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PRACTICAL ON-LINE PARTIAL DISCHARGE TESTS FOR TURBINE GENERATORS AND MOTORS

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Abstract - Several utilities have found partial discharge testing to be very useful for identifying motors or generators with deteriorated stator winding insulation. Such partial discharge tests are sensitive to problems associated with overheated insulation, loose stator bars, and pollution, all of which can cause in-service failures with long associated outages and high repair/rewind costs. Unfortunately, the partial discharge test is not widely applied since present test methods require considerable skill to perform, and/or require machine outages. These problems are due to the stator winding partial discharges being masked by high levels of internal and external electrical noise. Partial discharge tests have now been developed which eliminate the effect of noise, thus allowing plant personnel to perform the test without any machine outage.

Two broad types of noise exist: arcing from slip rings, shaft grounding brushes, etc. within the machine (internal noise); and arcing and partial discharge from the bus connecting the machine to the power system (external noise). Installations on several machines have shown that external noise can be eliminated by a pair of capacitive couplers (bus couplers) mounted on each phase of the output bus. Sensors which are mounted within the slots of the stator winding (SSCs) have been shown to eliminate both external and internal noise. An instrument called the TGA has been developed to measure the signals from either type of sensor, distinguish noise from stator winding partial discharge, and perform a pulse height, pulse phase analysis on the partial discharge signals. Using the TGA, deteriorated windings have been found to have as much as 20 times higher partial discharge activity than good windings. The SSC type of sensor is best for use on large turbine generators or other critical machines, due to its ability to effectively eliminate false indications of deteriorated windings.

Key Words: partial discharge, stator, insulation, motor, generator

INTRODUCTION

Over the past 15 years, many utilities have adopted partial discharge testing as a means of determining the health of the high voltage groundwall insulation in large motors and generators [1-3]. Partial discharge tests have been found to be sensitive indicators of the most common stator winding deterioration problems, including poor impregnation [1,4], delamination due to overheating or cyclic operation [1,5], degradation of the semiconductive and stress grading coatings [6], loose wedges and slot discharge [7,8], and polluted windings [6,9].

All of these deterioration mechanisms can occur in machines rated 6000 V or more, although some problems such as delamination have been observed on stator windings rated as low as 4000 V. The high pressure hydrogen cooling common in large turbine generators does reduce (but not eliminate) the magnitude of partial discharge activity [7-9].

The purpose of partial discharge testing is to detect whether any of the above problems is occurring in a high voltage stator winding before failure occurs. Experience has shown that most stator windings gradually deteriorate over years, if not decades. By routinely measuring the partial discharge activity every 6 months or so, symptoms of insulation deterioration can be quickly identified, and appropriate maintenance performed. Maintenance can be performed at a convenient time and at a fraction of the cost of replacing a failed winding. Of even greater importance, failures and consequential damage to other components can be avoided, and often the effective life of a stator winding can be considerably extended before rewinding is necessary [6,9].

In spite of all the advantages of motor and generator partial discharge testing, such testing is only routinely applied to hydrogenerators [6]. Few utilities perform partial discharge tests on gas or steam turbine generators, or even motors. Although partial discharge testing has proven to be useful on such high speed machines [2,4,7-9], the test is difficult to perform routinely. This is because all the conventional test methods require considerable operator skill to perform. In particular, a very experienced person is needed to distinguish the stator winding partial discharges from similar signals due to electrical interference [2,9], or alternatively, an outage is required to do the test in a noise-free environment [3,10]. If an outage is required to perform the test, the test can only be done every 5 years or so, during which time the insulation can change from good to severely deteriorated. The PDA partial discharge test for hydrogenerators [6] has become popular because special arrangements were made to eliminate the most common types of noise in hydro generating stations, resulting in a test which can be performed reliably by generating station staff during normal hydrogenerator operation.

In a Canadian Electrical Association research project over the past 12 years, improved methods of measuring partial discharges in motors and turbine generators have been investigated. The principle focus of this research was the nature of the electrical interference in such machines, and methods of extracting partial discharge signals from the noise. The result of the work is the development of new on-line partial discharge test methods for motors and turbine generators which, like the PDA test, can be performed by station personnel with no machine outage. This paper presents the test methods developed for motors and turbine generators.

