Unusual PD Pulse Phase Distributions in Operating Rotating Machines

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ABSTRACT

The position of partial discharges (PD) with respect to power frequency phase position has long been known to provide useful information on the nature of deterioration of electrical insulation. In the past, virtually all such data has been from PD tests performed in the laboratory on static models or equipment. Improvements in the past 15 years in noise elimination technology have made it possible to monitor the PD activity (number, magnitude and phase position) in the HV stator windings of operating motors and generators. Over a two year period, the PD activity was recorded on more than 100 motors, hydrogenerators and turbine generators, and the pulses analyzed with respect to the ac phase position, with a resolution of 3.6°. In the majority of stator windings, the PD pulses occurred in the expected portion of the ac phase, i.e. between 0 and 90° as well as between 180 and 270°. However a significant number of instances were recorded where the pulses appeared to be shifted ~ 30°. This is probably due to the phase-to-phase electric stress which occurs in the endwinding portion of a three phase stator winding. In many other machines, the PD phase positions were very different from the expected patterns determined from static tests. In some of these cases, such results were obtained on machines with suspected loose stator windings. It seems reasonable to conclude that the unusual PD patterns may be due to the influence of moving stator coils on the PD patterns. Such an influence is not easy to simulate in static laboratory tests. PD pulse phase analysis is shown to be a useful means of helping to determine the main deterioration mechanisms of stator insulation systems of operating motors and generators.

1070-9878/95/$3.00

1. INTRODUCTION

PD tests have been used for over 40 years as a means of determining the insulation condition of rotating machine stator windings [1, 2, 17]. In particular, PD are a symptom of thermomechanical deterioration, contamination from conductive films, as well as loose windings (slot discharge). The most common means of recording PD activity is pulse height analysis (PHA) [3]. In the PHA plot, the positive and negative PD pulses are recorded according to magnitude and number of pulses. The ratio of positive to negative PD peak magnitude activity has been found to be useful in identifying some of the root causes of stator winding deterioration [4].

In the early 1970's, Kelen introduced another means of categorizing the PD activity in rotating machine insulation [5]. In addition to recording the number of discharge pulses per second and their magnitude, the location of each PD pulse with respect to the power frequency phase position was also digitally recorded. The resulting three dimensional plot presented a simple means of permanently displaying the PD activity in a way similar to that which could only be temporarily shown using an analog oscilloscope display.

Since the introduction of PPA (PD pulse phase analysis), numerous studies have been performed to determine the characteristics of the PD pulse pattern with respect to the ac phase. In general, PD with a solid dielectric boundary have been found to occur between 0 and 90° of the ac phase (negative pulses) or between 180 and 270° (positive pulses) [5–9]. The polarity of the pulses with respect to phase position will depend upon the method of detection. Furthermore, statistical and neural network pattern recognition techniques have been researched which can summarize and differentiate between the patterns [8, 10, 11]. Virtually all results to date were obtained in laboratory tests on insulation models, or on electrical apparatus which is tested off-line (*i.e.* with the apparatus externally energized). On-line measurements of the pulse phase distribution were not practical due to the presence of electrical interference from the operating plant which tended to obscure the actual PD activity. For the specific case of motors and generators, new methods have been developed recently which enabled the accurate measurement of the PD pulse phase distribution on operating machines [12]. Such measurements are of interest since the PPA may provide additional means of distinguishing electrical noise from PD, as well as providing further insight into the actual deterioration processes of the stator winding insulation system, thus allowing improved diagnosis of the insulation condition of motor and generator stator windings. This in turn will enable plant operators to plan corrective maintenance, and thus prevent unnecessary stator winding failures.

This paper outlines the results culled from hundreds of PD tests on operating motors and generators, and presents many examples of the pulse phase analysis. A discussion of the means for detecting PD without interference from electrical noise is first presented.

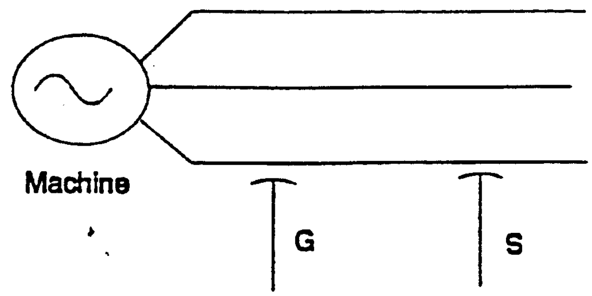

Figure 1.

Schematic of two sensors per phase (usually 80 pF HV capacitors), connected to eliminate electrical noise from the power system. The output coaxial cables from the two sensors on each phase are the same length.

2. PD DETECTION ON OPERATING MACHINES

Although many organizations monitor the PD activity (sometimes also referred to a radio frequency monitoring or RIV testing) of operating motors and generators, most of the techniques are dependent on real-time observations of the PD by an expert. An expert is needed to distinguish the stator winding PD activity from the electrical interference (noise) due to such sources as slip-ring arcing, stator core lamination sparking, corona from the transmission system, as well as the general arcing and sparking occurring from power tools, arc welding, *etc.* within the plant. To facilitate an on-line PD test which can be performed by a nonspecialist, the electrical noise must be eliminated automatically. Over the past 15 years three different techniques using specialized sensors have been developed to separate PD from noise. These techniques identify noise and PD on a pulse-by-pulse basis. Two decades of research indicated that different techniques of detection were needed due to the different physical arrangements of machines, as well as the different noise environments of motors, hydrogenerators and high speed turbine generators. Since noise reduction is a necessary prerequisite to reliable, objective PPA of operating rotating machines, the measurement technique for the three different types of machines is first reviewed.

2.1. MOTORS AND SMALL TURBINE GENERATORS

Due to their small size, sensors installed within a motor or small turbine generator are usually impractical.

