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3 - 5, rue de Metz
75010 Paris

1992 Session
30 August - 5 September

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11-303

A NEW ON-LINE PARTIAL DISCHARGE TEST FOR TURBINE GENERATORS

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ABSTRACT

The high voltage insulation in steam and gas turbine generator stator windings gradually deteriorates due to mechanical, thermal, electrical and environmental stresses. These stresses combine to result in loose windings, delamination of the insulation and/or electrical tracking of the endwinding, all of which can lead to stator failures. Many organizations have found that partial discharges are a symptom of such winding deterioration. For over 40 years, Ontario Hydro has been using partial discharge tests on its 40 turbine generators in nuclear and fossil plants. This testing has shown that if the partial discharge activity increases over time, the probability of one or more of these deterioration processes posing a risk to the winding increases. As a result, partial discharge tests identify those few machines which are experiencing insulation problems, permitting corrective action to be economically implemented and conveniently scheduled.

Unfortunately, the partial discharge test used by Ontario Hydro requires considerable expertise on the part of the test operator, thus preventing the wider application of this test in other utilities. Over the past 12 years, an extensive research project was undertaken to develop a superior partial discharge test for turbine generators. The result is the Turbine Generator Analyzer (TGA) test, which is designed to be performed by non-specialized generator station staff without a generator outage. The new test relies on a sensor called the stator slot coupler (SSC), which is installed within selected stator slots, and has no electrical connection to the winding. The output of the SSC is analyzed by the TGA instrument, which discriminates partial discharges from electrical noise on the basis of pulse shape, and quantifies the partial discharge activity. The main technical advantage of this test is that false indications of deteriorating insulation are virtually eliminated. With this new test, fossil and nuclear station personnel will be able to implement stator winding preventive maintenance programs.

Key Words: Preventive Maintenance, Turbine Generator, Stator Insulation, Partial Discharge

INTRODUCTION

Forty years ago partial discharge (PD) testing was introduced as a means of diagnosing the condition of the high voltage groundwall insulation in generator stator windings [1,2]. For example, delaminations within the groundwall of generator windings resulting from overheating or many generator load cycles give rise to PD [2]. Loosening of wedges and slot packing, caused by gradual shrinkage over the years, gives rise to stator bar movement and partial (slot) discharges [3,4]. Contaminated stator endwindings arising, for example, due to problems with seal oil or bearing oil systems, lead to electrical tracking with associated discharges external to the stator slot. Thus many of the deterioration mechanisms which ultimately determine the useful life of the high voltage insulation in stator windings, and thus the life of the stator itself, are accompanied by PD. This has led many investigators to research the ability of PD tests to determine the condition of the stator insulation. With a successful PD test, expensive failures such as the recent breakdown of a 418 MVA, epoxy-mica, coal-fired steam turbine generator [3], or similar problems in other hydrogen-cooled machines [4], could be avoided. Also, since many types of stator winding deterioration problems can be easily reversed with suitable

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maintenance (e.g. cleaning, rewedging, replacing ripple springs, etc.), winding life can often be extended at a relatively modest cost.

Although partial discharge testing is normally done with the generator out of service (off-line), to minimize test costs and inconvenience utilities prefer an on-line test, i.e. a test which requires no generator outage, and which can be performed by generator station personnel. Avoiding unnecessary outages for testing is important since past experience has shown that a generator is most prone to failure because of accidents which occur during or immediately after an outage. In addition, certain types of stator winding problems, such as slot discharge, are not as apparent during off-line PD tests since stator winding movement is not occurring [5]. Finally, on-line PD testing makes it practical to test the generator more frequently. The typical 5 year interval between off-line tests (i.e. PD tests done during a suitable outage) is too long a period compared to the time it takes for some problems to originate and lead to failure. Thus utilities such as Ontario Hydro [5] and American Electric Power [6] have emphasized on-line PD testing, as opposed to tests performed during outages.

Although on-line PD testing has been widely applied to hydrogenerators [7], there is much less reported with regard to on-line PD testing of turbine generators. This paper describes Ontario Hydro's original on-line PD test for turbine generators, and presents data showing the usefulness of on-line testing. A new PD test which can be performed by fossil and nuclear generating station staff is then outlined.