ELECTRICAL INTERFERENCE

Partial discharges from stator windings are detected as very short duration voltage pulses. In normal nuclear and fossil generating stations there are many other sources of similar short duration voltage pulses which can be easily confused with stator winding partial discharges. In surveys of such noise signals in four large

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(fossil and nuclear) generating stations in Ontario Hydro, noise was identified as coming from a number of different sources. The sources can be broadly characterized as either internal to the motor or generator, or external to the machine.

Internal Noise

Any rapid interruption of electrical current causes noise, and thus creates a voltage pulse which can be confused with partial discharges. Within a machine, the following sources of noise have been identified:

- arcing from carbon brushes making imperfect contact to the dc field winding slip rings. In general, the larger the machine, the higher the field current necessary, and thus the greater the likelihood of slip ring brush noise at any particular time.
- arcing from the shaft grounding brush used on turbine generator rotors to remove the electrostatic charge caused by steam striking the turbine blade, unsymmetrical magnetic fields and axial magnetic fluxes. This noise only occurs in turbine generators, and empirically the greater the machine rating, the more likely is arcing at the shaft grounding brush.
- arcing from poor bonding of the stator core laminations to ground at the back of the stator core.
- electromagnetic groundrise of the stator core due to high frequency pulses elsewhere in the station.

These sources were identified by correlating the output of conventional partial discharge detectors with signals from RF current transformers or antennae placed near the noise sources [11]. Usually these internal sources of noise are not severe in motors, or in hydraulic generating stations which have few auxiliary systems which create sparking or arcing noise. However, in turbine generating stations, noise from slip ring brush arcing and shaft grounding brush arcing can reach several volts when detected by conventional generator partial discharge detectors (for example the system described in Reference 1). Of sixteen 500 MW generators at two Ontario Hydro plants, six had significant shaft grounding brush arcing.

External Noise

Noise from the connection of the motor or generator to the power system is defined to be external noise. Sources of external noise are:

- corona and partial discharge occurring in the switchgear unit transformers or switchyard. The higher the operating voltage, the more likely is this source of noise.
- partial discharges in the bus support insulators in the isolated phase bus from generators. Again, the higher the operating voltage the more likely is this type of noise. Weld splatter on insulators and/or small cracks (due to load cycling, installation abuse or fault currents) between the metal inserts and the porcelain in support insulators can cause partial discharges in isolated phase bus.
- contact arcing from deteriorated, oxidized or poorly installed connections on the isolated phase bus from generators. In the output bus from large generators, there are often hundreds of bolted connections which can gradually deteriorate over time. Only a few such bolts need to be arcing to cause considerable interference. The larger the generator, the greater the output bus current, the greater the number of bolts, and thus the greater the probability of some connection arcing.

In a survey of eight 500 MW generators (average age about 15 years) at one plant, three of the generators had significant connection arcing. The arcing was detected by RF current transformers mounted around the isolated phase bus sheath ground leads [11]. The voltage pulses detected at the generator terminals due to connection arcing using a conventional partial discharge detector [1] was sometimes up to 10 volts. (For comparison, significant levels of partial discharge when measured with a conventional partial discharge detection system correspond to about 100 mV [9].) Thus, connection arcing is a very significant source of external noise.

As a result of these investigations as well as data from other researchers [2,10], it was clear that there are different types of noise for the different types of machines. Motors primarily suffer from external noise, whereas large turbine generators are subject to both internal and external noise. Because of these differences, and since it is extremely critical not to give false indications of partial discharge activity, especially in turbine generators, two different methods of partial discharge detection have been developed. Both systems can quantify and sometimes locate the sources of noise, which can aid in planning maintenance for connected equipment.