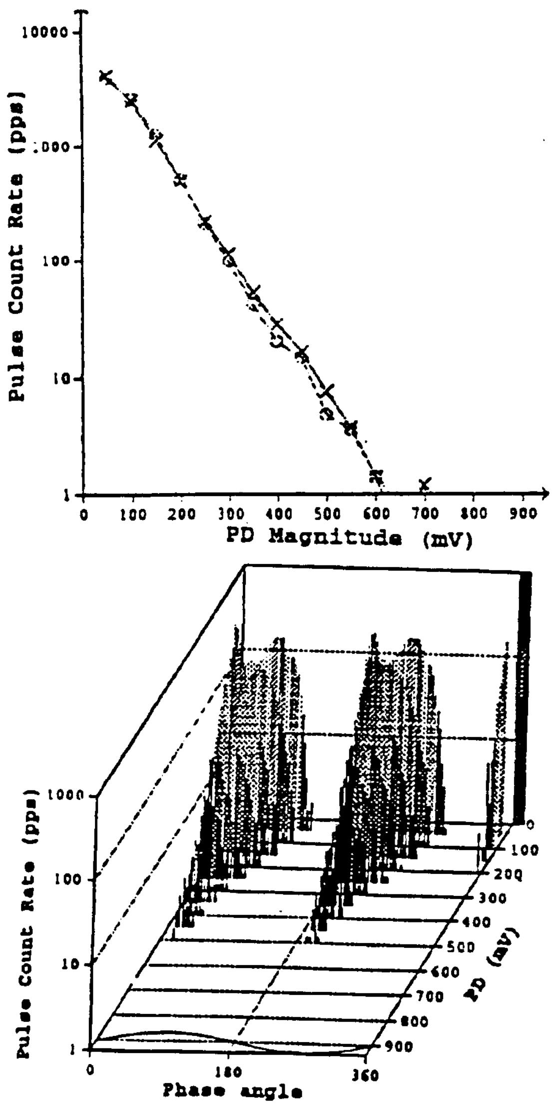

Figure 2.

Two dimensional (2-D) pulse height analysis plot and three dimensional (3-D) pulse phase analysis plots of the PD activity in an operating hydrogenerator stator winding.

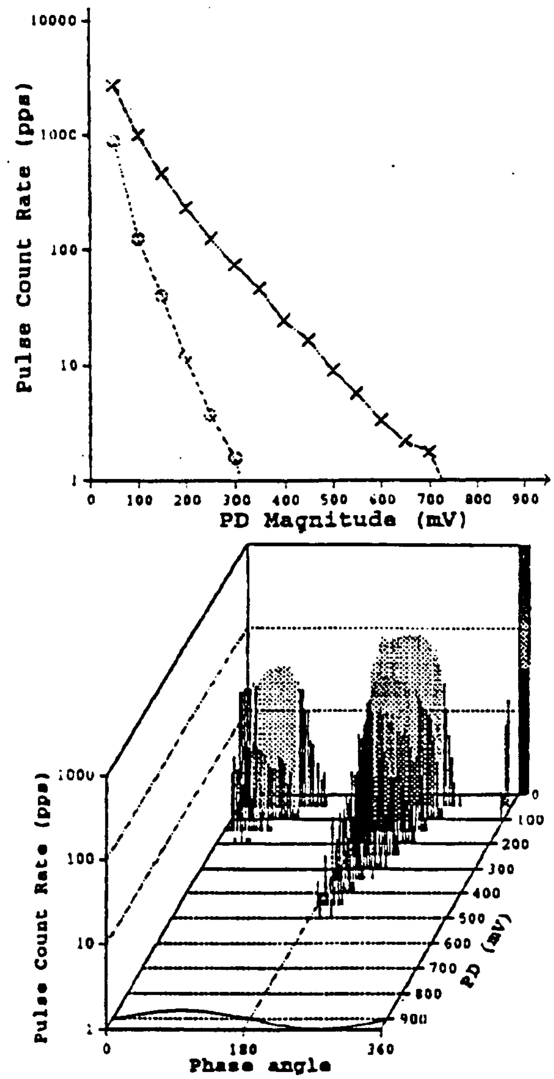

Figure 3.

Classic PD activity from slot discharge (loose windings) in a large hydrogenerator.

Also, the main source of noise is external to the rotating machine [12,13]. External noise can be reduced by installing two sensors per phase, usually at the machine terminals and at the switchgear (Figure 1). Since it takes some time for a noise or PD pulse to travel the distance between the two sensors on a phase, pulses first arriving at the coupler farthest from the machine are designated as noise. Signals detected first by the sensor closest to the rotating machine are classified as stator PD. Such sensors have been installed on ~ 150 motors and generators to date.

2.2. HYDROGENERATORS

Most hydrogenerators are similar to motors and small turbine generators in that most of the noise sources are external to the machine. However, the large physical diameter of a hydrogenerator makes it possible to cancel noise based on the time it takes a pulse to travel along the circuit ring busses in the stator. A noise elimination system was developed where in each phase, a pair of 80 pF sensors were installed where the coils are connected to the circuit ring bus. Since PD occurs in the HV coils near the capacitive sensors, they are detected first at the nearby sensor. However, noise pulses are coupled into the hydrogenerator from the generator HV terminal, and the sensing system is designed to have the noise pulses arrive at the same time at each sensor in a pair [14,15]. Thus noise is distinguished from PD based on