ORIGINAL ON-LINE PD TEST

Test Method

About 1951 Ontario Hydro developed an on-line partial discharge test which was adapted from the radio frequency (RF) monitoring approach used by Johnson to measure slot discharge in operating hydrogenerators [1]. Unlike the RF Monitoring approach where the PD was detected at the generator neutral, the Ontario Hydro version of the test used three 25 kV, 375 pF capacitors which were temporarily connected to the generator terminals [5]. Each of the "portable couplers" was connected to a simple 5 pole RC filter which had a pass band from about 30 kHz to about 3 MHz [5]. The output of the filter contained the high frequency pulse signals associated with partial discharges in the stator winding, which were displayed on a suitable (analog) oscilloscope. A phase-corrected 60 Hz signal proportional to the generator terminal voltage was also displayed on the oscilloscope to aid identification of the PD pulses.

Over 5000 individual measurements on about 150 hydrogenerators and 40 steam turbine generators in fossil and nuclear plants have been performed during the past 40 years. From 1951 to the late 1960's the measurements tended to be sporadic, since the value of the test had not been conclusively proven. Considerable time was required to learn how to classify the various signals on the oscilloscope, and to permit correlation of test results with actual insulation condition. By the end of the 1960's, the test had evolved into the following procedure.

To test a generator, a suitable location for applying the 375 pF portable couplers was determined (usually at the high voltage terminals of the generator potential transformers). With the generator operating normally, one portable coupler at a time was connected per phase to each of the generator output terminals. Since the buses were energized, strict precautions similar to those used for live-line work on distribution lines were employed. The partial discharge activity on each phase was then measured by a skilled operator, with the generator at full power. The generator output was then often reduced to 0 MW, and the readings were repeated. Monitoring the change in PD magnitude from low generator power to full power permitted the identification of loose windings [5]. The portable couplers were removed after the measurements were taken.

This test was performed twice per year on hydrogenerators and once every two years on turbine generators, since hydrogen-cooled generators tend to deteriorate more slowly. Virtually all measurements were done by the same operator over the past 40 years. The same person was required to do the test since considerable skill was needed to extract the generator partial discharge signals from noise (power system PD, arcing from slip rings and shaft grounding brushes, etc). Difficulties were experienced in only a few situations where the generator had surge protection capacitors attached to its terminals. Such capacitors had to be first removed in order to prevent the high frequency PD signals from being short circuited to ground. The on-line PD test took about 30 minutes to perform on a hydrogenerator and about 5 hours on a steam turbine generator (primarily for the long time needed to safely shed load for the low power measurement).

Comparison of PD Results With Winding Condition

The on-line test was first shown to be very valuable for hydrogenerator maintenance planning [5]. The test permitted Ontario Hydro to drastically reduce its hydrogenerator repair and rewind costs in the 1970's and 1980's since several years warning was given of problems such as loose wedges and delamination deterioration, permitting timely and inexpensive corrective maintenance. In both hydrogenerator and turbine generator testing, the key parameter which correlated with stator insulation condition was the peak observable magnitude of the positive and negative PD at normal generator operating voltage and power. The actual magnitude of the PD from a test was less important than the change (i.e. trend) in PD over the years. Doubling or trebling of the peak PD magnitude over a few years indicated that the insulation was deteriorating significantly. The following gives examples of data from tests on steam turbine generators rated up to 800 MW.

The stator winding condition in most of Ontario Hydro's turbine generators has been good, and stable PD measurements were obtained in such windings over as long a period as 15 years. For example, Figure 1 shows the PD activity measured in coal-fired Lambton TGS Unit 3 from 1975 (just after commissioning) to present on one phase while the generator was delivering about 490 MW at 24 kV. The generator has an epoxy-mica stator winding. Experience shows that it is not uncommon to have initial high PD readings on a new winding, until the winding "settles in". The vertical scale in Figure 1 is in millivolts, representing the highest positive and negative PD pulse measured on the oscilloscope. The inductive generator winding does not permit realistic calibration into picocoulombs [8].

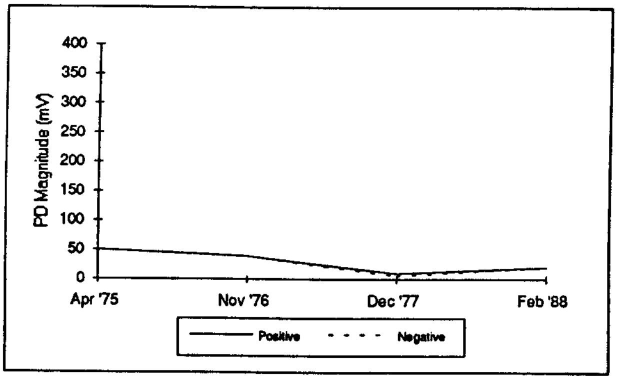

Figure 1. Peak positive and negative PD magnitudes from a 500 MW coal-fired generator which has a stator winding in good condition.

