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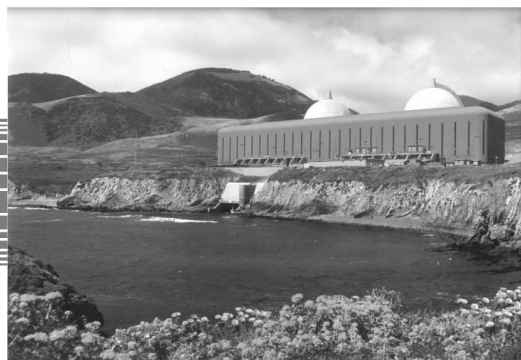
PARTIAL DISCHARGE TESTING OF ROTATING MACHINE STATOR WINDINGS

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PARTIAL DISCHARGE TESTING OF ROTATING MACHINE STATOR WINDINGS

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Technical Evaluation, December 2000

EPRI Project Manager

Jim Sharkey

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Abstract

This Technical Evaluation (TE) Report reviews the principles and practice of partial discharge (PD) testing as applied to rotating machine stator winding testing. A major objective of this TE Report is to introduce utility personnel, not necessarily expert in the field of PD measurements, to the basic theory of PD and industry-accepted methods of performing these tests. In addition, a review of current industry practices is presented.

The scope of this TE Report principally concerns the PD testing of large steam turbine generators in nuclear generating stations, although the technology is common to conventional, i.e., fossil and hydroelectric stations and many of the techniques can be applied to motors. The techniques described in this document cover all of the widely used methods in industry, both off- and on-line. Some techniques, which are either experimental or have not been widely applied, are omitted.

INTRODUCTION

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 focussed on the effects of localized gas breakdown, or PD, on the performance of solid insulating materials. From these studies arose the concept of using PD parameters as tools to aid assessment of insulation condition in power apparatus. While many utilities have for significant periods of time dating back to the 1950s used various off-line PD measurement methods, some of which will be discussed below, rapid growth in the penetration of PD-based condition monitoring technology did not occur until the mid to late 1980s. The increase in activity was fuelled in part by technology developments, that permitted non-specialists to perform PD measurements, even while the equipment was operating, and also by the growing acceptance within the electricity supply industry of the benefits of PD testing.

Partial discharge testing, specifically of rotating machines, has gained widespread acceptance as a valuable maintenance decision support tool for many utilities and manufacturers. Consequently, there are presently a relatively large number of suppliers of PD measurement technology and services. The question for many utilities, faced with this plethora of products, is which one provides the optimal solution to their condition monitoring needs. In the remainder of this document, basic information related to PD phenomena in rotating machines will be discussed. Further, the means to detect the PD signals will be outlined as well as some of the basic interpretation rules. Lastly, consideration will be given, based on existing industry practices, to the development of a PD monitoring program.

PARTIAL DISCHARGE THEORY

This section of the TE Report will discuss the basic theory underlying the mechanisms of partial discharge. In addition to a description of the pulse-type partial discharge, which is the parameter measured by the majority of partial discharge detectors, the so-called pulseless, or glow, discharge will also be discussed. Following these descriptions of the physical processes of partial discharge, circuit and electrostatic models of the partial discharge process will be introduced. However, in order to attain some consistency in the remainder of the text of this TE Report, the following sub-sections contain a description of commonly used terms in the partial discharge measurement field.

Pulse-Type Partial Discharge

Generally, for practical power apparatus we can consider three basic types of partial discharge, which are differentiated by electrode and geometric configuration. These conditions can be classified as,

- internal discharges, where the partial discharge occurs at a gaseous void in the bulk of the insulation material,
- surface discharges, where the partial discharge occurs at the surface of the dielectric
- corona discharges, which occur at sharp, metallic protrusions.

The latter term has, in the past, been used interchangeably with partial discharge, especially in North America. For the remainder of this document corona will be used only as defined above. Any process involving at least one dielectric covered electrode, will be termed a partial discharge.

Internal Discharges

The exact conditions under which a gas gap, bounded by a solid dielectric, breaks down to cause a partial discharge are variable and complex. Among the many parameters that are known to influence breakdown conditions are,

- the presence of free electrons to initiate the breakdown,
- the dimensions and shape of the void,
- the type, pressure and temperature of the gas in the void, and,
- the condition of the surface of the void walls.

Initiatory electrons are critical to the breakdown process and directly influence the voltage at which partial discharge inception occurs. Sources of free electrons include cosmic radiation, x-rays and ultraviolet light. In the absence of a ready supply of free electrons, the gas gap must be sufficiently overvolted such that the electric field is sufficient to produce enough free electrons

by collision ionization. This difference in the discharge inception voltage, with and without a sufficient number of free electrons, accounts for the phenomenon known as statistical time lag.

The shape of the void will influence the stress in the cavity and therefore the breakdown characteristics. For simple, idealized cases, the electric stress in the void can be estimated [1]. If a flat cavity is oriented normal to the electric field, the electric stress in the cavity will be that of the surrounding solid insulation multiplied by the dielectric constant of the solid dielectric. In the case of a spherical cavity, the stress in the void tends to be 1.5 times that in the solid dielectric, if the dielectric constant of the solid insulation is large. Geometric effects, i.e., disposition of the void with respect to the high and low voltage electrodes will be dealt with in sub-section 4.6.2.

The dimensions, gas type and pressure will influence the breakdown voltage in the void. Consequently, an approximate estimate of the breakdown voltage of a void can be obtained by consulting the Paschen curve for a given gas [1], Figure. The Paschen curve shows the breakdown voltage of a gap as function of electrode spacing times gas density and may be modified to show the electric stress at which the gas breaks down, Figure 2. However, in reality, the use of Paschen curve data to predict partial discharge inception in dielectric bounded voids is very limited. This limitation is due to the influence of the void walls that may contain deposited surface charge, from previous discharge events, or be partially conducting. Further, there may not be a supply of initiatory electrons and, generally, the parameters of the gas are not well characterized nor are they stable. Paschen curve data, by contrast, are obtained from gas breakdown between two metal electrodes under well-controlled conditions, including a steady supply of free electrons.

The above considerations demonstrate that a rigorous description of the partial discharge process in a void is very complex. Consequently, only an outline of the key concepts will be given in this document. For a more fundamental discussion of the problem, the reader is referred to, for example, the work of Crichton et al [2]. Qualitatively, one can consider the case of a void in a solid dielectric between two electrodes. If an increasing ac voltage is applied across the electrodes then at some critical value of the electric field, or the applied voltage, the so-called discharge inception voltage, the gas within the void will break down. The charged species, electrons and positive ions, resulting from the breakdown will redistribute within the void to cancel the electric field and at some point the discharge will extinguish due to the reduction in field. The charge flow caused by the charge redistribution produces the externally measurable partial discharge signal. The time-scale of this phenomenon is in the range of a few nanoseconds. Under the action of the applied ac voltage, the field in the void will again increase to the critical value required to again break down the gaseous medium in the void. This value of the field, or applied voltage may not be the same as for the previous discharge, because of the role of the void walls in changing the discharge conditions. Consequently, some variation in partial discharge magnitudes may be observed even for the case of discharge in a single void. An idealized partial discharge sequence over one power frequency cycle is illustrated in Figure 3.

The inception and extinction voltages of partial discharge can differ significantly. Normally, the inception voltage is higher than the extinction voltage because of the requirement of a supply of

free electrons to initiate the process. Conversely, as the voltage is reduced there will usually be an abundant supply of charged species drifting in the void, therefore the voltage at which the discharge is self-sustaining will be lower than the inception voltage.

Surface Discharges

In this case the partial discharges are occurring at the interface between metallic and dielectric-covered electrodes. Mason [3] found that, for the case of non-ventilated voids in a solid dielectric, the breakdown voltage was approximately 10 to 20% lower than that determined from measurements obtained with parallel-plate metallic electrodes. However, for the case of parallel-plate electrodes in which one of the electrodes was covered with a dielectric material, the breakdown voltage was found to be 25% lower. For both the latter two cases, involving insulating surfaces, the decrease in breakdown voltage is caused by field distortion due to the dielectric boundaries. In the situation in which only one of the electrodes is dielectric-covered, the field distortion is enhanced by the asymmetry of the whole electrode system.

Surface, or interfacial, discharge phenomena are more difficult to model due to this asymmetry and because the electric field in the gas gap is dependent not only on the potential across the electrodes but also the surface charge distribution on the dielectric. Furthermore, the occurrence of a discharge does not necessarily result in a complete relaxation of the field across the electrodes. This is because of the relatively low mobility of charge trapped on the surface of the dielectric. Consequently, and depending upon the surface area available, multiple discharge sites may be present on the surface of the insulation.

Corona Discharge

Corona discharge can be considered as a partial discharge that occurs at, or around, sharp metallic or insulating protrusions. In this case, the partial discharge does not progress to breakdown because the field decreases rapidly as a function of distance from the highly stressed point. This type of discharge, in many practical cases, is viewed as a nuisance or noise, however, in other situations it can provide valuable information regarding the condition of an insulation system.

Due to the ionization process, the conductor can be considered to grow or extend. Electrons will tend to rapidly drift toward the positive conductor whereas the flow of heavy positive ions will tend to proceed much more slowly. While the time scale for electron migration is in the range of nanoseconds to microseconds, positive ion drift can require milliseconds and greater. Consequently, many discharge detection systems, due to their bandwidth, only detect the electronic component of the signal. Corona signals tend to be quite consistent and repetitious in appearance. This is because little or no charge trapping occurs in this type of system. Thus, as the charge carriers are swept out of the immediate electrically stressed region, or recombine, the region returns to the initial conditions necessary to produce the next corona pulse.

The differences in ionic mobilities also produce a polarity effect in the behavior of the corona discharge. In air, negative partial discharges will normally appear before positive discharges.

The space charge produced by the negative corona effectively grades the conductor resulting in an increase in the inception voltage of the positive corona.

Pulseless Discharge

Under certain conditions, the discharge process within the voids may assume a pseudoglow or even a pulseless glow characteristic [1]. Pseudoglow discharges exhibit features common to both pulseless glow and pulse-type discharges. This characteristic is because although pseudoglow discharges exhibit a visual glow they consist of small pulses of long rise time. Due to the bandwidth of most pulse-type partial discharge detectors, such pseudoglow discharges will not normally be detected unless bridge methods are used. However, this lack of sensitivity to this type of phenomenon is not a serious problem because all three phenomena tend to coexist, i.e., pseudoglow and pulseless glow discharges are unlikely to be occurring in the absence of pulse discharges. Consequently, although pulse-type detectors may not be registering all of the partial discharge activity in the object under test, not every event associated with discharge has to be measured to obtain an assessment of the insulation condition.