ON-LINE PARTIAL DISCHARGE TEST USING HIGH VOLTAGE BUS COUPLERS

The main sources of noise in high voltage motors, hydrogenerators and synchronous condensers are usually external to the machine. A system of noise rejection based on couplers mounted on the high voltage bus connecting the machine to the power system was developed to eliminate such noise. Historically, this noise elimination technique was first investigated for large turbine generators, before the significance of internal noise was appreciated [12]. The couplers consist of high voltage capacitors which are mounted on the bus between the machine and the power system. Two couplers are installed per phase, or six per machine (Figure 1). In installations on 47 machines in four utilities, the capacitors range from about 5 pF to 80 pF. The couplers are separated by a distance of at least 2 m.

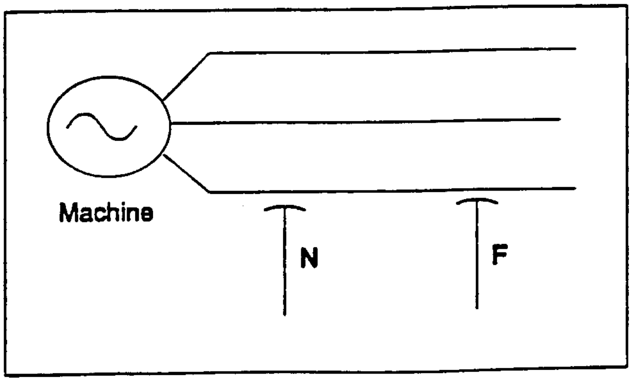


Figure 1: *Bus sensors installed on one phase of the output bus of a machine.*

External noise is differentiated from stator partial discharge by detecting from which coupler in a phase a pulse is first measured. Partial discharge from the stator will be detected at the coupler labeled N in Figure 1 at least 6 ns before being detected at F. The difference in arrival times is due to the speed of pulse propagation along the bus (about 0.3 m/ns). In comparison, a noise signal from the power system will be first detected at coupler F, and then 6 ns later at N. Thus discriminating between noise and partial discharge is reduced to detecting from which coupler a pulse is first detected.

In the early experiments with this noise rejection method, a delay line equal to the electrical length of the bus between N and F (typically 6 ns) was added to the signal from the F coupler [12]. This signal was then input into the PDA instrument [6], which subtracted the N signal from the F signal. Thus in principle, noise is subtracted in the differential amplifier input to the PDA, whereas the extra delay for a partial discharge signal from the machine to reach the F input results in a net output. This analog method of eliminating the external noise was found deficient since the pulse shapes from the N and F couplers were often significantly different, primarily due to the different surge impedances at the coupler sites (Figure 2) [13].

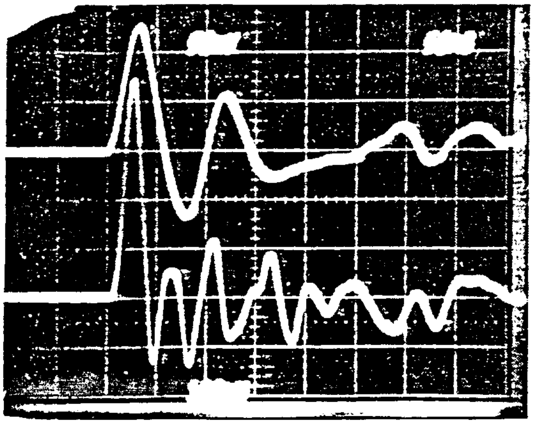


Figure 2: *Pulse responses from the N (upper trace) and F (lower trace) bus couplers to a pulse injected at the step-up transformer [13]. Extra coaxial cable was inserted into the line from the F coupler, to cause the simulated noise pulses to arrive at the same time. Unfortunately, since the signal from F is four times larger than pulse from N and has a different shape, the PDA interprets this noise pulse as partial discharge from the generator.*

More recently, an instrument called the TGA was developed which directly converts the pulses from each coupler to digital form. Digital electronics then compare the arrival time of the pulse at the N and F couplers. If the pulses are first detected from the N coupler, the signal is defined to be a partial discharge pulse from the stator, and further processing to determine the number and magnitude of the partial discharge pulses is done. Otherwise the signals are interpreted as noise. The digital method of rejecting external noise is significantly less influenced by pulse distortion between the pair of couplers, since only the arrival times of the pulses are compared, and not just the magnitude or the entire waveform.

