# System of Measurement and Analysis of Partial Discharges in Underground Power Cables

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**Abstract:** A partial discharge is a nonlinear phenomenon of electrical breakdown that is confined and localized in the region of an insulating medium between two conducting materials which are at different potentials. The damage of the insulating material, which is subjected to an AC voltage during the discharge process, can be directly or indirectly measured by the bombardment of energetic electrons. In this paper we propose a LabVIEW interface for acquisition, measurement, and analysis of partial discharges using hybrid programming. The proposed interface allows the simultaneous acquisition of sixteen input channels and a detailed analysis of the current signals in the underground electric power conductor is performed for each channel. The obtained results support the feasibility of the implemented configuration for measuring, monitoring, and analysis of several effects related to the partial discharges phenomena such as thermal, acoustic, and electrical, and thus to obtain important information about the insulating material status.

Key words: Hybrid programming, partial discharge, underground power cables.

## 1. Introduction

Transmission lines carry power from the generating plants to the distribution systems that feed electricity to domestic, commercial and industrial users. Normally, electricity is generated away from the load centers due to environmental and safety reasons since hydro resources may be at remote location. Electricity is distributed through overhead and underground transmission lines: electricity is usually sent over long distances through overhead power transmission lines while underground power transmission is used only in densely populated areas (i.e. large cities) because of the high costs and losses.

Frequently, a single power cable is not long enough to bridge the distance as desired by the distribution network design and multiple cable sections are cascaded. In practice, the different sections are interconnected by joints, which are assembled manually in the field. An important cause of cable system failures is a breakdown of the electrical insulation between the conductors, which may occur particularly within cable accessories, such as joints. For Example, in Mexico City's downtown there have been fires that are believed to be associated with failures in the connections between the cables and, in particular, with partial discharge (PD). PD are local electrical discharges that occur within insulation of high-voltage (HV) equipment such as switchgear, cables, transformers, motors, and generators. Since PD are the major responsible phenomena for insulation failure of HV power equipment [1], they have been widely studied and their measurement and continuous monitoring have become areas of great interest. Among the main

causes for deterioration of the insulating material are ageing, stress, manufacturing process, and installation procedures. As a part of condition assessment, several diagnostic methods are practiced to identify and locate weak components within the distribution network. Diagnostic methods based on PD detection provide a non-intrusive and mostly non-destructive testing to identify weak components at an early stage of deterioration [2].

The electrical signals resulting from PD are usually small quantities and they are overlapped or confused with noise, interference signals and unstable signals produced by the measuring system itself. Due to the above a band-pass filter is not suitable to effectively separate and then extract the PD signal, and it is necessary to adopt more sophisticated techniques to clearly measure it. Previous considerations must be taken into account to perform a correct, objective and accurate measurement of the PD [3].



Fig. 1. Structure of an underground electric power conductor.

In terms of power transmission lines, the structure of an underground cable is relatively more complex than regular conductors since it operates under aggressive environmental conditions (i.e. humidity and salinity). The traditional structure of underground power transmission cables is shown in Fig. 1 while the role of its most important parts is described below [4]. Conductor, to carry current and to withstand pulling stresses during cable laying. Insulation, to withstand the various voltage fields stresses during the cable time life. Metallic Screen, to provide an electric screen. Radial waterproofing, an active conductor for the capacitive and short circuit current.

Both insulators shown in Fig. 1 play a critical role in the PD phenomena since the insulating materials are closely related to the behavior of the PD including its arising and evolution.

It has been found that PD occur at defects, such as air-filled cavities, within the insulation material, when the local field strength exceeds some threshold level. Discharges further degrade the material; therefore PD is both a cause and an indicator of dielectric deterioration. It should be noted, however, that not all degradation phenomena may produce discharges, and in addition, the relation between PD activity and insulation condition itself is non-trivial. For this reason, the interpretation of partial discharge diagnostic tests is not straightforward [5].