Partial Discharge Models

A void can be considered as a gas-filled cavity in the bulk of the groundwall insulation system. The void contents will be of a lower permittivity, generally 1.0, than the heavily filled, organic solid insulation. The difference in permittivities results in an enhanced electrical field within the void so that, generally, the gas in the void breaks down before the solid insulation material. The detailed features of this PD event will be, as previously noted, a function of the shape, size and distribution of the voids. Further, the PD process will be affected by the PD itself, i.e., void characteristics such as temperature, pressure, wall conductivity, etc., will change under the action of PD. Thus, the PD process must be viewed as a dynamic process.

Partial discharges are extremely fast temporal phenomena. Typically, rise times are of the order of 1 ns or less, with pulse widths in the range of 1 to 5 ns. Presently, with the fastest analog oscilloscopes available, rise times as low as 350 ps have been measured in laboratory environment [4]. Of course, this raises the question of whether the rise time may be faster because at this speed the measurement becomes bandwidth-limited. These rise times refer to the transient or electronic component of the PD. In addition to the fast electronic component, there is also a much slower ionic contribution that can persist into the millisecond (ms) range. Because it is virtually impossible to measure both components, measurement systems usually are either designed to optimize detection of one or the other contribution. Those systems that detect, and attempt to retain the temporal information inherent in, the fast transient are generally referred to as ultra wideband measurements. Instruments, which essentially integrate the PD pulse to obtain the so-called apparent charge, are known as integrating or narrow band systems. These definitions are not completely rigorous as some refer to integrating measurements as wide band. Typically, these latter instruments are the ones which are commercially available from a wide variety of manufacturers and which have enjoyed widespread use and success. Generally, their measurement bandwidth ranges from a few kHz to about 1 MHz, depending upon the manufacturer. These types of measurement system are generally used in off-line PD tests and will

be dealt with later in the paper. Ultra wideband measurements have found application in the areas of on-line PD measurement for rotating machines and gas insulated switchgear (GIS) [5].

In most practical equipment, the extremely fast rise times and pulse widths described above are seldom observed. This is because the PD pulse energy propagates in the dielectric medium of the apparatus. Depending upon the type of insulation, this medium may be quite lossy resulting in significant attenuation of the PD pulse. The attenuation is frequency dependent with the higher frequencies being much more severely attenuated. Furthermore, most practical equipment is not configured as a simple transmission line with a well defined surge impedance, and thus further degradation of the pulse results from reflection and refraction processes at these impedance mismatches. Consequently, fast phenomena are generally only observed in systems such as GIS [4] or where the detection impedance can be placed close to the source of PD [5]. Hence, any consideration of pulse shape measured at the terminals of the device under test should account for the external circuit i.e., the apparatus being tested and the means of PD detection.

A rigorous description of currently accepted models to describe PD phenomena is beyond the scope of this paper. The aim here is to summarize the main results and implications from the theory. Presently, there are two basic models of PD phenomena; the so-called abc model due to Whitehead [6] and Kreuger [7] and an electrostatic model due to Pedersen [8]. The latter model is a relatively recent development that is still the subject of research by many groups around the world.

The ABC Model

The abc model uses a circuit theory approach to the problem of modeling PD processes. In this model, the case of a gaseous occlusion in a solid dielectric is represented as a capacitance network. A voltage is applied to the terminals of the network, a fraction of which will appear across the void. When the voltage is sufficient to break down the gas gap, the DIV, the voltage across the void collapses to approximately the value required to sustain the discharge. The charged species which remain in the void drift to the walls of the void causing a redistribution of charge. The net charge flow resulting from this process produces the externally measured signal. No further discharges will take place until the applied voltage again exceeds the DIV. In the case where the applied voltage is much higher than the DIV, multiple discharges will occur. For an alternating voltage, PD will occur on each half cycle. This relatively simple model has been used successfully for the past 40 years to predict PD behavior in a number of geometries and systems. However, there are a number of limitations to the approach due to the tendency to associate the model with the physical basis for PD. As Pedersen pointed out [8] this may lead to the situation in which concepts are introduced which may have profound implications for the circuit model but which are, from a dielectric sense, completely meaningless. One of the consequences of the circuit model is that the concept of void capacitance is introduced which strictly speaking is not correct. Furthermore, the capacitance values referred to in the abc model cannot be calculated. Consequently, prediction of PD magnitudes for a prescribed defect geometry cannot be readily calculated. However, despite these shortcomings, in many cases the abc model is still a valid approach.

The Pedersen Model

In order to remedy some the difficulties with the abc model, Pedersen [8] formulated the problem using classical electrostatic theory. This approach leads to expressions for the apparent charge and current due to PD for given defect geometries. In order to perform these calculations, the following data are required,

- the dimensions of the void as well as the minimum electric field required to cause breakdown in the cavity as a function of gas type and pressure
- the change in electric field in the void due to the discharge
- an expression relating the voltage across the sample and the electric field in the void to geometric factors
- the change in charge at the electrodes caused by the discharge as a function of system geometry and void contents.

The power of this technique is that PD magnitudes from specific defect geometries can now be quantitatively be determined. Furthermore, the expressions thus developed by Pedersen [8] show conclusively that a geometric scaling effect exists. This finding is of profound importance for practical insulating systems. What this conclusion implies is that detection of a void in a solid dielectric will be affected by the size of the dielectric component. For example, a defect that causes a PD pulse with a magnitude of 10 pC in one system will produce a PD magnitude of 5 pC in a system twice the size, if the defect remains in the same place. Consequently, this means that for equipment which operates at the highest voltages, and therefore is physically large, very high sensitivity measurements would be required to achieve the same quality control objectives available in lower voltage equipment.

Having discussed the two main theories of PD generation in cavities in solid dielectrics, a qualitative description of the PD behavior due to common problems in rotating machines is outlined.

PARTIAL DISCHARGE IN ROTATING MACHINES

Partial discharge occurs, to a greater or lesser extent, in the stator windings of most high voltage motors and generators. However, unlike organic insulation systems such as epoxy castings, used in gas insulated substation equipment, and cross-linked polyethylene (XLPE), used in distribution and transmission cables, stator winding insulation is filled with mica. The presence of mica, which is one of the most partial discharge resistant materials known, permits reliable operation of the machine even with significant levels of partial discharge at the operating voltage. Consequently, partial discharge in the stator windings of high voltage rotating machines may be viewed as,

- a deterioration mechanism, or
- a symptom of problems caused by, for example, thermal or mechanical stresses.

From a practical point of view, the latter of the two possibilities is of most interest to electric utilities or other users of high voltage rotating machines. This is because stator windings rarely fail due to the action of internal partial discharge alone. Even in cases where significant internal partial discharge activity has been detected, it is unlikely that immediate action will be taken simply because the only remedy is to replace bars or coils or perform a complete rewind. Often the maintenance engineer will use the presence of high levels of partial discharge to optimize major maintenance scheduling.

The principal use of partial discharge measurements in the utility industry is to monitor the effects of the operating stresses on the insulation system. In general, the four sources of partial discharge in rotating machine stator windings of most interest are,

- internal partial discharge in the groundwall insulation,
- surface discharges between the semiconductive armour of the bar or coil and the core iron,
- partial discharge at the interface between the copper conductors and the strand, turn or groundwall insulation, and,
- surface discharges in the stator endwindings.

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

Effects of Partial Discharge on Stator Insulation

Depending upon the location of the partial discharge source, various types of degradation will occur depending upon the type of material. As stated above, organic insulating materials have little resistance to partial discharge. Consequently, the organic components of the stator insulation, slot support and stress control systems are preferentially attacked under the action of

partial discharges. A partial discharge produces a number of species 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, there are electrons, photons and more exotic species such as Auger electrons produced. Further, the process usually results in heating of the void. In turn, the presence of these charged species, 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 sufficiently above the inception voltage, and 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 further change, for example, 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, failure is more likely to result from voids at the copper/insulation interface. In cases, where this type of deterioration has been observed in field, or laboratory, or laboratory aged samples, the failure path, between the initiation and puncture sites, tends to meander, or track, around the mica flakes or platelets, through the organic resin binder. Only in severely aged insulation systems is the mica consumed, normally by thermal as opposed to electrical degradation.

Partial Discharge as a Symptom of Other Defects

Although partial discharge can be a significant aging mechanism in stator winding insulation, due to 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 there is a 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 aid to maintenance planning decisions. This is because, as noted above, the deterioration of the stator electrical insulation system due to thermal, electrical, environmental or mechanical stresses can be detected by partial discharge tests. Further, the types of degradation can result in unique partial discharge characteristics thus enhancing the diagnostic power of the measurements.

Mechanisms and Consequences of Partial Discharge in Rotating Machines

Each of the principal deterioration mechanisms associated with the stator insulation, slot support and stress control system gives rise to characteristic partial discharge behavior. The purpose of this part of the TE Report is to provide a qualitative description of the mechanisms and their effect on the observed partial discharge activity.

Internal Groundwall Insulation Delamination

Prior to developing the theory underlying void discharge, a few comments on some significant factors affecting the interpretation of partial discharge are appropriate. The potential diagnostic capabilities of partial discharge testing can only be fully realized with the following data,

- machine design information,
- operation and maintenance history, and
- the type, manufacturer and vintage of the insulation system

This information is essential to enable proper conclusions to be made regarding the condition of the insulation system because age alone is a notoriously poor index of stator winding insulation integrity. For example, an older winding in which the resin component is an asphalt compound, i.e., a thermoplastic system, normally will exhibit significant partial discharge activity due to internal groundwall delamination caused by thermal migration of the resin. However, most systems of this type contain a very high volume of mica, usually of the large flake type. Hence, this type of system is very resistant to failure due to partial discharge alone. Further, the propensity of this type of insulation system to swell under the action of thermal stress can result in the coil or bar being locked into the slot. Thus, slot discharge problems were relatively uncommon with these older insulation systems which tended to conform to the slot shape. Of course, the dry, embrittled characteristics of the insulation due to thermal migration of the binder resin, resulted in machines which were vulnerable to failure caused by mechanical movement of the conductors, e.g. interturn failures in multiterm machines, or from short circuit forces associated with close-in faults. Rewedging of machines of this type in such a state of deterioration is usually not recommended because of the risk of damaging the brittle groundwall insulation.

Internal voids, in the groundwall insulation, result either from the manufacturing process or from delamination due to operating thermal and mechanical stresses. In general, a void-free stator insulation system is practically not achievable. The reasons for this are due to inevitable process control difficulties associated with taping, impregnating, pressing and curing the insulation system. Normally, quality control procedures and testing minimize the presence of gross defects in the groundwall insulation, however, usually some voids remain. In some cases, due to the operating stresses of the machine these voids may result in further delamination that may have more serious consequences for the integrity of the insulation system. If these voids occur at the interface between copper and groundwall insulation, e.g., due to the effects of load cycling in indirect-cooled machines, failure can take place within a relatively short period of time. However, breakdown of insulation due to voids distributed in the bulk of the insulation is relatively rare. In both cases there is little, or no, maintenance that can be performed to reverse the degradation. Usually, the only course of action is to determine the optimum time to rewind the machine.