Field Experience

The bus coupler partial discharge detection system was effective on hydrogenerators, synchronous condensers, and some turbine generators where there was little internal noise. Figure 3 shows the pulse height analysis of partial discharge data from a 160 MVA, 17 kV hydrogen-cooled synchronous condenser. The vertical scale is the number of partial discharge pulses occurring per second at the pulse magnitude indicated on the horizontal scale. Visual inspection of the stator winding in this machine showed the groundwall insulation to be eroded by slot discharge. The SSC sensors (see later) installed within this machine verified that slot discharge activity is probably occurring. Unfortunately with this detection system any discharges between the stator winding and the N coupler are incorrectly diagnosed as partial discharge, leading to a false indication of winding deterioration.

Due to the difficulty in eliminating internal noise, bus couplers are best applied to motors, or to machines which are known by the user to have little internal noise and no arcing problems on the bus. They can also be applied where there are other independent means of verifying stator insulation condition, or where the consequences of a mis-diagnosis (for example unnecessarily extending a maintenance inspection) are not great.

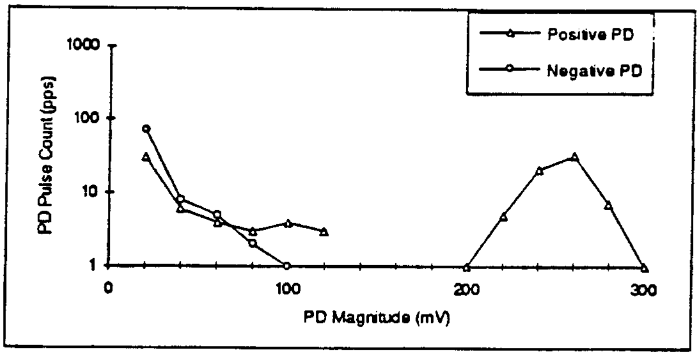


Figure 3: *Partial discharge activity in phase A of a synchronous condenser delivering 58 MVAr at 16.7 kV. The partial discharges were detected by bus couplers and the TGA instrument.*

ON-LINE PARTIAL DISCHARGE TEST USING INTERNAL COUPLERS

The high probability of internal noise occurring in turbine generators lead to the development of a completely different method of distinguishing between partial discharge and noise for such machines. This new technique is based upon a new sensor called the stator slot coupler (SSC) [14]. The SSC is an ultrawide band detector which is installed under a few stator wedges in slots containing stator bars connected to the phase end of the winding (Figure 4). The SSC detects any electrical signal within the slot having a frequency content from 10 MHz to over 1000 MHz. Experience with the SSCs on operating machines indicates that partial discharges in the same slot as the SSC or the immediate adjacent endwinding are detected as pulses which are from 2 to 6 ns wide. In contrast, all types of internal and external noise are detected as pulses which have a pulse width from 20 ns to 1 microsecond [14]. This difference in pulse width is due to the filtering effect (i.e. loss of high frequency components) of the stator winding as pulses propagate through the winding. Since pulses occurring in the same slot as the SSC undergo relatively little distortion, they are detected as very fast pulses. However, noise from the power system must pass through the inductance of circuit ring buses and stator endwindings, which broadens the width of the pulse. This difference in pulse width between partial discharge pulses and noise permits an absolute method of discriminating partial discharge from both internal and external noise.

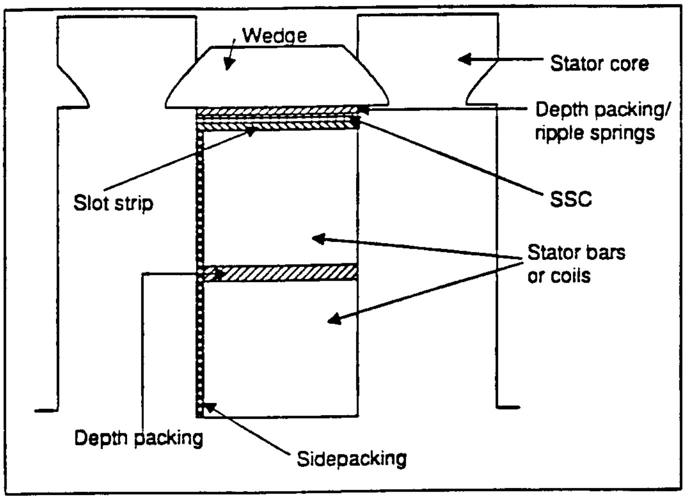


Figure 4: *Cross-section of a stator slot indicating the position of the SSC. The top stator bar is usually at the high voltage end of the winding. The SSC is 50 cm long.*