Several PD measurement techniques have been developed such as acoustic detection, chemical detection, electrical detection [2], and more recently optical detection [6]. The detection of PD based on acoustic effects is a popular method [7] due to its highly directional feature, which offers the advantage of precise fault-site positioning [8], nevertheless a short measurement distance is required since the sensors are placed outside the equipment, which results in a low energy signal affected by external acoustic sources [9]. In spite of several improvements for PD detection techniques based on acoustic effects have been reported [10]-[12], the problem resulting of the interference of external acoustic sources has not been fully resolved. On the other hand, chemical detection is performed by monitoring the changes of the chemical composition of the isolator through the gas production or the byproducts measuring; this technique is not suitable for

on-line analysis since it requires complex instrumentation and analysis procedures to continuously measure the evolution of gas [12]. More recently PD measuring systems based on optical techniques have been reported, some of them use optical fiber sensors [12]-[14], interference devices [15], and electro-optical modulators [16]. Optical sensors are immune to electromagnetic interference and have the advantages of direct measuring and measuring speed but they are also related to special equipment and need to be provided with complex instrumentation.

Since PD is an electrical phenomenon, a more direct detection based on the electrical effects can be achieved. The fundamentals of the PD detection based on electrical effects, which focuses on capturing the electrical impulses created by the current streamer in the void and impurities, lie in the fact that the generated pulses have measurable frequency components in a wide range about 10kHz-1MHz [2]. The electrical techniques most commonly used are Ultra-High Frequency (UHF) interference detection and the measurement of individual discharges using variety of sensors [10]. Detection techniques based on UHF interference have been widely investigated and commercial cost-effective devices have been developed [12]. Although this technique is practical and portable so it can be included in the routine patrols to direct measure individual discharges, it is often more recommended monitoring a rapidly increasing rate of PD.

Beyond the development of new methods of acquisition, it has recently been a growing interest in improving techniques of processing the acquired signals. Prediction and shape recognition systems based on fuzzy-logic and neural networks [17] are proof of the above.

In this work, we propose a continuous-monitoring LabVIEW interface for measuring thermal, acoustical and electrical effects related to the partial discharges phenomena. The developed graphical interface allows user to have all the information obtained from the measurements so opportune and adequate decisions based on the partial discharges evolution can be made.

#### 2. Partial Discharge Phenomenon

When an electric field is applied to two different dielectric materials of different permittivity  $\varepsilon$  (i.e.  $\varepsilon_1$  and  $\varepsilon_2$ ), a reduction in the value of the dielectric breakdown due to the gradient effect will occur in most of the dielectric systems. If one of these materials is a liquid or gas then the dielectric breakdown will be influenced mainly by the environment, thus causing partial discharge and field concentration on the material surface.

PD produces a local transient current typically in the range of ns- $\mu s$ . The transient current is a consequence of the so called "apparent charges" between the electrodes of the insulator and can be detected by using a sensing system to be further analyzed. The apparent charge is the electrical charge "mobilized" in the activity of the PD [18]. The voltage peak through which the PD is monitored is proportional to the apparent charge (see Fig. 2).

The location of the discharge may be a consequence of the increase of the electric field in a relatively small space (i.e. compared to the dimensions of the insulating medium). Increased field may be due to sudden changes in the nature of the insulation, which vacuoles can be induced in a solid or gas space between the surfaces of an insulator to a conductor or other insulators.



Fig. 2. Equivalent circuit of partial discharges.

The information usually extracted from a measurement of PD is the following:

- 1) The characteristics of PD signals: polarity, amplitude and frequency, and its relationship to the phase of the externally applied voltage.
- 2) Information relating to the structure of the insulation system, as local maxima of the field and internal propagation characteristics of the signal.
- 3) Physical models of defects in order to relate the apparent charge as the actual load on the defect and attach it later with the possible damage and risk of failure of insulation.

When the PD activity occurs in the insulating polymer normally associated with the formation of "trees" that it was demoted. These 'trees' are composed of micro-channels with material or low density material that can be rapidly vaporized but the onset voltage  $E_o$  partial discharge (i.e. breakdown voltage located at a point) also depends on the pressure, temperature, polarity of the PD, the involved gas, and to a lesser extent, humidity.

For the PD to be detectable it is necessary that the quantity of charge formed (i.e. approximately equal to the number of electrons by the charge of each electron) during the PD pulse must exceed  $q_c$  = 5 pC, so the number of electrons should be  $n_e$  > 3×10<sup>5</sup>.

Detection methods using broadband have observed that PD pulses can have a variety of well defined patterns depending on the electric field configuration and the presence of gas. The partial discharge pulses typically are about 3 to 300 ns in duration, therefore the DP falls under the category of "cold shock", where gas is ionized and the average energy of the electron is much smaller than the averaged energy of the heavy molecule, so that on a scale as reduced time the gas has not opportunity to warm up.