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. This problem can originate due to inadequacies in processing or from the differential axial expansion between the copper conductors and the insulation that occurs due to the I^2R losses. Ultimately, failure of the winding can result from one of two processes. If the delamination between copper and insulation is sufficiently widespread, the mechanical integrity of the bar or coil will be compromised. In the case of multiturn coils this can lead to relative movement between turns and consequently abrasion of the turn insulation leading eventually to interturn insulation breakdown. Similarly, erosion of the strand insulation in Roebel bars can result in excessive circulating currents and failure due to overheating. A second type of failure mechanism, found on multiturn coils, results from the occurrence of PD in the void formed by the delamination. Over a sufficiently long period of time carbonization of the insulation material can lead to interturn short circuits and consequently, failure of the groundwall insulation system.

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 above 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. This asymmetry produces a polarity effect that results in the predominance of negative PD pulses. Such a result can be predicted from gas discharge theory and some consideration of the charge mobility on the electrodes. On the insulating surface, the mobility of positive ions is much lower than that for negative species. Consequently, when the conductor is at high voltage, PD will occur preferentially on the negative half-cycle as negative species will be pushed out into the gas gap toward the positively charged insulating surface. Observation of a negative polarity dependence usually indicates that the bond between the conductor stack 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 can retard the deterioration process somewhat.

Slot Discharge

Slot discharge is the term generically applied to PD occurring between the semiconductive surface coating of the bar or coil and the grounded core iron. There are essentially two types of slot discharge which result from different mechanisms and which can have more or less 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, failure of hydrogen-cooled machines due to this mechanism has also occurred [9].

Slot discharge can originate either due to radial movement between the bar or coil surface and the core iron or because of mechanical or electrochemical erosion of the semiconductive coating. If the coil or bar becomes loose in the slot, due to a decrease in the pressures exerted by the wedges and, if used, the side packing, mechanical, and hence electrical, contact can be lost between the coil/bar surface and the core iron. The loss of contact will, generally, be quite localized and

problems can result if loosening of the winding causes 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 would in turn result in heating, burning or arcing which would inevitably erode both the semicon and, eventually if not arrested, the groundwall insulation.

A somewhat different mechanism, resulting in slot discharge, is when the relative movement between coil or bar and core causes abrasion of the semiconductive coating. Usually, because of the difficulty in keeping the core laminations in exact registration, this type of damage is quite localized. Abrasion of this nature can result in the production of isolated patches of semicon. Again, due to the effects of capacitive charging a substantial surface charge will be induced. If sufficient potential is built up on the isolated semicon, the gap between it and the core iron will break down. Because relatively large surface areas can be involved in this mechanism, significant energies are available in the discharge. Consequently, further erosion of the semiconductive coating and the groundwall insulation can occur. This mechanism, if not arrested or retarded can cause breakdown of the groundwall insulation and machine failure.

This mechanism can be treated by either restoring the semicon or by rewedging. The former repair is not completely effective as it is not permanent, however, it has been shown to increase the life of the winding [10].

Again, this geometry is asymmetric and hence a polarity effect will be observed. In this case, there will be a predominance of positive PD pulses. This is because, unlike the above situation for the defect at the conductor/insulation interface, the metallic electrode is grounded. Consequently, the relatively immobile positive space charge on the surface of the stator insulation will result in localized breakdown occurring predominantly on the positive half-cycle.

Endwinding Discharge

Partial discharges occurring in the endwinding can be either due to voids in the insulation or surface discharges due to contamination, poorly designed interphase clearances or the semicon/stress grading junction. Consequently, most of the discussion relevant to internal and external discharges outlined above apply. 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 is plotted as a function of power frequency phase angle, it is phase shifted because in many cases the discharges are taking place between phases rather than between a high voltage conductor and ground.

PARTIAL DISCHARGE MEASUREMENT CALIBRATION

A significant problem with PD measurement techniques is that results for different machines cannot be compared on the basis of PD readings. 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 available.

The reason for the problem is the lack of a standard calibration procedure that would enable test engineers to normalize their measuring equipment against a machine independent standard. This deficiency in PD calibration is also likely to become an issue with the proliferation of digital techniques applied to PD measurements. The fundamental problems inherent in quantifying a PD pulse due to the interaction between the pulse and the stator winding are briefly reviewed below.

Partial discharge tests are routinely performed on shielded power cables, switchgear, transformers and rotating machines. In certain types of apparatus, ad hoc standards exist which define an acceptable level of PD activity. For example, in transformers a maximum acceptable radio influence voltage (RIV) level is defined. In the case of some shielded power cables the discharge extinction voltage (DEV) is used as an index of acceptability [11]. Factory testing of gas-insulated switchgear is typically carried out to a minimum acceptable PD level of 5 pC.

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 on- and off-line PD detection schemes as long as the results for these machines are viewed from a single machine trending basis. That is, single sets of measurement results cannot be interpreted with confidence in isolation from other results for the same machine under similar test conditions and results from one machine cannot in general be compared with results from other machines. However, the availability of a standard transportable calibration method is desirable from two perspectives.

First, is the need to have a calibration standard for off-line acceptance and maintenance testing. The requirement for this is twofold. Presently, there are no PD based acceptance criteria for rotating machine stator windings. Second, there is no basis for making comparisons of the quality of stator winding insulation systems using PD measurements. Consequently, there is no objective PD standard upon which a measure of the long term reliability or integrity can be based. Presently, such judgments are made on the basis of experience and intuition. The reasons for this inability to obtain a reliable and repeatable calibration are outlined below. Presently, all that can be done is to establish a "calibration" for a machine on a unique basis, i.e. the "calibration" is only valid for one machine using the same measuring equipment and techniques, and in some cases the same test personnel. A transportable calibration standard, which would enable repeatable PD data to be obtained on a machine independent basis, does not, as yet, exist. In the remainder of this communication, the basic causes of the difficulties are discussed.

A further concern regarding this lack of a standard calibration, is that of the manufacturer and user of digitally based PD measurement equipment. Implicit in the dearth of a calibration technique is that there is uncertainty in the quality of the data derived by PD measurements. This ambiguity, while representing a problem for analogue techniques, can be compounded in a digital system due to the error sources inherent in digitizing devices. Therefore, an exposition of the sources of PD calibration difficulties, as well as possible solutions, are also of interest to instrumentation designers.

Basic Problems

The fundamental difficulty in attempting to establish a calibration standard for stator windings is, in part, the lack of an adequate model of pulse propagation through such a system. A number of workers in this area, e.g. Wilson et al [12], Henriksen et al [13], Wright et al [14], Miller and Hogg [15], have approached this problem from a variety of experimental and analytical points of view. However, despite increasing the basic understanding of what happens to a PD pulse as it propagates through a stator winding there is, as yet, no definitive theory to quantitatively describe the process. The lack of a high frequency mathematical model of the stator winding means that no methods exist for predicting the temporal or frequency characteristics of a PD pulse as it appears at the terminals of the machine. The only available method of obtaining this data is by experiment.

However, the consensus reached by the above cited authors [12 - 15], is that there are two main fundamental barriers to a repeatable calibration method. These are,

- the severe attenuation of high frequency signals in stator windings
- the geometry of the winding.

The physical causes of these effects and the consequent difficulties they cause in attempting to derive a calibration standard are discussed below. The following discussion will demonstrate how these two basic factors affect other practical considerations such as different measurement techniques, coupling methods, etc.

Attenuation Problems

The difficulties imposed by the propensity of stator windings to rapidly attenuate the high frequency components of PD signals are well documented [12, 13]. Recognizing the high frequency attenuation factor, imposes practical constraints on the selection of bandwidth of any PD detection system. In some on-line techniques [16] the attenuation of high frequency signals is used to enhance the capability of the PD detection system to detect PD pulses in the presence of severe electrical noise. However, the improved signal-to-noise ratio is gained at the expense of loss of widespread coverage of the entire stator winding. A high frequency coupler would produce results with a sensitivity biased towards the coils or bars located closest to the detector. In off-line measurements, generally the electrical noise levels are very much lower, especially when performed in the factory as part of the acceptance process. Hence, there is little point in

using a very high frequency technique for such testing. In order to satisfy the need for a test of the integrity of the whole winding the bandwidth of the PD coupling device should be chosen low enough to enable coverage of the whole winding in PD terms.

Geometrical Aspects

The geometry of the winding is also a critical factor for two principal reasons. First, there is the problem of resonance. Assuming that a stator winding can be treated as a transmission line, then each coil/bar will have an associated inductance and capacitance. Depending upon the length of the coil/bar and the number of coils/bars connected to form the parallel path, every winding 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. Kemp et al [17], from frequency response measurements and a simple resonant frequency calculation quite clearly demonstrated this effect.

A further consequence of winding geometry is the overhang region where the coil/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 coil/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 overhang region the bar/coil 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 coils/bars and further propagated into the stator winding. This PD pulse crosstalk 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 should be paid to the core end and length.

Unlike the resonance problem there may potentially be less variability of the impedance mismatch from machine to machine. Measurements of the surge impedance of a stator bar within a conductive slot falls within the range 20 - 30 Ω . These values are corroborated by a simple calculation of surge impedance assuming that the bar in the slot can be approximated by a coaxial system. The lack of variability of this parameter, if it can be proved to be general, offers the possibility of applying an analytically derived correction factor to account for the transition region.

Other Contributing Factors

In addition to winding geometry, other construction details may also require consideration. Whether the stator winding is composed of multi turn coils (mainly motors and small hydraulic generators) or Roebel bars (steam turbine generators and large hydraulic generators) will affect the inductance of the winding. This in turn can have an effect on the resonance frequencies discussed above. Further variables to be considered are the materials of construction. In this case, because the PD pulse propagates in the dielectric medium, the effect of the components of the stator insulation system should be considered. To date measurements performed on windings made from a range of materials from thermoplastic to thermosetting have not shown any materials related effects. This is probably because such effects are second order, and quite probably obscured by phenomena such as high frequency attenuation.

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 more fundamental issue is the degree to which the calibration pulse approximates a real PD pulse. However, quantifying the true temporal characteristics of a PD pulse is a research field in its own right [4] and further discussion is beyond the scope of this paper. Presently most work on calibration aspects is performed with pulse generators with variable pulse rise time and pulse width.

PARTIAL DISCHARGE MEASUREMENT INSTRUMENTATION BASICS

This section describes PD measurement techniques that are commonly used on rotating machine stator windings. Specific systems, manufactured by commercial organizations or used by certain utilities will be identified in section 10 dealing with industry practice. The purpose of this section is to identify the common components of any PD measuring system, discuss the merits of on- and off-line testing, and to identify the basic techniques found commonly in industry.

Introduction

All PD measurement equipment can be divided into,

- a detector,
- a display and/or recording device

At the most basic level, a human being can be considered as a PD measurement system, e.g., the blackout test, section 9.1, 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 [5] or incorporate statistical or neural network-based post-processing [18]. The following discussion will define more completely the types of detector and display/recording devices typically used in PD measurement systems.

