EXPERIENCE WITH ON-LINE PARTIAL DISCHARGE TESTING OF MOTORS AND GENERATORS

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Abstract

Deterioration of stator winding insulation continues to be one of the predominant causes of large motor and generator failures. Over the past several years, practical methods have been developed for measuring the partial discharge activity in the high voltage insulation of stator windings, since partial discharges are a symptom of most of the insulation failure mechanisms. One test, called the PDA test, can be performed by utility personnel during normal operation of a hydrogenerator. Several improvements have recently been made to the PDA test to help maintenance personnel interpret results and identify the root cause of any problems. A similar partial discharge test, called the TGA test, has now been specifically developed for turbine generators and large motors. The TGA test allows fossil and nuclear plant staff to reliably perform a partial discharge test on motors and turbine generators. This paper presents several case studies of the use of these new partial discharge test technologies on generators. Test results show that machines with deteriorated windings have a partial discharge activity at least 30 times higher than good windings. The availability of these test methods enables utilities to economically and reliably plan stator winding maintenance and avoid unexpected failures.

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Introduction

The high voltage electrical insulation in both air-cooled and hydrogen-cooled stator windings in large motors and generators gradually deteriorates over time [1,2]. Both types of machines may eventually suffer from loose windings (leading to slot discharge), partly conductive contamination (leading to endturn tracking), and delamination due to overheating or load cycling. Furthermore, air-cooled machines can deteriorate due to degradation of the semiconductive and grading coatings on the stator coil/bar surface. Partial discharges (PD) are associated with each of these deterioration mechanisms. For over 40 years, some OEMs and utilities have shown that by periodically measuring the PD activity, they can detect stator winding insulation problems well before failure would occur [3-6]. This early warning permits PD test users to plan corrective maintenance (such as cleaning or rewedging), change operation (such as restricting load or the number of starts), or rewind the stator. Such corrective action extends winding life, and/or at least prevents an unexpected machine failure.

Partial discharge tests can be performed either when the machine is not operating (off-line) or during normal operation of the motor or generator (on-line). Utilities prefer an on-line test since no outage is required, and the test can be performed more frequently. Although utilities such as American Electric Power, Virginia Power and Ontario Hydro have employed on-line PD tests for many years, most utilities have not used the test. An important reason for the relatively restricted use of PD testing is that an expert is required to perform most tests. Significant expertise is needed since the electrical partial discharge signals from the winding are often obscured by electrical noise occurring elsewhere in the plant. The expert can visually separate the noise from the PD on an oscilloscope or frequency spectrum analyzer. A non-expert performing the test will sometimes confuse the PD and noise, and if the noise is high, will incorrectly inform plant management that the winding is failing. If a visual inspection reveals that the winding is in good condition, plant management will henceforth not believe PD test results. Thus, non-experts performing the test can reduce the credibility of the PD test.

To reduce the reliance on experts (which are not economically available to most utilities), research has been conducted to develop on-line PD test methods which inherently reduce noise. If noise is eliminated, then electronic instruments can measure the PD activity without the intervention of an expert. The PDA test, developed in 1976, was one of the first techniques which inherently eliminated noise, thus enabling a PD test to be performed by non-expert utility staff during normal machine operation. Unfortunately, the operation of the PDA test depends on the large diameter of a hydrogenerator, and thus is only applicable to hydrogenerators [7]. Recently, other techniques for eliminating noise in turbine generators and motors have been developed using specialized sensors [2,8].

This paper briefly explains the method of noise rejection used for each type of PD test and presents several case studies of results obtained by plant staff with the on-line tests.

PDA Test For Hydrogenerators

The PDA test was developed for hydrogenerators about 15 years ago and is now being used on about 1000 hydrogenerators around the world. The PDA test requires the permanent installation of PDA sensors on hydrogenerators, as well as the use of a portable instrument called the PDA. One instrument can be used to measure the PD activity on all the hydrogenerators in a utility. The sensors are 80 pF, 25 kV capacitors which are installed at critical locations within the stator winding. The capacitors block the 60 Hz voltage, yet allow the very high frequency partial discharge voltage pulses created by each partial discharge in the winding to be conducted to the measurement apparatus. Usually two PDA couplers are installed per phase. The pair of PDA couplers is connected in such a way as to cancel out noise, while remaining sensitive to partial discharges located within the winding [1,7]. Installation of the couplers can usually be done by a two-person crew in three to four days during a suitable outage.

The PDA instrument is connected to a pair of couplers when the generator is operating normally. The PDA extracts the stator winding partial discharge signals from the electrical interference, and records the number of partial discharge pulses occurring per second, as well as their magnitude. The normal results from the PDA are plotted as a "pulse height analysis" of the partial discharges from one coupler. The horizontal scale is the magnitude of the partial discharges in millivolts. The vertical scale is the number of partial discharges occurring per second at a pulse magnitude corresponding to the horizontal scale. Both positive and negative partial discharges are simultaneously recorded. As with all PD tests, the results are trended over time, i.e., the most recent results are compared with previous results. In general, a generator with a more deteriorated winding will have much more partial discharge activity, represented as more discharges per second and higher magnitude discharges.

Since the introduction of the PDA test, there have been four generations of the PDA instrument. Each generation of PDA instrument has had significant improvements over the preceding version. The most recent version of the instrument, known as the PDA-IV, has the following improvements:

- The test can be performed on hydrogenerators with circuit ring buses as short as 1 m (instead of 2 m needed previously).
- Improved noise rejection since distortion of pulses as they travel through the generator no longer impairs noise rejection.
- Pulse phase analysis, which measures where the partial discharge pulses occur with respect to the 60 Hz phase position.
- Direct plotting of trends in partial discharge activity (for example the peak partial discharge magnitude and the NQN) over time, which together with a full-color display, enable users to more easily detect if winding problems are occurring.

