ON-LINE PARTIAL DISCHARGE TESTING ON GENERATOR STATOR WINDINGS

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1 ABSTRACT

On-line PD measuring systems have been promoted as a means to assess the condition of the stator winding insulation system, without a prolonged shutdown of the generator for off-line tests and inspections.

A 10-year EPRI project was initiated in October 1997 with the goal of providing the power generation industry with information to assess the strengths and limitations of various systems used to measure on-line partial discharge (PD) activity in large generators. The overall approach was based on literature search and direct, comparative tests on selected generators using PD assessment systems.

This EPRI project was managed by the author during its first five years of activity. This paper is closely based on the EPRI project and will provide:

- Background on the evolution and capabilities of partial discharge testing.
- Description of the test instrumentation, including sensors and reading devices.
- Comparison of the capabilities and limitations of the various systems in use today in evaluating condition of a stator winding based on PD readings.
- Overall summary and recommendations on the use of partial discharge readings in the assessment of turbine-generator stator windings.

Please see the Acknowledgements at the end of this paper.

2 PARTIAL DISCHARGE IN ROTATING MACHINES

2.1 Evolution of PD Testing

The phenomenon of partial discharge (PD), or more generally, electrical breakdown of gases, has been extensively studied over the past 100 years. Over the past 50 years, research has focused on the effects of PD on the performance of solid insulating materials such as used in turbine-generators. From these studies arose the concept of using PD parameters as tools to aid in assessment of insulation condition in power apparatus. While many utilities have used various off-line PD measurement methods, rapid growth in the understanding and use of on-line PD condition monitoring technology did not occur until the mid 1980s. The increase in activity resulted in part from technology developments which allowed more accurate discrimination of actual stator winding-generated PD signals from stray electromagnetic signals. These stray signals are commonly referred to as “noise”. These noise signals may be generated from sources within and external to the generator as well as external to the power plant. In-plant noise signals may come from such sources as collector brush sparking, shaft grounding brushes, welding equipment, and electrical tools. Noise signals generated external to the plant include AM and FM radio transmission and power line carrier frequencies.

Simultaneously to the development of better methods of discrimination of true signals from noise signals, PD signal interpretation capabilities have greatly improved. This increased capability has allowed much more meaningful interpretation of the actual on-line PD measurements.

Partial discharge testing of rotating machines has now gained widespread acceptance as a valuable maintenance decision support tool within the power generation industry, both with users and manufacturers of power-generation equipment.

There are presently several suppliers of PD measurement technology and services, some of which have participated in the EPRI study. The questions for many utilities are: 1) is PD measurement a useful tool for assessing stator winding condition, and 2) which of the available systems provides the optimal solution to their specific condition-monitoring needs. This paper will provide information on the strengths and limitations of the various approaches to measurement of PD, as well as guidance on the capability of the various systems to assess condition of generator stator windings.

Partial discharge testing has been the topic of many industry papers over the previous 30 years. Available at this conference is the writer's recent paper illustrating the power of PD testing through the statistical analysis of the data base of one of the large testing companies: "Partial Discharge as a Stator Winding Evaluation Tool". [1] This document includes a list of several reference papers on partial discharge testing and evaluation.

2.2 Types of Partial Discharge

Partial discharge is, by definition, an electrical breakdown (discharge) that does not bridge the entire distance between two conductors, in other words, an incomplete breakdown. In power apparatus, three basic types of partial discharge occur, as differentiated by electrode and geometric configuration. These conditions are classified as:

- Internal discharges, where the partial discharge occurs at a gaseous void under or within the bulk of the insulation material.
- Surface discharges, where the partial discharge occurs at the outside surface of the insulation.
- Corona discharges, which occur at sharp metallic or insulation protrusions. (The term, "corona", has often been incorrectly used interchangeably with "partial discharge".)

Partial discharge of these 3 types occurs at several locations within or on a stator winding. See Section 2.6.

2.3 Partial Discharge as a Deterioration Mechanism

Organic insulation systems, which have relatively low partial discharge resistance, can be used where the insulation system can be designed to be essentially PD free. This requires that the insulation contains no internal voids and that surface voltage grounding and grading systems prevent surface discharge. These conditions can be met in many applications where uncomplicated physical configurations exist. Thus, for example, it is permissible to use epoxy castings in such applications as bushings and stand-off insulators on gas insulated substation equipment, and cross-linked polyethylene can be used for insulating distribution and transmission cables.

However, the physical configurations of a stator winding are much more complicated. As a result, PD is always present to some degree within and/or on the surface of the high voltage stator winding insulation, i.e., windings operating above about 4000 volts. (PD may also occur under some conditions on stators rated less than 4000 volts.) PD results from the fact that voids and voltage gradient discontinuities cannot be completely precluded from all locations on or within the stator winding insulation. PD will occur in these locations, and PD of this nature will attack the insulating materials. Thus, if a layer of *non-conductive, non-micaceous* insulation is inserted in the stator bar groundwall insulation, it is likely that damaging PD will initiate in this layer of material. However, mica strongly resists deterioration in the presence of even quite severe PD. As a result, mica is almost always used exclusively as the main insulating component in the manufacture of large stator windings. Also, great care is taken to assure that the outer surface of the insulation is securely grounded by effective semiconducting paint or tape, thus forcing the voltage drop to be confined to the micaceous layers of insulation.

Note: In generator stator terminology, the terms "bar", "half-coil" and "coil" are used somewhat interchangeably. In this paper, the term "bar" will be used exclusively to delineate the stator winding half-coil.

Partial discharge in the stator windings of high voltage rotating machines may be viewed as:

1. an electrical deterioration mechanism, or
2. a symptom of problems caused by other operating duties on the insulation system, i.e., mechanical, ambient and/or thermal.

Generator stator windings have historically rarely failed due to the action of partial discharge alone. Even in cases where significant partial discharge activity has been detected, it is unlikely that immediate action will be required because deterioration from PD activity alone tends to be slow.

From a practical point of view, the latter of the two above listed possibilities has been of most interest to users of high voltage rotating machines because high levels of PD may be an indicator of other difficulties: wear from loose parts or foreign material, deficient insulation system, failing corona grading system, stator bar slot vibration, loose end windings, failing electrical current connections, contamination. Thus the presence of high levels of partial discharge has commonly been used as a tool for monitoring winding condition and for optimizing maintenance plans and schedules. However, damage related to non-electrical causes is likely to be dispersed randomly throughout the winding, thus deterioration that occurs in the lower voltage portions of the winding will result in lower PD reading. As a result, this damage is less likely to be detected by PD readings. This situation is exacerbated by the fact that PD sensors tend to be located at the high voltage end of the winding, and may not be sensitive to PD remote from the sensor location.

In general, four sources of partial discharge in rotating machine stator windings are of primary interest:

1. partial discharge at the interface between the copper conductors and the strand, turn or groundwall insulation,
2. partial discharge within the body of the groundwall insulation,
3. surface discharges between the semiconductive paint/tape of the bar and the core iron, and
4. discharges in the endwinding between bars operating at high voltage difference, or at the junction between the endwinding voltage grading system and the slot grounding system.

Each of the above processes will be discussed in turn in Section 2.6, with emphasis being placed on the cause of the deterioration which gives rise to partial discharge and the consequences for the type of partial discharge activity observed.

2.4 Long-time Effects of Partial Discharge on Stator Insulation

Depending upon the location of the partial discharge source and the materials involved, various types of degradation will occur. As mentioned above in Section 2.3, organic insulating materials have little resistance to partial discharge. Consequently, the organic components of the stator insulation, slot support and stress gradient control systems are preferentially attacked under the action of partial discharges.

A partial discharge produces a number of effects across the electromagnetic spectrum. At the low frequency end, the partial discharge results in slow ionic processes as well as vibrations in the audio and ultrasonic frequency ranges. At the other end of the frequency spectrum, electrons, photons and more exotic species such as Auger electrons are produced. Further, the process usually results in heating of the void. In turn, the presence of these charged species, combined with heat and ultraviolet light, can modify the conditions in the void. A well-known example of this modification is the behavior of partial discharge in a void as a function of time. Assuming the test object has been raised to a voltage above the discharge inception voltage, and that no other conditions change, typically a gradual reduction in partial discharge activity will be observed. This reduced activity is due to factors such as the increased pressure in the void resulting from heating, and increases in conductivity on the void walls. This phenomenon does not imply that the discharge process is self-limiting because, over time, conditions within the void will likely further change in the negative direction. For example, deterioration rate may again increase due to discharge erosion caused by charged particle bombardment and burning of the organic binding resin in the insulation.

Typically, the type of deterioration described above occurs in voids at the interface between the copper conductors and the insulation, or within voids in the bulk of the insulation. Usually, because of the higher electrical and thermal stresses at the copper conductors, damage is more likely to result from voids at the copper/insulation interface. In cases where this type of deterioration has been observed in service, or in laboratory aged samples, failure initiation tends to originate at the corners of the bare bar. (By definition, the “bare bar” is the consolidated copper strand package onto which the “ground insulation” is applied.) The failure path then meanders, or tracks, around the mica flakes or platelets, through the organic resin binder. Only in severely aged insulation systems is the mica consumed, normally by thermal or mechanical, as opposed to electrical degradation.