SSCs have been installed in over 60 motors and generators rated up to 800 MVA in nine utilities since 1989. Usually six SSCs are installed per generator, during an outage where the rotor has been removed. The SSC is essentially a 50 cm long, 2 mm thick stripline antenna, with a coaxial output cable at each end [14]. The two outputs permit distinguishing between partial discharge from the slot and partial discharge from the adjacent endwinding on the basis of pulse arrival time at the two ends. Since the SSC is installed under the wedge, yet outside the grounded semiconductive coating of the stator bar, the SSC is not exposed to any high voltage electrical stress. Over the past three years SSCs have operated without incident in the high temperature, high mechanical stress and high magnetic field environment of the stator slot.

Although SSCs are primarily intended for large turbine generators where internal noise is particularly severe, SSCs have been installed in critical motors (such as reactor coolant pump motors), stand-by generators and synchronous condensers. Since the SSCs reduce the effect of both internal and external noise, the use of SSCs will ensure that false indications of stator winding problems are not given, as could occur with bus type couplers responding to internal noise.

TGA Instrument

An instrument called the TGA has been developed which can be used with either bus-type couplers or SSCs. When used with SSCs, the instrument measures the width of each pulse from both ends of the SSC. If the pulses are wider than 8 ns, then the pulse is categorized as noise. If the pulses are less than 8 ns wide, the pulse is defined to be partial discharge, and processed further.

Very high speed emitter-coupled logic devices are used in the front end electronics of the instrument. The input signal from each end of the SSC is initially sampled about every 2.5 ns by a comparator (after 5 samples, the sampling is performed every 10 ns), and the output of the comparator after each sample is recorded by a 9 bit shift register. Once the output of the comparators are stored by the shift registers, slower CMOS logic is used to decode the contents of the shift registers. This logic determines the width of the pulse, and hence if the pulse is due to partial discharge or noise. The relative arrival time of the pulse from each end of the SSC is also decoded. If the signal was detected 2.5 ns (the electrical length of the SSC) earlier at the end of the SSC closest to slot exit, the pulse is assumed to originate in the endwinding. Pulses arriving first at the end of the SSC within the slot, are assumed to originate within the slot. If the difference in arrival time is less than 2.5 ns, then the pulse is assumed to be directly under the SSC.

The TGA is controlled by a 386-type computer which is incorporated in the instrument. The embedded computer also facilitates a hundred channel (3.6 degree resolution) pulse phase analysis. This permits the partial discharge pulses to be located with respect to the ac phase position. Pulse phase analysis may help users to distinguish between different types of partial discharges, particularly endwinding discharges between phases [15]. The computer stores the number of partial discharge pulses per second according to pulse magnitude, pulse polarity, phase position, and location of the partial discharge (endwinding or slot). Output is via plots on a color LCD display, or data files stored on floppy disk which can be analyzed on a separate computer at a later time.

Figure 5 shows the TGA testing the SSCs in a 160 MVAr, 17 kV synchronous condenser, while the machine is normally operating. A test can be performed by generating station personnel. Testing all 6 SSCs in a machine takes about 30 minutes, and no outage is required. Based on past experience with conventional partial discharge test methods [9], the test should be performed about every 6 months, since most stator windings take at least this long to degrade.

