Using Diagnostic Technology for Identifying Generator Winding Maintenance Needs

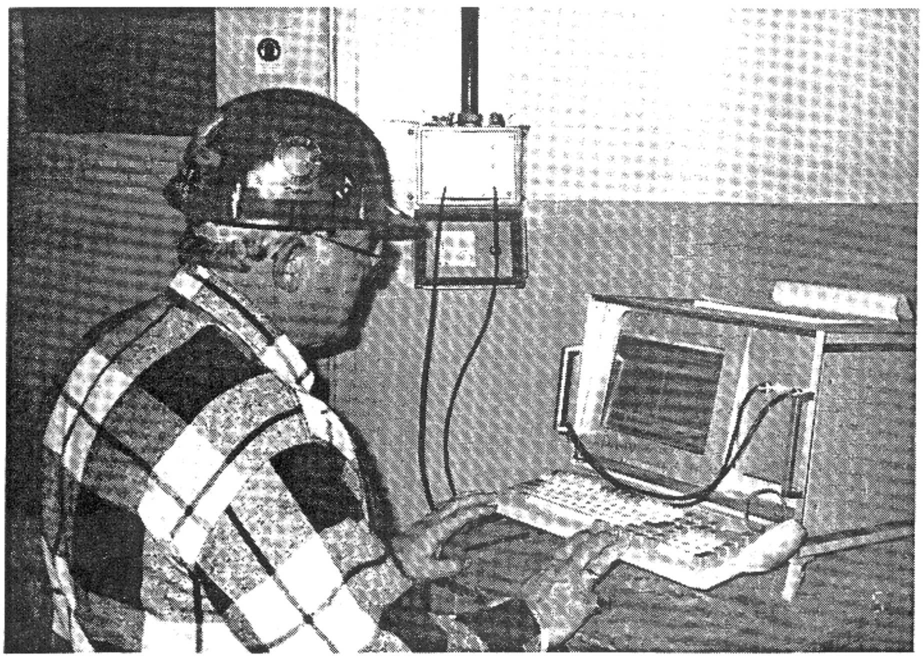
Detecting deterioration in generator winding insulation can help hydro O&M staff plan needed maintenance. One approach is analyzing the partial discharge (small electrical sparks) activity in the insulation; the more of this activity, the closer the winding is to failure. Instruments are available for measuring partial discharge during normal generator operation. Ontario Hydro is saving millions of dollars in avoided rewinds using this approach.

By John F. Lyles, T. Earl Goodeve, and Gregory C. Stone

The reliability and availability of a hydroelectric generating station is affected by the high-voltage insulation in the generator's stator winding. Surveys have repeatedly shown that deterioration of this insulation is a significant cause of plant outages.[1,2] However, if deterioration is detected at an early enough stage, many of the problems that lead to winding failure can be corrected by relatively minor maintenance. Thus, the winding can be restored to "as-new" condition, eliminating the risk of a forced outage and extensive generator damage. Selective re-sidepacking, rewedging, cleaning of endwindings, and restoring cooling system effectiveness all can be relatively easily performed on a planned basis to reduce the risk of failure.

John Lyles is the supervising engineer, electrical, and Earl Goodeve is an electrical engineer for Ontario Hydro's Hydraulic Stations Department. Greg Stone is the director of research for Iris Power Engineering in Ontario.

This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.



John Lyles, electrical engineer for Ontario Hydro, performs a PDA test while an 80-MW generator at the Sir Adam Beck 2 Generating Station is in full operation. The outputs from the couplers attached to the generator are in the termination box mounted on the wall of the generator enclosure. A pair of coaxial cables connects the couplers from each generator phase to the PDA instrument.

The effectiveness of these maintenance procedures is directly proportional to how early winding problems are discovered. The sooner problems are identified, the more likely it is that the winding can be restored through maintenance.