2.5 Partial Discharge as a Symptom of Other Defects

Although partial discharge can be a significant aging mechanism in stator winding insulation, because of the presence of mica the time-to-failure is usually very long. In fact, the time-to-failure due to the action of internal partial discharge in voids in the groundwall insulation is such that generally there is a much higher probability of machine failure due to some other problem. Consequently, most users of partial discharge measurements on electrical machines view the data as a valuable condition monitoring aid and to assist in making maintenance planning decisions. This is because, as noted above, the deterioration of the stator electrical insulation system due to thermal, environmental or mechanical stresses often can be detected by partial discharge tests. Further, different types of degradation can result in unique partial discharge characteristics, thus enhancing the diagnostic power of the PD measurements.

2.6 Mechanisms and Consequences of Partial Discharge in Rotating Machines

Each of the principal deterioration mechanisms associated with the stator insulation, slot support and voltage stress control system gives rise to characteristic partial discharge behavior. The information which follows will provide a qualitative description of the mechanisms and their effects on the observed partial discharge activity.

2.6.1 Delamination at the Copper Conductor/Groundwall Interface

This type of defect results from loss of bonding between the copper conductors, or strand insulation, and the groundwall insulation. Because of differences in coefficients of thermal expansion between copper and insulating materials, voids between the bare bar and insulation groundwall are almost inevitable on the newly manufactured bar. Internal electrical grading between the bare bar and groundwall may alleviate this condition to some extent.

In addition, voids can originate due to inadequacies in processing during the bar manufacturing cycle, or from the axial and radial differential expansions between the copper conductors and the insulation during operation. Ultimately, electrical failure of the winding can result.

If the delamination between copper and insulation is sufficiently great, the mechanical integrity of the bar may also be compromised. This can lead to relative movement between strands or turns, and the consequent abrasion of the strand or turn insulation may eventually lead to strand or interturn insulation breakdown. A further type of failure mechanism may result from the occurrence of PD in the void formed by a delamination. Over a sufficiently long period of time, PD attack on the strand or turn insulation material may lead to strand or interturn short circuits. Failure of the strand or turn insulation will in all probability result in failure of the groundwall insulation system, and consequentially the winding.

Unlike the case of a void in the bulk of the dielectric, metal and dielectric-covered electrodes bound the defect. The basic discharge mechanisms outlined for the case of the dielectric bounded cavity still apply. However, the system is no longer symmetrical, in the sense that the electrodes are comprised of dissimilar materials, i.e., insulation and copper. This asymmetry produces a polarity effect that results in the predominance of negative polarity PD pulses, which are observed on the rising positive portion of the sine wave (0 to 90 degrees). The polarity is designated as negative, since the partial discharge causes the applied line voltage to be partially shorted towards zero; therefore the PD applies the sinuate with a negative polarity pulse. Such a result can be predicted from gas discharge theory and some consideration of the charge mobility on the electrodes. On the insulation surface, the mobility of positive ions is much lower than that for negative species. Consequently, when the copper conductor is at high voltage, the insulation must act as the cathode and therefore supply negative ions, which it is more prone to provide than during the negative half-cycle. PD will occur preferentially on the positive half-cycle as negative species will be pushed out into the gas gap toward the positively charged copper surface. Observation of a negative polarity dependence, during the positive half-cycle (0 to 90 degrees), usually indicates that the bond between the conductor stack (bare bar) and the groundwall insulation is deteriorated. Similar to void discharge in the bulk of the groundwall insulation, no remedial action is possible for this type of deterioration, although maintaining a tight winding may retard the deterioration process somewhat.

2.6.2 Internal Groundwall Insulation Delamination

Internal voids in the groundwall insulation itself result from the manufacturing process and/or from delamination due to operating thermal and mechanical stresses. Because of the rectangular shape of armature bars, a void-free stator insulation system is practically not achievable. In addition, due to inevitable process control difficulties associated with taping, impregnating, pressing and curing the insulation system, voids are almost certain to occur. Normally, quality control procedures and testing minimize the presence of gross defects in the groundwall insulation; however, some voids are likely to remain. Furthermore, thermal and mechanical stresses resulting from operation of the machine may result in further delamination that may have serious impact on the integrity of the insulation system.

In the event of serious deterioration, there is little or no maintenance that can be performed to reverse this type of degradation. Usually, the only course of action is to determine the optimum time to rewind the machine.

Fortunately, breakdown of insulation due to internal voids has been relatively rare. This record of low failure rate due to PD, however, may change for the worse as manufacturers push the design envelop of air-cooled machines operating at higher winding voltages, and with thinner insulation operating at higher dielectric stress (volts/mm).

2.6.3 Slot Discharge

Slot discharge is the term generically applied to PD occurring between the semiconductive surface coating of the bar and the grounded core iron. There appear to be several types of slot discharge and details of each of the involved mechanisms are not fully understood. The resulting slot discharges can have minor or serious implications for the long term reliability of the stator winding. While slot discharge, when it occurs, has been found predominantly on air-cooled machines, deterioration of hydrogen-cooled machines due to this mechanism has also occurred.

A common form of slot discharge has occurred from excessively high semiconductor insulation resistance. This condition may result from deficient semiconductive paint/tape or when relative movement between bar and core causes abrasion and removal of the semiconductive coating. Due to the effects of capacitive charging across the groundwall, a surface charge is induced on the bar. If sufficient potential is built up on an isolated semiconductor, the gap between it and the core iron will break down. Initial conditions may involve only a small area and small energy. As deterioration progresses, relatively large surface areas can become involved, with associated significant energies available in the discharge. Consequently, further erosion of the semiconductive coating can occur, and as the discharges become more severe, erosion of the groundwall insulation itself can occur. This mechanism, if not arrested or retarded, can accelerate and cause breakdown of the groundwall insulation and subsequent machine failure. Deterioration from this problem will focus on the higher voltage bars in the phase belt, and is not necessarily associated with bar vibration.

A somewhat different and more severe deterioration mechanism resulting in slot discharge can originate due to the phenomenon of the previous paragraph combined with vibration between the bar and the core iron. If the bar becomes loose in the slot, vibration will wear the semiconductor paint/tape and further contact can be lost between the bar surface and the core iron. The initial loss of contact may be quite localized and unimportant. However, if more widespread contact is lost, the resulting loosening of the winding may leave too few contact points. This would result in significant capacitive charging current being constrained to flow through a relatively small volume, causing very high current densities at these points. This situation is exacerbated by bar vibration which can interrupt the ground current flow at the contact points at double generator operating frequency, typically 100 or 120 Hz. This, in turn, will result in heating, burning or arcing which would erode both the semiconductive material and eventually, if not arrested, the groundwall insulation. As in the previous example, deterioration from this problem will focus on the higher voltage bars in the phase belt.

A third, more subtle form of “slot discharge” may occur which is not preferentially associated with the high voltage portions of the winding. This problem is sometimes referred to as ***“vibration sparking”*** and appears to be associated with a combination of bar vibration and low semiconductor paint resistance. The same voltage that is generated in a single bar from end-to-end of the core is also generated on the slot semiconductor paint, typically about 50 volts per foot of core length. A small current will tend to flow in the paint, but if adequate contact is maintained between the bar and the core, localized energy accumulation will be small. However, if contact to the core is intermittent and also interrupted at double operating frequency, the resulting arcing can erode the groundwall at a significant rate. While significant winding deterioration due to “slot discharge” may require many years to develop, winding failure due to “vibration sparking” can and has occurred in months or a very few years of operation.

It may be possible to reduce the effects of these mechanisms to some extent by restoring the semiconductor coating or by preventing further vibration. The former repair may not be possible on generators designed without radial ventilation ducts, and furthermore, where access is available the treatment is unlikely to cover all worn semiconductor surfaces. Reduction or prevention of further bar vibration may be possible by rewedging the slots or by bonding the bars to the core. If successful, these repairs may extend the life of the winding somewhat.

Again, this electrical geometry is asymmetric and hence a polarity effect will be observed. In this case, there will be a predominance of positive PD pulses, which occur during the negative half-cycle (180 to 270 degrees). This is because, unlike the above situation for the defect at the conductor/insulation interface, the metallic electrode is grounded, while the applied voltage is negative. Consequently, the relatively immobile positive space charge on the surface of the stator insulation will result in localized breakdown occurring predominantly on the negative half-cycle which is due to the metallic electrode acting as the cathode and therefore supplying the negative ions.

2.6.4 Endwinding Discharge

Partial discharges occurring in the endwindings and connection rings can result from voids in the insulation, surface discharges due to contamination, inadequately designed interphase or ground clearances, or deficient connection between the slot semiconductor and end winding stress grading junction. Consequently, most of the discussion relevant to internal and external discharges outlined above applies.