Even when the energy of each partial discharge is quite small an important part of the electrons displaced during the PD may have energy greater than 10 eV. These significantly high-energy electrons can break molecular links when they impact thus causing chemical changes in the insulator (i.e. degradation).

Since PD is a process of dielectric breakdown in which the arc formed between two electrodes is partial and transient, and also with a very short duration and low energy content, partial discharges can be characterized in three different types depending on the properties of the medium between the electrodes: external, surface and internal, in function of the location of the phenomenon.

The electrical circuits which typically have been used to measure PD are divided into two groups depending on the frequency bandwidth: broadband and narrowband. In this case we proposed a robust acquisition system with high adaptability to the needs of the application that is required to implement.

The sensors for this application are typically based on inductive phenomena and they are able to detect minimal changes of the DP signal. Nevertheless, due to its own nature, PD can be monitored through several effects since the electrical breakdown in this phenomenon is related to changes in the local temperature as well as to the generation of acoustic signals due to the movement of the electrons in the transmission line.

#### 3. Experimental Setup and Acquisition System

Fig. 3 shows a schematic of the experimental setup for the study of partial discharge phenomenon. Several causes can originate the partial discharges, among which can be named the deterioration of the cable junctions and inadequate coupling between the terminals. In this particular case partial discharges in solid insulating material are provoked on the test terminal via cable degradation, which was produced by deliberately induced defects.

During the test, the voltage between the phase and ground terminals is set to be 15 kV which leads a current of 60 A to circulate in the measurement system. The electrical signal in the test system is measured through a current transformer, which is connected to a digital oscilloscope. The digital oscilloscope is then continuously monitored through the graphic LabVIEW interface described below.



Fig. 3. Schematic of the experimental setup.

The graphical interface of the proposed acquisition system is shown in Fig. 4. As stated before, the proposed interface can be used to monitor several effects related to the PD beyond the electrical behavior, such as the thermal and acoustical effects, by using an appropriate sensor.

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Fig. 4. Graphical interface of the acquisition system for PD monitoring.

The LabVIEW graphical interface allows sampling the signal at an appropriate frequency, developing the corresponding signals processing, and especially displaying all the information of the measurements to the user. The robustness and adaptability of the developed interface allow using it to monitor thermal, acoustical, and electrical effects through sixteen independent input channels. The interface is continuous and simultaneously monitoring all the sixteen independent input channels and since none of them is restricted to receive a specific type of signal, by using appropriate sensors (and their corresponding complementary circuitry if required) it is possible to implement a detailed instrumentation of the power transmission line, this way the user is able to monitor several effects (i.e. electrical, thermal or acoustic effects) at sixteen different locations or to monitor several effects at the same location of the transmission line. Information of the performed measurements (corresponding to all input channels) is available to the user all time through graphical and numerical indicators on the interface and it is continuously updating so it is feasible to make decisions in a reliable, safe and real-time manner.

The interface has a general purpose section that shows all the detected input signals both graphically and

numerically (i.e. Fig. 4). Furthermore individual detailed information from each input channel is available so user can dispose of it through four sections: general information section of the selected channel, graphics section, section of harmonic levels and, finally, section of information of the selected harmonic.

Parameters displayed to the user in the General Information section are the main frequency component of the signal and its corresponding amplitude (both in linear and logarithmic scales). The fundamental frequencies detected in the selected input channel are also displayed.

Furthermore in this section the user can select the signals of which is desired to export the graphs (i.e. input signal, noise, residual signal, or harmonics) and the amount of harmonics to be scanned and the exclusion of the harmonic aliasing illegible.

In the Charts section the exported graphics are shown to the user in both time and frequency. Fourier Transform of the measured signal on the selected channel and its corresponding graph of harmonics are also shown so the user can identify the relationship magnitude between the harmonics that are analyzed. In this section the harmonic levels are shown to the user numerically as well as the instantaneous values of magnitude identified for each of the harmonic analysis. The user, in the General Information section, can select the amount of harmonics to analyze.

Finally, in the Information section of the selected harmonic the user can select from the set of harmonics being analyzed a harmonic of interest to display particular information about frequency and amplitude so the user has the ability to track a specific harmonic, both graphically and numerically. This is of great importance because it has been found that there are harmonics that are directly related to certain types of insulation failure, revealing the information in a timely manner to prevent it, therefore, through monitoring of harmonics, can identify and even predict specific failures.

