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# Partial Discharge Diagnostics and Electrical Equipment Insulation Condition Assessment

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## ABSTRACT

**Partial discharge (PD) measurement has long been used as a test to evaluate different insulation system designs, and as a quality control test for new equipment. However, in the past 20 years, PD measurement has been widely applied to diagnose the condition of the electrical insulation in operating apparatus such as switchgear, transformers, cables, as well as motor and generator stator windings. Improvements in the capabilities as well the lower cost of sensors, electronics and memory is partly the reason for the increased popularity of PD diagnostics. Another reason has been the development of methods – including the use of ultrawide band detection – to improve the reliability of the PD measurement in the presence of noise. In addition, rapid progress is being made in automated pattern recognition techniques that also helps to suppress noise. This paper reviews the various PD measurement technologies that have been specifically developed to improve PD diagnostic methods, and outlines how they have been implemented for stators, cables, transformers and switchgear. Areas for further research are also presented.**

## 1 INTRODUCTION

**PARTIAL** discharges (PD) are small electrical sparks resulting from the electrical breakdown of a gas (for example air) contained within a void or in a highly non-uniform electric field. If the void is within an organic solid or liquid, the PD will degrade the organic material and may eventually cause the failure of the electrical insulation. The destructive nature of PD in oil-paper insulated high voltage cables, and more generally in other HV apparatus, has been known for over 70 years [1-3]. Therefore manufacturers of HV cables, transformers, capacitors and switchgear, where the insulation is primarily composed of organic materials (oil, paper, polyethylene, rubbers, epoxies and/or polyesters) must take care to design an insulation system that does not contain voids in regions of high electric stress.

PD, in addition to causing electrical aging as discussed above, may also be a symptom of thermal, mechanical and environmental aging in high voltage apparatus. For example, voids within epoxy mica insulation or oil paper insulation may occur as a result of operation at high temperature, which delaminates taped insulation systems or causes 'gassing' in systems containing oil [1-5]. Similarly mechanical stresses can lead to voids and thus PD [4]. In addition, contamination can result in partly conductive coatings which can lead to high, localized electrical stresses on insulation surfaces that result in discharges in the air [4]. Thus the presence of PD not only indicates that electrical aging is occurring, but that mechanical, thermal or environmental aging processes may be present.

Consequently it is no surprise that measurement methods to determine if PD is occurring, have been under development since the 1930's [1,6]. There are several reasons why PD measurement is done:

- *Design Test*: To evaluate the design of a new insulation system, to ensure the PD is non-existent (or below some specified level) under normal operation
- *Quality Assurance (QA) Test*: To ensure that no voids were introduced during manufacturing/processing of the insulation system
- *Diagnostic (Condition Assessment) Test*: To determine if the electrical insulation in equipment such as motors, transformers, switchgear and cables has not deteriorated due to electrical, thermal, mechanical or environmental stress during operation.

The aim of each of these tests is to ensure that the equipment has the expected service life – that is, the equipment is reliable. If PD is detected, or the PD levels are too high, it is likely that the insulation system will fail prematurely.

Although there have been many researchers, the pioneers of practical methods to measure PD during the 1950s to 1980s were Bartnikas [6], Kelen [7] and Kreuger [8]. These researchers developed the PD detection methods and data display methods that are still widely used today in laboratories and factories. Most of their work was focused

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on developing test methods for design or QA PD testing. Out of their work came some basic methods to suppress electrical interference using differential measurements, as well as approaches to display PD data using pulse magnitude analysis and phase-resolved pulse magnitude analysis (also known as pulse phase analysis).

In the past 20 years, the main focus of research has been to expand PD technology so it can be more practically applied to diagnostic testing to determine the condition of the insulation that has seen operation. That is, insulation condition assessment in cables, transformers, switchgear, etc, usually in the plant where the apparatus is installed (i.e. on-site). Condition assessment can include both on-line PD testing, as well as variations of the off-line testing that is used for design and QA testing. On-site testing required developing better and better ways of suppressing electrical inference (which can lead to false indications), as well as developing tools to make the interpretation of PD pulse phase analysis patterns more objective. The most prolific researchers for the past 20 years are perhaps Bartnikas, Boggs, Fruth, Gulski, Hampton, Montanari and Okamoto. These and other researchers have advanced the science of PD measurement technology to the point that off-line and on-line PD measurements at site are now routinely applied to a high percentage of transformers, cables, machines and switchgear that are operating in industrialized countries. The impact of these advancements is the improved reliability of high voltage equipment since degrading apparatus can be repaired or replaced before catastrophic in-service failure occurs. Of course these advances have also been applied to design and QA testing. It is important to note however, that diagnostic testing cannot give a reliable indication of remaining life. Instead the purpose is to warn of an impending problem, and perhaps identify the root cause of the insulation problem.

This paper will first summarize the key features of modern PD measurement systems, and review some of the technology advancements in the past 20 years. The paper then addresses the salient features of modern PD methods that have been developed for each type of electrical apparatus, and what questions remain.

## 2 FEATURES OF PD MEASUREMENT SYSTEMS

PD theory and a broad overview of PD sensors and measurement technology has recently been summarized by Bartnikas [1]. The following concentrates on the sensors, instrumentation technology and data displays that have, in the past two decades, become the most popular for equipment condition assessment.

### 2.1 SENSORS (COUPLING DEVICES)

When a partial discharge pulse occurs, there is a very fast flow of electrons from one side of the gas filled void to the other side. Since the electrons are moving close to the speed of lightextremely fast across a small distance, the pulse has a very short duration, typically a few nanoseconds [1]. The electrons carry a charge, thus each individual discharge creates a current pulse ($i = dq/dt$). In addition to the electron current flow, there will be a flow of positive ions (created when the electrons are ionized from the gas molecules) in the opposite direction. The PD current in the void creates a disturbance and results in pulse current and voltage that flows away from the PD site. A Fourier transform of a current pulse indicates that frequencies up to several hundred megahertz are created [1].

Any sensor (also called a PD coupling device) sensitive to high frequencies can detect the PD pulse currents. In an off-line PD test, the most common means of sensing the PD current is to use a high voltage capacitor connected to the high voltage terminal of the test object (Figure1).

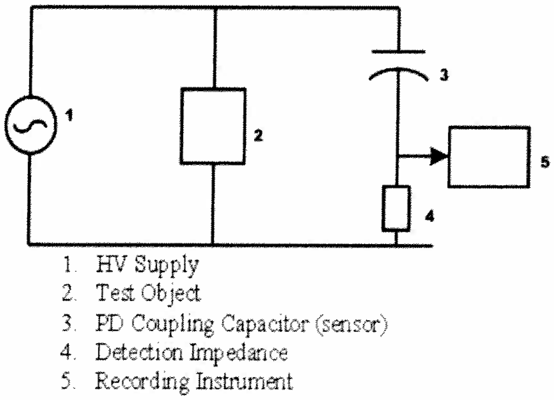

**Figure 1.** Typical off-line PD test arrangement.

Typical capacitances are 80 to 1000 pF. The capacitor is a very high impedance to the high ac voltage, while being a very low impedance to the high frequency PD pulse currents. The output of the high voltage capacitor drives a resistive or inductive-capacitive load called a 'detector' (see Section 2.2).