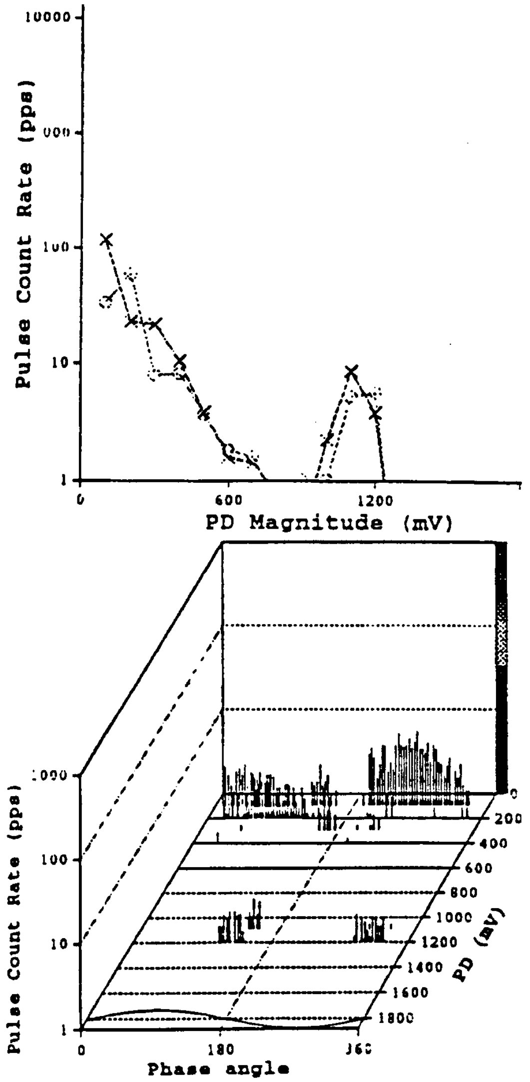

Figure 4.

Endwinding PD occurring at ~ 1200 mV on a 80 MVA hydrogenerator winding.

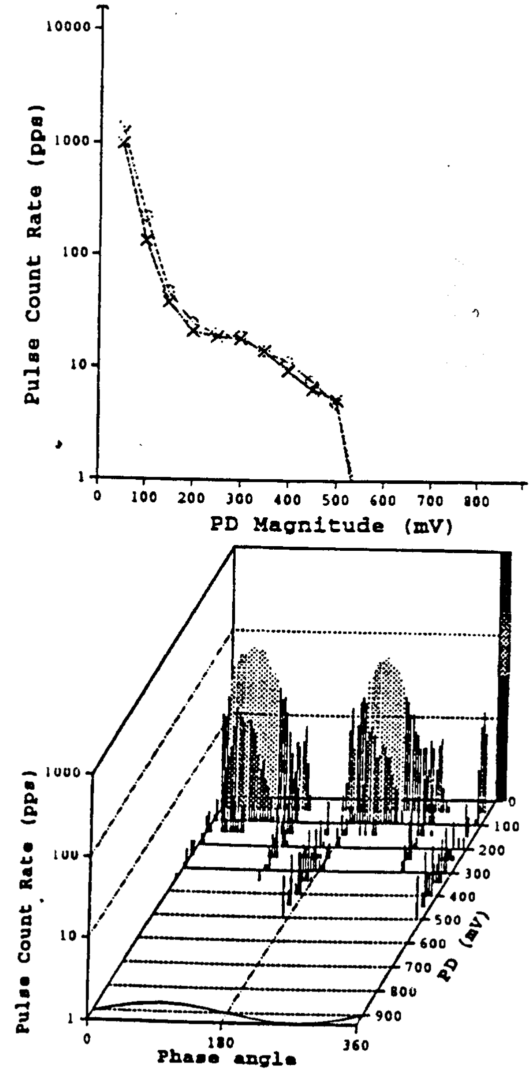

Figure 5.

Unusual 3-D pattern on a 70 MVA hydrogenerator.

time of pulse arrival. Suitable sensors have been installed in ~ 1200 hydrogenerators.

2.3. LARGE STEAM TURBINE GENERATORS

Extensive research had shown that sensors installed on the machine terminals were not adequate to eliminate the internal noise which could occur within the stator of a large turbine generators rated $\gtrsim$ 250 MVA. Specifically, sparking caused by loose stator core laminations could lead to false indications of stator insulation PD. A 1000 MHz antenna called an SSC (stator slot coupler) was developed to detect the PD within the stator winding slot. An extensive analysis revealed that PD occurring in stator bars within the slot were detected as 1 to 5 ns wide pulses, whereas any noise was detected as 20 ns or wider pulses [16]. The result was that any type of noise in large turbine generators could be distinguished from PD occurring within the monitored slot on the basis of pulse width. The sensor also has the capability of explicitly distinguishing between PD occurring within the slot and PD occurring in the endwinding (outside of the slot). More than 130 machines have been equipped with these sensors.

3. INSTRUMENTATION

Specialized instrumentation for each type of sensing system was developed to distinguish between PD and noise. In all cases, the approach to determining the number, magnitude and phase position of the PD pulses was

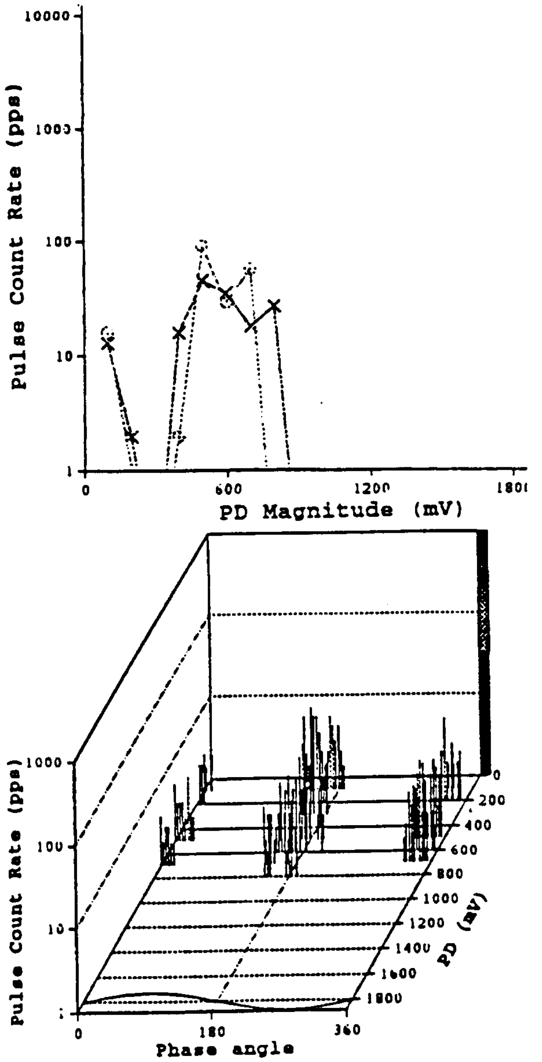

Figure 6.
Unusual 3-D pattern on a 60 MVA hydrogenerator.