The results from PD tests on a hydrogen-cooled generator experiencing slot discharge, as well as the effect of maintenance on the PD measurements, are shown in Figure 2. Hearn TGS Unit 4 was a coal-fired generator which had been rewound with an epoxy-mica winding in 1971. Unfortunately, the slot wedges had slackened over time, permitting the stator bars to move under the magnetic forces, causing sparking (slot discharges) in the winding. Based on the upward trend in PD activity, the generator was removed from service in 1976 and confirmed to have loose wedges and some erosion of the semiconductive coating. Rewedging was undertaken. Results from conventional PD tests after maintenance showed that the rewedging was effective since the PD activity was significantly lower and remained low until the station was decommissioned.

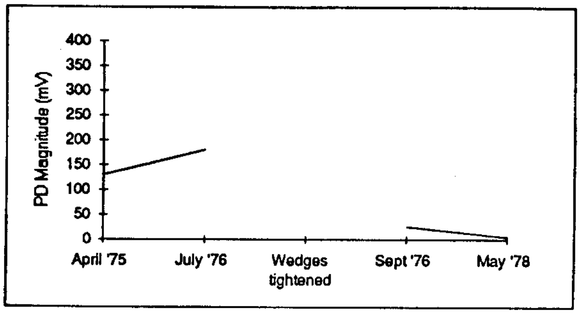

Figure 2. Effect of rewedging on PD magnitude from a hydrogen-cooled, coal-fired turbine generator at Hearn TGS.

Figure 3 shows the PD results from a small turbine generator in Ontario Hydro's oldest nuclear plant. This generator was installed in 1962 and had an asphaltic-mica stator insulation system. Due to persistent oil leakage problems from the bearings, the endwindings of this stator became severely contaminated, which resulted in discharges and electrical tracking in the endwinding area, i.e. outside of the slot, leading to increasing PD magnitudes. During a suitable outage in 1986, the endwindings were cleaned as much as possible. A PD test after maintenance showed the cleaning to be effective, with a significantly reduced PD magnitude.

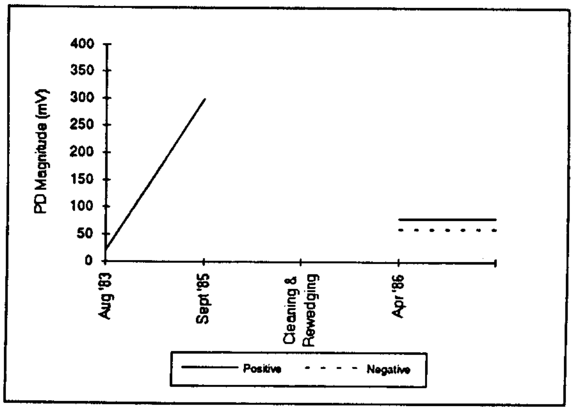

Figure 3. Effect on PD of cleaning the endwindings of the generator at NPD nuclear generating station.

Extensive PD testing over the past 20 years on hydrogen-cooled steam turbine generators indicates that if insulation system deterioration is occurring, the magnitudes of the PD pulses increase over time. The conventional on-line PD test has been able to identify turbine generators with loose wedges, delaminated groundwall insulation and polluted endwindings. Unfortunately, the electrical interference is almost always much more severe in steam turbine generator stations than in hydrogenerator stations, making the results from testing of steam turbine generators somewhat subjective.

Disadvantages of the Original On-Line PD Test

The main difficulty in performing an on-line PD test is not in detecting the PD signals, but rather distinguishing the PD from electrical noise. In hundreds of tests in fossil and nuclear plants, the noise was found to be very erratic over time, and sometimes as much as 1000 times higher than generator PD signals. With many years experience with the test, a skilled observer can differentiate between PD and noise with some confidence, permitting an effective on-line PD test. All existing on-line PD tests for steam turbine generators also need highly skilled observers to perform the test to ensure proper classification of the signals [6,9]. The requirement for skilled personnel makes conventional on-line PD tests relatively expensive to perform, and causes conflicts in scheduling tests on different generators. Furthermore, there is a problem with consistency between different skilled observers, and it is not uncommon to have noise mis-diagnosed as PD, and vice-versa, due to the widely differing characteristics of noise in different generating stations.