The most common winding problems are associated with thermal, mechanical, and/or electrical aging of the insulation, according to an Electric Power Research Institute (EPRI) report published in 1992.[3] This aging gradually occurs over a period of years. Experience at utilities such as Ontario Hydro and Manitoba Hydro in Canada and American Electric Power in the U.S. has shown that partial

What Are Partial Discharges?

Partial discharges (PD) are small sparks that can occur in any high-voltage insulation system. The sparks occur in air pockets (voids) within the insulation, or at the surface of the insulation. Ideally, modern, new windings contain no voids, and partial discharges do not occur. However, as a result of operating a winding at high temperature or owing to mechanical forces that can occur on generator load cycling, the epoxy-mica layers in the insulation may separate (delaminate). This delamination creates air pockets within the insulation. (Air can diffuse through the epoxy.) For windings rated about 6000 volts or higher, the electrical stress in the air pocket is enough to cause a spark: the breakdown strength of air is only about 1/100 of the strength of epoxy-mica. The spark does not lead to complete breakdown, though. Instead, it creates a "partial" discharge owing to the fact that the rest of the epoxy-mica layers stop the spark. Decades of experience have shown that as the delamination of the insulation becomes more severe, both the magnitude and the number of partial discharges increase. Thus, partial discharges are an excellent indicator of the severity of winding insulation deterioration.

Problems other than voids also can result in partial discharges. For example, if a stator bar is not tightly held within the stator slot, it tends to move under magnetic forces having twice the AC frequency (120 Hz). As a bar moves away from the stator iron, a small electrical charge is picked up on the surface of the bar's semiconductive coating. When the bar re-approaches and comes back in contact with the stator iron, the stored charge is shorted, causing a spark. In the early stages of this "slot discharge," the sparking is really an electrical contact noise. However, if the bar movement abrades away the semiconductive layer and even the epoxy-mica insulation, partial discharges similar to the delamination discharges can occur.

Partial discharges in hydro generator windings also can occur outside of the slot at the interface between the semiconductive coating and the voltage-grading coating. Conductive air pollution deposits on the endwindings also can lead to partial discharges and electrical tracking. These forms of partial discharge are usually not as dangerous to the winding as slot discharge and delamination discharge, but may lead to winding failure after many years.

Winding overheating, load cycling, and loose windings are common causes leading to stator winding failures. Partial discharges typically accompany such problems. Therefore, testing for the presence of partial discharges enables most of the common winding failure mechanisms to be detected without disassembling the generator.

---

discharges (previously referred to as corona) are a symptom of insulation deterioration. The accompanying article, "What Are Partial Discharges?" explains this in more detail. Experience at these utilities also has demonstrated that routinely measuring partial discharges in a hydro generator often gives years of warning of incipient problems in stator windings.[4,5] This warning is long enough to enable corrective maintenance to be implemented, avoiding unexpected winding failures.

By performing stator winding maintenance on an as-required but planned basis—based on data from partial discharge analysis (PDA)—Ontario Hydro has experienced a net savings of $4.2 million per year in rewind costs. (This savings is based on 150 hydraulic generators where the average rating is 40 MW.) The savings are achieved through timely preventive maintenance practices such as rewedging and repair to extend the life of a generator and avoid premature rewinding. Ontario Hydro also has reduced its number of outages owing to the confidence that maintenance personnel have in PDA analysis of the generator winding condition.

A Look at the PDA Test

A wide variety of partial discharge test methods (also known as radio frequency monitoring) have been used since 1951. Almost all of these methods either required a generator outage to perform the test, or, if performed during normal operation of the generator, required an experienced testing specialist. Either a unit outage or great experience was needed owing to the fact that many other electrical signals in a generating station have the appearance of stator winding partial discharges. Corona on the generator output bus, slip ring brush sparking, and commutator noise from power tools used in the plant easily can be confused with partial discharges. Such electrical interference can give false indications of stator insulation condition and thus make diagnosis of winding insulation condition unreliable.