the same. After each pulse was tagged as either a PD or a noise pulse, the magnitude of the PD pulses were determined by a single channel pulse height analyzer which was sequentially scanned through a preset range of magnitude windows. The more usual approach of employing a multichannel analyzer which categorizes the magnitude of each pulse was not possible, due to the very short duration of the detected PD pulses and the limited speed of available analog to digital converters. (A fast data acquisition speed was necessary since the PD pulses when detected by the above sensing systems are as short as 1 or 2 ns, and for this application there is no analog to digital converter available which can reliably detect the magnitude of such short pulses.) Since pulse waveform of an individual PD often are oscillatory, special electronics was incorporated to detect only the magnitude of the first peak of the pulse. The rest of the pulse waveform is ignored. The scanning of the pulse magnitudes is controlled by an embedded 386-type computer, which incremented the contents of a memory cell every time the first peak of a pulse of the appropriate magnitude and polarity was detected. Normally the pulses were grouped into 16 magnitude windows. Pulses with low magnitudes were ignored, thus reducing the total count rate.

The ac cycle is divided into 100 'phase windows', each 3.6° wide. A complete 16 channel, dual polarity PHA is associated with each phase window. The ac voltage phase reference comes either from a potential transformer on the generator output bus, or from the small ac voltage which is developed on the low voltage side of the 80 pF capacitors (where used).

In a typical test, the generator or motor is in a steady state operating mode, and is usually at full power. Depending on how fast the scan rate was set, the test takes ~ 20 s to 2 min per sensor (or pair of sensors), *i.e.* from ~ 1 to 6 min per motor or generator. The data is stored on a hard disk, in a commercial database format. The data is also simultaneously shown on a computer display in the form of two dimensional (conventional PHA) and three dimensional (PPA) graphs.

The PD is recorded in mV rather than the more traditional pC. This explicitly recognizes that the discharges in inductive apparatus such as stator windings are not calibrated in apparent charge [18].

4. PULSE PHASE ANALYSIS RESULTS

PD data was collected over a two year period from ~ 50 hydrogenerators, 25 motors, and 60 large steam turbine generators. All the data was collected while the machines were operated normally.

4.1. HYDROGENERATORS

Figure 2 shows typical PHA and PPA plots from one coupler installed on a 13.8 kV, 80 MVA hydrogenerator. The stator winding is insulated with asphaltic mica. The positive and negative PD activity is about the same in number of pulses and magnitude. Furthermore, the negative PD pulses occur primarily between 0 and 90° (with the lower pulse magnitudes centered on 45°) of the ac cycle, and the positive PD activity is between 180 and 270°C (with the lower pulse magnitudes centered on 225°). Higher magnitude pulses tend to occur closer to the 60 Hz voltage zero crossing. This is the classic result for PD occurring in voids, *i.e.* bounded by a solid dielectric [6, 7, 9]. Since asphaltic-mica insulation usually deteriorates by delamination of the groundwall insulation, the on-line PD pattern is consistent with off-line tests on stator coils and insulation models.