In addition to capacitors, high frequency current transformers (HFCTs) can be employed to detect the PD pulse currents. HFCTs typically measure the high frequency current that may flow in the ground lead from a test object. They may also measure the PD pulse currents from the test object to the HV supply. The HFCTs are often wound on split ferrite cores that can respond to frequencies in excess of 30 MHz. For HFCTs applied to HV leads, a large electrical clearance is needed, thus air-core HFCTs (usually a Rogowski coil) are used. Rogowski coils are considerably less sensitive than ferrite core HFCTs, and have a much lower bandwidth due to high inter-turn capacitance.

PD can also be sensed from the following physical attributes of discharge:

- Electromagnetic radiation
- Acoustic noise
- Visible and UV light.

Electromagnetic radiation can be detected with RF antennae. The TVA [4] and Lemke [9] probes to locate PD sites are good examples of this. The antennae are usually tuned to the 5 to 100 MHz range. Another antennae-like device, called the stator slot coupler, has also been used to detect PD in stator windings. It works in the 10-1000 MHz range [4].

If discharges are occurring on the surface of an insulation system, then the rapid flow of electrons and ions create a gas pressure wave, which can be detected acoustically. The acoustic pulse created by each discharge is concentrated in the 40 kHz (ultrasonic) range [10]. By using directional ultrasonic microphones, the location of surface PD on bushings, air-insulated switchgear and stator windings can often be identified.

The final popular method for sensing PD uses the fact that light is emitted from excited molecules, which lose their energy after the initial discharge. The most intense light occurs in the ultraviolet spectrum. Specialized imaging devices have been constructed to detect the UV components of the light [11]. Otherwise the naked eye can see the light from surface PD, if the test object is energized with the ambient light level very low (black out test).

Although many types of PD sensors are now available, HV capacitors are by far the most widely used sensors for diagnostic testing. The remainder of this paper will concentrate on the electrical measurement of the PD pulse currents, rather than on acoustic or UV detection. In the past 20 years, there has been little innovation in current pulse PD sensors.

## 2.2 DETECTORS

PD detection normally consists of converting the PD pulse current from the sensor to a voltage signal, since most measurement instrumentation is sensitive to voltage rather than current. The conversion occurs via a resistor or more elaborate detection impedance. A resistor yields a wide band detection system with the output normally measured in mV or μ V. However, if an RLC detection impedance is used, then the characteristics of the detector can be manipulated to integrate (low pass filter) the PD pulse current to yield a signal magnitude that is proportional to the apparent charge transfer in each discharge [1,6,7]. The RLC detection impedance is very popular since the rate of deterioration of organic insulation is often directly proportional to the total number of electrons and ions that bombard the insulation surface. That is, if the discharges are larger (consists of more electrons and ions) the insulation will degrade faster.

IEC 60270 and ASTM D1868 outline the types of detectors, and the RLC detector in particular. Narrow band detectors have a bandpass filter/integrator with a bandwidth of about 10 kHz or so, while wideband detectors have a bandpass filter/integrator with a bandwidth of 100 to 400 kHz.

In the past 20 years there has been a tendency to use sensors and detectors with a system bandwidth up to several hundred megahertz for equipment such as gas insulated switchgear (GIS) and rotating machines. Such detectors are not covered by ASTM D1868 or IEC 60270. The trend to higher bandwidths enables the use of improved noise suppression and facilitates PD location. However, higher bandwidth (often called ultrawide band) implies that the apparent charge (in pC) may not be directly produced by the detector, since the current is not being directly integrated.

## 2.3 INSTRUMENTATION

Electronic instrumentation is used to measure the signals from the sensors and PD detector combination.

Until about 20 years ago, the most popular measurement instrument for displaying PD signals was an analog oscilloscope. The pulses were measured in pC (vertical scale) versus the AC phase position. Due to the limited oscilloscope bandwidth at the time, it was often difficult to measure the true magnitude of the pulses since they appear only briefly on the oscilloscope screen. In addition, the PD pulse repetition rate was not measurable. For transformer and rotating machine PD detection, specialized tunable radio receivers called radio interference voltage (RIV) receivers were also used to display the signals from capacitors, HFCTs or antennae.

There have been many important developments of the measuring instrumentation over the past 20 years. Today, virtually all of the instrumentation uses digital technology, rather than analog. The adoption of digital technology has lead to developments that enable noise separation, PD site location and practical, continuous on-line PD monitors.

### 2.3.1 DIGITAL INSTRUMENTATION

Measurement today is usually by digital means. At its simplest, a digital oscilloscope can be used to measure and display the PD. Digital oscilloscopes can very easily detect and permanently display the magnitudes of the PD pulses. Thus more accurate measurement of the peak apparent charge is possible compared to analog oscilloscopes.

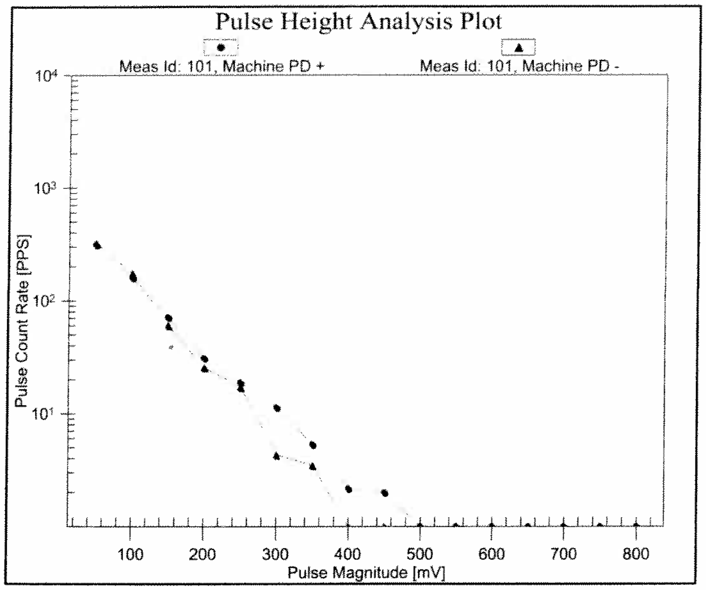

**Figure 2.** Pulse magnitude analysis (PMA) plot showing the PD pulse count rate per second per magnitude window versus the number of pulses per second in the magnitude window. Note the different plot for each pulse polarity. Users should be aware if the polarity refers to the detected pulse polarity, or the polarity of the ac cycle voltage.

However, the most profound change in the past 20 years has been the widespread adoption of digital recording using pulse magnitude analyzers (PMAs). First introduced to the PD community in the late 1960s by Bartnikas [12], the PMA does not use the typical oscilloscope display. Instead a digital circuit counts the number of pulses per second, and categorizes the count rate vs. the magnitude of the pulses (Figure 2). Most modern PMAs separately display the count rate for positive and negative pulses. (It is interesting to note that Europeans tend to assign the PD polarity by the polarity of the AC voltage at the time of the pulse, whereas in North America, the polarity of the pulse is the pulse polarity. The result is that with most of the common PD sensor locations, the European and North American polarity definition is reversed, which may lead to users to assume PD is occurring at (for example) the HV conductor, rather than near the ground. Virtually all commercial PD detectors made in the past decade use the PMA, since the plot is usually very repeatable, and gives an indication of the PD repetition rate, while the oscilloscope does not.