THE TGA ON-LINE PD TEST

The disadvantages of the original on-line PD test lead Ontario Hydro, with the support of the Canadian Electrical Association, to undertake research into an on-line PD test which could be easily used by many utilities. The requirements of such an improved test were that it:

- require no outage
- can be performed by generating station staff (i.e. no special skills required)
- is sensitive to generator PD
- causes absolutely no false indications of deteriorating insulation, and
- is safe for both personnel and the generator.

The PDA test for hydrogenerators was the first successful development from this research [10]. The PDA test is now used on over 750 hydrogenerators around the world [7]. Research to develop an improved on-line PD test for gas and steam turbine generators started in 1978, but achieving the objectives was much more difficult. After 11 years of research where several methods were investigated [10,11], a new sensor called the stator slot coupler (SSC) was developed. Unlike the capacitors or high frequency current transformers which have been used for PD detection in the past, the SSC is an RF transmission line coupler which detects the electromagnetic energy from PD and other signals. The SSC is installed under the wedges in stator winding slots containing stator bars connected as close as possible to the high voltage phase terminals. As described below, the characteristics of the PD and noise detected by an SSC are completely different, permitting reliable discrimination between PD and noise. Together with the Turbine Generator Analyzer (TGA), the SSC facilitates a test allowing generating station personnel to perform the PD test on gas or steam turbine generators without an outage.

Stator Slot Coupler

The SSC is a two-port stripline antenna. Each SSC is about 50 cm long, 2 mm thick, and is customized to be the same width as the stator slot. The substrate of the SSC is an epoxy-glass laminate onto which thin copper electrodes are deposited. All copper electrodes are covered by a thin layer of epoxy-glass laminate, so that no copper is exposed. Each end of the SSC is connected to a micro-coaxial cable. Thus each SSC has two coaxial cable outputs exiting from one end of the device, which are ultimately routed to connectors outside the generator. The SSC has a relatively flat frequency response in the range 30 MHz to greater than 1 GHz [12], due to its 50 ohm characteristic impedance and the 50 ohm coaxial output cables. Therefore the SSC can detect the true pulse shape of any high frequency signal propagating along the stator slot. Further details on the pulse coupling mechanisms of the SSC can be found in Reference [12].

Since the SSC is installed in the slot, on top of a stator bar (i.e. outside of the stator bar's grounded semiconductive coating), the SSC is not exposed to high voltages. However, the SSC is subject to thermal, mechanical and magnetic stresses within the turbine generator. Extensive calculations and laboratory testing of the SSC was conducted to ensure that the SSC would operate satisfactorily in this environment, and more importantly, not constitute any risk to the generator [12]. The results of this effort showed that the SSC was easily capable of withstanding both the installation process and generator operation.

SSC Installation

The optimum SSC location for partial discharge detection is as close as possible to the stator bar which may be subject to partial discharges. Thus the SSC is installed in slots which contain a stator bar in the top position at or near the phase end of the winding. To ensure that most of the high voltage portion of the winding is monitored, typically 6 slots are equipped with SSCs. Most of the SSCs installed to date have been placed just under the slot wedge (Figure 4). The thickness of the SSC is such that it substantially replaces the slot depth packing in the vicinity of the SSC. The SSC is axially located at one end of the slot or the other. The SSC output cables are routed from the slot end, over the core end plate and flux shield (if one is present) and around the core back to hydrogen-tight RF feedthrough connectors.

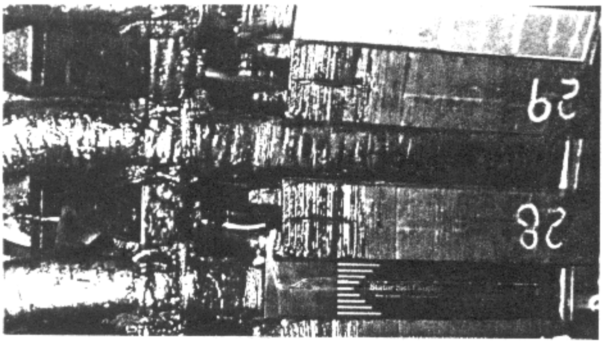

Figure 4. Photograph of the installation of an SSC under the wedges at the end of the slot in a 212 MVA coal-fired turbine generator installed in an American utility.