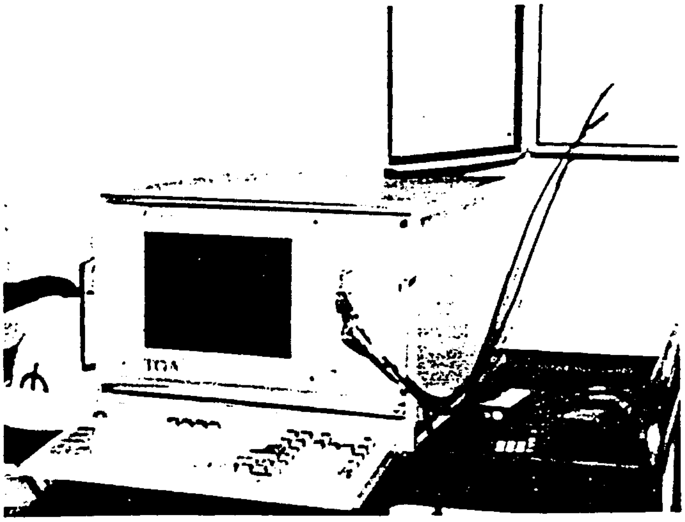
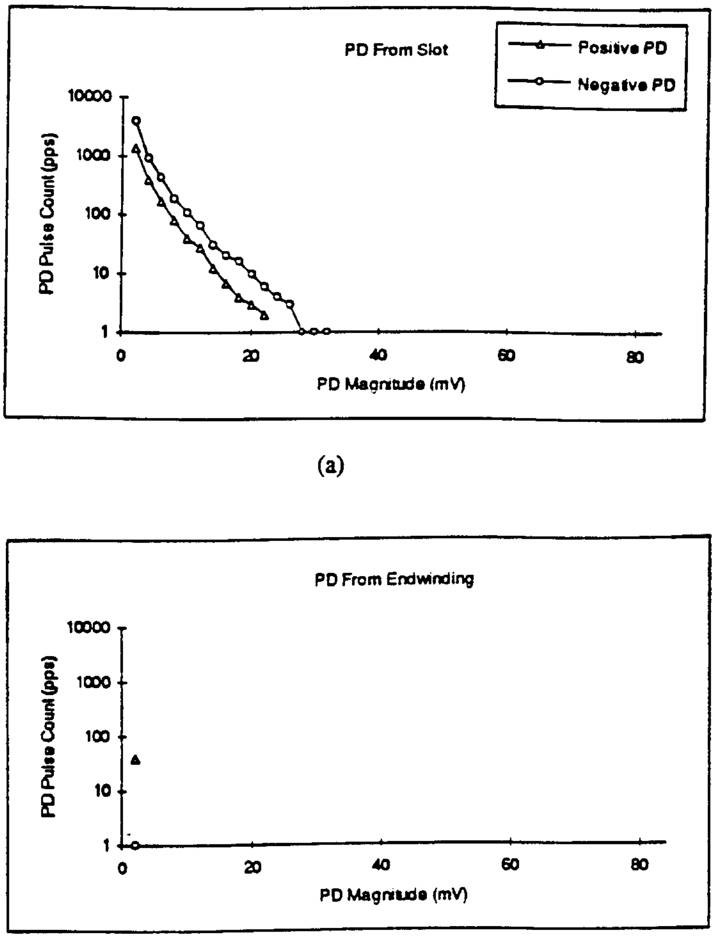


Figure 5: *The TGA instrument measuring partial discharges on an operating synchronous condenser. The SSC outputs are located in the upper right corner of the photograph.*

As indicated above, different detection electronics have also been developed for the TGA which permits distinguishing between external noise and PD, using bus couplers, based on time of pulse arrival.

Results with SSC Sensors

Investigation of the pulses from SSCs with digital oscilloscopes are described elsewhere [14]. Figures 6 to 8 show the partial discharge plots from SSCs installed in three different turbine generators. The data in Figure 6 was measured on a 212 MVA, 18 kV, 3600 rpm, direct hydrogen-cooled, coal-fired turbine generator which was recently rewound with an epoxy-mica winding. The measurement was taken a few months after the generator was returned to service. The partial discharge activity in this machine is amongst the lowest measured. At the time of the test, the generator was operating at 65 MW, +60 MVAr and 18 kV. Each plot shows both the positive and negative partial discharge pulses. Although the partial discharge activity is very low, pulses were detected occurring in the slot (Figure 6a), whereas essentially no partial discharge pulses were detected from the endwinding (Figure 6b). Based on the experience gained in interpreting PDA test data on hydrogenerators [6], the rough equivalence of the positive and negative partial discharge activity in Figure 6a indicates that the partial discharge is primarily from within the stator bar, rather than occurring between the stator bar and the stator core (i.e. slot discharge). The very low partial discharge activity in this generator is consistent with the partial discharge activity expected from a new stator winding.