Beginning in the early 1970's, Kelen introduced a primitive form of what is now called a pulse phase analyzer (PPA) also known as a phase-resolved pulse magnitude analyzer [8]. The PPA is similar to the PMA, with the exception that the phase angle of the AC cycle is also digitally recorded for each PD pulse. The result is a digital representation of the information that was originally measured over a complete AC cycle on an oscilloscope. The output of the PPA is a two or three-dimensional plot of the pulse count rate vs. the pulse magnitude vs. the AC phase position of the pulses. There are many ways to display this output. Fruth [13] and Fujimoto [14] popularized a two-dimensional colorized presentation of the PPA data (Figure 3). Usually the pulse repetition rate is displayed via a color code – which unfortunately is not standardized. Virtually all commercial PD instrumentation made in the past 10 years produces the PPA plots.

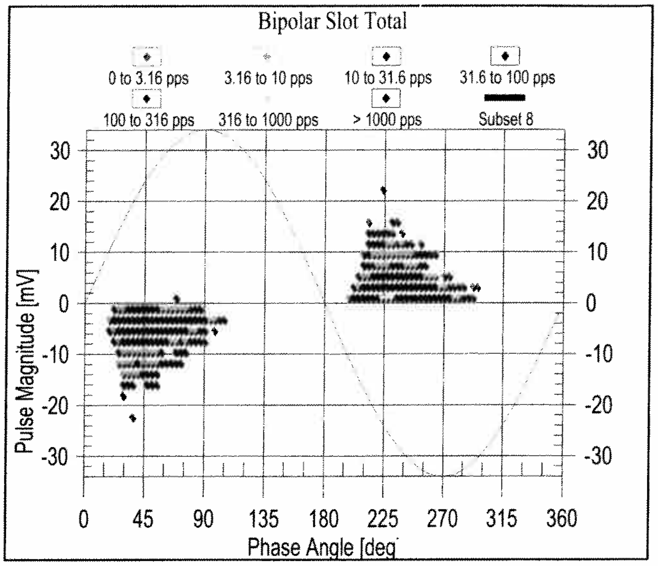

**Figure 3.** Pulse phase analysis (PPA) plot of the pulse magnitude versus AC phase position, with the pulse count rate in pulses per second represented as color.

The widespread use of digital instrumentation, which produces the PMA and PPA plots has reduced the need for human experts to be present at the PD test. With the older analog technology, the expert's presence during the test was needed so the expert could determine peak PD magnitudes from the flickering traces and determine if noise was present during the measurement. With digital instrumentation, and the permanent recording that it enabled, the expert could review the data transmitted by email to a lab or office. This facilitated a considerable productivity improvement for PD test experts, which in turn lowered test costs.

Most of the commercial PD instrumentation in use today uses an analog-to-digital converter with sampling rates of about 20 MHz, corresponding to a maximum analog bandwidth of about 10 MHz. These are completely compatible with IEC 60270 narrow band and wide band detectors. However, some suppliers are using digitizers with bandwidths up to 350 MHz to enable ultra wideband PD detection, with the consequent advantages of noise separation and PD site location [4,14,15].

### 2.3.2 NOISE SEPARATION

As condition assessment has become an important aspect of PD testing, the desire of users to do on-site and on-line PD testing has increased. Off-line testing requires a shutdown of the HV equipment, and often also requires a substantial HV test transformer to energize the capacitance of the test object. In contrast, on-line tests are done during normal operation of the HV equipment where the apparatus is exposed to realistic operational stresses, so no shutdown is required; and an HV test transformer is not required. Unfortunately, there is usually much more electrical interference to contend with in on-site and on-line testing, since the test object is connected or near to the power system. Electrical interference can come from corona on air-insulated transmission and distribution lines, power tool operation, arc welding, poor electrical contacts, electrostatic precipitators, etc., all of which produce sparks/discharges that create current pulses similar to PD. Separating this noise from test object PD is important since if the noise is mistaken as PD, a false indication of the insulation deterioration is given, reducing the usefulness and the credibility of the PD test.

Experts reviewing the PD patterns in PPA plots can usually separate noise from PD – although the separation is subjective. Automated pattern recognition (see Section 2.4) may also separate PD from noise. However, in the past 20 years some hardware (sensors and instrumentation) methods to separate PD and noise have also been implemented to separate PD from noise.

The most widely applied hardware methods are employed in on-line rotating machine PD detection. One method measures the risetime or width of the pulse: a fast risetime (<6 ns) pulse is likely to be PD in the stator winding; whereas a noise pulse tends to have a longer risetime, due to transmission line dispersion as the noise pulse propagates along a power cable to the motor or generator [4]. Another method depends on the propagation time between a pair of sensors. That is, two capacitive sensors per phase are mounted on the machine terminals, separated by at least 2 m (Figure 4). Since the current pulses have a finite transmission speed on a bus or power cable (typically 0.15 to 0.3 m/ns), PD pulses will arrive at the sensor closest to the stator winding first, whereas noise from the power system will arrive at the other sensor first. Digital logic can then determine on a pulse-by-pulse basis whether the pulse is stator PD or power system noise [4]. Both of these hardware based noise separation methods require the bandwidth of the measurement system to be several hundred MHz or more in order distinguish small differences in arrival time, or accurately measure the risetime/pulse width.

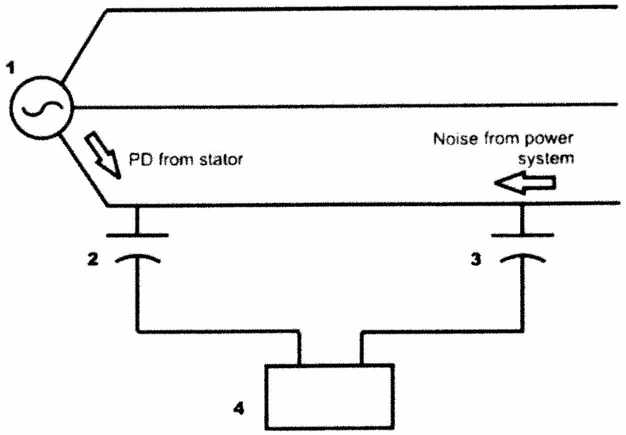

**Figure 4.** On- line method to separate PD from power system noise based on time pulse arrival at a pair of PD sensors.

Some types of noise can be suppressed using a gating approach (Figure 5). If a reliable 'noise signal' trigger is available, whenever the noise is detected above a user-set threshold, digital logic (a gate) can prevent the noise coupled via the PD sensor from being registered [16]. The key requirement for this approach is a reliable 'noise' trigger signal, which may be an antenna for general sparking noise, or a trigger to a thyristor switch that can also be used to gate out the switching noise detected by the PD sensor from the thyristor.

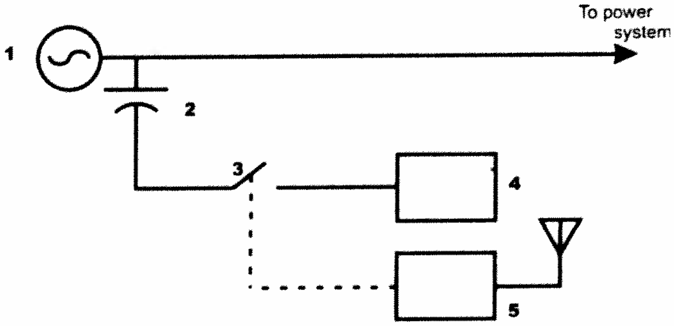

**Figure 5.** Using a separate noise signal to block noise from being recorded.

Finally, the time of flight method between ends of air-insulated bus or $SF_6$-insulated switchgear/transmission line apparatus can also be used to reject noise external to the switchgear or bus [21].