Eight installations of SSCs on large hydrogen-cooled turbine generators in the 200 to 500 MW range in five American and Canadian utilities have been made to the end of 1991. In addition, another 9 installations have occurred in other generators and synchronous condensers, including two standby generators manufactured by the global VPI process. At least 8 more turbine generator installations are planned during 1992. Unfortunately, SSCs can only be installed when the rotor has been removed. Installation, including routing the coaxial cables and installing the feedthroughs, takes about 3 days. With appropriate planning, the installation does not require a generator outage to be extended.

Two SSCs have been examined after they were installed for over one year in an operating 500 MW turbine generator at Ontario Hydro's Nanticoke TGS. One of these was removed for detailed examination in the laboratory. The SSCs were found to be in excellent condition, and there were no observable adverse effects in the generator. The SSCs were therefore reinstalled and the generator returned to service. Thus actual operating experience has confirmed that the SSC operating environment does not cause deterioration of the device. All of the more than 100 SSCs installed to date continue to operate reliably.

Comparison of Noise and PD

Due to its very wide frequency response, the SSC can detect faithfully the true pulse character of any signal created or induced within the stator slot. Measurements have been done on most of the SSC installations to determine the characteristics of PD and noise pulses. In most cases the generators were operating at full power.

Figure 5 shows a PD pulse obtained from a 500 MW, 22 kV steam turbine generator operating at full power, as recorded on a 1 GHz digitizing oscilloscope (Hewlett-Packard HP54111D). The most important observation is that the pulse has a width of only a few nanoseconds, that is PD yields a very fast pulse response. The very short duration is remarkably similar to the pulses shapes recorded in small-scale laboratory measurements, indicating the capability of the SSC to respond to the true PD signal. The trace marked "1" in Figure 5 is the output from the end of the SSC closest to the end of the stator slot. Trace "2" in Figure 5 is the output of the other end of the SSC which is located 45 cm further into the slot. Because trace "1" has been detected first, the response is due to a PD pulse propagating into the slot from the immediately adjacent endwinding. Further confirmation of the validity of this interpretation is the observation that the delay between the two pulses is equal to the electrical length of the SSC (2 ns).

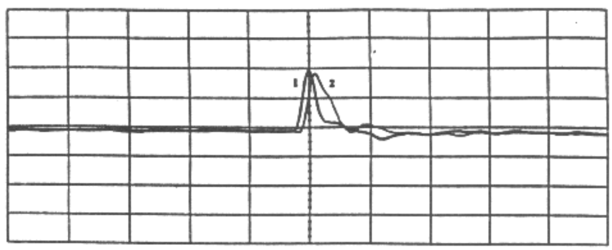

Figure 5. Response of both SSC outputs to partial discharge occurring just outside of the slot. The generator was operating at 22 kV, 500 MW. Vertical scale: 20 mV/div Horizontal scale: 10 ns/div

There are three major electrical, pulse-like noise sources associated with the turbine generator environment:

- arcing and PD occurring on the isolated phase bus (IPB) connecting the generator to the step-up transformer
- arcing from the turbine generator shaft grounding brushes
- field excitation thyristor transients and slip ring brush arcing.

The response of the SSC to each of these noise sources has been studied in several turbine generators [12]. As an example, Figure 6 shows the response of the SSC due to arcing on the generator output bus. The noise pulse detected at the SSC is very oscillatory and has a duration of more than 20 ns.

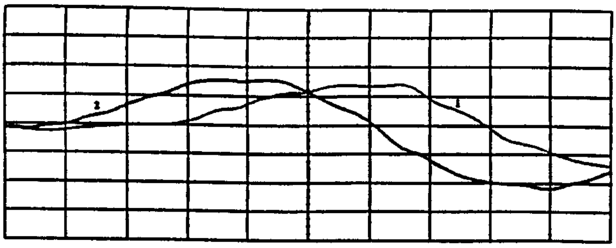

Figure 6. Response of both SSC outputs to arcing on the generator output bus. The oscilloscope was externally triggered by an RF current transformer on the generator IPB ground [11]. Vertical scale: 5 mV/div; Horizontal scale: 5 ns/div