From 1976 to 1979, Ontario Hydro, under contract from the Canadian Electrical Association, developed a new partial discharge test now known generically as the PDA test. Tele-radio Systems and FES International, Inc. were the first two companies granted licenses from Ontario Hydro to commercialize the test. Because Ontario Hydro did not patent the test, several companies have since built and now market the instrumentation.

Using the PDA test, hydro plant maintenance personnel can monitor partial discharges during normal hydro generator operation. The key to the test is reducing external electrical noise by using sensors installed in the stator winding. The sensors are 80 pF, 25 kV capacitors (known as PDA couplers) installed within the stator winding. The capacitors block the 60-Hz voltage, yet allow the very high frequency partial discharge pulses to be conducted to the instrument measuring partial discharge. At least two PDA couplers are permanently installed per generator phase. The pair of PDA couplers are connected so as to cancel out noise, while remaining sensitive to partial discharges within the winding. Installation of the couplers usually can be done by a two-person crew in three to four days during an outage. The accompanying article, "Reducing Noise in the PDA Test" provides a more detailed explanation.

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. Both positive and negative partial discharges are recorded simultaneously. In general, a generator with a more deteriorated winding will have much more partial discharge activity.

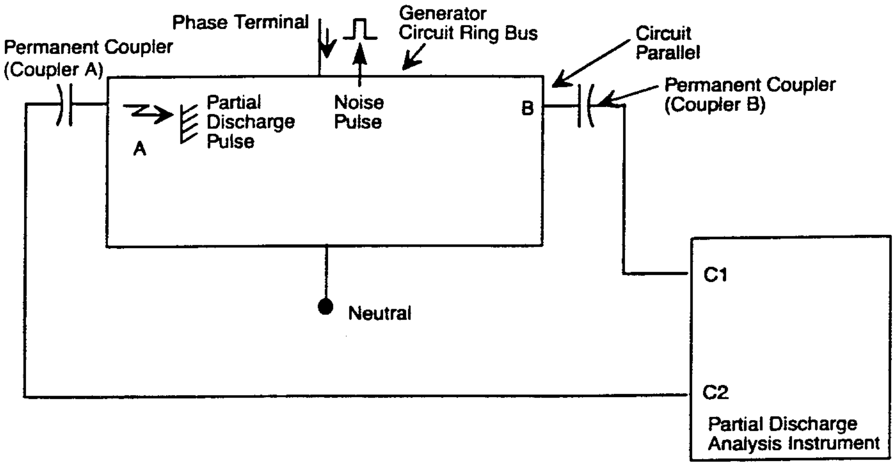
To help in the interpretation of the results, the total positive and negative discharge activity in the winding, termed NQN by the developers of the PDA test technology, is estimated.

Reducing Noise in the PDA Test

The unique feature of the partial discharge analysis (PDA) test is its ability to ignore other pulse-type electrical signals that can be confused with stator partial discharges. When a partial discharge occurs, a current pulse lasting only a few nanoseconds results. The current pulse causes a voltage pulse to propagate through the stator winding. In the PDA test, special high voltage 80 pF capacitive couplers are installed in the winding, usually at the connection point of the generator circuit ring bus to the coils. At least two couplers are installed per phase, at each end of the circuit ring bus. Arrangement of the couplers is shown in the figure below.

When a partial discharge pulse occurs, for example, near coupler A, the associated voltage pulse is immediately detected at coupler A. However, the pulse takes up to 50 nanoseconds to travel around the circuit ring bus to coupler B. The PDA instrument detects that the pulse arrived at the couplers at different times, and digital electronics identify the pulse as a partial discharge from A.

An electrical noise pulse (such as from corona on the generator output transformer) comes into the generator and travels along the circuit ring bus to both A and B couplers. If the circuit ring bus is the same length between the generator terminal and the coupler sites, the noise pulse is detected at the same time by both couplers. The PDA instrument detects this simultaneous arrival of the pulse, and defines the signal to be due to noise. Thus, noise is characterized by simultaneously arriving pulses, whereas stator winding partial discharge results in pulses arriving at significantly different times at the two couplers. There are many complications in hydro generators; however, methods have been developed by several PDA test manufacturers that enable the detection and, for the most part, elimination of noise on most hydro generators rated 10 MW or more.