### 2.3.3 PD LOCATION

The advances in digital technology have also facilitated the location of the PD sites in HV apparatus. PD site location allows maintenance personnel to concentrate repair efforts in the part of the HV apparatus most likely to be at risk – a considerable time saving when equipment such as GIS, power transformers and generators are very large.

Most of the practical PD site location methods depend on time domain reflectometry – i.e. when a PD pulse occurs, it will travel through the test object (typically a power cable, switchgear or winding) and reflect at the end of the test object (a bushing or terminal). By measuring the initial and reflected pulse at a PD sensor, the approximate location of the PD can be determined based on the time between the incident and reflected pulse. The most basic instrumentation that can be used is a digital oscilloscope. However considerable skill is required to interpret the output from an oscilloscope. As a result, several different instruments have been developed to make site location more reliable and easy to do. The instrumentation normally is customized for a particular type of HV apparatus.

Perhaps the most work has been devoted to PD site location in power cables and associated joints and terminations [1, 17-20]. The tests are usually done off-line, using a capacitor or an HFCT) as the sensor. Elaborate techniques based on variable gain amplifiers or auto-correlation are usually used to recover the low level reflected PD signals from the noise. The accuracy of the method strongly depends on the length of the power cable, and the dielectric material. The longer the power cable, the more difficult is the detection of the reflected PD pulse due to the attenuation. In addition, the pulse dispersion is greater for longer cables, thus accurate location of the PD site becomes problematic since the pulse risetime is longer. Some insulating materials such as oil-paper insulation have an extremely high attenuation and dispersion – making PD detection even a few meters from the sensor difficult. In spite of these issues, today there is a vibrant business in cable PD detection and location, from a variety of vendors.

Specialized PD location instrumentation has also been developed for $SF_6$ insulated transmission lines and switchgear [21,22], although a commercial vendor does not seem to exist. When compared to PD location in cables, GIS is ideal, since attenuation and dispersion phenomena are very small. Thus the pulse risetimes are very fast, enabling accurate location. The instrumentation typically has a bandwidth ranging up to 1 GHz. Although oscilloscopes can be used, auto-correlation methods have proven to be successful for locating the PD.

There has been considerable research in the past 20 years to locate PD sites in transformer windings and rotating machine stator windings [23-25] – however it seems no commercial devices easily used by non-experts, have been developed. Although time domain reflectometry may work in principle, this technique is rarely used due to the extreme attenuation PD pulses encounter as they propagate through windings. Instead, it has been recognized that there are two modes of pulse propagation in windings, and by measuring the relative time of arrival of the 'fast' and 'slow' modes at a PD sensor, the relative distance to the PD site can sometimes been determined. The fast mode is due to the relatively quick propagation of PD pulses through the capacitance between coils, yielding an almost immediate fast risetime pulse at the PD sensor. The slow mode produces a long risetime, low frequency pulse that propagates along the complex inductive-capacitive network of the coils. The fast pulse starts the timing to measure the delay time to the arrival of the slow mode pulse. Unfortunately, before this method can be used, the transformer or stator winding needs extensive testing/calibration where pulses are injected into different locations and the propagation delays are measured between the fast and slow modes. Of course ultrasonic, RF or optical methods are also available to locate PD in windings - however the transformer or machine winding must be physically accessible.

Although perhaps it is outside of the scope of this paper, an interesting method has been developed to locate PD using a combination of PD pulse current measurement and a focused beam of X-rays [26]. In this method, first proposed by Mole and Parrott, a narrow beam of X-rays is scanned over the surface test object (for example a large epoxy spacer for GIS), while a conventional or ultrawide band detector measures the PD. When the X-ray beam is focused on a void, the PD will increase in activity due to the large number of initiatory electrons released, and the location can be inferred.

### 2.3.4 CONTINUOUS MONITORS

Continuous monitoring of PD in HV apparatus will give the maximum warning time of a developing insulation problem, allowing insulation system maintenance to be planned at the most convenient time for the user. In addition, continuous monitors will facilitate alarming to warn of rapidly developing problems, reduce labor costs to collect the PD data and reduce travel costs to the equipment site.

With very few exceptions, on-line continuous PD monitoring was not applied more than 10 years ago. Partly this was due to the lack of effective noise separation techniques (clearly noise must be automatically separated from PD in a continuous monitor – otherwise a human expert is needed to review all the data – which is prohibitively time consuming and expensive). At least for apparatus such as GIS and rotating machines – such noise separation methods are now available (see Section 2.3.2).

In addition, the hardware and memory to store the vast amounts of data collected by a continuous monitor was too expensive many years ago. The tremendous reduction in integrated circuit and memory costs, together with the huge progress in microprocessors, firmware and software to process the PD data has also tended to make continuous PD monitors more cost effective.

The most widely applied PD current continuous monitors are used on motor and generator stators windings [27, 28], and the latest versions have a broad range of communications capabilities allowing testing of rotating machines from anywhere in the world via the internet or a modem. Although some continuous on-line PD monitors have been made for transformers, they are based on acoustic detection [29].

### 2.4 PATTERN RECOGNITION

Over 35 years ago, CIGRE published a catalogue of typical PD patterns that might be displayed on an oscilloscope [30]. It was clear from these patterns that different locations of PD (for example near the HV conductor or near the ground) produced different patterns with respect to the ac phase angle and with regard to polarity predominance. This same catalogue also indicated that corona in air and sparking due to poor electrical connections produced a distinctive pattern on the oscilloscope display. Thus the oscillographic display of PD current pulse patterns could be used by experts to:

- Differentiate PD from noise
- Distinguish the root cause of the PD when one or more failure mechanisms are occurring.

The modern digital display of the phase-resolved PD pattern now allows experts to analyze the pattern after the test is done, and back at the office – reducing test costs. Many papers have been published with typical PD and noise patterns measured with modern PD instrumentation on various types of HV apparatus, allowing experts to better diagnose the condition of the electrical insulation [31-33]

Today perhaps the most actively researched field in electrical insulation diagnostics is concerned with the techniques to automate the pattern recognition process, in an attempt to lessen the need for a human expert either to separate noise from PD, and/or determine the root cause of the measured PD. Unfortunately, although there are hundreds of published papers on this subject, very little independent corroboration of the methods have been published. The users of the pattern recognition methods tend only to be the developers of the method. Bartnikas gives an overview of most of pattern recognition approaches [1], and the following merely itemizes the approaches that are under active development. Perhaps in a few years, this research will yield a practical method that has been independently verified, and which can be used by non-experts on a variety of equipment.