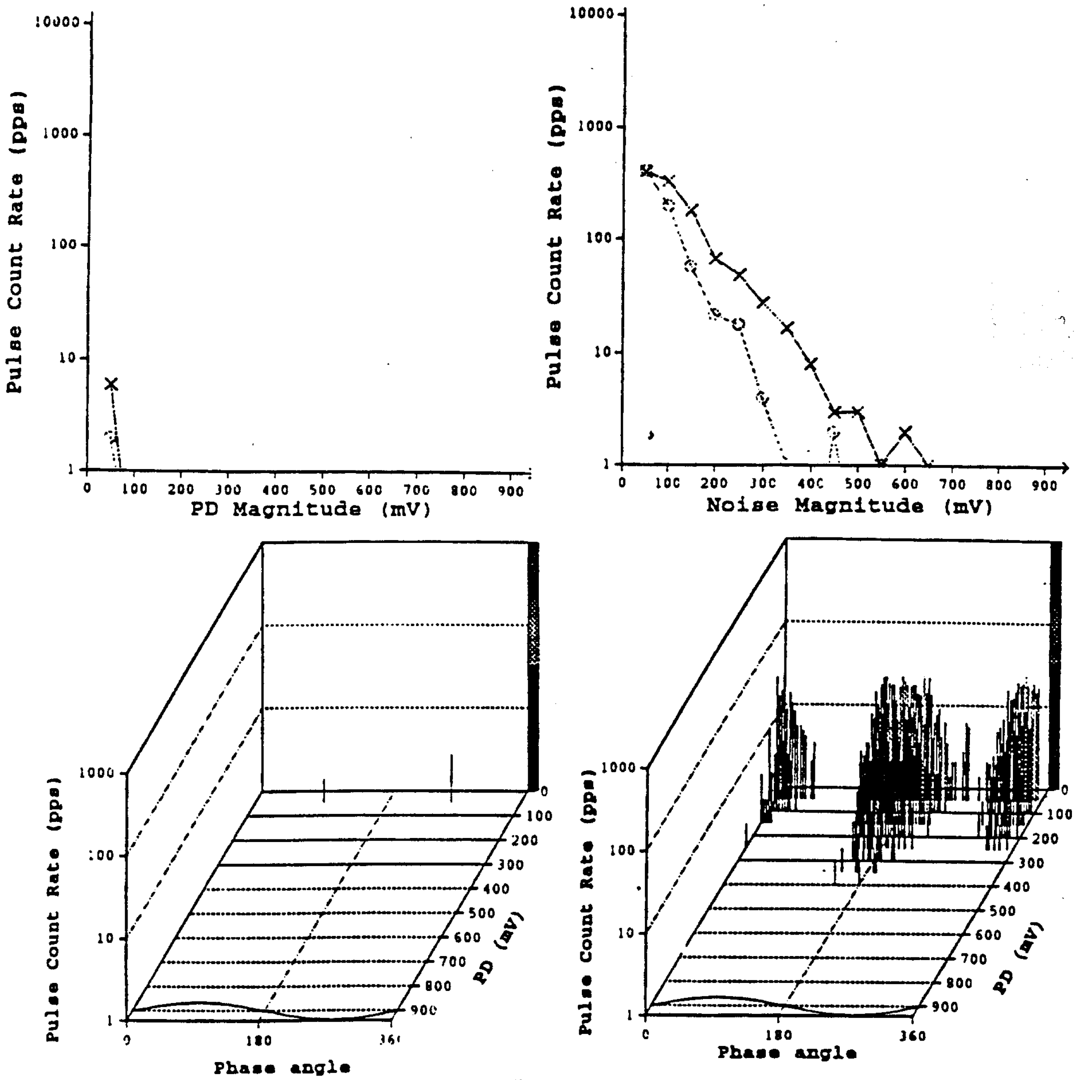

Figure 7.

Electrical interference probably from an arcing contact in the switchgear controlling a 4 MVA gas turbine generator. The PD activity in the stator winding is on the left.

The PD activity in a hydrogenerator in one phase on one parallel circuit operating at 265 MW suffering from advanced slot discharge is shown in Figure 3. Slot discharges are PD which occur as a result of loose coils in the stator slot where the semiconductive armor and the groundwall insulation is abraded away. The PD occurs between the surface of the stator coil and the grounded steel stator core. Both the PHA and PPA plots show that the positive PD magnitude is at least 2× larger than the negative peak magnitudes. Also, as expected, the low magnitude discharges are centered on the 45 and 225° phase angles.

Some types of PD activity occur as a result of the phase-to-phase ac voltage. Figure 4 shows the activity which is believed to be occurring in the endwinding (*i.e.* the portion of the coils which are outside of the stator slot). In most hydrogenerators (as well as other types of machines), coils in one phase which are connected to the HV terminal are often adjacent to a HV coil which is in another phase. When slightly conductive pollution is present (for example from moisture or oil films mixed with dust or carbon brake particles), then electrical tracking and PD can occur across the blocking spacers between the coils. Alternatively, PD can occur across the air gap between the end arms of bars/coils if this air gap is too small. Since the phase-to-phase voltage is shifted 30° from the phase-to-ground voltage (which is the voltage reference used to determine the phase position in the

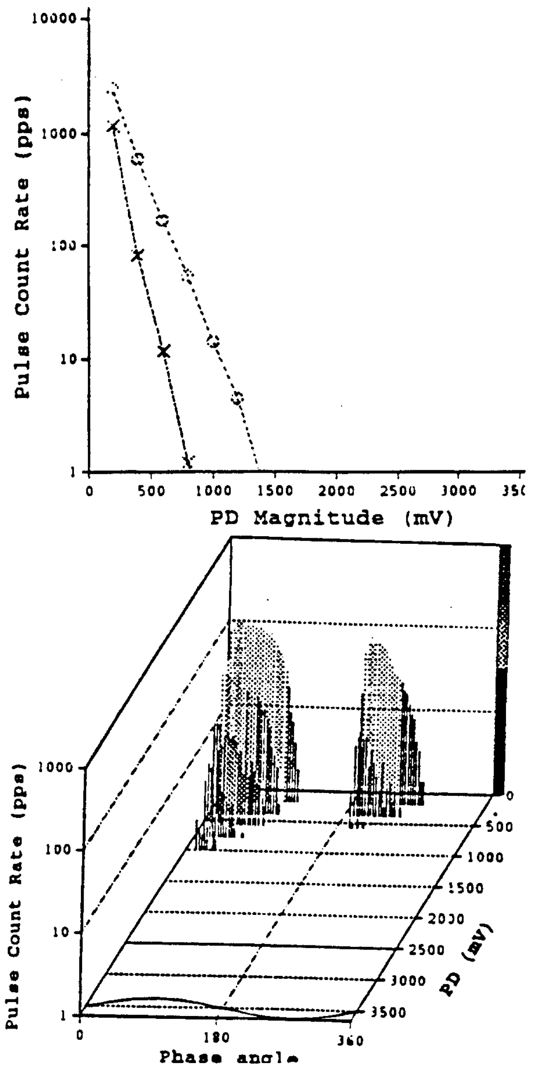

Figure 8.

Classic PD activity from discharges occurring adjacent to the copper conductors.