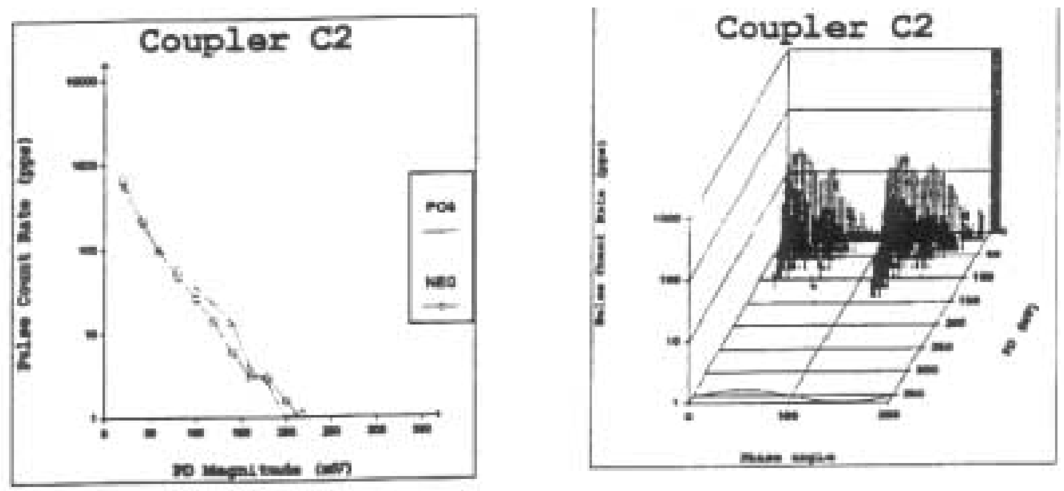
The first two improvements result from replacing the analog differential input of earlier PDAs with 800 MHz digital electronics which directly measure the time-of-arrival of the pulses from a pair of couplers [9]. Noise pulses are those which arrive within 6 ns of one-another. Since only the time-of-arrival of the pulses is compared in the new instrument, and not the whole waveform (as was used in previous PDAs which had an analog differential input), greater noise rejection is obtained since differences in pulse shapes no longer cause a noise pulse to be interpreted as a partial discharge pulse.

Researchers around the world have noted that pulse phase analysis can help in identifying the causes of partial discharges in electrical insulation. The addition of pulse phase analysis capabilities to the PDA test may permit a more accurate diagnosis of hydrogenerator stator winding problems.

Case Study 1 - 80 MW Hydrogenerator

Many papers have been presented on interpreting PDA test results [6,7]. In general, if the PD activity doubles every year or so, then the stator insulation is significantly deteriorating and further testing or inspections are warranted. Furthermore, by examining the ratio of positive to negative PD activity, and/or the dependence of PD on load and temperature, the type of insulation deterioration can sometimes be determined [7]. The addition of pulse phase analysis enables even more information on the condition of the winding to be determined.

Figure 1(b) shows a three-dimensional plot of the partial discharge activity from one coupler mounted on an 80 MW hydrogenerator at Ontario Hydro's Sir Adam Beck GS. The vertical axis is the number of pulses occurring per second. The horizontal scale shows where the pulses are occurring with respect to the 60 Hz ac cycle. The axis coming out of the page indicates the magnitude of the partial discharges. As is well known by researchers using a parallel PD sensor, negative partial discharge pulses normally occur between 0^{o} and 90^{o} of the ac cycle and positive partial discharges occur between 180^{o} and 270^{o}. The pattern is easily seen in Figure 1. This generator also has peaks in the PD activity at about 100^{o} and 280^{o}. These peaks are most likely due to discharges from pollution/electrical tracking of the endwindings which causes the usual pattern to shift to the right by about 60^{o}, since the PD is driven by phase-to-phase voltage rather than the more normal phase-to-ground voltage (in the slot). Visual inspection of the hydrogenerator has indicated that endturn PD is occurring. Thus pulse phase analysis can add a significant new dimension in test interpretation.



(a) (b)

Figure 1 Partial discharge activity on Beck Unit 21, while operating at 76MW. Plot (a) shows the conventional pulse height analysis while (b) shows the number and magnitude of the PD pulses with respect to the ac phase angle.

Bus Coupler Test For Motors and Small Turbine Generators

The method used in the PDA test for eliminating electrical interference in hydrogenerators depends on the relatively long circuit ring buses which are common on hydrogenerator stator windings [1,7]. The circuit ring bus in high speed turbine generators and large motors is usually much shorter, or non-existent. Furthermore, the electrical noise environment in fossil and nuclear plants is often much more severe than in hydrogenerator plants. Thus, it was apparent that the PDA test method would not be effective for motors and turbine generators since there would be a high probability of false indications of stator winding problems due to electrical interference. Therefore, research was conducted into on-line partial discharge test methods which would be effective for large motors and generators.

For on-line testing of motors, relatively small turbine generators and synchronous condensers, the electrical noise environment was found to be mainly due to corona, discharging or poor electrical contacts which were external to the machine. A method was developed to eliminate this external noise using two high-voltage capacitors (or other electrical sensors such as Rogowski coils) per phase, i.e. six per machine (Figure 2) [8,10,11]. The capacitors are similar to the PDA couplers, and are installed in a few days during a short outage. The capacitors, termed "bus couplers", block the 60 Hz voltage while passing the very high-frequency voltage pulses that accompany partial discharge. Each partial discharge within the stator will create a very short-voltage pulse which will travel through the stator winding, and eventually appear at the stator terminals where the bus couplers will detect the voltage pulse. However, PD-like noise can also come from the power system - especially arcing and corona from the switchyard and switchgear. Such signals can be misinterpreted as PD from the stator.

