the assets, modules and control the data taken. With a variety of tools implemented by National Instruments there is also the possibility to elaborate and analysed all the parameter recorded by the modules.

[6] See §2.3 for more details about DAQ systems made by National Instruments

This system could be considered as an IoT[7] solution, implemented for a measurement system. It includes the possibility to have a private or public cloud where the server can work and where data can be saved. In conclusion it could be another possibility to have remote access of data and in this case, having the entire real-time control of all the assets that are taking measurements in a test station.

[7] Abbreviations of Internet of Things.

Conclusion

Starting from a long theory analysis, it was possible to know that leakage current is closely related to aging effects on insulators. Different kinds of insulator designs could have different issues, but hydrophobicity and hydrophilicity are the most common important parameters for all of them. The first one guarantees a good performance of insulators to repeal the polluted water droplets presents on their surfaces. Nevertheless, this characteristic could decrease during time due to a deterioration of the material and so, leakage current magnitude increases. To detect this low current, three different transducers could be used: shunt resistances, Rogowski coils and current transformers. Each one has got its advantage and disadvantage. The shunt resistance is cost effective, but it has limitations in high frequency due the presence of parasitic inductances and moreover, since it is considered as a direct method, it can modify the electrical circuit behaviour. The Rogowski coil works as an indirect method. Furthermore, it doesn't suffer the core saturation, but it is a passive transducer that need power to work correctly. On the contrary, the current transformer is an active sensor self-powered, but it suffers the core saturation.

These limitations could be visible in the experimental test in the laboratory. During the transducer characterizations, the shunt resistance has provided good response for the detection of the leakage current magnitude. The high frequency current transformer the same, but the Rogowski coil had a severe problem of electromagnetic interferences. It has been fixed later, but for the insulator test only the shunt resistance and the current transformer have been used. During these tests it was possible to see the high hydrophobicity of the textured polymeric insulator. This fact didn't give the opportunity to create a good water film on the shed surfaces and so, the leakage current measured still had a capacitive behaviour. Anyway, increasing the voltage it was possible to see a lot of partial arcs along the shank and the sheds. This means that the electrical field distribution on the insulator changed and due the power dissipation, there were many dry bands formation that evolved in arc discharges. All that discharges have been detected by the two transducers. Comparing the signals, it was notable that both the shunt and the current transformer detected the current spikes at the same time. This justified a good response of them. Anyway, the magnitude of the current they detected was different by a 50% factor approximately. This problem can be correlated to some parasitic inductances present in the shunt resistance box that can create a higher voltage drop at high frequencies. That problem suggested the utilization of different type of transducers during this kind of measurements, in order to find a compromise and have a wide range of information that come from the opportune transducer.

Finally, the great number of results that a data acquisition device could have in output put the basis of a great challenge for storage and send them through internet. The NAS server can be a good opportunity to manage storage devices and give them the remote access for clients that want analyse them from other countries. Anyway, big problems arise due the huge storage that is needed and the cost correlated. The Raspberry Pi NAS could be a compromise with the cost, but the problem of the privacy is not negligible.

In conclusion, suggestions for other challenges can include the creation of a centralised measurement system which can automatize the measures. From the detection of the signals by the transducers, to their elaboration, it could be useful to have a centralised web portal where all the assets can be monitored and all the measurements can be available remotely.

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