The major difference between this type of discharge and one occurring in the slot portion of the winding is that no well defined ground plane exists in the end region. Hence, the PD behavior is relatively unstable, i.e., this type of discharge appears to move around on an oscilloscope display. Furthermore, if the PD data are plotted as a function of power frequency phase angle, it is likely to be phase-shifted because in many cases the discharges are taking place between phases rather than between a high voltage conductor and ground.

3 USE OF EMI IN PARTIAL DISCHARGE ANALYSIS

Electromagnetic Interference (EMI) is a term used to describe unwanted radio frequency signals generated by electrical devices, including generator stator windings. The application of EMI diagnostic techniques for the in-service evaluation of rotating electrical machines began with hydroelectric generators in about 1980. The radio frequency (RF) spectrum of interest in generators ranges from 10 KHz to about 1 GHz. This broad spectrum of frequencies includes numerous transmitters used for many purposes: aircraft navigation, AM and FM radio broadcast, communication carrier frequencies, cell phones. Power system lines act as an antenna and receive many of these broadcast signals, transmitting these ambient signals into the stator winding.

A wide variety of defects in generator stator windings may develop EMI signatures that can be analyzed. Separating the defect-related EMI from the ambient RF signals requires experience, sophisticated test equipment and a skilled technique. Thus, this technique remains an technical-expert-based system.

3.1 EMI Noise

Noise is the reception of a signal that contains no data of interest. A very wide spectrum of frequencies is necessary to describe the EMI generated by the various defects in power systems and generators. With EMI analysis very few signals that can be detected are considered noise. Diode cut off transients from an exciter provides information on the condition of both control and power electronics. Arcing patterns may be the result of rough slip rings or broken strands in a winding connection. High EMI signal levels may indicate power cables are wet. Slot discharges can be measured as low as 14 kHz, while loose hardware in an Isolated Phase Bus can generate signals up to 500 MHz. Power line carriers, and AM and FM radio stations, are valuable benchmarks for trending future tests and to confirm the accuracy of a first-time evaluation.

Experience has shown that an EMI pattern found over a wide frequency range is often a system defect, while patterns found at specific frequencies are often generated by machine defects. This is due to the electrical response of each device to a partial discharge or other electrical disturbance generating the EMI.

3.2 Generation of EMI Signals

EMI analysis of the RF spectrum that results from a PD impulse relies on the damped oscillations produced by each impulse. This pattern or signature is unique for each location in the machine winding. Since machines are constructed from numerous identical coils or stator bars and these are connected in repeated patterns, coupling between sections of the windings at these resonant frequencies is very good. The original PD impulse remains but can only be detected at the specific frequency that is generated by the resonance of the circuit surrounding the discharge location. EMI can be either radiated or conducted from this site. That part of the energy that is conducted can be measured with radio frequency current transformers (RFCTs). Wide bandwidth RF current probes or RFCTs are available with a variety of characteristics. When terminated with the correct impedance, faithful reproduction of RF signals from low kilohertz to hundreds of megahertz can be expected.

In the frequency domain, coupling between the various stator winding sections is very good and there is no need to place a coupling device on the high voltage end of the winding. Cross talk between phases is likewise very good and only one coupler is needed to detect discharges in any part of a stator winding. This one-point detector can therefore be located at the stator neutral or other low voltage location. Signal levels are in the microvolt range. This is overcome with high gain amplifiers tuned to the frequency being investigated. Many EMI frequencies generated outside the stator are also present at a winding neutral. Some of these are at very high amplitudes while others are severely attenuated. EMI amplitudes are presented on logarithmic scales to better represent both lower and higher values on one chart. Amplitudes from one microvolt to one millivolt, with frequencies ranging from 10 KHz to 100 MHz on one spectrum plot, are not unusual.

3.3 Required Equipment

A simple RF receiver or spectrum analyzer may not be able to capture a complete EMI signature.

Specifications for EMI diagnostic receivers and how they are used are described by several international standards such as CISPR Publications 11 and 22 as well as FCC Parts 15 and 18. It is imperative to utilize an instrument such as a RF voltmeter with a variety of detectors and wide frequency range. EMI instrumentation system consists of: precision radio frequency selective voltmeter, split core broad-band RF current transformer, double shielded coaxial cable, portable computer for system control and data storage, high resolution oscilloscope to monitor video patterns, speaker to monitor audio patterns, printer to display detector outputs, and hand-held EMI detecting equipment.

EMI receivers have preselectors that eliminate gain compression and overload. Bandwidth is selectable and sufficient to capture impulse or incoherent noise sources. It can be converted into a spectrum analyzer capable of displaying activity in numerous bands from 10 KHz to 1000 MHz with a dynamic range of 150 dB.

The EMI current transformer typically has a frequency response of 10 KHz to 100 MHz, with a transfer impedance of about 5 ohms. Two physical sizes of RFCTs have proven adequate, one with a 3 cm center window to fit around small or uninsulated cables, and a larger RFCT with a 12 cm opening to go around grounding transformer bushings and conductors that require insulation..

EMI spectrum analysis is essentially the capture and classification of all signals generated by devices and natural phenomena at a given measurement location. EMI patterns are evaluated in the frequency domain as well as visually (what does the discharge look like) and audio (what does the discharge sound like). A typical survey requires less than an 1 hour to complete at each RFCT location.

3.4 EMI Signature Measurement and Capture

The signal from the RFCT is usually in the range of 10 to 100 microvolts. It is amplified and presented by several methods: video for an oscilloscope, audio for a speaker, and either peak, CSPR, quasi-peak, rms, or average for the EMI spectrum plot. Specific types of discharges may occur only at discrete frequencies; these are recorded from the oscilloscope for classification and future reference. Amplitude, repetition rate and resonant frequencies are measured and noted for each type of electrical discharge seen.

Signal display for impulse type noise is very sensitive to the detector used. The rise and fall time of each detector and any averaging that may result will have significant impact in the measured EMI signal level. Because of this, EMI analysis requires use of several detectors of different time constants to scan the spectrum and help the investigator isolate meaningful data from background noise. Peak, quasi-peak, CSPR, average and RMS detectors are used. Video detector and AM audio detector circuits are also necessary to see and hear the signals for proper classification.

A computer generated plot of detector (QP, CSPR, AV or PK) amplitude Vs frequency is developed and salient features are documented through video documentation and audio recordings.

Spectrum amplitude analysis is important for trending, but detailing what is occurring at each frequency is essential for accurate fingerprinting and comprehension of the defects monitored.

The RF spectra usually contains a number of continuous fixed frequency signals emanating from standard broadcast stations, navigation beacons, and utility company power line carrier transmitters. These signals are useful as spectrum benchmarks to determine relative EMI levels and to ensure repeatability of each subsequent test setup.

3.5 EMI producing Discharges

Power frequency systems have been found to generate five fundamental types of EMI patterns when defects are present. All EMI signature analysis is based on isolating and identifying these basic patterns. These five discharges are classified as: Arcing, Corona, Gap Discharges, Microsparking, and Random Noise. Each will be discussed, as they relate to EMI testing, in the paragraphs which follow.

3.5.1 Arcing

Arcing is a low voltage electrical discharge involving power frequency current several orders of magnitude greater than that produced by partial discharges. Arcing results from loss of continuity in conductors, loss of contact between stator bar grounding paint and core, loose bolted or crimp joints, or broken conductors. Sliding contacts like shaft grounding brushes, exciter commutator brushes or collector brushes are frequent sources of arcing-type noise

3.5.2 Corona

Corona is an electric current discharging in air or hydrogen. Corona appears during both positive and negative cycles. The audio component has a sound similar to that of bacon frying. Corona is usually found on conductors operating above 4000 volts to ground and at frequencies below 10 MHz. Low frequency corona is a common signature for asphalt mica flake insulated machines. Dirty and contaminated windings often produce corona even at 4 kV.

3.5.3 Gap Discharges

A gap discharge is produced when two surfaces, separated by a gap, are at potentials sufficiently different to spark over the gap and generate a partial discharge. This can occur once or numerous times during each half of the power frequency cycle. The rise and fall time of each discharge is extremely fast. Usually pulse repetition frequency (PRF) is fixed at 1 to 15 events per half cycle and is synchronized with machine phase voltage. The detected audio component of the phenomena is characterized by a “popping” or “rasping” sound depending on the source PRF.

3.5.4 Microsparking

Microsparking is similar to gap discharges, except the gap is extremely thin, usually in the order of 0.4 mm. The discharge PRF is 15 to 30 pulses per each power frequency half cycle as opposed to gap discharges which occur at PRF of 1 to 15. Each microspark is over very short duration. Often isolated phase bus or transmission line hardware microsparking will be measured at a generator neutral. The detected audio component of microsparking is a “buzzing” sound that is a function of the PRF.

3.5.5 Random Noise

Random noise is similar to the white or pink noise used to test audio circuits. It results from the contamination of high voltage insulation with conductive material. This “white” noise can be broadband or centered around 1 to 3 specific frequencies with a spectrum response similar to a signal transmitter, but with a much wider bandwidth. When surface contamination is involved, ambient humidity changes may influence discharge activity. The detected audio component sounds like an AM radio receiver or television set when tuned between stations. Contamination in the insulation, e.g., wet stator bars, may also produce random noise.