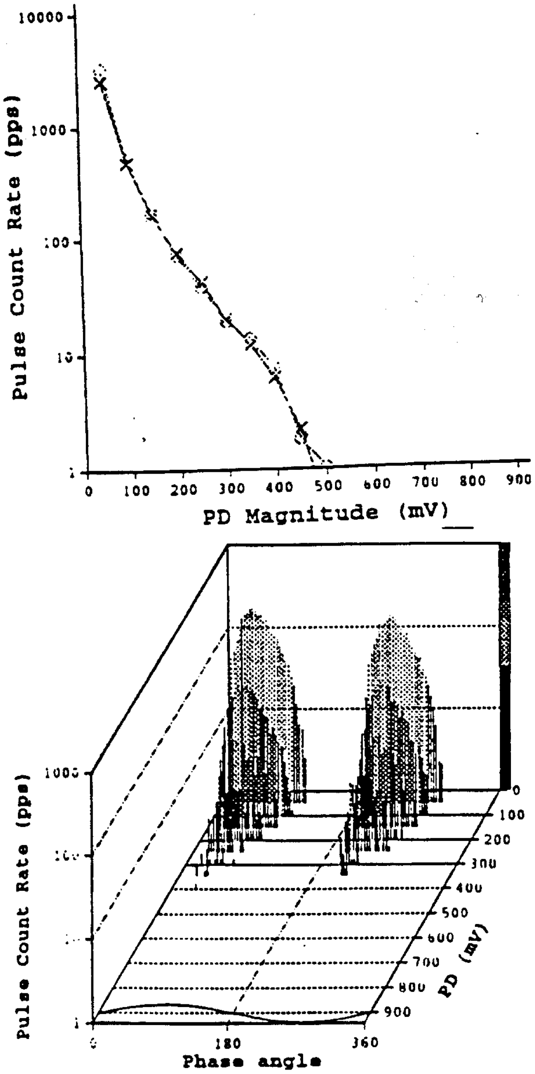

Figure 9.

Classic internal PD in voids in an epoxy-mica motor winding.

instrumentation), this should cause some apparent phase shift in the PD pattern. In Figure 4, the PD is centered ~ 100° and 300° of the ac cycle. Some of this phase shift from the expected position (45°and 225°) may be due to the 30° shift in the applied 60 Hz voltage. This pattern is apparent with the high magnitude pulses measured on a 80 MW hydrogenerator with suspected endwinding discharges (Figure 4).

The above PPA plots are readily understood in part from conventional PD theory. Such results form the majority of patterns found in operating hydrogenerators. However, a number of alternative patterns have also been recorded on operating hydrogenerators. Figures 5 and 6 show the activity in two hydrogenerators which display unusual PPA plots. Care was taken to ensure that the ac phase reference was accurate. Conventional PD activity is apparent at low magnitudes. However, at higher PD magnitudes, the PD is not in the expected phase position, and is clumped. We do not know the cause of these odd patterns or are aware of any specific stator winding insulation problems in these machines.

4.2. MOTORS AND SMALL TURBINE GENERATORS

The results on these machines were obtained from pairs of capacitive sensors installed externally (Figure 1). Figure 7 shows the PPA from the stator winding as well as the electrical noise from the power system in a 4 kV,

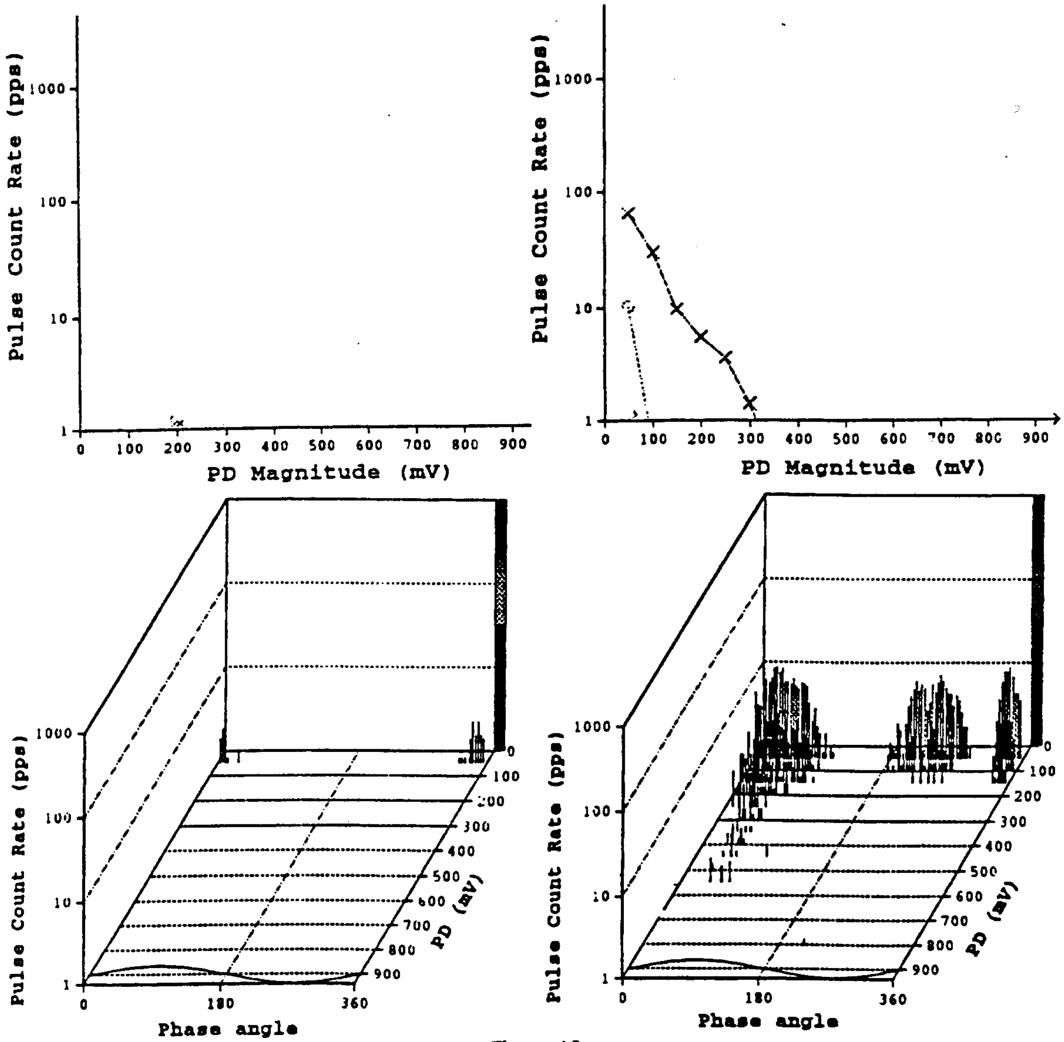

Figure 10.