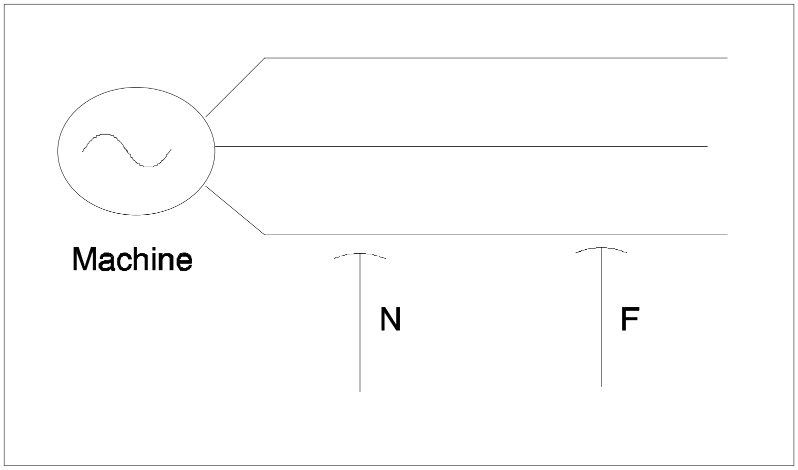


Figure 2 Schematic of capacitive bus couplers on a motor feed.

By installing two couplers per phase, and separating these couplers by at least 1 m, the noise from the power system can be distinguished from stator PD by examining the direction of pulse travel [8,10,11]. In comparing the time-of-arrival of pulses at the two couplers in a phase, if a pulse is first detected at the coupler nearest to the stator winding (N in Figure 2), then the pulse is assumed to be caused by stator PD, and should be counted. However, if a pulse is first detected at the coupler closest to the power system, i.e., at the coupler furthest from the stator (F in Figure 2), then the pulse is due to noise, and should be classed as noise. Similarly, arcing or discharges that arrive at both N and F couplers within the electrical time difference between the two couplers, indicates that noise is occurring within the cable or bus, perhaps from poor connections or PD, and should be counted and classed as bus noise. The presence of bus noise could be an indicator of noise between the N coupler and the stator, depending on the actual location of the N coupler.

A version of an instrument called the TGA compares pulse arrival times from the pair of bus couplers on a phase, automatically determines which pulses are due to PD from the stator, and determines the magnitude, number and phase position of such PD pulses. The plotting of PD data, including trends in NQN and peak discharge magnitude as well as the pulse phase analyses, is similar to that in the PDA-IV, and thus data interpretation is the same as for the PDA test.

Bus couplers have been installed in about 50 machines since they were first developed in 1978. The N couplers are usually mounted in the machine terminal box, whereas the F couplers are mounted at a PT cubicle or at the switchgear. If surge capacitors are mounted on the machine terminals, the bus coupler approach can not be directly applied, since the surge capacitors short the high-frequency PD pulse signals to ground. Alternative methods are then used to detect the pulses. Although the TGA can be used with only a single sensor per phase (i.e., only the sensor at N in Figure 2), there is no independent method a non-expert can use to verify that any high readings are not due to interference. If a single sensor is used and high readings are measured, the test would have to be repeated by an expert, usually at high cost.

Case Study 2 - 6 MW Turbine Generator On Oil Plattform

Capacitive bus couplers were installed on four 6 MW global-VPI turbine generators which were mounted on an oil platform. Capacitors were installed in the switchgear as well as within the generator terminal box. The generators were connected to the switchgear by means of about 50 m of shielded power cable. None of the stators had significant PD activity. However there was considerable external noise. Figure 3 shows both the normal pulse height analysis data (2-dimensional plots), and the pulse phase analysis (3-dimensional plots). There is relatively little PD activity, which was confirmed by a visual examination of the stator, indicating that the endturns, at least, were clean and dry.

Past experience has indicated that it is prudent to plot both the PD and the electrical noise activity. The pulse height analysis plots reveal that the noise is about 5 times higher than the stator PD. If only a single coupler were used to measure the PD on that phase (instead of two), the stator would have been diagnosed as being in poorer condition than is the case. Further observation of the 3-dimensional plots showed that the electrical noise was primarily occurring at the 0^{o} and 180^{o} portion of the ac waveform on A phase. This was the same for the other three generators. This indicates that there are some poor electrical contacts somewhere on the platform on A phase. Platform personnel confirmed that there had been previous problems with bad electrical contacts.

Case Study 3 - Old Turbine Generator

A 188 MVA hydrogen-cooled turbine generator located in Kansas has an original, 25-year-old epoxy-mica winding. The utility needed to determine the condition of the winding in order to assess whether a rewind was necessary in the next few years. Since the utility was aware that interpretation of PD tests is based on the trend in PD over time, and since only a short outage time was available for installing sensors, bus couplers were installed on the machine terminals.