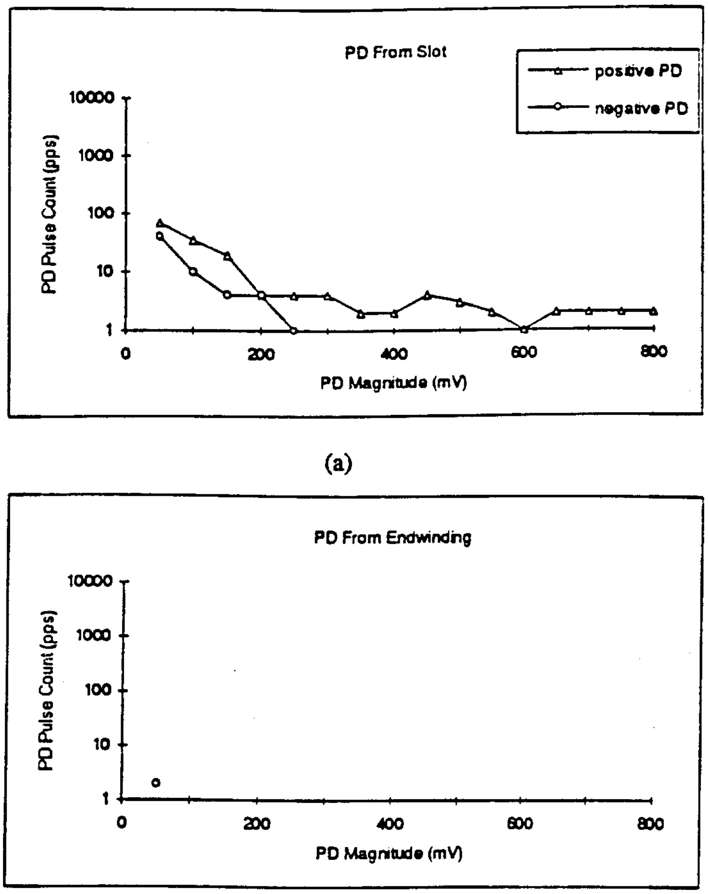


(a)

(b)

Figure 6: *Partial discharge activity from an SSC in a turbine generator operating at 65 MW, 60 MVAr. Most of the discharges are occurring in the slot.*

Figure 7 shows the opposite extreme, that is very high partial discharge activity in a degraded stator winding. The data was recorded from an SSC installed in a 588 MVA, 3600 rpm, hydrogen-cooled coal-fired turbine generator. At the time of the test, the generator was operating at 500 MW, +260 MVAr, 22 kV with a 51C stator hotspot. The magnitudes of the partial discharge pulses from this generator are about 20 times higher than the pulses shown for the new stator in Figure 6. As in the previous case, most of the partial discharge is originating with the stator slot (Figure 7a) rather than the endwinding (Figure 7b). The very high partial discharge activity in this generator has been independently confirmed by a conventional partial discharge test used over the past 40 years [9]. This stator winding has an epoxy-mica insulation system. The stator contains several stator bars which sustained damage during a previous core fault and subsequently repaired.