Straight Detection Methods

In these types of systems, a measuring impedance is connected to the test object by means of one of the connection schemes illustrated in Figure 4 a, b, c, etc. Normally, in stator winding PD testing, the measuring impedance is connected as shown in Figure 4 (a). In this case, some form of impedance, e.g., an RLC network, is connected between the low voltage electrode of the coupling capacitor and ground. One function of the high voltage coupling capacitor is to present a high impedance to the high voltage power frequency signal while passing the high frequency PD signals. In some connection schemes, Figure 4 (b), the measuring impedance is connected in series with the test object, i.e. the coupler will be at the same potential as the test object. This method, by virtue of eliminating ground paths, offers advantages in being able to reject ground loop-induced electrical interference. However, in order to ensure personnel and equipment safety, such schemes normally employ optical isolation that increases the complexity and the cost of the method. In yet another variant of this method, an impedance is introduced between the low voltage electrode and ground, Figure 4 (c). This latter method is often employed in laboratory-based ultra wideband studies of PD phenomena.

Of the above methods, the most commonly employed is that illustrated in Figure 4 (a). Most commercial systems as well as those developed in-house by some utilities use this variant. The basic difference between these various systems depends upon the measuring impedance used. In many cases, the impedance consists of a RC or RLC network, which can also be termed an input

unit or, in the case of European experience, a quadripole. Essentially, the occurrence of a PD pulse shocks the network and this response is fed to an amplifier. Obviously, these networks can be considered filters, therefore selection of the type of filter should take into account the test object and the frequency response of the amplifier. Thus, careful attention should be paid to the frequency response of the total system, i.e., test object, coupling impedance, amplifier and display/record device. For example, there is little point designing a coupling impedance with a frequency response exceeding the capability of the display device, e.g., an oscilloscope. A further important, and sometimes controversial, point for the case of stator windings, is that these objects because of their distributed inductance and capacitance are inherently low pass filters. Thus, if the aim of the measurement is to detect PD from all parts of the winding, the so-called ultra wideband systems, with bandwidths in the hundreds of MHz range would not be appropriate. The selection of appropriate bandwidth will be dealt with later. The overwhelming majority of commercial systems employ detectors with bandwidths in the range of a few kHz up to 1 MHz.

Balanced Detection Methods

Balanced detection is similar to straight detection except that additional measures are employed to reject electrical interference from sources such as the power supply, test leads and other connected equipment. The balanced method is essentially a bridge technique and two forms are illustrated in Figure 5 (a) and (b). The circuit shown in Figure 5 (a) employs a Schering bridge. A pulse transformer is connected across the measurement points of the bridge such that when the bridge is balanced, an external noise pulse occurs, a pulse is induced in both of the low voltage resistive arms of the bridge and the noise is minimized by the pulse transformer. In the case of a valid PD pulse in the test object, a voltage pulse is induced in only the detector impedance. An improvement on this method, that can only reject interference down to about 20 dB, uses a capacitor, with a dielectric loss similar to that of the test object, instead of a standard capacitor [7]. Balanced detection methods will be discussed further in this section when specific instrumentation is discussed.

Loss Detection Methods

Loss detection methods employ a Schering or transformer ratio-arm bridge to measure the losses in a dielectric material. In both types of bridge, balance is achieved at the specified voltage level and error signal, or out of phase component of the loss current, is read as the dielectric loss, also known as the power or dissipation factor. The origin of the losses due to PD were described above in section 4, i.e., when a PD pulse occurs, energy is dissipated due to heat, light and sound inherent in the PD process. Consequently, dissipation factor should be proportional to void content in the solid dielectric material. Normally, in high voltage stator windings the so-called dissipation factor tip-up is measured. This quantity refers to the difference in dissipation factor between a high and a low voltage. In practice, the lower voltage is selected below a level at which PD inception is likely to occur, usually about 20% of the nominal line-to-ground voltage of the winding. Usually, but not always, the higher voltage is the nominal line-to-ground operating voltage of the machine. Dissipation factor measurements are routinely used to assess the uniformity of processing of coils and bars [19].

Despite the widespread, and long, use of loss detection methods there are a number of disadvantages.

- the contribution of the solid insulation, which is strongly dependent on resin chemistry, cannot be separated from the loss component associated with void discharge,
- the total loss, or dissipation factor, is averaged over the whole coil, bar or winding, i.e., there is no possibility of locating the source of PD, nor can the contribution of one large void, a potentially fatal defect, be discriminated from that of hundreds of small voids, a relatively benign problem,
- interpretation of dissipation factor measurements on complete windings is made difficult by the presence of nonlinear stress grading coatings or tapes in the end regions of the winding. In some cases, depending on the formulation of materials used or the ratio of coated overhang to slot cell length, the contribution of the stress grading compounds can predominate.

Consequently, while such techniques continue to be used, and will be examined in detail below, when assessing the condition of the stator insulation of complete windings, the interpretation of the data should be treated with caution.

Detection Methods Employing Antennae

Thus far, the discussion on detectors has focused on methods that normally employ some form of galvanic connection between the test object and the coupling impedance. In addition to these techniques, various types of antennae or inductively coupled devices have been employed by various groups and are the basis for many commonly accepted practices for PD detection within industry. These devices have been used to implement a variety of off- and on-line PD detection techniques as well as probe methods for location of significant PD sources. These implementations will be discussed in more detailed in subsequent sub-sections. However, generally, these types of sensors can be categorized as,

- radio frequency current transformers which have frequency responses in the range of 100 kHz to 300 MHz,
- stripline antennae, with frequency responses stretching into the GHz band, and
- search coils, with bandwidths in the range of 5 MHz.

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.

Oscilloscopes

Oscilloscopes are 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, preferably greater, than the bandwidth of the detector. Alternatively, the bandwidth required can be obtained from the simple relationship, $BW = 0.3/\text{rise time (ns)}$. Thus, to observe a 1 ns rise time pulse on an oscilloscope without introducing distortion requires a bandwidth of at least 300 MHz.

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 throughput, 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.

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. Note that this is a distinctly different operation than that performed by a fast Fourier transform (FFT). Again, just as for the case of an oscilloscope, careful attention should be paid to the bandwidth of the spectrum analyzer that should be equal to or greater than that of the coupling device. Nowadays, instruments with bandwidths from a few kHz to a few GHz are readily available commercially, however, measurements made at the extreme low end of the frequency response need to be treated with some caution. Spectrum analyzers have been applied to measurements of the frequency content of PD pulses as well as apparatus such as GIS [20] and rotating machines [21]. From the above discussion on pulse propagation and attenuation in rotating machines stator windings, section 6, the resultant frequency spectrum is usually very complex due to resonances in the winding structure. In some cases, usually with an experienced observer, this complex frequency response may be used to determine the source of the PD.

Integrating Detectors

The majority of commercially available dedicated PD measuring instruments fall within this category. These instruments measure the so-called apparent charge and, according to various standards [22], can be calibrated, although in reality the calibration is a scaling. 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. However, IEC 270 [22] defines more precisely the bandwidths of what are termed narrow and wide band detectors,

Narrow band

$$9 \text{ kHz} \leq \Delta f \leq 30 \text{ kHz}$$

$$50 \text{ kHz} \leq f_c \leq 1 \text{ MHz}$$

where, Δf is the bandwidth and f_c is the centre frequency.

Wide band

In this case, upper and lower frequencies, f_1 and f_2 respectively are defined as well as the bandwidth, Δf , such that,

$$30 \text{ kHz} \leq f_1 \leq 100 \text{ kHz};$$

$$f_2 \leq 500 \text{ kHz};$$

$$100 \text{ kHz} \leq \Delta f \leq 400 \text{ kHz}.$$

Quasi-Peak Pulse Meters and Radio Influence Voltage (RIV) Meters

The largest void 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 s to several seconds. A simple analog or digital meter displays the peak magnitude in terms of microvolts, milliamps or pC.

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 [23, 24]. 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. Early work on this method of measurement [23] used multichannel analyzers of the type encountered in nuclear physics. The number of channels commonly used was in the range of 256 to 8192. A typical means of determining the pulse height was to trigger a clock and count the number of clock cycles until the pulse fell below a certain threshold. The number of clock cycles determined which channel the pulse would be allocated. Unfortunately, these multichannel

analyzers were inherently slow and could only cope with PD pulse rise times down to about 250 ns. Thus, normally some type of integrating or stretching circuitry was required to reliably acquire pulse height information. In many cases, a conventional integrating detector, of the type described above, was used as the front end of the pulse height analyzer.

In order to overcome this limitation, which prevented statistical analysis of PD measured by ultra wideband techniques, single channel pulse height analyzers were constructed [25]. In this case, instead of determining the magnitude of the first pulse to trigger the electronics, the instrument, in a prescribed time period, only counts pulses within a single magnitude window. Once, the prescribed time period has elapsed, the next magnitude window is selected and so on. Due to the need to record events that occur in the ns to sub-ns time scale, most devices of this type have required the use of ECL technology. Whether, this type of pulse height analyzer is used, or one based on multichannel technology, both are limited by the phenomenon of dead time. This term is applied to quantify the time period in which the electronics cannot process new, incoming PD pulses. Dead time is inevitable because a finite period must elapse in which the PD pulse is acquired, its magnitude determined, and the result stored in an appropriate counter. Consequently, no PD instrument is capable of measuring all PD events. In the case of rotating machine stator insulation, because of the inherent PD resistance and the slow nature of the deterioration processes, this is not 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 and is familiar to any individual who has observed PD on an oscilloscope. 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.

The Merits of Off- and On-Line PD Testing

Prior to discussing specific techniques and instrumentation commonly found in industry, some of the advantages and drawbacks of off- and on-line test methods will be discussed. Before describing technical details, the decision whether to implement a test program based on either, or even a hybrid of both, methods is often not made on a completely technical basis. For example, decisions may be made on the basis of investment in existing equipment, if any, the type, operation and maintenance history of the machines, 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 off-line, on-line and even no PD testing, there is probably no true objective means of quantifying the benefits of this type of testing. Hence, the remainder of this discussion will focus on technical elements of the industry debate between off- and on-line PD testing.

Off-line PD Testing

This type of testing offers the advantage that it has been performed, albeit with various methods, for many decades on literally thousands of machines. Consequently, there is a very large base of knowledge and experience available to users. Further, when these tests are properly conducted and interpreted, experience has shown that off-line testing is a valuable tool for commissioning and maintenance purposes. Essential prerequisites for an off-line test are,

- a high voltage power supply, free of PD at, at least, the maximum test voltage,
- a coupling impedance, which passes the high frequency PD signals and blocks the power frequency component,
- some form of display/recording device.

The definition of what constitutes a PD-free power supply is largely determined by the noise floor of whatever instrument is used to measure PD on the power supply. However, in general, most measuring systems are capable of at least 5 pC sensitivity, thus, as a general guide the DEV of the power supply should be at least 20% above the maximum test voltage. This figure is a minimum requirement and it is recommended that the DEV be much higher than this level. Similar arguments can be applied to the coupling capacitor and the test connections. In the case of the coupling capacitor, in addition to ensuring the integrity of the measurement, the requirement of a PD-free component is also a safety issue because the presence of PD is indicative of a weakness in the insulation. Electrical failure of this component can constitute a significant hazard for personnel and connected equipment.