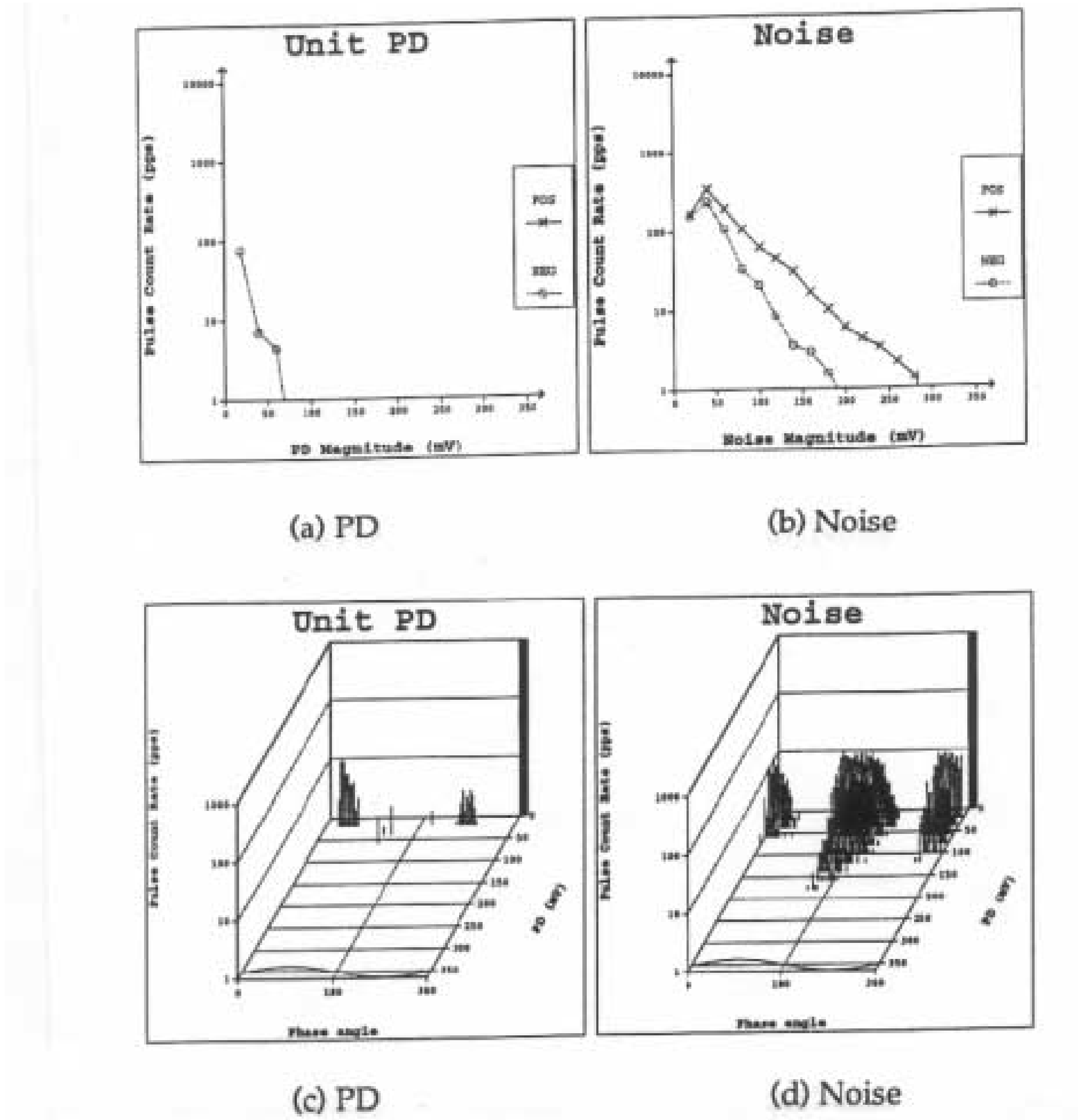


Figure 3 Pulse height and pulse phase analysis plots of A phase of an operating 6 MW stator.

Six 80 pF couplers were mounted on the machine, three on the bushings from the generator to the isolated phase bus (Figure 4), and three in the PT/surge capacitor cubicle. Figure 5 shows the PD and noise activity. The external noise is relatively low, probably due to the surge capacitor which tends to short the external pulses to ground. The noise occurs over the entire ac cycle, whereas the PD, at least at high pulse magnitudes, occurs primarily between 0^{o} and 90^{o} or 180^{o} and 270^{o}, as is typical for PD. Thus, we have confidence that we are actually measuring PD, and not internal noise, for example from slip ring or shaft ground brush arcing.