This figure illustrates how high voltage 80 pF capacitive couplers are installed in a generator stator winding. The couplers, shown here as A and B, usually are installed at the connection point of the generator circuit ring bus to the coils. C1 and C2 are the input terminals of the PDA instrument.

Modern PDA instruments calculate and display the NQN, which allows easy trending of the partial discharge activity over time.

The PDA test is usually done twice per year, typically in the spring and in the fall. Regular testing of each generator permits the trends in partial discharge activity to be monitored over the years. A sudden increase in partial discharge activity is indicative of winding deterioration.

A test takes about 15 minutes to set up and perform. Results are collected when the generator has thermally stabilized at "no-load" and "rated-load" conditions. The rated-load test is performed first with the no-load test performed immediately after. The difference in the winding temperature between tests should not exceed about 5° Celsius. If the rated-load positive NQN is significantly greater than the no-load positive NQN, the winding is loose and experiencing slot discharge.[6] This problem often can be corrected by rewedging. Since the partial discharge activity is affected by generator voltage, load, and winding temperature, it is important to keep these quantities the same in repeat tests on the same machine.

Using the PDA Test To Plan Maintenance

Since their introduction in 1978, the PDA couplers have been installed on at least 800 hydro generators throughout the world. The PDA test has been performed on each of these generators usually dozens of times, using PDA instruments from various manufacturers. Owners of these machines report that data collected from PDA tests are useful in planning stator winding maintenance.

The key factor in interpreting PDA test data is to perform the test on a regular basis for determining if the partial discharge activity is increasing from year to year. If rapid increases in results are detected, the winding should be visually inspected and/or other diagnostic tests performed to verify the presence of deterioration. It is also possible to extract more information on the nature of the winding deterioration from a careful examination of PDA test data.[6] If the generator is critical to the plant owner, the winding's original equipment manufacturer (OEM) or an experienced consultant can confirm a diagnosis and recommend repair alternatives. The main purpose of the PDA is to identify those hydro generators that need further attention.

Ontario Hydro, the provincially owned utility in the province of Ontario, is using the PDA test at most of its generating stations, including Beck, Wells, Lower Notch, Arnprior, and Abitibi with good results. In all, 141 of Ontario Hydro's hydro generators are equipped with couplers. The utility owns six PDA test instruments.

Beck Generating Station 2: Unit 14

After only 18 months of service, the windings in this 80-MW, 13.8-kV, epoxy-mica generator stator developed excessive surface partial discharge activity, which was identified by the PDA test. No-load and full-load activity levels were similar, indicating the problem was not a loose winding. Instead, the semiconducting coating, which grounds the stator bar surface, effectively ceased to perform its intended function. The deterioration of the coating caused very high surface partial discharges in the coils operating