One of the principle advantages of off-line testing is the relative lack of electrical interference compared with measurements performed with the machine operating. This advantage permits the use of relatively simple, low frequency, coupling schemes. The majority of off-line measurements performed on rotating machine stator windings are made at low bandwidths. In view of the comments regarding the propensity of stator windings to attenuate and distort higher frequency components of PD signals, the use of lower frequency coupling devices permits the

possibility of observing PD occurring further down towards the neutral end of the winding. The value of this information will be considered below.

A non-trivial requirement of off-line testing is the need for a high voltage power supply capable of energizing at least a complete phase of the winding. For large generators, this requirement can be extremely onerous, due to the charging current, and is the reason most high voltage maintenance testing has utilized dc excitation. Possible ac sources include,

- power transformers with sufficient capacity to supply the charging current,
- resonant transformers which supply only the losses to the winding, or
- very low frequency power supplies, e.g., 0.1 Hz.

The principle problem in using power transformers is their physical size which can present severe problems in transportation and getting them physically close to the test object. For factory-type tests such transformers do not represent a problem, however their use in generating stations is necessarily limited. One solution to the problem is to use a resonant power supply that removes the charging current requirement. In this case, the inductance of the power supply is tuned to the capacitance of the stator winding so that a resonant condition exists. At this point only the losses are being supplied to the winding. The need to obtain resonance can cause some problems in cases where there is very severe discharge activity. However, this approach permits the construction of power supplies, that are capable of energizing windings with capacities in the hundreds of MVA range, with physical dimensions that permit easy transportation and plant access. The use of very low frequency high voltage power supplies is motivated by the fact that the capacitive charging current scales with the frequency. Hence, at 0.1 Hz the charging current requirement is 600 times lower than that at 60 Hz. Consequently, the physical dimensions of 0.1 Hz power supplies can be minimized to afford ease of transportation. However, despite the significant amount of work performed on this type of excitation and the availability of commercial equipment [26], use of these power supplies has not become widespread for rotating machine testing. This is in part due to the cost of the equipment but also due to switching noise in these supplies which caused problems in making very sensitive measurements. Latterly, with the introduction of solid state switching techniques many of the zero crossing point switching problems were minimized, however, the use of low frequency power supplies in stator winding PD testing is still very infrequent.

A further problem with off-line testing is that the entire winding, or segment of the winding under test, is at high voltage. In operation, only the line end coils or bars are exposed to the full line-to-ground potential. Consequently, coils and bars closer to, or at, the neutral end of the winding may be driven into PD. While it can be argued that if this is the case, then these coils or bars contain defects, in practice these areas of the winding are unlikely to ever be significantly electrically stressed. Thus, an overly pessimistic view of the condition of the winding insulation may be given. In cases where high levels of PD are encountered when performing off-line testing, it may be prudent, where feasible, to determine the location of the high activity using one of the probe techniques to be described in section 9. This point regarding the significance of PD in lower voltage areas of the winding also has relevance to the use of low frequency detectors

which can measure PD in these locations. Again, being able to measure PD in all locations of the winding does not necessarily have the same long term implications for the health of the insulation system that PD in the more highly electrically stressed areas has.

The use of off-line tests also raises the issue of conditioning of the stator winding insulation. In this case, conditioning is used to define the well known observation that, at a fixed voltage level, PD activity will, in general, vary as a function of time. In many cases, the magnitude and repetition rate of PD will decline as a function of time at voltage. This phenomenon is due to the dynamic process of PD in gaseous voids. Initially, once the DIV has been reached, or exceeded, the gas gap is generally heavily overvolted and significant PD activity occurs. However, after a period of time the heat generated by the discharge process will increase the void gas pressure which will increase the breakdown voltage of the gap, or at least, make breakdown less probable. In addition, the conductivity of the void walls will be modified by the PD process, usually in such a way as to increase the conductivity thus relieving the stress enhancement factor and reducing the space charge. Exactly, how long is required to observe this phenomenon is dependent on several factors including the dimensions and distributions of the voids and the details of the interaction of the discharge with the void walls. The net effect of this conditioning is that measurements of PD made immediately after achieving the prescribed test voltage may produce higher magnitudes than if the test object was permitted to remain at the test voltage for a finite period before the test was performed. Consequently, some organizations insist on a conditioning period, of up to one hour, before measuring the PD activity. In many cases, this requirement may be impractical due to power supply constraints, economics, number of test objects, etc. Therefore, the solution in such situations is usually to perform the test with no conditioning period. In order to maintain consistency, and not to bias the tests unfairly, if such a policy is adopted it must be applied in every case.

On-line PD Testing

On-line PD tests refer to measurements performed while the generator or motor is operating normally. Such tests can be performed using coupling devices which are temporarily or permanently installed. A range of such techniques have been developed by a number of organizations, some of which are commercially available. Detailed discussion of these devices and methods will be given in section 9. 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, if the measurement is performed properly, this method affords the highest probability of assessing the ability of the machine to continue to provide reliable operation. On-line PD testing affords the following advantages,

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

The first condition reduces the risk of obtaining overly pessimistic PD results on the machine as it renders the measurement preferentially sensitive to the more highly electrical stressed areas of

the winding. The second advantage is also extremely important because of the well known temperature dependence of PD in rotating machines as well as other insulating systems. In addition to the influence of temperature on void characteristics, temperature fluctuation is also known to have profound 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.

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

- the terminal voltage,
- real and reactive power,
- stator temperature, and
- stator current.

The terminal voltage should ideally be within $\pm 2\%$ for each test [27] and the stator temperature should be within $\pm 5^\circ\text{C}$ of the previous reading. The unit loading conditions should be broadly similar in order to maintain similar bar forces. In some cases, where measurements indicate that the winding could be loose, or to establish the existence of semicon 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. Ideally, the test should also be performed at no load, however, in many cases bearing vibration under these conditions will cause the unit to trip before a measurement can be made. Hence, the minimum load measurement usually performed with a few MW loading. As noted above, the PD behavior is also influenced by winding temperature, an effect that can be hard to separate from the influence of bar force modulation. Hence, ideally the measurements are performed by reducing the load to the minimum condition or increasing the load to full power, as quickly as possible in either case. From the perspective of power system security, reducing the load is preferable because such a test can be performed when a unit is being removed from service, hence, in the event of a unit trip, the consequences are not as serious.

The ability to perform PD tests in the presence of the operating stresses is the major advantage of on-line techniques over their off-line counterparts. While off-line tests, when properly performed and interpreted can provide valuable insight into insulation condition, some uncertainty remains because generally the temperature is significantly different and there are no bar forces. For this latter reason, off-line PD testing cannot determine whether the winding is loose, unless the semicon abrasion resulting from the relative movement between coil/bar surface and core iron is very severe.

There are however, some disadvantages to on-line PD measurement techniques. These are,

- 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 for users monitoring large numbers of machines, 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. Clearly, further work is required in this area before reliable systems can be expected. Similar comments apply to data interpretation. While, there are some basic interpretation rules, which have also appeared in the literature [10], complete understanding of the significance of certain types of observed PD behavior is still far away. Despite claims of success for statistical post-processing of PD data [28], automated interpretation which can provide the same level of confidence as the skilled and experienced observer is also some way into the future.

Electrical Interference

The noise problem associated with performing measurements on operating rotating machines is by far 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 [29]. 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 are required rather than a single method to obviate the difficulties introduced by these multiple noise sources. Section 9, will describe the most commonly encountered on-line PD monitoring technologies and describe their inherent noise rejection capabilities. The remainder of this section will identify the origin and sources of the major electrical interference sources encountered in generating stations.

Electrical Interference – Internal to the Machine

The basic sources of noise internal to the machine are,

- switching transients from the excitation system,
- the shaft grounding brushes, and
- arcing due to loose core laminations.

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, albeit inefficient 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, which are installed to minimize electrostatic charging of the shaft due to triboelectrification caused by steam flowing over the turbine blades, can also result in the emission of unwanted RF energy. Again, the main vector for this type of noise is the rotor circuit.

In situations where stator core laminations at the back of the core become loose, back of core arcing and burning can occur. Again these arc events produce energy in the RF spectrum which can interfere with the reliable operation of PD monitoring equipment.

Electrical Interference – External to the Machine

Within this category of noise sources the principle ones are,

- the power system and connected equipment,
- the isolated phase bus (IPB), and
- other extraneous sources, such as welding machines, precipitators, etc.

Partial discharge is a problem for most other power apparatus, including transformers and circuit breakers. Because oil/paper insulation systems, which are used in transformers, are relatively PD tolerant, such equipment can be a source of PD which, by definition, will 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.

One of the most significant noise sources, and one of the most difficult to cope with, is the IPB. Partial discharge, or PD-like noise, can be 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 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, results from the inevitability of a few loose bolted connections among the thousands necessary to construct the IPB.

Methods of circumventing the problems resulting from these noise sources will be discussed below. 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 the signals. The

selection of the noise rejection scheme can also depend on the level of interference encountered in the plant that is often a function of the number and size of the generators. As a general, but not rigid, rule, the noise level increases with increasing unit capacity. However, in most cases a survey of the noise environment is not usually performed and unless individuals with the necessary skill and experience are available, it is usually prudent to employ the technique with the highest noise rejection ratio.

PARTIAL DISCHARGE TEST METHODS

In this section the various off- and on-line methods employed in performing PD tests will be reviewed. Partial discharge probe measurements will also be considered in some detail.

Off-line Test Methods

The most commonly encountered off-line PD test method, in fact probably the most common of all PD measurements, consists of a coupling capacitor, typically in the range of 100 - 1,000 pF and some form of inductive network. The inductive network is usually matched according to the capacitive load presented by the test object. Partial discharge signals detected in this way are amplified, often integrated by means of a low pass filter, and displayed on a cathode ray tube or some other device such as an analog or digital meter. In some cases, further processing of the pulses is done to provide a pulse height analysis or a derived quantity such as average discharge power. The frequency response of these detectors generally falls within the range of 10 - 500 kHz, although some manufacturers offer equipment with several frequency responses into the low MHz range.

A typical off-line test arrangement is illustrated in schematic form in Figure 6 and an actual test set up is shown in Figure 7. Normally, for this type of testing complete isolation of the winding is required, i.e., the phase terminals are isolated and the neutral, if accessible, is broken and isolated. Temporary grounds are installed at each of these points until the tests are performed. How much of the winding is energized is dependent upon the capability of the power supply, however, typically one phase is energized at a time. While it is common, where possible, to energize the complete winding, testing one phase with the other two at ground potential enables potential defect or contamination sites in the endwindings to be identified. Such a test strategy also enables problems due to incorrect design or construction of interphase spacing to be identified.