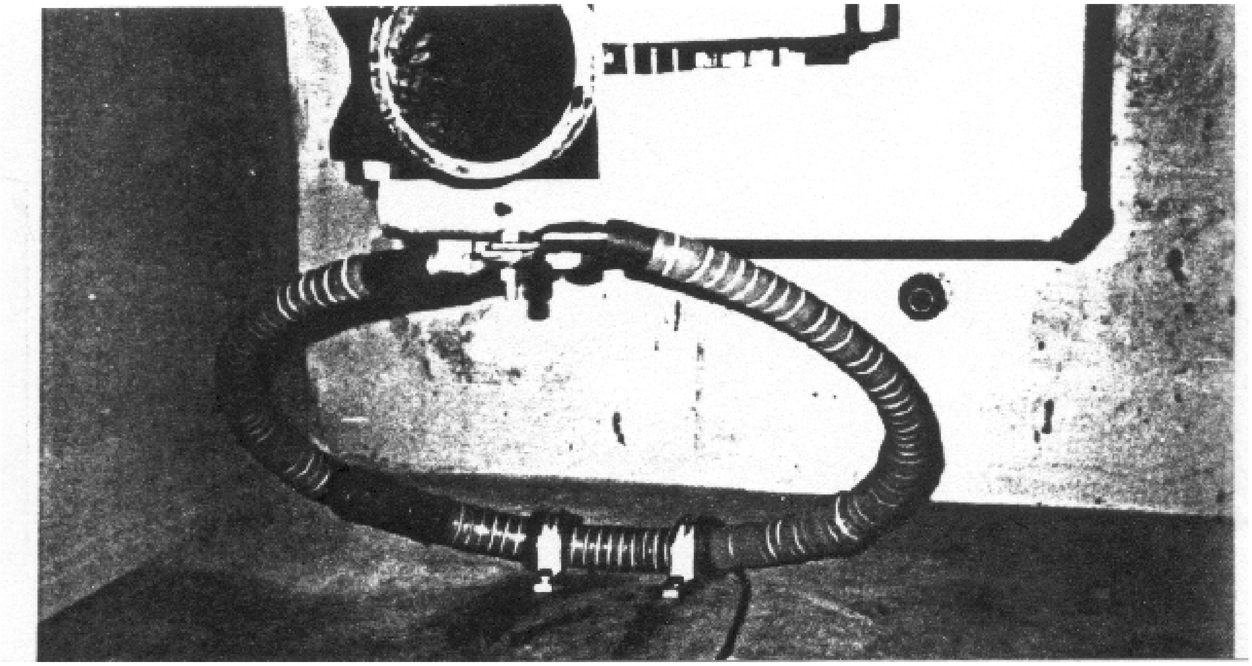


Figure 4 Photograph of a capacitive coupler installed on the generator bushing on one phase

phase

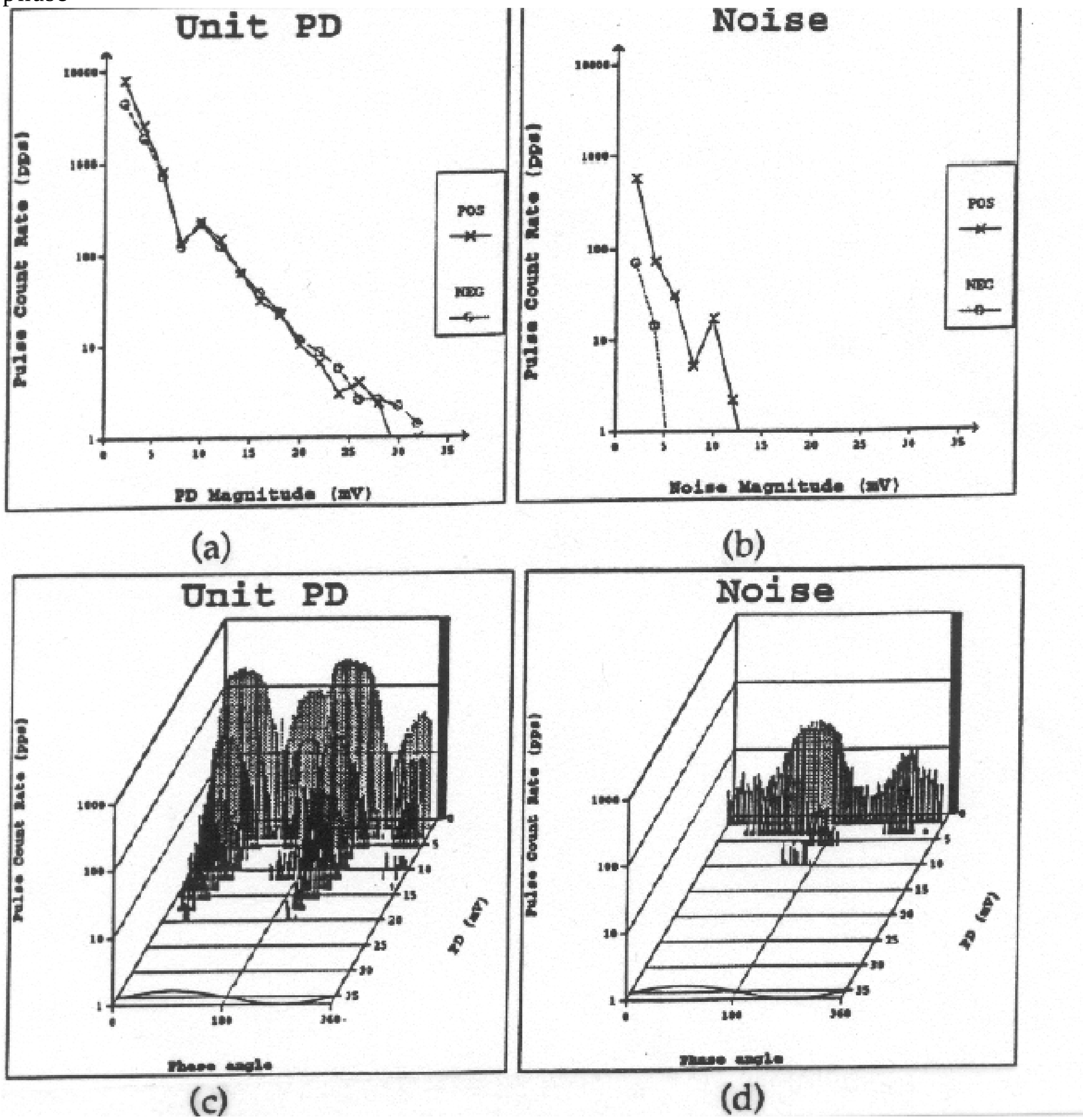


Figure 5 PD and noise activity on one phase of a turbine generator operating at 221 MW, equipped with bus couplers.

The PD magnitudes are relatively low, but this is typical of hydrogen-cooled machines where the hydrogen pressure tends to reduce the PD magnitudes for the same level of insulation deterioration relative to an air-cooled machine. Firm conclusions on the insulation condition will have to wait for two or so years, when the trend in PD activity over time can be measured.

SSCs For Large Turbine Generators

The on-line partial discharge test using bus couplers was found to be unreliable for large turbine generators. In virtually all large turbine generators there are significant sources of "internal noise", and the test results could not be correlated with known turbine generator winding condition [8]. Internal noise can occur from slip ring and shaft ground brush arcing, as well as sparking between core laminations and the key bars, as the stator core relaxes over time. The realization that the bus coupler method could not eliminate such internal noise lead to the development of a new type of PD sensor called the stator slot coupler (SSC).