### 2.4.1 STATISTICAL ANALYSIS

This approach uses the probabilistic quantities: mean, standard deviation, skew and kurtosis to summarize the shape and location of the positive and negative PD pulse patterns with respect to the ac phase angle. Each type of PD mechanism and each type of noise is presumed to have a unique set of mean phase angle, standard deviation, skew and kurtosis (for each polarity). It is perhaps the first of the automated pattern recognition methods that were researched. The raw data comes from the PPA plot (Figure 3). Okamoto and Gulski were early pioneers of this approach, and it is embedded in some modern commercial

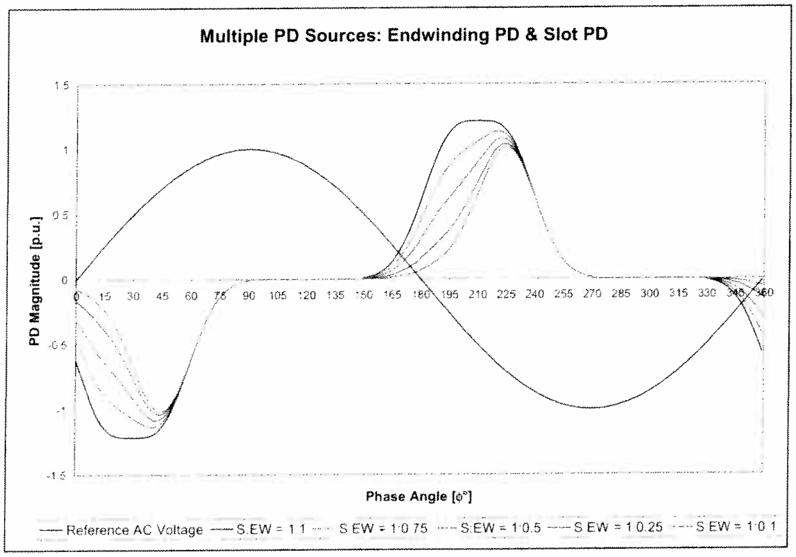

**Figure 6.** Two separate PD mechanisms (slot discharge and endwinding discharge in a stator winding) mix to change the shape of the PD pattern. which can be described by different skews and kurtosis.

PD instrumentation [34,35]. Figure 6 shows how the PD pattern changes as the ratio of two discharge sources change. The pattern shapes are reflected in changes in the mean, skew and kurtosis with respect to phase angle. This approach seems to be fairly effective when there is a single root cause for the PD, however, if there are multiple mechanisms or the PD is mixed with noise, the probably of an incorrect diagnosis seems to be relatively high, and so the analysis must be verified by an expert. A variation of this method is to use the mixed-Weibull probability distribution to analyze the pulse magnitude plot (rather than PPA data) [36]. The premise is that each failure process or noise source will have its own Weibull distribution (with its own scale and shape parameters). If there are two or more discharge patterns, goodness-of-fit tests can be used to separate the two distributions. Aside from the developers, this technique has not been widely adopted.

### 2.4.2 NEURAL NETWORKS

A tremendous number of researchers have been applying this method (developed to emulate human cognitive processes) to partial discharge pulse current pattern recognition [1,37,38]. Regrettably, to date it seems only researchers are using the method, since there is little practical application by HV equipment owners. However, research continues and eventually this approach may prove to be effective in recognizing different patterns with a low probability of error while being useable by non-researchers and needing only short computation times. The raw data (or 'features') derived from instrumentation that the neural networks process might include pulse shape, time between successive pulse, phase position, magnitude, and pulse polarity. Alternatively the neural network can process data that has already been statistically pre-processed. A feature of neural networks is that they must first 'learn', by processing PD data where one supplies the cause of the PD pattern. After learning, unknown PD patterns are then processed and the software yields the most likely cause (specific failure process or noise source). With some types of neural networks, 'learning' may be on-going. In comparison to other pattern recognition systems, a prodigious amount of computation is needed, and there is still considerable disagreement amongst researchers as to the best neural network method for PD.

### 2.4.3 FUZZY LOGIC

This has been applied as a pattern recognition technique in its own right [39, 40], and also as a tool to be used with neural networks or time-frequency clustering (see below). The occurrence of PD in a void depends upon a very large number of variables, each of which has an element of randomness. These include void shape, gas pressure, previous discharges (and the resulting space charge), and the presence of an initiatory electron. Thus when a stream of PD occurs even in a single void, there is a lot of possible causes for variation in PD magnitude, repetition rate and phase position. When there are multiple voids, the variations are even more complicated. Such a complicated and variable process has been called 'fuzzy'. Fuzzy logic allows one to use vague or non-specific rules to characterize the PD, for example big pulses are associated with big voids and small pulses are associated with small voids under comparable void space charge and pressure conditions. In fuzzy logic, real data such as pulse magnitudes are 'fuzzified' by making them variable, and then a set of rules (an inference engine) deduces what the pulses are caused by. Fuzzy logic was first applied to PD patterns in the early 1990s, and receives some attention from researchers today, although not at the same level as neural networks. To date, the goal of fuzzy logic, as a pattern recognition tool is often limited to defining the size of voids in a test object – rather than the larger (and more important) issue of sorting amongst a variety of completely different failure and noise processes. Also a large number of rules have to be devised to implement this approach – and the knowledge underlying the rules is often unknown for real world insulation systems.

### 2.4.4 WAVELET TRANSFORMATION

The pattern recognition approach that has been receiving increased attention in the past 5 years is the wavelet transformation [41,42]. The main use of the wavelet transformation to date has been to reduce the influence of noise in a PD plus noise signal. As such, it is a software-based complement or replacement of the hardware-based approaches to separate PD from noise (Section 2.3.2). The raw data comes from an oscilloscope-type A/D converter that presents a digitized version of the PD and noise pulse train to the software for transformation, processing and inverse transformation. The outcome is a PPA plot that has the noise suppressed. In addition to 'de-noising', the wavelet transformation may also be a future tool for locating the PD sites in windings (since the PD pulse shape changes as it propagates along the winding), and perhaps to identify the root cause of the PD, since different insulation deterioration mechanisms may produce different pulse shapes. Apparently, the wavelet transformation can be rapidly computed, as compared to the neural network approach. However, there is still controversy about the optimum approaches to implementing the wavelet transformation for the different PD processes. Wavelet transformation seems to have promise, but more research seems to be required before it becomes practically applied.

### 2.4.5 FRACTAL ANALYSIS

Fractals are a means of describing the shape of objects, and thus can be used to categorize the different three-dimensional patterns that are created by a PPA [43]. With this analysis method, different failure mechanisms will produce identifiable clusters on a plane of fractal dimension vs. 'lacunarity'. In recent years there has been relatively little effort devoted to this topic, at least for PD phase-resolved pulse magnitude analysis.

### 2.4.6 TIME VS. FREQUENCY CLUSTERING

This is a relatively recent analysis method developed by Montanari and his colleagues [44,45]. The basic approach is to have hardware that provides an oscilloscope type of A/D conversion. A transformation is then performed that allows a plot of time vs. frequency to be constructed. Different noise and PD sources apparently cluster in unique portions of the t vs. F map. Fuzzy logic (similar to that described above) is then used to automatically identify the clusters. Each PD or noise pulse is tagged as being from one of the clusters, and conventional PPA plots can be made only from the pulses associated with a particular cluster, so that PPA plots can be made with the noise sources or other PD failure processes suppressed. This technique has been applied to many practical applications, perhaps with the greatest success in HV power cables. It also seems to have some efficacy when applied to on-line PD measurements of stator windings.

## 3 APPLICATION OF PD DIAGNOSTICS TO SPECIFIC EQUIPMENT

The following briefly reviews how the sensor, instrumentation and pattern recognition technology discussed above is applied to each major type of HV equipment.

### 3.1 POWER CABLES

Oil-paper power cables can experience PD (and eventually failure) as a result of oil starvation (due to leaks) and overheating. Terminations and joints may suffer from the same issues, in addition to thermal cycling and poor manufacturing problems. Diagnostic testing of cables using PD current pulse detection seems to be mainly applied to the terminations and joints, since PD more than several tens of meters from the measurement points is largely ineffective due to the severe attenuation and dispersion of PD signals propagating in oil paper. PD can propagate much farther in cross-linked polyethylene and EPR power cables. However, since these materials tend to have a very short life (less than days?) in the presence of PD, unless there is continuous monitoring (which to date is rarely implemented), PD monitoring of the bulk cable is probably not too useful. In contrast, detecting problems in terminations and joints of XLPE and EPR power cables is considered useful, since the PD tends to exist for much longer periods of time prior to failure in these accessories.