In a typical test, the voltage is raised until PD inception occurs, or the PD magnitudes exceed a predetermined level, the DIV is recorded and the voltage is raised usually to the nominal line-to-ground operating voltage of the machine. At this level, the magnitude of the maximum partial discharge magnitudes in both the positive and negative half cycles of the power frequency are recorded. In some cases, more sophisticated data acquisition and processing is possible, however, the aforementioned parameters are the minimum data requirement. A conditioning period may be required before this data is recorded, normally this requirement will be agreed prior to testing. The voltage is then steadily decreased to the point at which PD is either no longer observed to be occurring or has fallen below a prescribed magnitude. This voltage is the DEV and is also recorded. The voltage is then reduced to zero, the power supply switched off and temporary grounds reapplied. There are a number of variants of this scheme which consist of different coupling impedances and means of acquiring and analyzing the data. Some of these techniques are unique to certain organizations and countries or the bulk of practical experience resides within these bodies and countries.

Another common off-line technique is the dissipation factor and tip-up test. This test may also be known as the power factor or $\tan \delta$ test, the basis of which was discussed in section 7 above. A typical test set up is illustrated in Figure 8 and is demonstrated in Figure 9. The test equipment consists of a high voltage power supply and a Schering or transformer ratio-arm bridge which measures the capacitance and dissipation factor of the winding. There are several commercial suppliers of such bridges. Unlike tests performed on individual coils and bars as part of the manufacturers QC process, in which the test object is not grounded, the stator winding is solidly bonded to the station ground. Consequently, the bridge should be capable of working with grounded specimens or the instrument should be operated ungrounded. This latter condition is potentially very hazardous, thus only well-qualified personnel should perform the test with the bridge floating.

The test procedure is standardized in publications such as IEEE 286 and IEC 894, and these documents should be consulted for guidance. However, normally a test on a complete stator winding, usually energized one phase at a time with the other two grounded, consists of the following,

- the portion of the winding under test is raised to a voltage level below DIV. Normally this level is about 20 - 25% of the nominal line-to-ground operating voltage of the machine. Thus for a 13.8 kV winding, the initial measurement would be made at 2 kV. The bridge is balanced, either manually or automatically, and the capacitance and dissipation factor values are recorded.
- the voltage is then raised to the nominal line-to-ground voltage of the machine, the bridge is balanced and the capacitance and dissipation factors are recorded. The voltage is reduced to zero and the temporary grounds reapplied. The above is repeated for the other two phases.

In some cases, the procedure may require that more readings at other voltage levels are obtained, e.g., some countries specify readings commencing at 1 kV with 1 kV increments up to the rated phase-phase voltage of the machine. This method provides a means of determining the knee-point of the curve, i.e., the voltage level at which the dissipation factor starts to significantly increase. However, for most maintenance purposes the two level procedure is adequate. As mentioned in section 7 above, in machines with stress grading compounds applied, some caution must be exercised when examining the dissipation factor and the tip-up. In cases, where the ratio of slot cell length to length of stress grading application is low, there will be a higher influence of the nonlinear stress grading compound. However, as a general guide, for windings in which epoxy or polyester resins are used the tip-up should be below 1%. In older asphaltic or shellac-micafolium insulated windings significantly higher tip-ups can be tolerated, although, if regular testing of this type is performed, signs of upward trends should be examined carefully.

Variants of the above methods which use Schering or transformer ratio-arm bridges also exist. One of these, the dielectric loss analyzer (DLA), was developed and principally used in the United Kingdom [30]. The other technique is the parallelogram or loop-trace method principally developed by Westinghouse in the late 1950s [31]. Essentially the technique consists of a bridge and an oscilloscope, Figure 10. The vertical deflection plate of the cathode ray tube is connected

to the detector terminals of the bridge; the horizontal deflection is made proportional to the applied test voltage by means of a resistive divider. The test procedure consists of raising the voltage to a level at which no PD occurs, at which point the bridge is balanced. Under the balanced condition, there will be no potential across the detector terminals, thus there will be no vertical deflection potential and consequently the oscilloscope will display a horizontal line, proportional to the test voltage. As the voltage is increased beyond DIV to the prescribed test voltage, the bridge will then be out of balance and the oscilloscope display will resemble a parallelogram. The discharge energy per cycle and the charge transfer per cycle can be derived from the dimensions of the parallelogram [31]. This technique is mentioned for completeness because the majority of loss measurements are made with Schering or transformer ratio-arm bridges.

In situations where high PD activity has been recorded by any of the above techniques, or by an on-line method, various types of probe can be used to aid in the location of the source of significant PD. The most commonly used probes are,

- the TVA probe,
- the radio frequency (RF) probe, and
- the ultrasonic probe.

The TVA probe, named for the Tennessee Valley Authority, the first major, systematic user of the technique, was developed by Westinghouse in the late 1960s [32]. Essentially, the probe consists of a half-toroid, or a U-shaped piece of, ferrite core around which are wound a few turns of number 14 insulated wire. The exact number of turns varies between three up to about 10 depending upon what frequency response is required to optimize the performance of the probe. The antenna is connected, via RG58 coaxial cable to a quasi-peak power meter of the type described in section 7 above. For optimum sensitivity, usually 5 MHz, the peak-pulse meter is tuned to the resonant frequency of the probe coil and the associated cable and detector input capacitance. These meters are commercially available, alternatively a design for such a device was published in the 1970s [33]. The probe is mounted on a long insulating handle to maintain electrical isolation between the winding and the probe operator.

The probe is positioned over the stator slot, such that the ferrite core is in contact with the iron core tooth on each side of the slot, Figure 11. In this way, the core iron completes the magnetic circuit with the half ferrite core. The total magnetic circuit resembles a current transformer in which the coil or bar in the slot is the primary and the core/probe combination is the secondary. The probe is designed to be sensitive to the RF energy emitted by PD processes occurring in voids in the insulation. Consequently, as the probe is scanned up or down the slot the reading on the meter should increase with increasing proximity to the discharge source. Thus the test procedure consists of energizing the stator winding to the prescribed voltage level then systematically scanning the probe along the length of each of the slots. As a hydraulic generator may contain over 500 slots, probe testing can be time consuming and tedious, however, industry experience with this test has been very positive. With respect to previous comments that off-line tests have a low probability of detecting slot discharge, and also because no polarity information

is available, the test is probably optimum for determining the sites of severe delamination in the groundwall of the machine.

Some organizations in North America and Europe who use TVA probing extensively not only for maintenance but also commissioning testing have suggested levels [27], based on experience, above which there may be concerns with the insulation condition which would warrant further investigation. These values are,

- 100 mA for asphalt-mica windings,
- 30 mA for polyester-mica windings, and
- 20 mA for epoxy-mica windings.

Because the test procedure requires control of the position of the probe with respect to the stator slot, the operator is required to be in fairly close proximity to the winding which is at high voltage. Consequently, extreme caution should be exercised in performing the test and should only be performed by those individuals with the necessary training and experience in high voltage testing. In some organizations, this type of testing is not permitted due to the implications of what constitute safe limits of approach. A further practical point concerns whether the rotor need be removed for such a test. In the case of turbine generators, invariably the rotor must be removed to perform such a test. For hydraulic generators, depending on the size of the air gap between the rotor pole face and the core iron, it may be possible to insert the probe between these surfaces. Where dimensions preclude this possibility, an alternative approach is to probe those slots which can be accessed by inserting the probe in the gap between the poles. Once all of the accessible slots have been scanned, the rotor can be moved around by a few slots to provide access to untested slots. This process is repeated until all accessible slots have been probed. However, some slots will normally remain inaccessible, especially on machines in which the bearings are mounted above the generator, due to obstructions imposed by the support brackets.

Another type of probe is the RF probe, which is simply a hand held antenna, normally tuned in the range of few MHz. The output of the antenna could be fed to some form of meter similar to that of the TVA probe, however, the RF probe is used to determine the general location of PD sources, not to quantify them. Consequently, often the probe signals are fed to a simple FM radio tuned to the appropriate frequency. Detection and location are accomplished by the simple expedient of pointing the probe in the vicinity of the energized test object. Once PD is detected, which is indicated audibly by the radio in the form of static noise, the probe is scanned about the PD source until the location at which the audible noise is maximum. Although somewhat crude, the technique can be quite effective, although usually only in the absence of high background noise, which may occur on units with significant endwinding discharge. The same comments with respect to operator safety are applicable for this test also.

Ultrasonic probes, usually optimized for frequencies in the range of 40 kHz have been routinely used in transmission and distribution applications to find cracked or contaminated insulators or defective bushings. Similarly, this type of probe has found application in rotating machines to

detect surface-related problems such as deterioration of semiconductive armour and surface PD in the endwinding region. The probe consists of a directional microphone connected to a meter which normally reads in units of dB. The test procedure is very similar to that of the TVA and RF probes; the winding is energized and an operator scans the probe over the length of the slot and the endwindings. Again, great caution should be exercised by the operator to ensure that the probe does not contact the energized winding.

Before the advent of commercially available PD detection systems, many users and manufacturers of rotating machines used what is commonly known as the blackout test to determine the existence of surface PD or corona activity. This test consists of energizing the stator winding, usually to at least nominal operating voltage in almost complete darkness. The visible light emitted by surface PD could be used to determine the presence and location of problems such as interphase clearance defects, surface contamination, etc.

On-line Test Methods

Numerous organizations worldwide have developed means of detecting PD while the machine is operating normally. In some cases, PD couplers are installed permanently for routine monitoring, in others couplers are installed temporarily, usually in situations where a problem is suspected. A survey of the literature shows that many different detection and monitoring schemes are available, however, all of them are based on the use of one of the coupling methods discussed in section 7 above. In this section descriptions of systems based on the use of capacitors, stripline antennae and RF current transformers will be given.

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. Two couplers are used to implement noise rejection schemes based on differential or directional principles [25, 34, 35, 36]. In the case where only one coupler per phase is installed, a so-called single ended arrangement, some expertise on the part of the test operator is required to determine which signals are PD in the presence of noise. Alternatively, some commercially available PD instruments perform sophisticated statistical processing of the signals to discriminate against electrical interference [37]. One of the earliest forms of on-line PD monitoring involved temporarily installing capacitive couplers at the potential transformer terminals and observing the resultant output, via a high pass filter, on an oscilloscope [25]. This test has been used since the mid-1950s and continues to be used today.

Techniques Based on Stripline Antennae

Couplers, which are essentially stripline antennae, generally have very wide bandwidths, ranging from the MHz to the GHz. This ultra wide bandwidth presents the possibility of being able to preserve the temporal characteristics of the PD pulse, assuming such a coupler can be installed close enough to the source of PD in the winding, i.e., in the stator slot. The high frequency characteristics of such couplers render them very location sensitive and typically the amount of

winding by one coupler is quite limited, usually to one slot. Consequently, to obtain complete coverage of the winding implies installing one coupler per slot which is impractical. However, by concentrating attention on the most highly stressed part of the winding, i.e., the line end coils or bars, which have the highest probability of PD occurrence, an adequate monitoring scheme can be implemented with a limited number of such couplers.