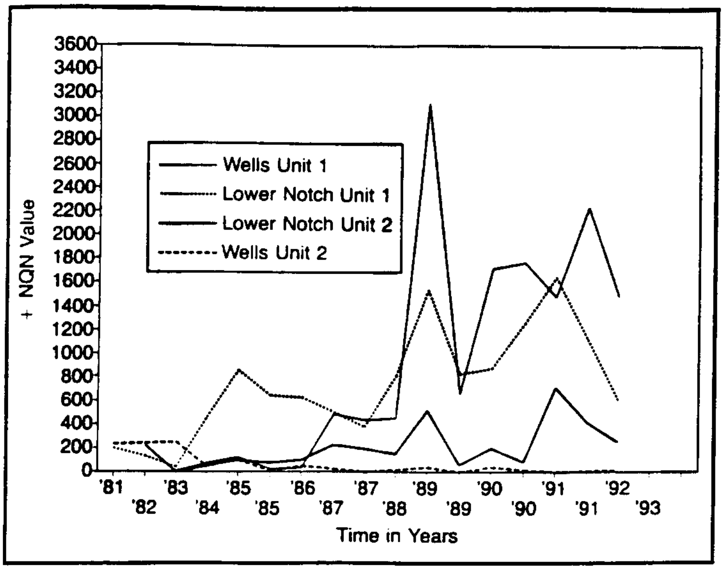


Figure 1: This plot shows the trend in positive total partial discharge activity (NQN) for four generators at the 232-MW Wells and 270-MW Lower Notch generating stations. The CRTV (conductive room temperature vulcanizing) injection and rewedging repair in 1975 for Lower Notch Unit 2 and Wells Unit 2 has been more successful (as demonstrated by lower partial discharge activity) than the earlier repairs to the other units.

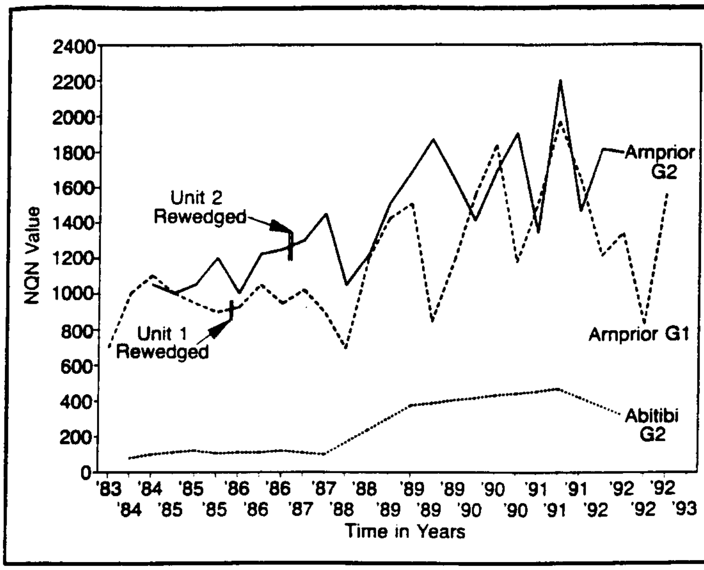


Figure 2: This graph compares the total discharge activity of three similar windings installed in the mid-1970s. The two Arnprior generators have high partial discharge activity caused by ineffective semiconducting coatings. Unit 2 at the Abitibi Generating Station has relatively little partial discharge activity, and visual inspections revealed no signs of deterioration.

at high voltage. As is typical with such deterioration, the positive partial discharge activity was substantially higher than the negative.

By closely monitoring the unit through PDA tests, Ontario Hydro operated this unit for 14 years before replacing the winding. At one point, ozone levels in the unit reached levels of 2.75 parts per million (ppm). Without the data from the PDA tests, Ontario Hydro might have decided to take action earlier owing to high levels of ozone—a condition that typically indicates a winding problem. However, based on the rate that the surface discharge activity was causing the insulation system to deteriorate (determined through data collected during the PDA test), the utility postponed rewinding. Thus, it deferred expense and maximized the return on its winding investment.

The new stator winding was manufactured and installed in accordance with Ontario Hydro's stringent rewind guidelines, the power factor tip-up test values, and voltage endurance test criteria. The replacement winding has had very little partial discharge activity and is in good condition.

Wells, Lower Notch Generating Stations

The two generators at Ontario Hydro's Wells station are rated 107 MVa and have epoxy-mica windings. The two units at Lower Notch also have epoxy-mica windings and are rated 120 MVa. The first 11 years of partial discharge monitoring of these units, after *in situ* repairs for loose windings in 1975, indicated satisfactory results. However, beginning in 1988, Unit 1 at both stations became significantly worse in terms of partial discharge activity, as seen in Figure 1. Interpretation of PDA data, coupled with detailed knowledge of physical construction and visual inspection of the units, confirmed that the major source of partial discharge activity in the units was restricted to the first five bottom stator bars at the high-voltage end of the winding in one of the circuits. Because these bars were in the bottom of the stator slots, it is likely that the 1975 repair procedure was much less effective than for the rest of the winding owing to difficult access. The deterioration of these bars apparently was caused by significant slot discharges occurring due to semiconducting coating deterioration.