## 4. Results

As previously stated, several effects related to the PD phenomenon, such as thermal, electrical and acoustical, can be simultaneously monitored. In this particular case, the proposed experimental protocol consists on monitoring the electrical and thermal effects of the high-voltage system simultaneously using two independent stages.

On the one hand, the electrical behavior of the system is monitored through the graphic LabVIEW interface allowing the measurements information to be available graphically and numerically; on the other hand, the region of interest (i.e. location where the failure occurs) is identified and thermally analyzed through the infrared image processing.

Fig. 5 shows the pictures of the test terminal under white-light and infrared palettes, respectively. As can be noticed, the infrared images show the temperature scale based on the previous calibration of the camera thus allowing measuring the temperature over several regions of the test terminal.



Fig. 5. Pictures of the test terminal where partial discharges are induced. a) White-light picture, and b) infrared-palette picture.

Despite an accurate contactless temperature measurement can be achieved by a good calibration of the infrared camera, the proposed image processing is not based on this calibration but on the textures defined

by the gray levels that naturally arise due to thermal effects.

In order to orientate the analysis of the thermal effects to the region of interest (ROI), infrared images of the experimental setup where digitally processed by using segmentation and extraction algorithms based on texture and morphological image analysis [19]-[22].



Fig. 6. Results of two different measurements.

Fig. 6a) and Fig. 6b) show the result of a processed picture of the experimental setup after segmentation and extraction, respectively. These processes, through which the ROI (i.e. region where the partial discharges are induced) is discriminated from the entire environment, allow not only having a calibrated measure of the temperature over several regions of the experimental setup but also accurately extracting the physical location where the failure is occurring.

It is worth to mention that the thermal analysis based on the digital processing of infrared images allows remote and uninterrupted *in situ* measurement since any disconnecting of the involved elements is required. This thermal monitoring also allows contactless instrumentation, which overall results in safe, continuous, and effective thermal analysis.

In order to understand the electrical behavior of the studied phenomenon using the proposed experimental setup, the interface showed in Fig. 4 was modified to monitor only two input channels, as shown in Fig. 7. For simplicity and demonstrative purposes, both input channels monitor the electrical effects at two different locations of the transmission line: the first of the input channels reads the reference signal while the second input channel monitors the region of interest where the partial discharges are externally induced.



Fig. 7. Displayed results for normal operation (left) and failure condition (right).

Fig. 7 shows the results displayed on the LabVIEW interface for normal operation (left) and for failure condition (right) for the particular case in which current leakage is induced due to insulator degradation. As marked on the figure, qualitative general changes on the monitored waveform can be easily noticed in the

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Chart section but more important, the electrical behavior of the system operation under failure is numerically disclosed in the General Information section of the interface, where a summary of the information corresponding to a specific channel is displayed, allowing to compare it with the results of the normal operation. Furthermore, the electrical behavior of the induced partial discharges can be directly related to the measured signals by the harmonic analysis leading to an accurate characterization of the PD phenomenon that allows discriminating between a variety of causes and different origins of the PD.

## 5. Conclusion

The proposed monitor and analysis system allows inducing a variety of controlled failures in order to accurately characterize the electrical behavior of the partial discharges phenomenon. This detailed characterization can lead to diagnose end prevent a variety of failures in further applications.

In this particular case, partial discharges are studied by inducing cable defects in the test terminal and the electrical behavior of this phenomenon is not only analyzed by using the LabVIEW interface but its corresponding thermal effects are also monitored via infrared imaging processing.

Despite the information of the electrical signals of the DP phenomenon is displayed on the developed interface both graphically and numerically, the most relevant data are disclosed by using the harmonic analysis. In this regard, the proposed graphic interface allows analyzing several failures that can directly manifest by changes on specific harmonics.

The location where the induced failure occurs is confirmed by the processing of infrared images based on texture segmentation and morphological extraction algorithms thus allowing relate changes in the electrical behavior only to the induced failure, resulting in reliable performance of the proposed measurement and analysis system.

As stated before, a variety of different failures are directly related to well-defined changes in specific harmonics. The section of the harmonic analysis of the proposed interface leads to a detailed characterization that can be used to accurately model and further diagnose, prevent, and even predict failures in the electrical system.

In this regard, since all the proposed analysis system performs *in situ* and continuous measurements, the proposed interface allows developing flat models for modeling and then designing and evaluating new insulating materials for power transmission cables in a very reliable manner, which becomes cost- and time-effective from the point of view of safety and maintenance, as well as from the effectiveness of the resources involved in the manufacturing processes.

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