Unlike the PDA couplers and the bus couplers which are usually high-voltage capacitors, the SSC is not connected to the winding. The SSC is an antenna (10 MHz to 1000 MHz bandwidth) which detects the electromagnetic energy from PD and other signals. The SSC is installed in stator winding slots containing stator bars connected to the phase terminals. The present version of the SSC is installed underneath the wedges (Figure 6). Each SSC is about 50 cm long, 1.7 mm thick, and is custom made to be the same width as the stator slot. Usually 6 SSCs are installed per generator. Over 70 machines have been equipped with SSCs to date.

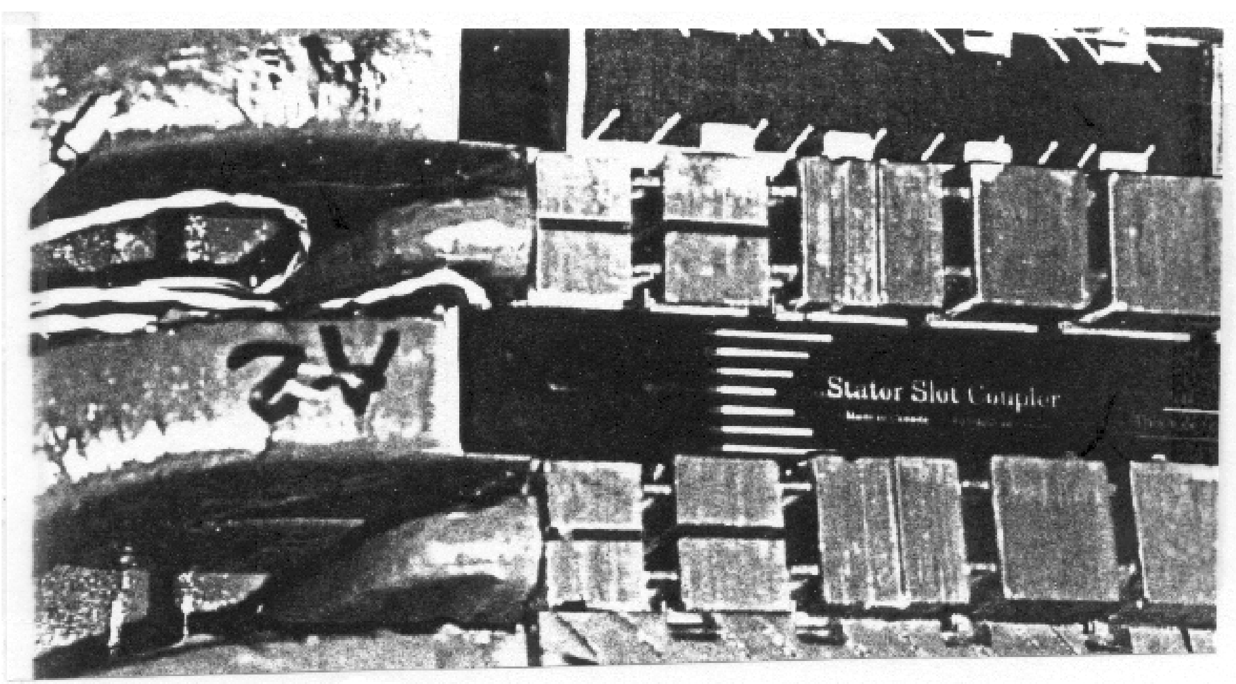


Figure 6 Photograph of an SSC being installed under the wedge in a large turbine generator.

The main advantage of the SSC is its ability to produce significantly different pulse responses to PD and electrical noise, thus enabling noise rejection. Theoretical considerations, as well as practical measurements have shown that PD pulses within the stator winding result in voltage pulses which last only 1 to 5 ns [2]. However, because of the natural filtering effects of the stator winding, all pulses not due to stator PD have a pulse width in excess of 20 ns [2]. Thus, even shaft ground brush noise and arcing at the terminals create relatively long-duration voltage pulses when measured by the SSC embedded in the stator winding. This clear difference in pulse shapes permits distinguishing between all noise (external and internal) and stator PD. Therefore, good windings are very unlikely to be classed as deteriorated.

A version of the TGA instrument described above has been developed which measures the pulse width of all signals coming from SSCs, on a pulse-by-pulse basis. If pulses have a width greater than 8 ns, then the pulses are categorized as being from noise, and are ignored. If the pulses are shorter than 8 ns, the pulses are from stator PD, and further processing is done to determine the number, magnitude and phase position of these PD pulses. Over the past 2 years, the TGA has been used on most of the machines equipped with SSCs, and has been shown to be effective in eliminating noise, while remaining sensitive to stator partial discharges.