Radio frequency (RF) Current Transformers

One of the earliest forms of on-line discharge monitoring involved the installation of an RF current transformer (CT) 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 [38]. Partial discharges also produce RF energies so it was a logical extension to use the RFCT as a PD detector [39]. The output of the CTs, the frequency response of which are in the range of 20 kHz - 50 MHz, are generally connected to an oscilloscope or spectrum analyzer [21]. In general, this type of sensor will probably be able to provide coverage of the whole winding. However, in large steam turbine generators, which can have very high levels of electrical interference, interpretation of the resultant signals can be very difficult because of the problem of separating the PD signals from noise. Although this technique has been shown to provide good diagnostic information, the technique has not become widespread amongst electrical machine users because of the need of an expert to properly interpret the data.

An alternative location for RFCTs is at the phase terminals of the machine. In some cases, because of concerns with regard to the capability of turn insulation under the influence of steep-fronted switching transients [40], surge capacitors are installed between the phase terminals and ground. These devices are designed to protect the motor by presenting a low impedance path to the high frequency signals associated with switching. Unfortunately, they also short circuit the high frequency PD signals to ground, greatly reducing the effectiveness of PD measurements using capacitive couplers. A solution to this problem is to install a RFCT around the grounding lead of the 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 [41]. In some cases, it has been possible to implement directional schemes using RFCTs or a combination of RFCT and capacitive coupler. In this way, automated noise rejection can be implemented.

INDUSTRY PRACTICES

The following discussion aims to review the methods and practices of PD testing of rotating machines which are commonly used in industry. For the purposes of this document, the discussion largely considers North American experience. Where appropriate, methods used in countries outside North America will be described.

Within North America, development of rotating machine PD measurement techniques and interpretation has been an active area for many decades. Research and development work has been performed by machine manufacturers, e.g., Westinghouse and General Electric, utilities, e.g. Ontario Hydro, Manitoba Hydro, American Electric Power, US Army Corps. of Engineers, Tennessee Valley Authority, etc., and instrumentation manufacturers, e.g., AVO International (formerly Biddle), Doble Engineering, Hipotronics, etc. Similarly, developments in Europe have been driven by manufacturers and utilities, e.g., ABB, Siemens, CEGB, EdF, etc. Thus there is a large body of laboratory and field experience available. .

Off-line PD Testing

Off-line PD testing is practiced by all of the major machine manufacturers and many utilities. Manufacturers have traditionally used PD tests in developing new insulation systems as well as in performing field service. However, recently attention has started to focus on the use of PD testing for QC purposes [42]. This development is relatively recent, and it should be recognized that presently a direct correlation between PD activity and service life at the operating voltage has not been established. One study [42], has been published in which some evidence of a relationship between PD activity and voltage endurance test life was found. Utilities tend to use this type of PD testing for commissioning or maintenance testing. The extent of these programs will depend upon such factors as the expense of the testing relative to the criticality of the machine and the existence of on-line PD monitoring programs. Some utilities, only perform off-line testing of machines which either have indicated potential problems through on-line PD testing or have suffered an anomalous event or are deemed critical but presently have no possibility of on-line monitoring.

There are several manufacturers of off-line PD test equipment with varying degrees of sophistication, including PD probes, such as AVO International, Hipotronics, American High Voltage Test Systems, etc., in North America. Similar equipment is also available from European manufacturers, e.g., Tettex, Power Diagnostix GmbH, Lemke, etc. Some organizations use their own custom built equipment.

On-line PD Testing

On-line RF Monitor

This technique was briefly described above, in section 9.2.3, and consists of a RFCT connected around the lead between the generator neutral point and the neutral grounding transformer. A 1 MHz bandpass filter was applied to the signal and then fed to a device known as the radio

frequency monitor (RFM). This technique was developed by Westinghouse in the early 1950s, originally to detect broken strands in the stator winding [38]. Breaks in the conductors result in arcing which can be detected by the RFCT. This type of device can also be used, in principle, to detect PD by monitoring the output with an oscilloscope or spectrum analyzer. In the early 1980s, this step was taken by Westinghouse and AEP Service [21, 39]. While both of these organizations were able to demonstrate good results and experience in diagnosing and rectifying stator winding problems, discrimination of the PD signals from noise remains a major problem. The bandwidth and location of the RFCT implies that the sensor will detect virtually all sources of RF energy, thus the technique is not only sensitive to PD in the winding but all of the noise sources described in section 8.3 above. Thus, very often, unless very severe discharging is occurring, it is very difficult, for non-specialists, to observe PD. Consequently, significant experience and expertise is required to properly interpret the results of the test. For this reason, the test, although demonstrated to be effective, has not been used widely in North America, outside of the aforementioned organizations. Within Europe, positive experience with RF monitoring has been reported by Siemens [41] and ABB [37], although supplementary sensors were used to overcome the problems mentioned above.

Methods Employing Capacitive Couplers

An on-line test, in which capacitive couplers, fabricated from appropriately sized lengths of 28 kV, cross-linked polyethylene distribution cable, are temporarily installed at the phase terminals of the generator was developed in the mid-1950s by Ontario Hydro [25]. The low voltage electrode of the coupler, which has a nominal capacitance of 375 pF, is the concentric neutral of the cable. A length of 50 Ω coaxial cable connects the coupler, via a high pass filter, to an oscilloscope on which the high frequency PD signals are observed with the power frequency cycle superposed. The coupler has a lower frequency cutoff of about 8 MHz, thus this type of coupler will tend not to detect PD throughout the winding because of the attenuation of high frequency components of the PD signal.

One coupler per phase is installed, usually at the potential transformer cubicle, while the machine is operating. Consequently, this test should be considered as having an element of live-line work and should not be undertaken by personnel unfamiliar or not trained in high voltage work. In any case, extreme caution on the part of the test operator is required for the safe performance of this test. In addition to personnel hazards, improper technique while connecting the coupler to the high voltage bus may cause operation of the generator protection system, resulting in an unplanned outage. Within Ontario Hydro, this test has been performed on over 100 generators, well over 1,000 times, without incident. However, for the above reasons, this test has not become widespread and is virtually unique to Ontario Hydro.

A further barrier to greater use of the test is one common to most on-line tests, electrical interference. Great skill and years of experience on the part of the test operator are required to properly discriminate PD from noise and determine the possible source of the PD activity. Since the test was first developed and began to be used systematically, several potential insulation problems on large steam turbine generators have been detected and remedied [43]. Further, the

use of the technique has helped to reduce costs by indicating those windings, usually the vast majority, which do not require significant maintenance or expensive testing.

On-line PD Tests Using Permanently Installed Capacitive Couplers

One obvious means of eliminating the hazards associated with temporarily installing capacitors on operating generators is to permanently install couplers during a planned maintenance outage. Within North America, one of the first systems of this type to be introduced in the late 1970s was the PDA (Partial Discharge Analyzer) [25]. The system, developed by Ontario Hydro with support from the Canadian Electrical Association, was designed specifically for application on hydraulic generators. This method employs 80 pF capacitors, permanently installed in pairs on the circuit ring bus. There is a pair of couplers on each phase. The output from the couplers is connected, via coaxial cable, to the PDA instrument which performs the noise rejection algorithm and a single channel pulse height analysis on the resultant PD pulses. A schematic representation of the system is illustrated in Figure 12.

Essentially, reduction of electrical interference is performed by a time-of-flight technique. On each phase, a coupler is located in each split in such a way that the propagation path, consisting of the circuit ring bus, the coupler and its associated coaxial cable, are the same for each split. Consequently, according to Figure 12, in the presence of common mode noise, these signals will radiate into both couplers and thus the noise pulses will arrive simultaneously at the PDA instrument, the input circuit to which contains a differential amplifier. Thus, the pulses will cancel out and the noise pulse will be rejected. When a PD pulse occurs, e.g., in the line end coil of one of the splits, it will be detected first at the coupler associated with that split. The pulse will also propagate to the other coupler and be detected there, however, because the electrical paths are equal from the coupler to the PDA, the pulse from the nearest coupler will arrive first at the PDA and be counted. The electronics are inhibited from a period to prevent detection of the pulse coming from the second coupler.

This system has been commercially available for about twenty years, with various modifications and improvements that take advantage of technological progress in this period. One of the principle advances has been to replace the analog differential amplifier with digital circuitry which times the delay time between arrival of the two pulses on each split. A delay time of 5 ns or less results in the pulse being designated noise and consequently rejected. The advantage of this technique is that the relative magnitudes of the pulses are not important. Older analog systems would suffer from the problem that unless the pulse magnitudes were virtually identical, a non-zero response may be obtained even when the pulses were coincident. This problem limited the PDA to recovering PD in noise environments of 20 dB or less. A further development of this technique has been the introduction of compact epoxy-mica capacitors as an alternative to cable-type couplers which still constitute the majority of installations. The PDA technology and its variants are offered by a number of commercial vendors such as Iris Power Engineering and Adwel International. Similar systems, employing substantially the same concepts, are available from other organizations such as ABB.. Presently, there are well over thousands installations of this technology, principally in North America, but with significant numbers of installations in, for example, South America, Europe, Africa, Australia and New

Zealand. The technology has, over the 20 year period of its systematic use, proven useful as an aid to maintenance engineers and has enabled many users to make the transition to a condition-based maintenance policy.

Unfortunately, direct transfer of this technology to steam turbine generators was not possible. The reasons for this difficulty are,

- the lack of an adequate length of circuit ring bus to implement the noise rejection algorithm,
- the higher noise environment inherent in large turbine generators, and
- concerns regarding the dielectric qualification of the original cable-type couplers used in hydraulic applications at the higher terminal voltages used in turbine generators.

Consequently, an alternative coupling scheme was required which would provide the same high level of noise rejection as for the PDA in hydraulic applications. A directional noise rejection scheme was implemented by installing two couplers per phase [36]. One of the couplers was located as close to the generator terminals as possible and the second coupler was positioned at least two metres away from this point. The minimum spacing was determined by the capabilities of the available electronics.

In the case of a noise pulse occurring in the IPB or the power system, this would be detected first at the system-side coupler. This pulse would continue to propagate towards the generator and would be detected a few ns later at the generator-side coupler. The signal from the system-side coupler was delayed by a time equivalent to the electrical length between the two couplers such that the detected noise pulse from both couplers would arrive coincidentally at the inputs of a differential amplifier and the noise pulse would thus be cancelled. A PD pulse propagating from the stator winding would be detected by the generator-side coupler first and would arrive at the input to the differential amplifier before the delayed subsequent pulse from the system-side coupler and would be subsequently amplified and subject to single channel pulse height analysis. In order to prevent the same pulse from being counted twice, the acquisition electronics were inhibited for a specified period after the generator-side coupler triggered the electronics. This system was known as the PDA-T [44].