In all the pulse shape studies in all of the generators equipped to date with SSCs, the PD pulses tend to be non-oscillatory, and have a pulse duration of less than 5 ns. In contrast, the electrical noise pulses are oscillatory, and have a duration of 10 ns to microseconds, depending on the source of the noise. This clear distinction in pulse shape can be used to distinguish between noise and PD. The PD pulses are short because the basic PD phenomenon lasts only a nanosecond or so, a stator bar in a slot constitutes a distortionless (although lossy) RF transmission line, and the SSC has the bandwidth to faithfully capture the true pulse shape. Noise pulses have a longer, more oscillatory shape because the noise signals must first propagate through the connection rings and endwindings of the stator, which is actually an inductance, rather than a well-defined transmission line. Noise from the rotor is also waveshaped, since the rotor is not a good high frequency antenna.

In addition to studies of the temporal nature of the PD pulses detected by means of the SSC, preliminary studies were made into the comparability of the SSC technique with the original Ontario Hydro on-line PD test described above [13]. The results indicate that there is general agreement between the peak PD pulse magnitude detected by the SSC and the peak PD pulse detected by the conventional test.

Turbine Generator Analyzer

An instrument called the Turbine Generator Analyzer (TGA) has been developed to take signals from the pair of coaxial cables from an SSC and perform the following functions:

- determine which signals are PD and which are noise, by measuring the pulse width (pulses longer than 10 ns are categorized as noise)
- perform a dual-polarity pulse height (32 channels), pulse phase (100 channels) and pulse width (12 channels) analysis on the pulses
- by comparing the arrival time of the pulses at the two ends of the SSC.

The TGA distinguishes between noise and PD on a pulse-by-pulse basis. Since the pulses have a duration of only a few nanoseconds, very fast electronics are required to process the signals. Figure 7 shows the block diagram of the TGA, which is controlled by a 386-type computer.

The design is such that the TGA test can be performed by generator station personnel. Data analysis will be similar to that used for the PDA test [7,10], that is the ratio of positive-to-negative partial discharge magnitude and the effect of generator load on PD magnitude can be used to identify the nature of any winding deterioration. In addition, the trend of the PD over time will indicate the severity of the winding deterioration. Measurements from SSCs with the TGA instrument are expected to commence in December 1991.

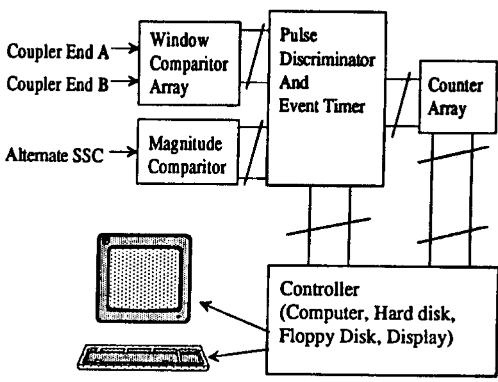

Figure 7: Block diagram of the TGA, used to distinguish between noise and PD, and to analyze the PD data

CONCLUSION

Considerable experience accumulated over the past few decades indicates that on-line partial discharge testing will identify those few steam turbine generators in a utility which are deteriorating. The trend in results from the on-line PD test will give sufficient warning to permit timely modification of generator operation or implementation of relatively inexpensive stator winding maintenance. Thus on-line PD testing facilitates extending winding life and reduces overall maintenance costs by avoiding in-service failures and resulting premature rewinds.

Although the on-line PD tests used for more than 40 years have been effective, they could only be performed by specialists, due to the possibility of false indications of insulation problems caused by electrical interference. Attempts to duplicate human expertise using signal processing or other statistically-based analysis were unsuccessful, since some false indications still occurred. However, a new on-line PD test has been developed which reliably eliminates all interference, thus preventing false indications. This test can be performed without interrupting turbine generator operation using non-specialized generating station staff. The improved test will enable the use of partial discharge testing by many more utilities. The new test is being applied by several American and Canadian utilities in gas and steam turbine generators, as well as motors.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. R.C. Anderson for his patience and persistence in performing most of the on-line partial discharge tests over the past 40 years, and for establishing that meaningful data can be extracted from chaos. We also thank Mr. J.F. Lyles and Mr. R.J. Gray (retired), the Ontario Hydro maintenance engineers who encouraged this testing, and applied the results to predict generator maintenance requirements. Finally, we thank Mr. W. McDermid of Manitoba Hydro and Mr. R. Bussey of TransAlta Utilities for their technical advice over the years and their willingness to apply new technology on their own generators.

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