3.5.6 Combinations

Most EMI signatures are a combination of the five basic types, and they are always combined with a variety of man-made noise sources. Gross problems such as broken or shorting conductor strands, slot discharges, arcing collector brushes, and broken insulators are usually obvious and easy to identify. Other problems such as loose wedging, contamination and internal corona are more subtle to isolate, particularly when deterioration is in the early stages of development.

3.6 Shifts in EMI Patterns

Detecting what operating conditions modify an EMI spectrum is valuable in determining the location of deterioration or incipient fault. When a severe problem is detected, additional testing with changes in operating conditions may provide this information. For example, there is an inverse relationship between gas pressure and partial discharge activity. If the stator bars or coils are loose, EMI levels will change with stator current.

4 USE OF THE PD SYSTEMS IN PARTIAL DISCHARGE ANALYSIS

A significant characteristic of PD measurement techniques is that conditions of different machines cannot be directly compared on the basis of PD readings alone. In the same way, different measurement techniques applied to the same winding will, in general, produce different values of PD magnitude. Hence, neither well defined and broadly accepted measurement techniques, nor a standard value for acceptable PD magnitudes that can be written into commissioning and maintenance tests, are presently available in industry standards. However, individual testing companies have developed databases from their own tests. These databases range in size from rather small to very large. [1]

Despite advances in methods of PD detection, pattern recognition, and noise elimination, the fundamental problem of establishing a global PD calibration technique for stator windings remains. The lack of such a standard technique does not invalidate current PD detection techniques, as long as this limitation is kept in mind. In the past, the readings for a given machine have been viewed primarily as a trending tool; however, with the more sophisticated analysis tools which are becoming available, absolute readings may result in recommendations to shut a machine down for further investigation.

As databases have grown, it has become possible to compare a given machine with the results of the fleet of similar machines. In general this comparison is done by the testing company from their internal record of tests.

However, one of the participants in the EPRI study has a vary large database, and this information has been put into the public domain. Users of this particular equipment can thus make a direct comparison of data taken by the user. Thus, for example, a specific generator may be said to have PD readings higher than 85% of the fleet of similar machines. This does not say that the specific machine is in worse condition than 85% of similar machines; it simply raises a concern that the machine may require closer monitoring and perhaps further investigation.

Furthermore, as improved noise isolation and analysis techniques have evolved, it is becoming possible to monitor the PD readings of a single machine, and with some degree of confidence assess the rate of deterioration of the machine. At least one testing company has a PD monitoring system with 3 indicating lamps; data from a generator in the “warning” range is taken and transmitted electronically to the testing company. The generator owner is then provided with a specific recommendation for action on that generator.

4.1 Basic Problems

Beyond noise rejection, there are four main fundamental challenges to the direct and simple calibration and interpretation of the PD signal output:

- The severe attenuation of very high frequency signals in stator windings.
- The geometry of the winding.
- Location of the bar in the phase belt, i.e., operating voltage of the specific bar.
- Difference in response of a close PD Vs a distant PD in the winding.

The physical causes of these effects and the resulting consequent difficulties are discussed below. This following discussion will demonstrate how these four basic factors affect other practical considerations such as different measurement techniques and coupling methods.

4.1.1 Attenuation Problems

The difficulties imposed by the propensity of stator windings to rapidly attenuate the high frequency components of PD signals has been extensively studied. The high frequency attenuation factor imposes practical constraints on the selection of bandwidth of any PD detection system. In some PD systems, the attenuation of high frequency signals is used to enhance the capability of the PD detection system to reject electrical noise. However, the improved signal-to-noise ratio is gained at the expense of loss of widespread coverage of the stator winding. A high frequency coupler would produce results with a sensitivity biased towards the bars located closest to the detector. For this reason, this type sensor is generally located in the vicinity of the high voltage bars where PD activity is likely to be most prominent and most damaging.

However, in order to satisfy a need for a test of the integrity of all portions of the winding that are under significant voltage stress, the bandwidth of the PD coupling device would be chosen low enough to enable coverage of essentially all of the winding without over-riding attenuation.

4.1.2 Geometrical Aspects

For two principal reasons, the geometry of the winding is also a critical factor. First, there is the problem of resonance. A stator winding can be treated as a complex transmission line, with each bar having an associated inductance and capacitance. Depending upon the length of the bar and the number of bars connected to form the parallel path, every winding design will possess a unique set of resonant frequencies. If the pass band of the coupler/detector system coincides with one or more of these frequencies, then the PD magnitude measured will be anomalously high.

A further consequence of geometry is the endwinding region where the bar makes the transition from core iron to free space and back to the core iron again. In transmission line terms, the transition constitutes an impedance mismatch, i.e., the stator winding in the core has a well defined ground plane, and consequently a well defined surge impedance. However, once the bar is in free space there is no longer a well defined ground plane and hence there is no longer a surge impedance in the conventional sense. The implication for a PD pulse propagating from within the slot portion of the winding is that upon reaching the end of the core iron, a proportion of the pulse energy will be reflected back into the slot portion of the winding.

Further energy losses are suffered by the transmitted component of the pulse because in the endwinding region the bar is no longer shielded. Consequently, a component of the transmitted pulse will be lost as radiated energy. These radiated components are in turn coupled into adjacent bars and further propagated into the stator winding. This PD pulse cross-talk is potentially a source of error and can give rise to false counts of PD if pulse counting equipment is used.

Thus the end of core region introduces a significant attenuation factor. This factor is extremely important for the interpretation of the received signal at the terminals. No matter whether capacitive coupling at the phase terminals or inductive coupling at the neutral terminal is employed, the impedance mismatch will always be present. In addition to the attenuation of the transmitted pulse, attention must also be paid to the reflected component. This is because the reflected pulse may also be detected, thus representing an anomalously low reading. Practically, in some cases the reflected pulse will be too damped to be detectable. However, the potential for error from this source exists and attention has to be paid to the core end and core length.

4.1.3 Effect of Voltage on PD

The voltage applied to a stator bar will have a strong impact on the magnitude of the PD which occurs on that bar. For example, if the voltage on a bar is doubled, it is not uncommon for the PD magnitude to increase 10 times. Thus bars operating at the high voltage end of the stator winding will have much higher PD than a bar with the same amount of deterioration operating at the midpoint of the winding. This voltage effect implies that even those detectors which operate in a relatively low frequency band to reduce the effect of attenuation (Section 4.1.1) may not be able to detect stator winding problems in bars in the half of the winding closest to neutral.

Only off-line tests, where the all bars are energized at full operating voltage, can detect insulation problems throughout the winding.

4.1.4 Distance

Another aspect of the PD coupling device is the response to PD which is close to the coupler versus distant PD within the winding. For example, if no voids or significant PD activity exists in the region of the coupling capacitor, then a lower-bandwidth PD coupling device will identify PD activity deeper within the winding. But, if during the measurement cycles, an incidence of high PD activity should develop at or near the coupling device, then the resultant high PD measurements will give a false indication of apparent PD deep within the winding, whereas this PD may be actually localized to the coupling device area. For this reason, some users prefer to also measure PD using sensors installed within the winding itself, since this additional analysis provides the much needed information if an outage is being scheduled solely for this purpose.

Another option is to conduct a quasi-calibration by the injection of a known charge into bars in the end-winding areas at the line-terminal area and into several nearby slots, while measuring the output of the various PD sensors - either at the line-sensors, slot couplers or RTDs. These calibrations have shown a response of a line-terminal mounted PD coupling device of 10 times greater for PD near the line terminal versus PD deep within the winding. For the above reason, it is difficult to identify if a high PD measurement at a line coupling device is minor PD activity near the coupling device, or severe PD activity deep within the winding. To effectively monitor both the line terminal/connection area, and the insulation deeper within the winding, some PD vendors recommend a combination of PD line-sensors in the line-terminal areas and slot couplers within the stator winding.

4.1.4 Other Contributing Factors

In addition to winding geometry, other construction details also require consideration. Whether the stator winding is composed of multi-turn coils or bars (mainly motors and smaller generators) or Roebel bars (larger steam, gas, and hydraulic generators) will affect the inductance of the winding. This in turn can have an effect on the resonance frequencies discussed above.

Apart from the fundamental difficulties discussed above, there are other practical issues relating to the calibration problem. A somewhat obvious point is the type of calibration signal to be used. Questions that arise in this case are specification of pulse rise time and pulse width. Both of these parameters ultimately affect the frequency content of the detected signal and influence the selection of an appropriate detection bandwidth. A still more fundamental issue is the degree to which the calibration pulse approximates a real PD pulse.

5 EMI/PARTIAL DISCHARGE INSTRUMENTATION

PD measurement systems can be divided into two general components:

- detectors or sensors, and
- display and/or recording devices.

At the most basic level, a human being can be considered as a PD measurement system, e.g., the blackout test requires visual and/or aural observation of surface PD in a dark environment. On the other end of the spectrum, systems have been constructed with ultra wideband detectors or incorporate statistical or neural network-based post-processing.

The following discussion will define more completely the types of detector and display/recording devices typically used in PD measurement systems.