Unfortunately, this technique was not found as reliable as the various implementations of the PDA method for hydraulic generators. Field evaluation of the instrument in generating stations with multiple large capacity steam turbine generators demonstrated that, in comparative tests using the conventional on-line PD test, the technique would not reliably discriminate against noise. There are several reasons for this finding, the major ones are,

- a principal assumption of the noise rejection algorithm is that all pulses originating from the generator are due to PD. However, the foregoing discussion on noise sources shows that some electrical interference can be expected internal to the machine, e.g., from shaft grounding brushes. Furthermore, as a noise pulse, originating on the system-side of the IPB, propagated to the generator bushings it would experience a reflection due to the

impedance mismatch at this point. If the generator-side coupler was relatively remote from the generator, this reflected pulse may reach the generator-side coupler after the inhibit command has been removed from the pulse acquisition electronics of the PDA-T.

- any noise occurring in the portion of IPB between the couplers would be counted as valid PD.
- due to the impedance mismatch at the generator bushings, a significant proportion of the energy in the PD pulses originating in the winding is reflected. Consequently, in order to detect these signals the PDA-T was required to operate with a relatively high gain which had the inevitable effect of amplifying the noise as well. This problem was exacerbated by the use of modified hatch plate covers as capacitive couplers in the original installations. These couplers were essentially parallel plate air-dielectric capacitors fabricated by positioning another plate over the inspection hatch cover with insulating standoffs. The hatch plate cover in turn was insulated from the IPB sheath to form the low voltage electrode. which was connected, via a 680 Ω resistor, to a coaxial cable which was used to connect to the PDA-T. The resistor was required to prevent the whole assembly from floating up to the line-to-ground potential of the bus. The capacitance, and hence coupling efficiency, of this method was very low.
- coupling of noise pulses, originating in one phase of the IPB into the other phases, was considered to be symmetrical. Later work [45] demonstrated that this assumption was not always valid. Hence, the algorithm used in the PDA-T to reject such noise was often ineffective.

Consequently, this technique was not employed on large steam turbine generators in noisy environments. However, the method was found to be effective in smaller stations, with lower noise backgrounds and skilled personnel who could properly interpret the data obtained. One utility, Manitoba Hydro, has very significant positive experience using this technique [36].

Latterly, this method has been increasingly used on small generators, up to about 150 MVA, and on large, critical motors [46]. In these applications where the noise environment is relatively low, good experience has been obtained. Additionally, the advent of fast, inexpensive digital electronics has enabled the replacement of the analog differential amplifier with circuitry designed to measure the delay between time-of-arrival of the pulses, viz., the aforementioned evolutionary improvements to the PDA. This development not only enables measurements to be made in higher noise backgrounds but also permits discrimination against noise pulses occurring in the IPB between the two couplers.

Again, other organizations, have also demonstrated good experience with similar types of couplers applied to condition monitoring of high voltage generators [37, 41, 47].

The Stator Slot Coupler

These considerations led to the development of a new sensor and a different method of PD detection [16]. The sensor, known as the stator slot coupler (SSC), is an ultrawide band antenna, 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 risetime from this sensor. The noise pulses, having a similar shape and frequency at their origin, must travel some distance through the circuit ring, the endwinding, along the laminated core or through the rotor circuit. This relatively long propagation path broadens 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 at the sensor locations, is the basis for separation of PD from internal and external noise sources.

An instrument, known as the TGA-S, was developed to acquire the signals from the SSCs, determine their width, and count them as PD or noise [46]. The SSCs have outputs from both ends; 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. Presently, this technology is available from only one supplier, Iris Power Engineering. Globally, several hundred large steam turbine generators have been equipped with SSCs. Experience to date with this technology [48] has demonstrated that it is effective in discriminating PD from noise signals in the environments encountered in large generating stations.

Some organizations have sought to utilize the embedded resistance temperature detectors (RTDs) in the stator winding as PD sensors [49, 50]. The principle advantage claimed for this method is that of convenience because there is no need to install additional PD couplers. This method has been applied in North America [50] and Japan [49]. However, there are some serious reservations regarding the effectiveness of the technique, including,

- 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 great care is exercised, the output leads from the RTDs may become sources of PD if they are run in close proximity to the high voltage conductors.
- RTDs are not designed to be antennae, hence, their high frequency properties are not optimized for the purposes of efficient PD detection.

Consequently, the efficacy of PD testing based on this coupling is questionable, especially if performed by individuals without particular expertise in this field.

DEVELOPING A PARTIAL DISCHARGE TESTING PROGRAM

Many organizations contemplating application of PD measurements as part of a predictive maintenance program encounter a number of questions which require resolution before the first measurement can be made. Obviously, cost is one of the first considerations, however, numerous other issues, which can also relate to cost, need to be identified and resolved. Among these issues are,

- selection of appropriate technology,
- who performs the testing and the subsequent data interpretation?
- what test strategy or policy should be adopted?

The cost element, insofar as the cost of specific equipment or sensors, will not be dealt with in this document. Given the numerous suppliers of PD measurement devices and services worldwide, the market, or the negotiating skills of the individual, will largely dictate the price. However, the purchaser should consider the value or criticality of the machine with respect to the cost of the PD monitoring technology. The following discussion focuses on the latter issues raised above.

Questions to be considered when specifying or purchasing PD measurement equipment include, the type of sensor and the output format from the system. Issues associated with sensor selection revolve around whether the equipment is to be installed on a new machine or retrofitted to an existing generator, reliability of the coupling device and credibility of the output of the sensor. Generally, on new machines the cost of the PD couplers is a very small fraction of the total cost of the generator. Further, installation of these devices on a new machine is very much simpler to engineer than when retrofitting to an existing unit. Consequently, sensors can be specified that are installed either in the winding, e.g., SSCs, or very close to the machine terminals, e.g., capacitive bus couplers. The advantage with couplers located in close proximity to the stator winding is that they are closer to the source of PD in the generator and tend to be less prone to noise, or at least, there is a higher probability of successfully rejecting the noise.

In most cases, utilities are specifying PD monitoring systems for existing machines, thus a greater emphasis is placed on ease of installation. Often, the time frame during a maintenance outage, within which the coupler installation takes place, is quite short. Consequently, retrofitability of the couplers is a prime consideration. In general, all couplers fit into one of three categories with respect to the ease with which they can be installed.

1. Sensors which are installed in the machine, which require an outage with the rotor removed. Stator slot couplers fall within this category.
2. Sensors which are installed in the machine, which do not require that the rotor be removed. Capacitive couplers connected to the IPB or circuit ring bus belong to this group.

3. Couplers which do not require a high voltage connection that are installed either at the high or low voltage connections to the generator. Radio frequency current transformers, described in section 9.2.3, are such devices.

Couplers which fall within the first category above require a major outage, such as those taken to perform various inspections of the rotor. Typically, such outages occur every 6 to 10 years. Thus, sensors of this type usually imply that the utility or machine user has a long term policy of installing such couplers during outages of this nature. Installation of sensors in the second category also requires a machine outage. However, because the rotor can remain in situ or, if installing IPB couplers, no access to the generator is required, the sensors can be installed during very short outages. Couplers in the last category, while also requiring an outage, require the least time because no high voltage connections are made. In summary, the above list can be considered in descending order of difficulty. Alternatively, the coupling methods are arranged in order of decreasing outage time.

Another factor involved in the selection of suitable sensing devices is that the coupler be compatible with electrical, mechanical, thermal and environmental stresses of the host machine. For example, high voltage coupling capacitors designed to be installed in the IPB should have the same dielectric qualification as the bus, under the same operating conditions. Presently, there is very little, if any, evidence of PD sensors causing machine damage or resulting in unplanned outages.

Often, the choice of instrument, is determined by the couplers, or noise rejection scheme, selected. In principle, because some of the sensors and coupling schemes are similar, e.g., the widespread use of 80 pF capacitors deployed in either differential or directional modes, the user is not necessarily committed to purchasing couplers and instruments from the same source. The number of instruments required depends on the number of machines being monitored as well as geographical factors. Generally, because of the relatively slow degradation rates involved a policy of making PD measurements once every six months is adequate. Hence, only one instrument may be required to service this need. Of course, where the stations are physically far apart, or depending upon the interface between different functional groups within the utility, more than one instrument may be required.

Some instrument manufacturers offer continuous on-line PD monitoring systems. Such equipment is useful where the generating station is in remote location where the travel costs are prohibitive. Alternatively, there may be some additional value to using such a system on a generator that is considered to have a temperature or load dependent problem. However, such systems, which presently are significantly more costly than conventional instruments for periodic use, are not recommended for general application. In addition to the higher cost, there are practical problems associated with the volume of data that such instruments have the potential to generate. Any utility contemplating the purchase of a continuous PD monitor should consider the budgetary implications of maintaining and analyzing a database of this size.

Regardless of the choice of instrument or whether periodic or continuous on-line, a significant issue for most utilities is who performs the testing and the subsequent data interpretation. Some

organizations have the capability to handle these functions in-house, whereas others contract these services out. Another option is, depending on the equipment, to have the test performed in-house and transmit the data to a third party for interpretation. Contracting out both testing and interpretation has advantages in that the utility is largely free of the overhead burden of owning the instrument and employing the appropriate expertise. However, this approach has the disadvantage that the utility partially loses ownership of maintenance process for the machine. That is, when there is no individual assigned responsibility for this process within the utility there is a risk of the PD results, and their implications, being ignored. Further, the interpretation of data by a third party tends to be very conservative because of the liability issue. In cases where the interpretation is performed by a machine manufacturer there is the potential for a conflict of interest. Overall, the operational and technical needs of the utility are best served if testing and interpretation are performed in-house. Initially, in some situations, the utility may not be comfortable with analyzing the data. In such cases, they may consider engaging a third party to provide interpretation and training services, so as to effect an orderly technology transfer to their own personnel.

Where, the latter policy of acquiring and analyzing the data in-house is selected, there must be a commitment from the utility to assign the appropriate staff, usually a test technician and another individual to interpret the data. These tasks are not necessarily full-time jobs, however, unless the responsibilities are defined and the individuals given clear mandates for these functions, the policy will be ineffective.

No matter which technology is selected or who performs the testing and analysis, the output from the PD monitoring program needs to be integrated with operations and maintenance policies. Unless this link is made, there is little or no point investing in this technology. Often, the connection between test results and maintenance actions is lost because the individuals concerned are in positions not directly related to operations, e.g., they belong to a research or testing group. Success is more probable if the station staff are able to perform the testing themselves. Further, the individual responsible for data interpretation should be either on-site or part of a central engineering group with input into maintenance policy.

In some cases, condition monitoring programs, and not just those based on PD, fail because expectations are too high. In the case of PD monitoring, the systems are often sold on the basis that can prevent machine failure. While this is true, the key point to remember is that failure prevention or minimization is driven by maintenance and operation decisions, in which correctly interpreted PD information assist. Further, in many cases a properly run PD test program can provide significant avoided cost savings by reducing unnecessary maintenance.

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