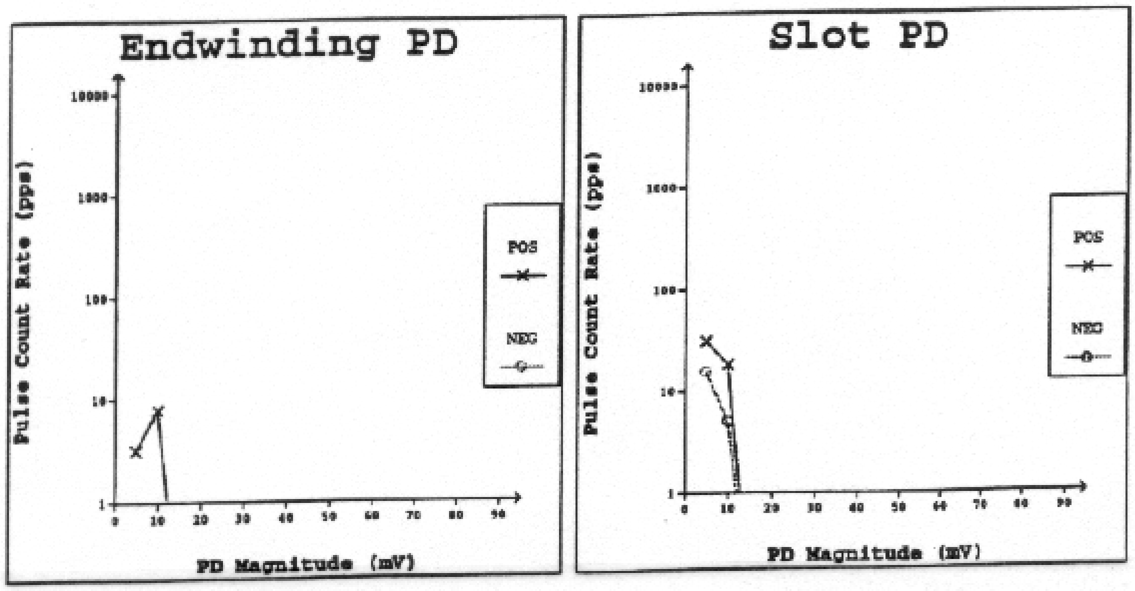
Case Study 4 - New Stator Winding

Six SSCs were installed on a new 122 MVA hydrogen-cooled turbine generator which has an epoxy-mica winding. The plots shown in Figure 7 represent an initial fingerprint of the PD activity. The PD activity is very low, as expected for a new machine. The PD activity is categorized as PD in the slot (due to overheating or loose windings) or endturn discharge (usually due to partly conductive contamination). The SSC combined with the TGA directly measures slot and endturn PD separately [8]. This enables plant personnel to predict the particular maintenance required on a machine prior to a major outage. Although very low, mainly slot PD is measured in the new stator. Endwinding PD is usually very small in a new, clean machine.

Considerable experience with PD testing has shown that it is common for brand new windings to have high PD activity until the winding "settles in", i.e., the semiconductive coating on the stator bar surface has good and frequent electrical contact to the stator core. Thus, high PD in the slot in the first few months of operation does not necessarily indicate that the winding is bad.

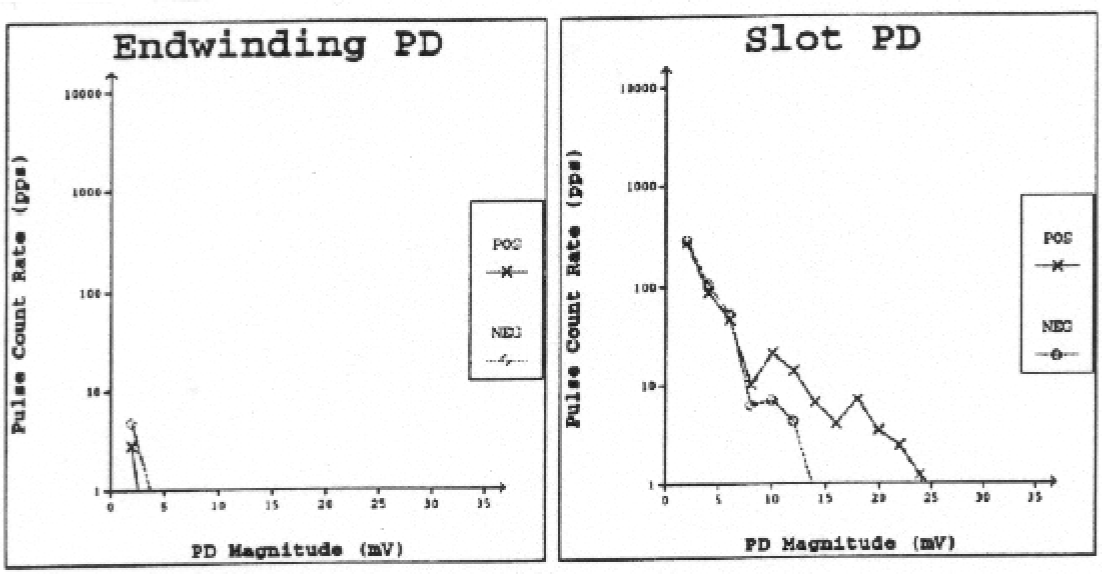
Case Study 5 - Old 450 MVA Turbine Generator

Six SSCs were installed in a 450 MVA oil-cooled turbine generator in Florida Power and Light's Turkey Point GS. The generator is about 30 years old and has an original epoxy-mica insulation. Visual inspection prior to SSC installation had shown the winding to be relatively tight in the slot and the endturns relatively clean after maintenance was performed. The PD activity, shown in Figure 8, is almost as low as the new stator in Case Study 4. Most of the PD is in the slot.



a) (b)

Figure 7 PD pulse height analysis plots for an SSC installed in a new 122 MVA generator.