5.1 Methods of Detecting Partial Discharge

A partial discharge is a very sharp "peak-like" pulse at the point of origin. This pulse provides practically a continuous spectrum of frequencies from near zero to several hundreds of megahertz. In other words, a partial discharge can theoretically be detected by measuring any frequency one chooses to measure below perhaps a gigahertz. Commonly, PD equipment measures at frequencies between 10 KHz and 150 MHz, although some systems may read up to 800 MHz. This is a very wide range, almost 3 orders of magnitude.

At the lower end of this frequency spectrum exists a number of common signal sources, including AM radio. At the higher end exist other signal sources, including FM radio and some power line carrier frequencies. Any type of sparking (brush sparking, arc welding, or inadequate electrical joints) commonly has the same frequency content as a PD pulse. Therefore, these sources can impact both high and low frequency ranges. When measuring PD, these signals are interpreted as "noise", and tend to interfere with detection and measurement of true PD signals. There are several methods for removing the "noise" from the total signal. Methods vary in complication and capability. Following is an incomplete list of noise rejection techniques:

- Read in frequency ranges generally above the range of the noise sources.
- Discriminate between the directions from which the signals are coming.
- Discriminate between arrival times of signals.
- Identify and eliminate all signals in the range of known noise source frequencies.
- Discriminate based on the shape of the detected pulses.
- Convert PD signals into digital format and apply specific algorithms to recognize and reject noise pulses.

As previously mentioned, further complicating the measurement issue is the fact that signals are attenuated (dampened) as they pass through the winding, because of winding inductance and capacitance. The high frequencies attenuate much more rapidly than the low frequencies. Thus frequencies in the order of 30 to 50 MHz can only be read if the PD source in the winding is within close proximity of the sensor location, perhaps the 10 to 15% of the winding nearest the sensor. On the very high frequency ranges, the area of view may be as short as a few feet beyond the sensor location.

5.2 Sensors

PD signals are obtained from the winding by several methods, depending on the testing organization preference. Some of these devices are discussed below.

5.2.1 Line Capacitors

These sensors are connected to the stator winding leads, usually the line buses. On large units, they commonly are mounted within the isophase enclosures and/or the transition compartments between the generator terminals and bus. The sensors appear physically similar to a small standoff bushing. The bus is connected to the high voltage end of the "bushing" and the signal is taken from the ground end of the "bushing". Voltage isolation is accomplished by use of a high voltage capacitor. Capacitor size may range from as low as 80 pF to as high as 9,000 pF, or more.

(Note that the value of a picofarad (pF) of capacitance is very small: pF = Farad x 10^{-12}. The value of capacitance is also sometimes stated in nanofarads (nF): nF = Farad x 10^{-9}, or one nF = 1000 pF. For simplicity reasons, this paper will always express these values in picofarads, pF.)

Depending on the circuit impedances, the former will predominately transmit frequencies above 40 MHz. The latter may transmit frequencies as low as 10 KHz. Photos 1 & 2.

Photo 1. Iris Power Engineering Capacitor

Photo 2. Portion of an Adwel sensor and the Cable Penetrating the Bus Enclosure.

5.2.2 Stator Slot Couplers

These sensors are physically similar to a slot resistance temperature detector (RTD). Photos 3 & 4. The stator slot coupler (SSC) separates noise from PD based on pulse rise-time and the amount of ringing. (PD in the slot or associated endwinding is non-oscillatory and has a width less than 6 ns. Noise is wider, and is oscillatory.) Electrical connections are made to both ends, and by measuring the comparative signal arrival times at the two ends, the direction source of the signal can be determined. This sensor can thereby discriminate between signals generated in the slot, and signals generated in the end winding, or beyond. These sensors are inherently high frequency devices, reading at frequencies above about 10 MHz.

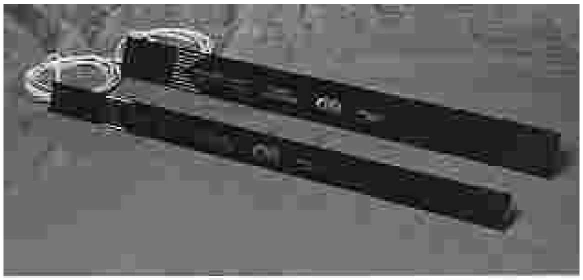

Photo 3. Stator Slot Couplers

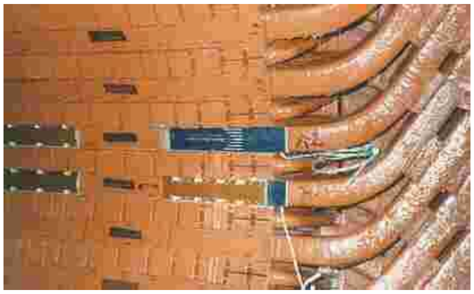

Photo 4. SSCs Installed in 2 Stator Slots

5.2.3 Radio Frequency Current Transformers (RFCTs) on Neutral Ground Cable

The EMI evaluation equipment uses an RFCT sensor for picking up the frequency domain signal sweep of PD occurring in the winding. Photo 5.

Photo 5. AEP Sensors for Reading EMI. New RFCT Installed Below the Original RFCT.

Other PD systems may use small RFCTs located on the leads from the line capacitors to pick up the PD signal. Photo 6.

Photo 6. Alstom/ABB Current Transformer Located on Lead from Adwel Capacitor on Outside Surface of Isophase Enclosure. (Size shown by pen in background).

5.2.4 Miscellaneous Sources

Some success has been had in reading PD signals directly from slot RTDs, from the stator frame, from ground leads of surge arrestors, and from other sources. These methods, while not in general use, have been shown to be useful, particularly as screening tests.

In particular, RTDs are believed by some to be a sensitive and potentially valuable PD detector. Due in part to their widespread distribution throughout most stator windings, they provide the possibility of a means to use these RTDs as a signal source, without the required work to install permanent slot couplers. Others, however, believe the RTD has major limitations due to low signal strength, distortion and noise.

Those who are working with this technology find that obtaining useful data requires the use of sophisticated software which eliminates any cross-talk between RTD wires. As a minimum, it appears that RTDs may allow useful information for the identification of machines which may require additional line coupling devices for further analysis.

The use of these miscellaneous sources is a technology that is currently in transition.

5.3 Display and Recording Devices

There are many commercially available PD measurement systems; however, these instruments will utilize one or more of the following display and/or recording devices.

5.3.1 Oscilloscopes

Oscilloscopes have been widely used to perform PD measurements in applications ranging from routine field measurements to laboratory-based research. Selection of an appropriate oscilloscope depends upon the bandwidth of the PD detector being used. As a minimum requirement the analog bandwidth of the oscilloscope, i.e., the frequency response of the amplifiers, should be at least equal to the bandwidth of the detector.

Traditionally, measurements made with analog oscilloscopes used direct observation of the PD behavior, in which characteristics such as magnitude, polarity and phase position were recorded. The position of the PD activity with respect to the power frequency cycle was recorded by adjusting the time base of the oscilloscope so that half or all of the cycle could be observed with the horizontal scale at full scale deflection. Permanent records were made using photographic techniques. However, in recent years the introduction of digital oscilloscopes with sufficient bandwidth has increased the ease of acquiring permanent records as well as enabling a range of measurements to be made on the time and frequency domain characteristics of the PD pulses. In most cases, digital oscilloscopes can be easily integrated with computers to perform measurements and acquire data automatically. However, the use of digital oscilloscopes as platforms for PD instruments is limited by their slow through-put, typically less than 10 records per second. Hence, in most cases where oscilloscopes are integrated into PD instruments, their function is usually limited to an analog display of PD activity.

5.3.2 Spectrum Analyzers

A spectrum analyzer records the magnitude of a signal with respect to its frequency content. This function is performed by scanning a reference signal, generated by the spectrum analyzer, over a prescribed frequency range and mixing it with the input signal from the test object. Again, just as for the case of an oscilloscope, careful attention should be paid that the bandwidth of the spectrum analyzer be equal to or greater than that of the coupling device. From the discussion on pulse propagation and attenuation in rotating machines stator windings, Section 4, the resultant frequency spectrum is usually very complex due to resonances in the winding structure. However, in some cases, an experienced observer may be able to determine the source of the PD from this complex frequency response.

5.3.3 Integrating Detectors

The majority of commercially available dedicated PD measuring instruments fall within this category. These instruments measure the so-called apparent charge. They are known as integrating detectors because they integrate the current pulse associated with the PD pulse to produce a quantity that is related to the apparent charge at the terminals of the test object. The integration is performed by an amplifier with a low pass filter. Generally, the bandwidths of these detectors lie in the range of a few KHz to a few MHz. Photo7.

Photo 7. Eight-channel PD Scopes with Log-Amplifiers.