Both off-line and on-line diagnostic testing is used on oil paper and synthetic power cables. Off-line testing may be done at rated or elevated voltage, using either resonant AC or an oscillating surge [19, 46]. Normally off-line tests are done with capacitors or HFCTs installed on sheath grounds or cross-bonding connections. On-line testing almost always uses HFCTs as the sensor [20]. On-line testing is most likely to find termination and joint problems. The main issues tend to be interference and PD site location. Usually all the methods discussed in Section 2.4 have been applied to noise separation, with the time-frequency clustering technique having some notable recent success [47]. The time domain reflectometry technique, and its more recent hardware implementations, seems to be capable of locating cable PD sites, at least in shorter lengths of synthetic-insulated cable (Section 2.3.3). Clearly there is scope for considerable increase in PD testing and monitoring in power cables, now that at least some of the methods seem to have been proven useful.

Continuous PD monitoring may be useful for power cables, although the attenuation and dispersion effects will limit how much of the cable the PD monitor would 'see'. Some research installations of continuous monitoring have been implemented, but so far there has been little widespread acceptance of the need for the technology.

### 3.2 POWER AND INSTRUMENT TRANSFORMERS

Today, high power transformers still use oil-paper as the main insulation. Power transformers for distribution class voltages may be either oil-paper or 'dry-type', that is the use fiberglass together with epoxy or polyester as the main insulation. The same is true for voltage and current instrument transformers.

The main diagnostic tests for oil-paper transformers are the power factor and gas-in-oil tests, which are beyond the scope of this paper. PD is still rarely applied as a diagnostic test, at least at site. Partly this is because PD is not necessarily a symptom of many of the failure processes that can occur in oil-paper transformers. In addition, even with off-line testing, there is a considerable amount of noise present when doing an off-line test in a HV substation. Most of the diagnostic PD tests are done off-line, and on-line testing, where applied, tends to use acoustic methods [29, 48].

For most off-line PD current pulse measurements on HV transformers, the capacitive tap on the HV bushing is the PD sensor. Alternatively, an HFCT on a ground lead can provide electrical PD signals. Most of the developments in the past 20 years have revolved around noise separation, since the utility substation has many sparking and corona sites. To date, it seems that considerable experience and expertise is still required to separate noise for transformer winding PD (Section 2.3.2). However, many of the pattern recognition techniques have been applied to transformers, and perhaps one or a combination of these methods may reduce the need for a very experienced expert while maintaining an acceptable false positive and false negative alarm rate.

As discussed in Section 2.3.3, once a transformer is known to have PD, PD site location becomes important due to the size of the transformer, and the difficulty in disassembling it. Although considerable work has been done for PD pulse current location, it seems that acoustic location methods are still preferred.

PD is much more likely to be a symptom of insulation problems in dry type transformers, where poor manufacturing, thermal deterioration and winding contamination are all likely processes that create PD. Due to the relatively low commercial importance that dry-type transformers have in most plants/systems, less effort has been devoted to such apparatus. However, most of the techniques that have been applied to motors will also work with dry-type transformers, should the economic need be there.

## 3.3 SWITCHGEAR

In this section, we are referring either to air-insulated distribution class, metalclad switchgear or to SF6 insulated switchgear, usually at the transmission class level.

### 3.3.1 METALCLAD SWITCHGEAR

Metalclad switchgear suffer from several insulation failure processes, all of which produce PD [10]:

- Electrical tracking on organic insulation surfaces
- Insufficient separation between HV conductors in different phases
- Electrical treeing of PTs and CTs within the switchgear, due to poor manufacturing or cracks that develop from thermal cycling or through faults.

The PD may not appear for 20 or 30 years, depending on the root cause of the failure process. Once the PD does occur, it may operate for months or longer before failure is likely, thus periodic or continuous monitoring can be useful for diagnostic testing. To date diagnostic testing has not been widely applied, possible because of the relatively low economic impact of a switchgear insulation failure, or because the metalclad switchgear most likely to have insulation problems, are only now approaching 30 or more years of service, and the need was not apparent beforehand.

Off-line PD test methods using conventional narrow band or wide band detectors (IEC 60270) are easily performed and interpreted. Any PD that is detected can be easily located with ultrasonic and RF probes [10]. However, such off-line testing is rarely performed on-site, since a suitable outage is difficult to arrange because of the extensive customer or plant outage that normally results. Also, the phase-to-phase insulation is not tested – which tends to be a weak link in metalclad switchgear. Thus on-line testing is preferred.

Where applied, on-line testing is done with previously installed capacitors or HFCTs. In North America, 80 pF capacitors have been installed in a large number of switchgear. The on-line detection methods tend to be of the ultrawide band approach, in an attempt to maximize the PD signal to noise ratio [14]. The time of flight method has also been commercially applied to both aid in external noise separation and to locate PD sites on-line [14]. Other on-line methods based on using RF antenna or specialized probes that measure the difference in potential that can occur between different parts of the metal enclosure have also seen application, at least in the UK [49].

In the petrochemical industry, where a switchgear can have important safety and environmental consequences, continuous monitoring using 80 pF PD sensors is gaining wider acceptance.

### 3.3.2 GAS INSULATED SWITCHGEAR

Diagnostic PD testing of $SF_6$ insulated switchgear has gained significant acceptance in the past 2 decades. Such switchgear has a number of failure processes that produce PD or discharges as a symptom or a cause of failure, including:

- Electrical treeing or tracking of epoxy spacers or control mechanisms
- Metallic particles that may bounce in the switchgear due to electromagnetic forces
- Poor electrical connections, either on the HV or ground conductors

Off-line testing is relatively straightforward in GIS, although the sensitivity required for detecting small voids within the epoxy may be an issue. As with other apparatus however, GIS owners prefer on-line testing. Specialized capacitive or antenna-type sensors have been developed for this purpose. The coaxial structure of GIS and the low transmission loss in gas dielectrics make the detection of PD pulse currents straightforward. Virtually all detection systems use frequencies in the hundreds of megahertz, both to optimize the signal to noise ratio [22, 50], as well as to facilitate PD site location using time domain reflectometry principles (Section 2.3.3). These methods are well advanced and widely applied today, although there are few reports of commercial continuous PD monitors for GIS.

## 3.4 ROTATING MACHINES

PD pulse current monitoring is perhaps most widely applied to stator winding insulation system monitoring. The first commercial systems were installed about 20 years ago, and it seems that over 50% of North American utility generators now use on-line PD testing as a diagnostic test to plan stator winding maintenance [51]. PD turns out to be a symptom (although rarely a cause) of the most common stator winding failure processes, including:

- Overheating
- Load cycling
- Contamination by partly conducting materials
- Loose windings in the stator slot
- Various manufacturing issues such as poor impregnation and inadequate separation between HV components.

As with on-line electrical PD testing of other apparatus, the key issue is separation of the PD pulse currents from electrical noise. The most applied method uses 80 pF capacitive sensors permanently mounted within the stator or on the stator terminals. Ultrawide band detection is used to enhance signal to noise ratio and to implement time of flight and pulse shape analysis techniques to further distinguish between PD and noise [4]. Unlike other equipment where PD should not be occurring at operating voltage, stator windings are unique in that PD normally does occur within windings rated 3.3 kV and above, usually without reducing winding life. The resistance to aging by PD itself is due to the high percentage of mica in stator winding insulation. Thus interpretation of the PD is more difficult with stator windings, since some PD is expected – it is only a problem if the PD levels are 'too high'. Since PD sensors are now installed on many thousands of motors and generators, and data has been collected on these machines for as long as 20 years, there is now some statistical basis for determining when the levels are 'too high'. Tables of high PD levels have recently been published [51].