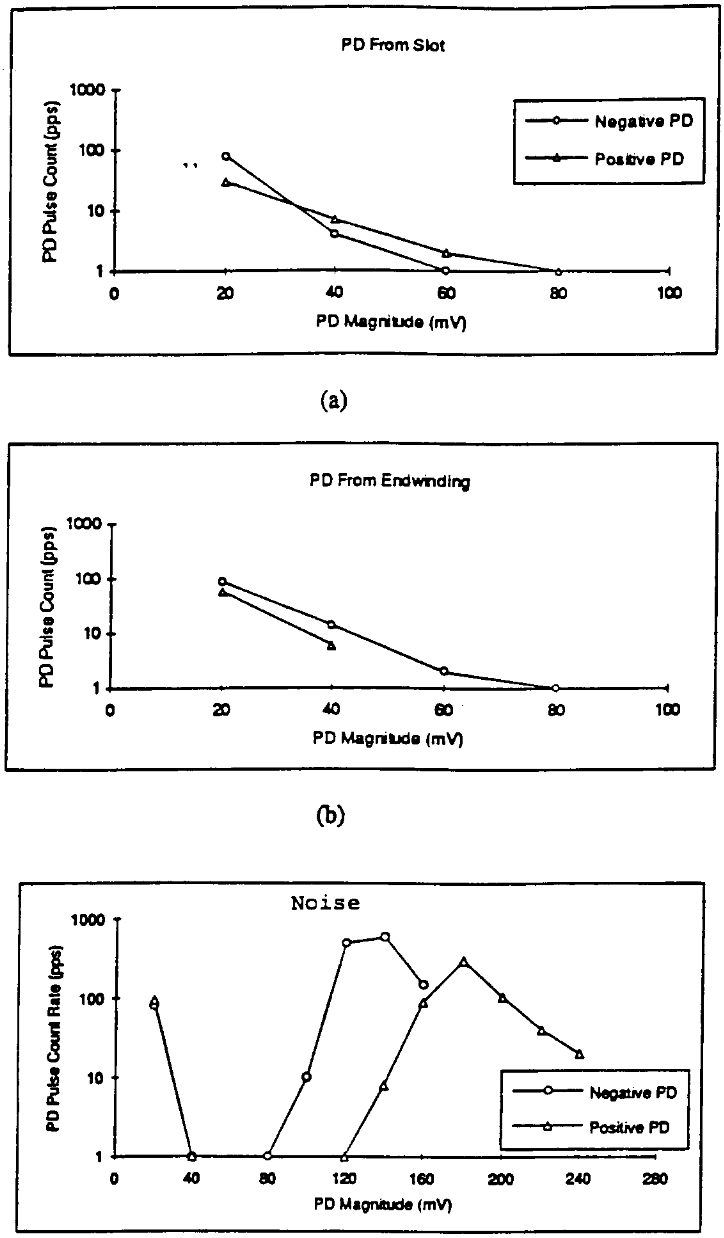


(a)

(b)

Figure 7: *Partial discharge activity from a turbine generator operating at 500 MW, 260 MVAr. Most discharges are occurring in the slot.*

Endwinding discharges were detected in a refurbished 355 MVA, 3600 rpm hydrogen-cooled turbine generator (Figure 8). This machine has a 30 year old asphaltic winding which was heavily contaminated with oil and pollution, and had intense endwinding partial discharges prior to the refurbishment. The data in Figure 8 was measured a few months after cleaning and rewedging. The refurbishment was largely successful, but it appears that some endwinding discharges are still occurring, probably since it is virtually impossible to completely clean an endwinding. Figure 8c indicates the high noise environment in this generator. Noise pluses have a pulse width of 8 ns or more.



(a)

(b)

(c)

Figure 8: *Endwinding and slot partial discharges from an operating turbine generator, as well as the noise environment.*

The interpretation of the basic TGA data seems to be very similar to that found with the PDA [6]. This will help in rapidly gaining experience in interpreting test data. The significance of the pulse phase analysis in practical partial discharge tests on operating machines has yet to be established.

CONCLUSION

The success of an on-line partial discharge test for hydrogenerators has lead to the development of on-line partial discharge tests for motors and turbine generators. Two different test methods have been developed, due to the different electrical interference conditions found in motors and turbine generators. When properly applied, both methods have proven to be effective in reducing the effects of noise, yet remain sensitive to stator winding partial discharge. Tests have shown that there is as much as 20 times more partial discharge activity from a deteriorated stator winding as from a good stator winding. This clear difference in activity makes it easy to identify which machines are in need of further inspections, testing and/or maintenance. Since the tests can be done by generating station staff with no outage, the on-line partial discharge test is an effective tool to implement predictive machine maintenance. Tests on the machines equipped with the necessary sensors will continue over the next several years to further improve the ability to interpret data.

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