Classic advanced-stage slot discharge in a large hydrogen-cooled epoxy-mica turbine generator stator winding with the SSC sensor, discharges in the slot (right) and discharges in endwinding (left) can be separated.

4 MW gas turbine generator operating on an oil production platform. There is very little PD activity in the stator. However significant external electrical activity (noise) is occurring, with the main activity occurring on the A phase, at the zero crossings of the voltage waveform. Observation of activity at the zero crossings can be an indication of contact noise. Subsequent inquiries indicated that arcing on the A phase bus on the platform was in fact occurring. Thus the PPA noise plots sometimes can help to identify potentially harmful problems external to the machine.

Figure 8 shows the PD activity on a five year old polyester mica splitting winding in a 65 MVA gas turbine generator. It is believed that the copper has separated from the groundwall insulation, resulting in more negative than positive PD.

The PPA plot of the PD activity in a 13.8 kV, large nuclear pump motor with known problems caused by delaminated insulation is shown in Figure 9. As expected, and consistent with Figure 2, the positive PD activity (between 180 and 270°) is essentially the same as the negative activity.

4.3. LARGE TURBINE GENERATORS

The PHA and PPA plots of the PD activity in both the slot region and the endwinding region of a turbine generator operating at 365 MW is shown in Figure 10. The endwinding and slot PD activity could be explicitly distinguished since an SSC was used as the sensor

[12]. Clearly, the main PD activity is occurring in the slot region. Visual examination of the winding had indicated that there was extensive greasing (a viscous, oily buildup) on the winding at ventilation ducts and at the slot exits. This is a strong indication that slot discharges due to loose coils in the slot are occurring, and it is likely that the semiconductive armor has been abraded away at some locations. Most of the (low magnitude) discharge activity is centered on the 45° and 225° phase positions, as expected.

Figure 11 shows the PD activity in the slot of a generator operating at 96 MW shortly after a new epoxy-mica stator winding was installed. Most of the slots had essentially no PD activity (< 25 mV), and no activity was measured on the endwindings. However, two slots had a few large pulses, ⩽ 80 mV, in the slot (Figure 11). The PPA plot shows that the pulses are occurring at unexpected positions of the ac cycle. The ac phase reference was from a potential transformer. Since the new winding had only been installed for a few months, and there would not have been enough time for the semiconductive armor on the coils to have been destroyed by vibration, the pulses are probably not due to standard (Townsend) PD. A more likely explanation is that the pulses are due to contact noise, *i.e.* sparking which occurs when the semiconductive surface of the coil comes in contact with the grounded stator core. In a new winding, the semiconductive armor may not be in good electrical contact with the core all along the length of the slot. If the coils are free to move, the semiconductive surface of the coil may pick up a small voltage due to a capacitive voltage division effect because the magnetic field pulls it away from the core. When the magnetic forces allow the coil to reconnect the core (twice per ac cycle), the small surface voltage will be discharged, and the spark is detected as a voltage pulse. Since the pulses are due to contacts, and not due to PD, there is no reason to expect that the phase position will be dependent on the electric field as determined by the ac voltage. This perhaps explains why the PPA in Figure 11 is not of the usual form. However, such patterns may be an example of the very early stages of stator winding looseness, before the semiconductive armor has been removed.

The results from an epoxy-mica stator winding in a turbine generator operating at 650 MW, which is known to be contaminated with oil (from the hydrogen seal oil system) are shown in Figure 12. The PD activity was measured by the SSC sensor. Significant PD only occurred outside of the slot. The higher magnitude discharges in Figure 12 are occurring at a phase position which is a little more than 30° from the normal position. The presumption is that the endwinding discharges are due to phase-to-phase ac voltage. As found in Figure 4 for the hydrogenerator, a likely cause is PD due to electrical tracking between coils in different phases.

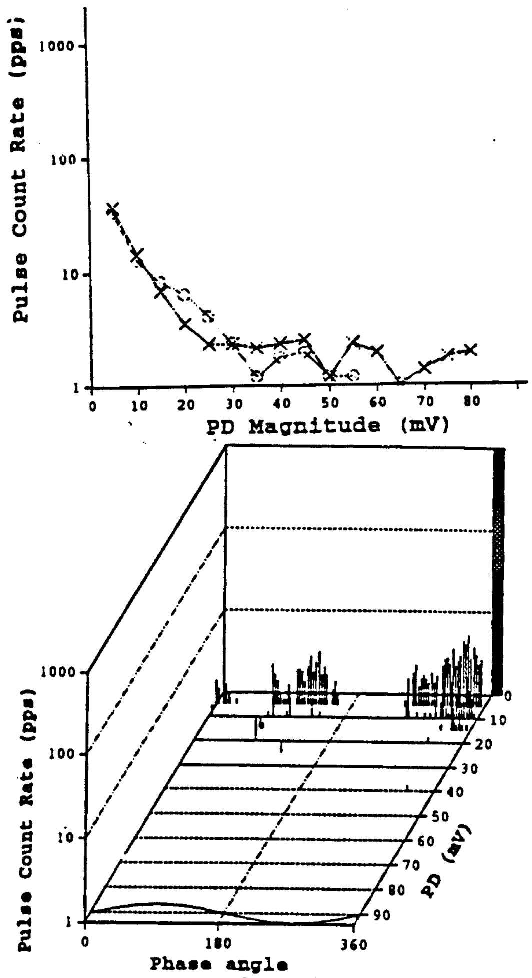

Figure 11.

The early stage of slot discharge in a large hydrogen-cooled turbine generator winding.

Figure 13 shows a pattern that is difficult to understand. The data was measured on a turbine generator equipped with SSC operating at 80 MW. The stator winding was made from polyester and mica splittings. Such abnormal patterns tend to occur on generators with moderate PD activity, and thus may due to very erratic PD. Furthermore, several different PD mechanisms may be occurring at the same time.