5.3.4 Quasi-peak Pulse Meters and Radio Influence Voltage (RIV) Meters

The largest voids within the insulation, or most significant sites of PD activity, usually have the largest magnitudes or repetition rates associated with them. Thus a means of determining the severity of damage involves the use of a detector which is weighted to respond to the largest PD pulses. Quasi-peak pulse meters and RIV meters are analog means of being preferentially sensitive only to the largest PD pulses rather than all PD pulses. Such instruments incorporate some variation of peak sample-and-hold circuitry, which effectively retains the magnitude of the largest

PD pulses detected with a time constant extending from about 0.1 second to several seconds. A simple analog or digital meter displays the peak magnitude in terms of microvolts, milliamps or pC.

5.3.5 Pulse Height and Pulse Phase Analyzers

Many commercial and research-grade PD instruments incorporate some form of either or both pulse height and pulse phase analysis. The origins of these types of analyses can be traced back to the 1960s. The purpose of pulse height analysis is to provide a means to quantitatively determine the repetition rate of PD pulse of a certain magnitude or magnitudes.

No PD instrument is capable of measuring all PD events. In the case of rotating machine stator insulation, because of the inherent resistance of the insulations systems to PD, and the slow nature of the deterioration processes, this is not necessarily a limitation.

Pulse phase analysis, which is usually incorporated into pulse height analyzers, is a quantitative means of determining the position of occurrence of a PD pulse with respect to the power frequency cycle. Such information can aid in discriminating against electrical interference as well as potentially permitting location of the PD source. Although commercial instruments that provide this capability are relatively new, the concept is not. Usually, PD measurements made by observing the output from a coupling impedance, via a power frequency filter, display the PD pulses with the power frequency signal superposed on the display. Traditionally, most observers have used the relative position of the PD with respect to the power frequency to augment the traditional measurements of pulse magnitude and polarity.

6 MERITS OF ON-LINE PD TESTING

The decision whether to implement a test program is generally not made on a completely technical basis. More likely, decisions will be made on the basis of investment in existing test equipment, the type, operation and maintenance history of the machines, and the financial consequences of an unplanned or extension to an existing outage. Although cost benefit analyses have been performed, to justify the implementation of programs based on on-line PD testing, there is probably no truly objective means of quantifying the benefits of this type of testing. Hence, the remainder of this discussion will focus on technical elements of on-line PD testing.

6.1 Technical Considerations of On-line Testing

On-line PD tests refer to measurements performed while the generator is operating normally. The coupling devices (sensors) can be temporarily or permanently installed. The principle advantage of on-line measurements is that they are recorded with the rotating machine experiencing all of the operating stresses: thermal, electrical, environmental and mechanical. Consequently, in comparison to off-line testing, if the measurements are performed properly, on-line testing affords a higher probability of assessing the ability of the machine to continue to provide reliable operation. On-line PD testing affords the following advantages:

- voltage distribution across the winding is correct,
- measurements can be made at operating temperature, and
- normal mechanical forces are present.

The first condition reduces the risk of obtaining overly pessimistic PD results on the machine, as on-line testing renders the measurement preferentially sensitive to the more highly electrical stressed areas the winding experiences in actual operation. The second advantage is also important because of the well known temperature dependence of PD in rotating machines. In addition to the influence of temperature on void characteristics, temperature fluctuation is also known to have effects on PD behavior through such mechanisms as thermally induced differential axial expansion between the copper conductors and the insulation, and radial expansion of the insulation in the case of thermoplastic insulation systems.

The third advantage is important, since some of the more common winding failure mechanisms relate to mechanical forces and vibrations in the winding.

Consequently, it is essential to ensure that the machine operating conditions remain substantially the same when tests are performed. The principle operating parameters of relevance are:

- stator terminal voltage
- stator current
- stator temperature, and
- gas pressure.

The terminal voltage should ideally be within about ±2% for each test and the stator temperature should be within ±5 C of the previous readings. The unit loading conditions should be broadly similar in order to maintain similar bar mechanical forces. In some cases, where measurements indicate that the winding could be loose, or to establish the existence of semiconducting material deterioration, the load, and hence the bar forces, may be varied to determine whether the PD activity is modulated by this variation. Generally, the two load conditions that are used are full and minimum load.

As previously discussed, there are some disadvantages to on-line PD measurement techniques. These include:

- electrical interference
- volume of data, and
- interpretation.

The first of these disadvantages, the problem of electrical noise, will be discussed at length below. Volume of data can become a problem, even in situations in which the testing interval is of the order of six months. This problem is further compounded when using continuous on-line techniques. The obvious answer is to use some form of data compression or alarm processing such that only excursions from the norm are considered worthy of further attention. Techniques such as artificial neural networks and expert systems are, in principle, suited to this task. Unfortunately, with the present understanding of the causes, mechanisms and effects of PD, it is difficult to define fully the decision points necessary for such automation. Work is being done in this area, but clearly, further work is required before reliable systems can be expected. Similar comments apply to data interpretation. Basic interpretation rules and complete understanding of the significance of certain types of observed PD behavior, are evolving but continue to represent a major challenge.

6.2 Electrical Interference

The noise problem associated with performing measurements on operating rotating machines is the greatest challenge to those working toward implementing reliable on-line PD testing systems. For example, measurements in generating stations with high-voltage, high-power generators have demonstrated that the noise levels can be up to 1,000 times higher than the PD signals. This noise can emanate from a number of different sources, some of which may be unique to a particular generating station. Consequently, often a range of noise rejection techniques is required rather than a single method to obviate the difficulties introduced by these multiple noise sources. Section 7 will describe the most commonly encountered on-line PD monitoring technologies and describe their inherent noise rejection capabilities. The remainder of this present section will identify the origin and sources of the major electrical interference sources encountered in generating stations.

6.2.1 Electrical Interference - Internal to the Machine

Primary sources of noise internal to the machine are:

- collector brush sparking
- switching transients from the excitation system,
- the shaft grounding brushes
- arcing due to failing electrical connections, deteriorated insulators, or loose core laminations.

Collector brush sparking may emit troublesome noise if any sparking is occurring.

Transients caused by thyristor operation in the excitation system have the characteristics that they are relatively large in magnitude, slow, and synchronous with the power frequency cycle. These transients couple into the measuring system either directly or via the rotor circuit which functions as an antenna broadcasting the switching transients into the stator winding. Generally, switching noise is not a serious problem because it is synchronous, common mode and slow. Thus, techniques such as gating and differential rejection schemes can easily remove these transients.

Shaft grounding brushes, if not properly functioning, will result in the emission of unwanted RF energy, which must be separated from the PD signals from the armature winding. This can be done by recognizing that signals from the rotor, when coupled to the stator, lose their high frequency components. Thus analog filtering or digitally differentiating pulses on the basis of pulse rise-time can be used to separate brush sparking interference.

In situations where electrical connections or stator core laminations become loose, arcing and burning will occur. These arc events produce energy in the RF spectrum which can interfere with the reliable operation of PD monitoring equipment.

6.2.2 Electrical interference - External to the Machine

The principle noise sources of this category are:

- the isolated phase bus (IPB)
- the power system and connected equipment
- radio stations and carrier frequencies
- other extraneous sources, such as welding machines, electrical hand tools, precipitators, etc.

One of the most significant noise sources, and one of the most difficult to cope with, is the IPB. Partial discharges, or PD-like noise, are encountered in many IPBs. This interference can be generated by cracked or contaminated bus support insulators, weld debris or other metallic particles floating up to the bus potential and generating sparking, and transient ground rise of the grounded metallic IPB sheath. This phenomenon, in which the sheath floats up to high voltage for a few nanoseconds, can result from a loose bolted connection in the IPB system.

Partial discharge occurs in most other power apparatus, including transformers and circuit breakers, and their inter-connections. Such equipment can be a source of PD which can have very similar characteristics to that of rotating machine PD. Consequently, connected power apparatus can result in electrical interference. In addition, any transient events in the power system may also interfere with the PD measurement.

Methods of circumventing the problems resulting from these noise sources will be discussed below in Section 7. In general, noise rejection is based on one of two general approaches. Interference can be removed by the type of coupling method employed, or by post-processing of the signals from the PD sensors. The selection of the noise rejection scheme can also depend on the level of interference encountered in the power plant.

7 PARTIAL DISCHARGE TEST METHODS

Many different detection and monitoring schemes are available; however, all are based on the use of one of the coupling methods discussed in Section 5, above. In this present Section, descriptions of systems based on the use of RF current transformers, capacitors, and stripline antennae will be provided.

7.1 Radio Frequency Current Transformers (RFCTs)

One of the earliest forms of on-line discharge monitoring involved the installation of an radio frequency current transformer (RFCT) on the neutral grounding lead of the generator between the generator and the neutral grounding transformer. The original purpose of the installation was to monitor for the presence of broken sub-conductors in the stator bar which would give rise to arcing and thus the emission of RF energy. Partial discharges also produce electromagnetic interference (EMI) so it was a logical extension to use the RFCT as a PD detector. The output of the RFCTs, the frequency response of which are in the range of 20 KHz - 50 MHz, are generally connected to an oscilloscope or frequency spectrum analyzer. In general, this type of sensor will be able to provide coverage of the whole winding. In large steam turbine generators, which can have very high levels of electrical interference, interpretation of the resultant signals can be difficult because of the problem of separating the PD signals from noise.