In rotating machines, it is common to have hundreds of PD sites that are simultaneously active. Also, there can be several root causes for the PD occurring at the same time. If there is a single dominant failure process, there are fairly simple procedures for deciding what the root cause is [4]. However, with multiple mechanisms occurring, deconvoluting these mechanisms in the PD pattern can be difficult. Most of the pattern recognition approaches described in Section 2.4 have been applied with greater or lesser success. It is still unclear how well these approaches will work in the hands on maintenance engineer, rather than the developer of the technique.

As discussed in Section 2.3.3, experimental methods have been developed to locate the source of the worst PD in a stator winding. However few are in practical use. The reason is unclear, but it may be that the need to precisely locate the PD is not as great in stator windings, since machine disassembly is required to confirm any location, and usually a quick visual examination will identify the worst insulation deterioration sites fairly quickly and easily.

## 4 FUTURE DIRECTIONS

The above provided a summary of research into insulation condition assessment over the past 20 years, together with opinions on what seems to have worked. To achieve a wider acceptance of PD testing for equipment condition assessment, effort into the following areas may be useful:

- A large number of approaches to pattern recognition have been explored. Unfortunately, the specific approaches developed have usually only been evaluated for effectiveness by the proposer. To date there is a relatively low level of credibility associated with most pattern recognition techniques, since many developers (probably including this author) have sometimes over-claimed effectiveness. Only independent evaluation can prove effectiveness and increase acceptance, and effort needs to be devoted to obtaining this independent validation.
- For rotating machine applications in particular, where multiple deterioration processes may be occurring simultaneously, methods need to be developed and validated that are effective in automatically separating PD associated with each failure process. Such separation is needed to determine what insulation repair options should be applied. Although some progress has occurred via pattern recognition, much more refinement and independent confirmation is needed.
- Noise continues to be a large issue in on-site and on-line PD testing, especially with HV transformers. To move PD testing of transformers from the domain of the expert to that of the plant engineer, more effort in hardware- and software-based noise separation is needed.
- Continuing effort is needed to reduce the cost of continuous on-line PD measuring systems for all types of apparatus. Since insulation failures are rare, continuous monitoring will only be widely applied if it is cheap enough to be applied to all equipment.
- Equipment owners, who are mainly non-specialists, for the most part want to be able to do their own testing and interpretation. To do this, pattern recognition, noise separation and results interpretation need to be made as simple and reliable as routine vibration analysis or insulation resistance testing.
- Finally, equipment owners would prefer the testing provides not pC or mV, but the remaining life of the insulation. As discussed in [52], this is

probably not feasible, at least with PD alone. But it is still an area for continued research.

## CONCLUSION

1. The application of PD technology to diagnose the condition of the electrical insulation in high voltage equipment has grown dramatically over the past 20 years. The technology has been widely accepted for rotating machine stator windings, and to a lesser degree, cables, transformers and switchgear.
2. The consequence has been that insulation problems are sometimes found before catastrophic failure, and HV equipment maintenance costs are reducing.
3. Some of the pressure to introduce PD diagnostics is because 'time-based' maintenance – that is regular equipment shutdowns for inspections – is no longer popular due to lack of manpower and the recognition of its high cost. In addition, PD diagnostics has also gained favor due to cost reductions in testing with the introduction of new sensors, cheaper electronics and memory, as well as powerful software tools.
4. The strongest trend in the past 20 years has been the proliferation of pattern recognition tools to aid in separating PD from interference, as well as to identify the root cause of any PD that is detected. A second trend has been the move to ultrawide band PD detection, since it facilitates interference suppression as well as the ability to locate PD sites.
5. PD diagnostics are useful because they give a warning to equipment owners that there is a problem. However, as has been discussed in the past, PD does not appear to be capable of providing a tool to estimate remaining insulation life.

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## REFERENCES

[1] R. Bartnikas, "Partial Discharges. Their Mechanism, Detection, and Measurement", IEEE Trans. Dielectr. Electr. Insul., Vol. 9 , pp. 763-808, 2002.

[2] C.L. Davies, P.L. Hoover, "Ionization Studies in Paper Insulated Cables", AIEE Trans Vol. 45, p. 141, 1926.

[3] D.M. Robinson, *Dielectric Phenomena in HV Cables*, Chapman and Hall, London, 1936.

[4] G.C. Stone, E.A. Boulter, I. Culbert and H. Dhirani, *Electrical Insulation for Rotating Machines*, Wiley-IEEE Press, 2004.

[5] J.P. Vora and S.L. Foster, "Power Transformers and Corona Testing", IEEE Trans PAS, Vol. 84, pp. 707-714, 1965.

[6] R. Bartnikas and E.J. McMahon, Editors, *Engineering Dielectrics Volume 1 – Corona Measurement and Interpretation*, ASTM Publication STP 669, 1979.

[7] F.H. Kreuger, *Discharge Detection in High Voltage Equipment*, Butterworth-Heinemann, 1989.

[8] A. Kelen, "The Functional Testing of HV Generator Stator Insulation", CIGRE Paper 15-03, 1976.

[9] E. Lemke, "Progress in PD Probe Measuring Technique", Paper 72.01, ISH, Dresden, 1991.

[10] R. Van Haeren, G.C. Stone, J.Meehan and M. Kurtz, "Preventing Failures in Outdoor Distribution Class Metalclad Switchgear", IEEE Trans PAS, Vol. 104 , pp. 2706-2712, 1985.

[11] K. Forsyth, US Patent 5,886,344,"Coronona Detector with Narrow Band Optical Filter", March 23, 1999.

[12] R. Bartnikas and J. Levi, "A Simple Pulse Height Analyzer for PD Rate Measurements", IEEE Trans. IM, pp. 341-345, 1969.

[13] B. Fruth and J. Fuhr, "PD Pattern Recognition as a Tool for Diagnosis and Monitoring of Aging", CIGRE Paper 15/33-12, 1990.

[14] G.C. Stone, H.G. Sedding, N. Fujimoto and J.M. Braun, "Practical Implementation of Ultrawideband

PD Detectors", IEEE Trans. Electr. Insul., Vol. 27 , pp. 70-81, 1992.

[15] P. Morshuis, "Assessment of Dielectric Degradation by Ultrawide Band PD Detection", IEEE Trans. Dielectr. Electr. Insul., Vol. 2 , pp. 744-760, 1995.

[16] M. Kurtz and G.C. Stone, "Diagnostic Testing of Generator Insulation", Canadian Electricity Association Final Report, Part III, Project RP76-17, 1980.

[17] M. Beyer, W. Kamm, H. Borsi and K. Feser, "A New Method for Detection and Location of Distributed PD in HV Cables Under External Interference", IEEE Trans. PAS, Vol. 100, pp. 3451-3438, 1982.

[18] J.P. Steiner, P.H. Reynolds and W.L. Weeks, "Estimating the Location of PD in Cables", IEEE Trans Electr. Insul., Vol. 27, pp. 44-52, 1992.

[19] M.S. Mashikian, R. Luther and J.C. Juricision, "Evaluation of Field Aged Crosslinked PE Cables by PD Location", IEEE Trans. Power Del., Vol. 9, pp. 620-628, 1994.