5. CONCLUSION

MULTIPLE PD measurements on > 100 operating motors and generators have been reviewed. In the majority of results, the position of the PD with respect to the 60 Hz phase angle was as expected from conventional PD theory, as well as laboratory experiments. However,

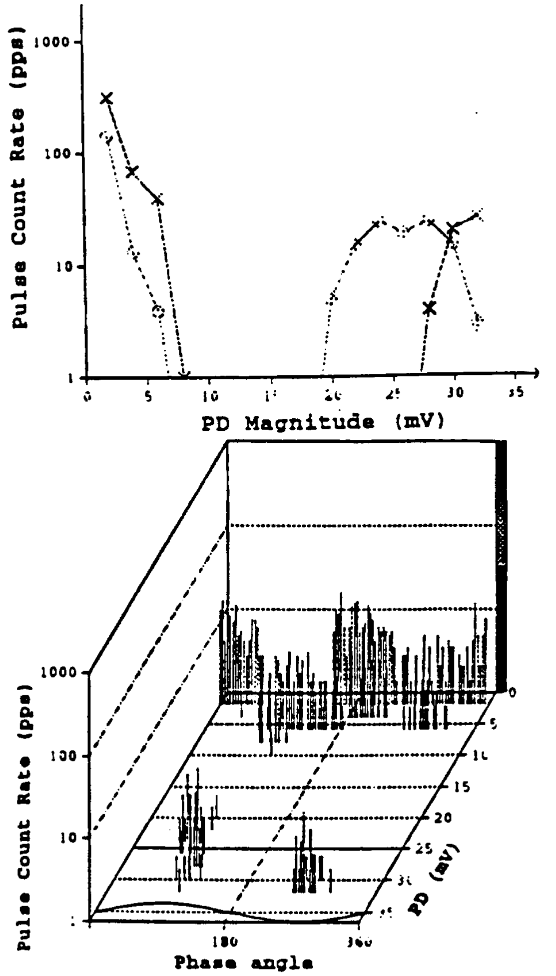

Figure 12.

PD pattern associated with phase-to-phase endwinding discharges in a large hydrogen-cooled turbine generator.

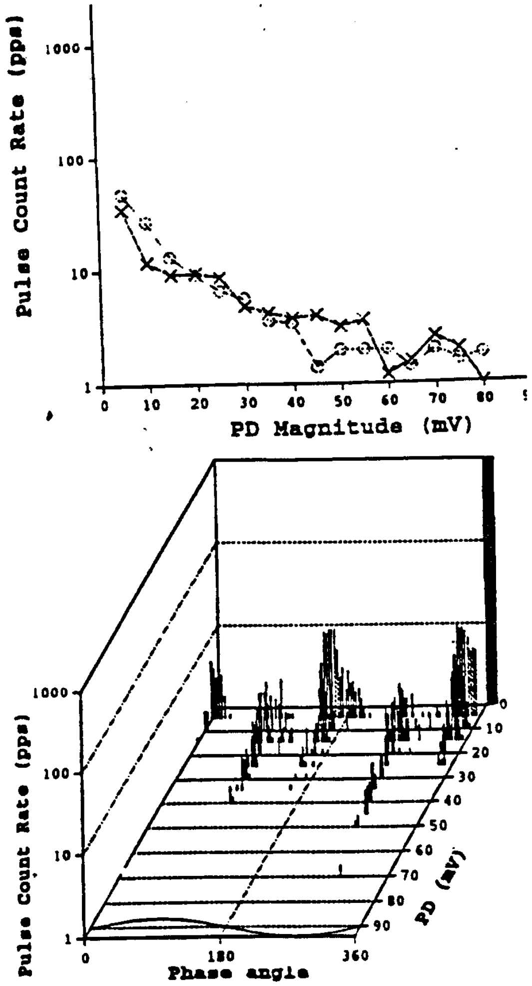

Figure 13.

Unusual PD pattern from the slot of a hydrogen-cooled turbine generator.

perhaps 25% of the PPA plots were abnormal in some way. That is the PD occurred in unexpected portions of the phase, or unusual clumping of the pulses was present. Explanations for some of these abnormal patterns were apparent. For example, endwinding discharges due to electrical tracking between coils in different phases may cause a 30° phase shift in the pattern. In addition, for windings in the early stages of slot discharges (before the semiconductive armor has been eroded), the pulse phase position may be determined by the mechanical forces acting on the coil, rather than the electrical stress. However, several patterns have been observed that have no readily apparent explanation. Yet these patterns are real, and are not due to noise nor are they artifacts of the measurement system.

Clearly, further investigation is required under controlled circumstances to confidently understand the causes for the abnormal patterns. The results acquired on operating motors and generators are uncontrolled, since it is often difficult to be sure what the true cause of the discharges are (machines are not disassembled on the whim of a researcher), and often multiple types of discharges may be occurring in any one machine. Laboratory studies which include the three phase electrical stress distribution and/or the mechanical forces which act on a winding would be most beneficial.

The anomalous results described above clearly indicate that further significant work is required in order to properly understand and interpret pulse phase distributions. Researchers who are employing statistical, neural network or other types of pattern recognition on static insulation models should be aware that the PD patterns obtained from such models may be overly simplistic. In actual equipment, multiple types of discharges may be occurring at the same time, and the influence of mechanical forces and three phase stresses may greatly increase the number of patterns possible, and thus increase the complexity of the pattern recognition process.

ACKNOWLEDGMENT

The sensors and instruments used in this study were developed under Canadian Electrical Association research contracts 738 G631 and 9010 G789, Mr. A. E. Kingsley Program Director. The authors thank Ms. V. Warren of the US Army Corps of Engineers, who identified some errors in early versions of the manuscript and developed hypotheses for some of the pulse phase patterns.

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Manuscript was received on 3 May 1995.