Although the EMI technique has not as yet become widespread among electrical machine users, this technique has been shown to provide valuable diagnostic information, and can rapidly identify those machines that may need other types of PD detection.

An alternative location for RFCTs is at the phase terminals of the machine. In some generators, surge capacitors are installed between the phase terminals and ground. These devices are designed to protect the unit by presenting a low impedance path to the high frequency signals associated with switching. These devices short circuit the high frequency PD signals to ground, reducing the effectiveness of PD measurements using line capacitive couplers. A solution to this problem is to install a RFCT around the grounding lead of a surge capacitor. Normally, the metallic case of the surge capacitor is bolted to the grounded frame of the terminal box, thus it is often necessary to insulate the case of the capacitor from ground to maximize the flow of high frequency currents through the ground lead. The output of the RFCT can be monitored using an oscilloscope, spectrum analyzer or other more sophisticated systems.

7.2 Systems Based on Capacitive Couplers

In this case, high voltage capacitors are installed at, or close to, the phase terminals of the machine. Typically, one or two capacitors are installed per phase, and generally in the IPB on large machines. It is common to use two couplers per phase to implement noise rejection schemes based on differential or directional principles. In the case where only one coupler per phase is installed, some expertise on the part of the test operator is required to discriminate between PD signals and noise. Alternatively, some commercially available PD instruments perform sophisticated statistical processing of the signals to discriminate against electrical interference.

7.3 Stripline Antennae (SSCs)

Stripline antennae can be installed in the slots, and by proper instrumentation can readily discriminate between PD sources within and external to the winding.

The high frequency characteristics of such couplers render them very sensitive to PD location, but typically the amount of winding covered by one coupler is quite limited, usually to a portion of one slot. However, by locating sensors in the most highly stressed parts of the winding, with the highest probability of PD occurrence, i.e., the line end bars, an adequate monitoring scheme can be implemented with a limited number of such couplers.

These considerations led to the development of the stator slot coupler (SSC). Presently, this device is available from only one supplier. The SSC is a wide band antenna, and is usually installed on top of the stator winding bars, under the wedges, at the ends of core slots. This antenna detects any electrical signal in the frequency range of 10 MHz to 1000 MHz. From tests on operating generators, it has been determined that the winding PD pulses close to their origin are 2 to 6 ns wide and have a 1 to 2 ns rise-time from this sensor. The noise pulses, having a similar shape and frequency at their origin, must travel some distance from their origin: through a circuit ring, from the endwinding, along the laminated core, or through the rotor circuit. These relatively long propagation paths broaden the width of these pulses beyond those of the winding PD occurring in the vicinity of the antennae. This difference in pulse width, between PD and noise, is the basis for separation of PD from internal and external noise sources. The SSCs have outputs from both ends of the sensor, thus the direction the pulse travels can also be determined by counting the pulse arrival times at each end. This permits separation of PD occurring in the slot section of bars from the surface discharges in the endwindings.

A special instrument was developed specifically to acquire the signals from the SSCs, determine their width, and count them as PD or noise. Globally, several hundred large steam turbine generators have been equipped with SSCs. Experience to date with this technology has demonstrated that it is effective in discriminating PD from noise signals in the environments encountered by large generators in power stations.

7.4 Other Sensing Devices

Some organizations have sought to utilize the embedded resistance temperature detectors (RTDs) as PD sensors. RTDs are commonly installed in stator windings. The principle advantage for this method is that of convenience because there is no need to install additional PD couplers. However, there are some reservations regarding the effectiveness of the technique, including:

- Many generators have RTDs with shielded cable that may seriously distort and attenuate a PD signal which may have been detected by the RTD.
- Some manufacturers do not use shielded output leads on the RTDs. Hence, the leads may be prone to electrical interference and will not be efficient transmitters of high frequency signals.
- Unless the RTD leads were properly routed such that they do not run in close proximity to the high voltage conductors (stator bars in the endwinding), the output leads from the RTDs may become sources of PD.
- RTDs are not designed to be antennae, hence, their high frequency properties are not optimized for the purposes of efficient PD detection.

For the above reasons, the use of RTDs should be investigated to verify the output performance of the RTD as an effective PD sensor on the specific machine. This can be done using temporary sensors, by correlation to other sensors, or by calibration. Due to the existence of RTDs embedded in many machine windings, this effort can be completed without the purchase of additional permanent PD sensors.

8 CAPABILITIES OF PARTIAL DISCHARGE TESTING

The afore mentioned EPRI project was initiated to determine the merits of the varies methods of using partial discharge measurement to assess the conditions of high voltage stator windings. In particular, an objective was to compare the merits of the relatively infrequently used EMI to the more classical and much more widely used PD systems. As the work progressed, it became clear that the two systems, EMI and PD, are not in competition with each other. Rather they are in many ways complimentary to each other. Each overall approach has strengths and limitations, and fortunately taken together, considerably more information can be gained on the condition of the stator winding, and related components, than either system alone.

The sections which follow will consider the strengths and limitations of:

- EMI testing
- PD testing in general
- Each of the various PD test systems and approaches evaluated in this project.

8.1 EMI Testing

Testing of power plant equipment by use of EMI has been done for 50 years or more. But its application to high voltage generator stator winding evaluation has only been done in significant amounts during the last 25 years, and then primarily only by one organization, American Electric Power. Basically, EMI examines the electrical impulses generated by PD within the generator on a frequency-domain basis. That is, the entire spectrum of frequencies generated by PD within the generator and associated equipment is examined for magnitude. The frequency-magnitude curve thus produced is then manually evaluated on the basis of historical experience and standing wave theory. General location of PD sources can thereby be predicted with some accuracy.

8.1.1 Strengths of EMI testing:

- Properly done, valuable information can be obtained on the stator endwindings, stator slots, lead areas, collector, excitation equipment, shaft grounding brushes, isophase bus, transformers, switchgear.
- The sensor, RFCT, is relatively inexpensive, and can be installed without machine shutdown.
- Sensor is located in a low voltage region.
- Data is quickly taken by a competent, trained person.

8.1.2 Limitations of EMI testing:

- Since data is taken on the connected neutral ground, the information cannot differentiate between phase locations.
- Data is unable to give much information as to location of PD within the stator bar cross-section, i.e., against bare bar, within the insulation groundwall, on bar surface.
- Reading instrument is relatively expensive.
- Interpretation of results takes considerable training, good judgment, and some experience.
- Few users results in limited experience and limited technical support.
- As yet, no published database of results to define high or low levels of activity.

Because of the low rate of usage, the future of EMI testing of generators appears uncertain. But overall, the test is capable of alone identifying several important generator degradation mechanisms. Further, it is powerful screening tool for evaluating power plant equipment, as well as the generator. There appears to be high benefit potential and opportunity for growth of EMI as a generator maintenance tool within the power generation industry.

8.2 PD Testing

8.2.1 General

Serious efforts to use PD testing for evaluation of the condition of stator windings began about 30 years ago in North America. Ontario Hydro in Canada was a major contributor to these early efforts. This work focused on noise separation and PD data interpretation. As capability and use expanded, beginning in the mid 1980s, the project was spun off to separate companies. Concurrently, other users and manufacturers have also expanded their efforts, and there are now several companies supplying this service. Primarily, the signals are obtained from sensors connected to the high voltage line leads (bus couplers) for the 3 phases of the generator, or from SSCs. However, some work is being done reading other signal sources such as RTDs, surge arrestor ground leads, and frame grounds.

One of the major challenges in PD testing is establishing the calibration of signals received. For this reason, some testing companies will inject a PD signal of known size into a winding and read the response of the sensing system. It is thereby possible to estimate a relationship between the size of the PD signal obtained during on-line testing to the severity of the discharges occurring in the winding. In this regard:

- The amount of damage resulting from the partial discharge activity is related to the pico-coulumbs of the discharge activity, not the actual millivolt level measured.
- But partial discharge sensing equipment measures the millivolt drop of the PD signal effect on the sinusoidal waveform. The equipment does not detect absolute "pico-coulumbs" of the actual discharge.
- For this reason, partial discharge sensing equipment assumes a calibration level between the millivolts measured and the pico-coulumbs which relate to the intensity of the actual PD activity.

Each of the testing approaches will be discussed in the paragraphs which follow. For convenience, the test approaches will be divided into several categories:

- Low capacitance bus couplers, typically 80 pF.
- Intermediate capacitance line sensors, typically 500 to 1000 pF.
- High capacitance line sensors, >1000 pF.
- Stator slot couplers.
- Other signal sources, including RTDs.

8.2.2 Low Capacitance Systems

This type bus coupler has been installed on over 1000 machines since their introduction in 1978. This system consists of a set of two 80 pF capacitors per phase (6 total). One coupler per phase is mounted near the generator terminals. A second coupler is installed on the bus a pre-determined distance away from the first coupler and the stator winding. This system is sensitive to PD signals in the relatively high frequency range of 40 – 350 MHz.