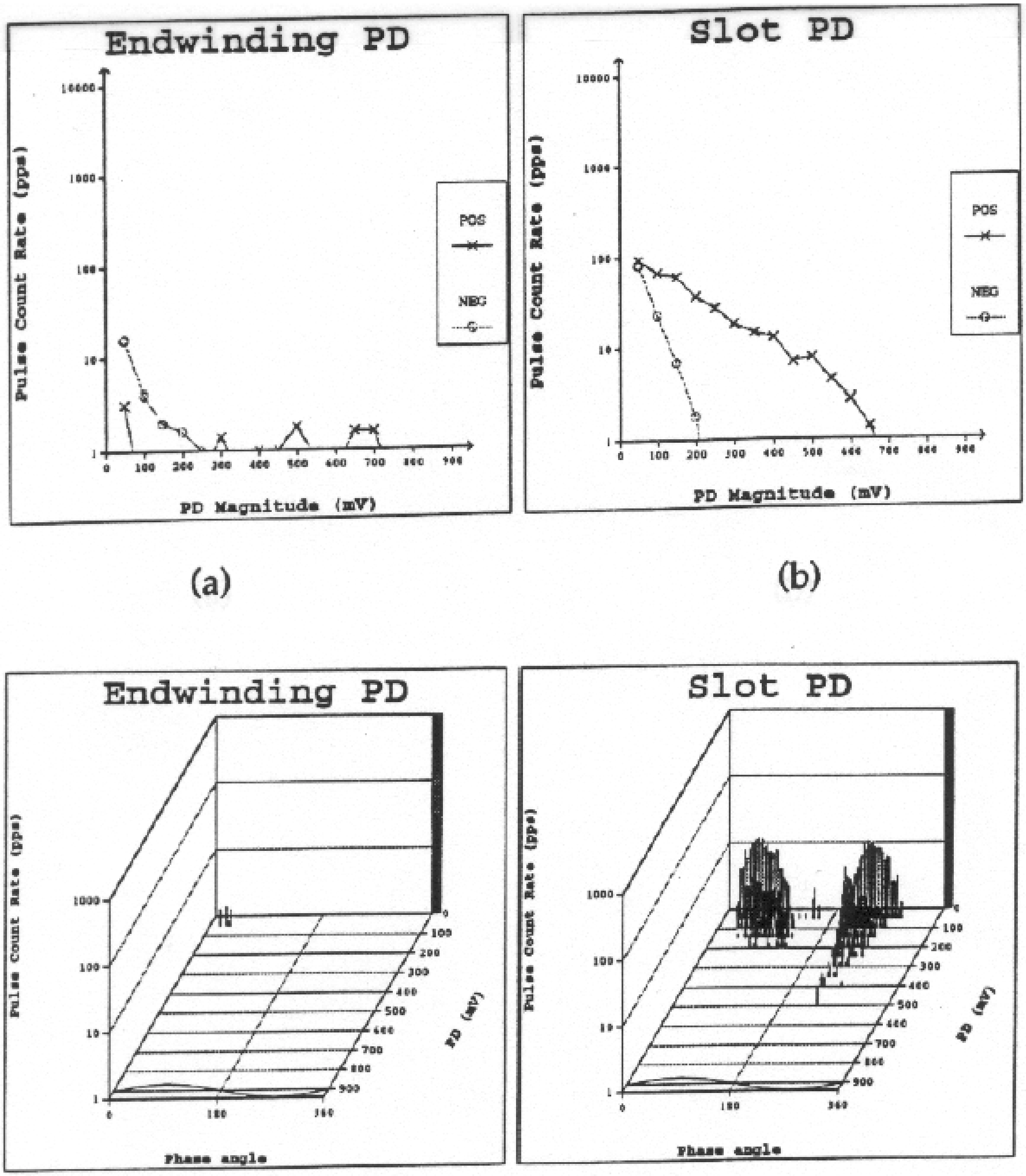


(a) (b)

Figure 8 PD activity in the slot and endwinding with the Turkey Point Unit 1 generator operating at 460 MW.

Case Study 6 - Old 450 MVA Turbine Generator

At the Florida Power & Light Riviera plant, the 350 MVA turbine generator is of the same vintage and manufacturer as the unit in Case Study 5. Six SSCs were installed and some of the data is plotted in Figure 9. The PD activity is over 30 times higher on this generator than the worst phase in the similar Turkey Point generator. At the time of the SSC installation loose wedges, loose windings, and greasing were present indicating relative movement. The endwinding was then cleaned and the wedges tightened. However, the high PD activity indicates that problems may still be present. Further investigation of this winding, including trending of the PD activity over time, is planned. As is consistent with PDA results on hydrogenerators with slot discharge, the positive PD is more than two times higher than the negative PD.



(a) (b)

(c) (d)

Figure 9 PD activity with the Riviera unit operating at 365 MW.

The comparison of the PD results from two similar generators, one of which is clearly more deteriorated, indicates that any machines which are experiencing insulation problems are easily identified. The MICAA expert system can directly interpret results from the PDA and TGA instruments [12].

Conclusions

1. Partial discharge tests can determine which motor and generator stator windings are experiencing insulation problems. A deteriorated winding has a PD activity which can be 30 times or more higher than a winding in good condition. This great difference in PD activity enables maintenance personnel to identify the few motors or generators in a company which need further investigation and / or maintenance. Machines in good condition require less attention, and therefore require fewer maintenance dollars to be spent. The overall effect is lower maintenance costs.

2. Since most machines are in good condition, few utilities are willing to spend significant funds to test all machines to find the few machines in trouble. Thus the (marginal) cost of each test must be almost insignificant in order to be widely applied in a company. The PD tests discussed above cost virtually nothing to perform, once the sensors are installed, since existing plant staff can do the tests in about 30 minutes during normal motor or generator operation.

3. The key to a PD test which can be performed by plant staff during normal machine operation is to eliminate electrical interference. Unfortunately, more than 15 years of research on many dozens of machines has shown that no single technique will work for all types of machines. This research has shown that any one type of sensor is likely to give false indications of problems, and thus reduce confidence in the test results, if the sensors are not properly applied. Different sensor systems have been found to be necessary for each of hydrogenerators, turbine generators and motors.

Acknowledgments

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