[20] N.H. Ahmed and N.N. Srinivas, "On-line PD Detection in Cables", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 181-188, 1998.

[21] S.A. Boggs, "Electromagnetic Techniques for Fault and PD Location in Gas Insulted Cables and Substations", IEEE Trans. PAS, Vol. 101,pp. 1935-1941, 1982.

[22] M.D. Judd, O. Farish and B.F. Hampton, "Broadband Couplers for UHF Detection of PD in Gas Insulated Substations", IEE Proc. Science, Measurement and Technology, Vol. 142, pp. 237-243, 1995.

[23] R.E. James, B.T. Phung and Q. Su, "Application of Digital Filtering Techniques to the Determination of PD Location in Transformers", IEEE Trans. Electr. Insul., Vol. 24, pp. 657-668, 19861989.

[24] J. Fuhr, M. Haessig and P. Boss, "Detection and Location of Internal Defects in the Insulation of Power Transformers", IEEE Trans. Electr. Insul., Vol. 28, pp. 1050-1067, 1993.

[25] J. Simpson, R.C. Tychsen, Q. Su, T.R. Blackburn and R.E. James, "Evaluation of partial discharge detection techniques on hydro-generators in the Australian Snowy Mountains scheme. Tumut 1 case study", IEEE Trans E.C., Vol. 10, pp.18 – 24, 1995.

[26] S. Rizzetto, G.C. Stone and S.A. Boggs, "The Influence of X-rays on PD in Voids", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 89-94, 1987.

[27] B.A. Lloyd, S.R. Campbell and G.C. Stone, "Continuous On-Line PD Monitoring of Generator Stator Windings", IEEE Trans E.C., Vol. 14, pp. 1131-1137, 1999.

[28] Marsh, T. Laird and M. Hoof, "Real Time Assessed Condition Trending Using Continuous PD Monitoring", EPRI Conf. Utility Generator Predictive Maintenance and Refurbishment, New Orleans, 2001.

[29] J.W. Harley, Task Force 2 Report, Transformer Colloquium, CIGRE Study Committee 12, Budapest, 1999.

[30] CIGRE Working Group Report, "Recognition of Discharges", Electra, No. 11, 1969.

[31] G.C Stone, T.E. Goodeve, H.G. Sedding and W. McDermid, "Unusual PD Pulse Phase Distributions in Operating Machines", IEEE Trans Dielectr. Electr. Insul., Vol. 2, pp. 567-577, 1995.

[32] J. Fuhr, M. Haessig, B. Fruth and T. Kaiser, "PD-fingerprints of some high voltage apparatus", IEEE Intern. Sympos. Electr. Insul. (ISEI), pp.129 – 132, 1990.

[33] CIGRE Technical Brochure 226, "Knowledge Rules for PD Diagnosis in Service", 2003.

[34] T. Okamoto, T. Tanaka, "Novel PD Measurement Computer Aided Systems", IEEE Trans. Electr. Insul., Vol. 21, pp. 1015-1021, 1986.

[35] E. Gulski and F.H. Kreuger, "Computer Aided Recognition of Discharge Patterns", IEEE Trans. Electr. Insul., Vol. 27, pp. 82-92, 1992.

[36] M. Cacciari, A. Contin and G.C. Montanari, "Use of a Mixed Weibull Distribution for the Identification of PD Phenomena", IEEE Trans. Dielectr. Electr. Insul., Vol. 2, pp. 1166-1174, 1995.

[37] N. Hozumi, T. Okamoto and T. Imajo, "Discrimination Of Partial Discharge Patterns Using A Neural Network", IEEE Trans. Dielectr. Electr. Insul., Vol. 27, pp. 550 – 556, 1992.

[38] M. Salama and R. Bartnikas, "Determination Of Neural-Network Topology For Partial Discharge Pulse Pattern Recognition", IEEE Trans. Neural Networks, Vol. 13, pp. 446 – 456, 2002.

[39] D. Wenzel, H. Borsi and E. Gockenbach, "Partial Discharge Recognition And Localization On Transformers Via Fuzzy Logic", IEEE Intern. Sympos. Electr. Insul. (ISEI), pp. 233 – 236, 1994.

[40] M. Salama and R. Bartnikas, "Fuzzy Logic Applied To PD Pattern Classification", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp. 118 – 123, 2000.

[41] X. Ma, C. Zhou and I.J. Kemp," Interpretation Of Wavelet Analysis And Its Application In Partial Discharge Detection", IEEE Trans. Dielectr. Electr. Insul.,Vol. 9, pp. 446 – 457, 2002.

[42] L. Satish and B. Nazneen," Wavelet-Based Denoising Of Partial Discharge Signals Buried In Excessive Noise And Interference", IEEE Trans. Dielectr. Electr. Insul.,Vol. 10, pp. 354 – 367, 2003.

[43] L. Satish and W.S. Zaengl, "Can Fractal Features Be Used For Recognizing 3-D Partial Discharge Patterns", IEEE Trans. Dielectr. Electr. Insul.,Vol. 2, pp. 352 – 359, 1995.

[44] A. Cavallini, A. Contin, G.C. Montanari and F. Puletti, "Advanced PD Inference in On-Field Measurements, Part I, Noise Rejection", IEEE Trans. Dielectr. Electr. Insul.,Vol. 10, pp. 216-224, 2003.

[45] A. Cavallini, A. Contin, G.C. Montanari and F. Puletti, "Advanced PD Inference in On-Field Measurements, Part II: Identification of Defects in Solid Insulation Systems", IEEE Trans. Dielectr. Electr. Insul.,Vol. 10, pp. 528-538, 2003.

[46] E. Gulski, F. Webster, J. Smit and P. Seitz, "Advanced Partial Discharge Diagnostic Of MV Power Cable System Using Oscillating Wave Test System", IEEE Electr. Insul. Mag., Vol. 16, No. 2, pp. 17 – 25, 2000.

[47] A. Cavallini, G.C. Montanari, F. Puletti, S. Franchi Bononi, F. Ombello and J. Butt, "Experience Of Testing Polymeric HV Cable Systems By An Innovative Partial Discharge Measurement Approach", POWERCON, Singapore, pp., 2004.

[48] M. Haessig, R.Brumlich, J. Fuhr and T. Aschwanden, "Assessment of Insulation Condition of Large Power Transformers by On-Site Electrical Diagnosis Methods", IEEE Intern. Sympos. Electr. Insul. (ISEI), Anaheim CA, USA, pp. 368-372, 2000.

[49] P. Brown, "Nonintrusive Partial Discharge Measurements On High Voltage Switchgear", IEE Colloquium on Monitors and Condition Assessment Equipment, Digest No. 1996/186, pp. 10/1 - 10/5, 1996,

[50] S.A. Boggs, "Electromagnetic Techniques for Fault and Partial Discharge Location in Gas-Insulated Switchgear", IEEE Trans PAS, Vol. 101, pp. 1935-1941, 1982.

[51] G.C. Stone and V. Warren, "Effect of Manufacturer, Winding Age and Insulation Type of Stator Winding PD Levels", IEEE Electr. Insul. Mag., Vol. 20, No. 5, pp. 13-17, 2004.

[52] C. Laurent and C. Mayoux, "Limitations to PD as a Diagnostic for Deterioration and Remaining Life", IEEE Electr. Insul. Mag., Vol. 8, No. 2, pp. 14-17, 1992.