Use of two capacitors per phase allows separation of stator winding PD from external interference. A “noise” pulse from the power system will arrive at the second coupler before it arrives at the first coupler, which is closer to the stator winding. Similarly, a PD pulse from the generator will arrive at the first coupler before being detected at the second coupler. Very fast digital timing electronics in the recording instrument looks at the signal arrival time at the two sensors and determines the origin of each pulse – internal to the generator or external from the power system. The recording instrument then records the number, magnitude and ac phase position of each pulse. This system can also determine if there are problems on the bus or cable between the pair of capacitors by measuring the relative arrival times from the pair of couplers. In addition to separating PD from noise on the basis of pulse arrival times, the research that lead to this technology also showed that noise, as detected by a wide bandwidth sensor, tends to have a longer rise-time, and is more oscillatory, when compared to stator winding PD. The recording devices thus can separate PD from noise on the basis of pulse shape.

8.2.2.1 Strengths of the low capacitance systems include:

- Relatively easy to use by utilities that wish to install their own sensors, perform their own tests, and interpret their own results. Users can perform and interpret their own tests with about 2 days of training.
- No adjustments required by user, such as filter frequencies or gating thresholds.
- Very large database of test results has been accumulated. A statistical summary of this database is published to the industry every year to allow users to determine the relative condition of their machine in comparison to other similar machines.
- Accurate determination of the electrical noise environment, including the ability to locate the noise sources with the bus couplers.
- Test can be performed by plant staff with a handheld portable instrument in about 15 minutes.
- Continuous monitoring version available to allow users to remotely determine stator winding condition via a modem, LAN or WAN.
- Can quantify and locate many sites of arcing/sparking/PD which are external to the generator.

8.2.2.2 Limitations of the low capacitance systems include:

- Because the small capacitance passes only high frequencies, the system reads only the portion of the winding, about the 10 to 15%, closest to the line terminals.
- Elimination of lower frequencies restricts amount of data available for analysis.
- Calibration of the line PD sensor to nearby versus distant PD activity within the winding is difficult due to the differences in response levels of nearby versus distant PD.

8.2.3 Intermediate Capacitance Line Sensors

Typically sensors of this category have capacitances in the range of 500 to 1000 pF. Adwel International, Cutler Hammer and others have used sensors of the range.

8.2.3.1 Strengths of intermediate capacitance systems include:

- Good compromise at mid range, with a wide range of frequencies for study and evaluation.
- Instrumentation can be quite flexible, but requires high level of experience to adjust the various controls.
- Moderate size data base.

8.2.3.2 Limitations of this system include:

- Instrumentation, although simple to use, requires a high levels of training and experience to visually separate the PD from other signals.
- Relatively few installations compared to that in Section 8.2.2.
- Unless test is performed by a well qualified person, there is a possibility that a good stator winding may be incorrectly assessed as being deteriorated, due to the influence of noise.
- Calibration of the line PD sensor to nearby versus distant PD activity within the winding is difficult due to the differences in response levels to nearby versus distant PD.

8.2.4 High Capacitance Line Sensors

Sensors of relatively high capacitance are now being used in testing generators. Some testing companies, including Alstom (ABB), have moved to sensors in the order of 9,000 pF. This allows PD signals from deep in the winding to be read by the system. However, these sensor pass a wide range of noise. Separation of PD signals from the noise signals tends to require sophisticated data screening instrumentation and final analysis is done by highly trained experts. As a result, immediate on-site interpretation of data is not possible. Suppliers of this type equipment, therefore, must provide skilled analysis from a central location.

However, rough data analysis can be performed by on-site instrumentation. This device will allow signally by indicator lights of the level of PD activity as safe, concern and needs attention. When a level of concern arises, a full set of information can be collected for expert analysis.

8.2.4.1 Strengths of this class of systems:

- Wide range of frequencies for study and evaluation.
- Ability to reach relatively deeper into winding.
- Data analyzed by automatic expert system and confirmed by a specialist in PD analysis.
- Substantial data bank available for reference.

8.2.4.2 Limitations of this class of systems:

- Require analysis by the equipment supplier.
- Data analysis is sophisticated, and results are not immediately available.
- Database is not in the public domain, and thus the analysis may appear subjective to the generator owner.
- Use of RFCT to read signal off sensor requires increased amplification of signal and may cause some lose of sensitivity.
- Calibration of the line PD sensor to nearby versus distant PD activity within the winding is difficult due to the differences in response levels to nearby versus distant PD.

8.2.5 Stator Slot Couplers

This type coupler is supplied only by one testing company, Iris Power Engineering, primarily in larger generators. These sensors have been installed on over 400 large turbine generators. The SSC is a two-port, directional electromagnetic coupler (or antenna). The SSC separates PD from all types of noise on the basis of pulse shape: a non-oscillatory pulse with a rise-time less than 6 ns is classified as PD. All other pulses are classed as noise, although they are recorded. The portable recording instrument records the magnitude, phase position and number of pulses. PD is recorded as well as various types of noise.

8.2.5.1 Strengths of the SSC system include:

- Very high noise rejection.
- With modest, available training, plant personnel can interpret output with some accuracy.
- Allows for distinguishing PD internal to the winding from PD nearby to the line terminal coupling device.

8.2.5.2 Limitations of the SSC system include:

- Couplers can only be installed with the rotor removed.
- Material and labor costs can be substantial for installing the typically 6 couplers.
- Couplers tend to be sensitive only to PD occurring in the slot in which they are installed, and the immediate endwinding.
- Elimination of lower frequencies restricts amount of data available for analysis.
- As yet only one slot coupler system is available in the industry.

8.3 Other Signal Sources

In addition to the EMI and PD test approaches discussed above, other sources of PD are being used in PD evaluation of stator winding condition. These sources include:

- Surge capacitor ground cable
- Stator slot RTDs
- Stator frame

Each of these approaches will be considered briefly below.

8.3.1 Surge Capacitors

The surge capacitor is designed to pass high frequencies to ground. If the case is grounded through a cable, an RFCT can be placed on the cable and PD signals read from this source. (If the surge capacitor case is mounted directly to station ground, there is not a discrete location for obtaining the signal.) The surge capacitor approach is not commonly taken since many units do not have surge capacitors, often the capacitor case may be directly grounded, and the frequency range of the capacitor may not be adequate.

8.3.2 Stator Slot RTDs

In North America, Cutler-Hammer has been the primary user of RTDs as a signal source. This work is considered by others to be somewhat controversial at this time. However, the evaluations reported thus far suggest that RTDs may be a useful source of PD signal, particularly for screening information and for differentiating between PD activity within the winding versus PD activity nearby to the line terminal.

8.3.2.1 Strengths of the RTD approach include:

- On those generators with an RTD in every slot, wide coverage of the winding is possible.
- Available equipment can discriminate with some accuracy between noise and true PD signals.
- Pattern recognition approaches allow detection and interpretation of external PD, such as patterns related to sparking or arcing of non-insulation components.
- Allows for distinguishing PD internal to the winding from PD nearby the line terminal coupling device.

8.3.2.2 Limitations of the RTD approach include:

- The RTD reads high frequency signals, and thus is sensitive only to PD in the near vicinity of the RTD.
- The type of cable shielding can have a significant impact on the signal from the RTD source, either from attenuation or from pickup of spurious signals.
- Modification of the RTD cable may be necessary before useful data can be obtained.
- Data interpretation requires considerable skill and training.

8.3.3 Stator Frame

Some success has been reported reading PD signals directly on the frame, or from the stator ground cable. Work in this area has been limited, and most experts in the field suggest that this approach to obtaining PD signals will have minimal value.

9 SUMMARY

The principle purpose of on-line PD testing is to give users additional knowledge of the stator winding insulation condition, beyond the limited instrumentation available from “standard” monitoring devices. Testing organizations have the ability to make generally useful recommendations to the owner. These recommendations contain qualifications which reflect the fact that PD technology is capable at this time of giving valuable but limited assessment of winding condition. (See Reference [1].)

The primary challenges associated with EMI/PD testing remain signal attenuation, noise rejection and data interpretation.

EMI/PD evaluation remains imperfect, like other common generator stator winding evaluation methods, i.e., megohmmeter, power factor test, hipot, core monitor and visual inspection. However, EMI/PD testing has several important strengths:

- Testing is done on-line at normal operating conditions.
- There is no risk to the winding under test, providing a reliable sensor is correctly installed. (There are, however, personnel safety considerations.)
- Data acquisition is relatively simple, with no large equipment required.
- Assessment of some common stator windings deterioration mechanisms can be monitored on-line.
- The on-line monitoring capability offers the possibility for removing a rapidly deteriorating unit from service before in-service failure occurs.
- On-line monitoring may provide assurance to allow a unit to continue to operate with higher than expected PD levels, providing no increasing PD trend is evident

Considering the inherent value of EMI/PD testing, and the present level of industry effort, continued growth in EMI/PD test capability can be expected. While unlikely to ever become the “perfect tool”, EMI/PD capability will continue to grow and become an increasingly useful tool for monitoring and evaluating stator windings.

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REFERENCE

[1] “Partial Discharge as a Stator Winding Evaluation Tool”, Clyde Maughan, Iris Conference, Scottsdale, AZ, USA, June 2005.