Because Lower Notch and Wells operate as base load plants, Ontario Hydro is choosing not to shut them down for an outage (and consequently spill water) until the ozone concentrations in the powerhouses exceed the U.S. Occupational Safety and Health Administration (OSHA) limits, or until a stator winding bar failure occurs.

Even though the ozone levels of the generators are high, by conducting PDA tests on these units, Ontario Hydro is confident that the partial discharge activity is, so far, restricted to the surface of the stator winding insulation (i.e., high levels of positive pulses). Therefore, the utility can continue to operate the units. Interpretation of recent test results indicate the partial discharge levels are increasing. Ontario Hydro anticipates the need for a rewind of the units before they reach the "normal" end of their operating lives. By identifying and tracking the partial discharge activity through diagnostic testing, Ontario Hydro can plan needed maintenance well in advance.

Arnprior, Abitibi Unit 2 Generating Stations

Abitibi Unit 2 was placed in service in 1976, one year after the two units at Arnprior. All three units use epoxy-mica stator windings with a coil slot section painted with a semiconducting paint over which, on one side only, is applied a conductive silicone coating. Abitibi Unit 2 is rated 70 MVa; the Arnprior units are rated 39 MVa.

After five to seven years of operation, early partial discharge testing indicated that the Arnprior units were experiencing significant levels of discharge activity. Using PDA experience gained from tests on other units, Ontario Hydro predicted that partial discharge activity was at or very close to the surface of the stator coils. During outages for required rewedging detected by the PDA, physical examination of removed samples showed no visual indication of a surface discharge problem. However, when the resistance of the semiconducting coating was measured, it was found to be near infinite resistance. It had essentially stopped conducting, but displayed none of the visual signs that normally accompany such a problem. Testing revealed that the problem at Arnprior was related to a quality control problem with the batch of semiconducting material.

Ontario Hydro maintenance staff visually examined Unit 2 at Abitibi, and found none of the problems associated with Arnprior.

What PDA Testing Means For Ontario Hydro

The greatest savings for Ontario Hydro in using PDA testing has come from identifying generators with relatively low levels of partial discharge and tracking its activity. In this way, corrective action can be planned prior to any real insulation system damage. As a result, Ontario Hydro is avoiding unplanned outages and unexpected failures. The utility anticipates to achieve, on average, five to seven additional years of winding life on 141 units—a total of nearly 850 additional years of winding life for the utility.

Recent Advances in PDA Technology

Since its introduction more than 15 years ago, several improvements have been made to the PDA test, including improved couplers and better data analysis. For example, a variety of PDA couplers are now available from a number of companies such as FES, Iris Power Engineering, and General Electric that are easier to install than the original couplers.

Recently, Iris introduced a new generation of the PDA instrument, called the PDA-IV, that makes the test more reliable and easier to interpret. CEA has given Iris exclusive rights to manufacture and sell this new instrument.

The new instrument enables the test to be performed on generators with circuit ring buses as short as 3 feet instead of 6 feet, allowing the test to be applied to a wider range of hydro generators. It also improves noise rejection: distortion of partial discharge pulses as they travel through the generator winding no longer impairs noise rejection. These improvements result from replacing the analog differential input of earlier PDAs with 800 MHz digital electronics.

The new instrument also features pulse phase analysis, which measures where the partial discharge pulses occur with respect to the 60-Hz phase angle position. Figure 3 is a plot created from this analysis.

PDA-IV also features direct plotting of trends in partial discharge activity over time. Together with a full color display, this plotting enables users to more easily detect whether winding problems are occurring.

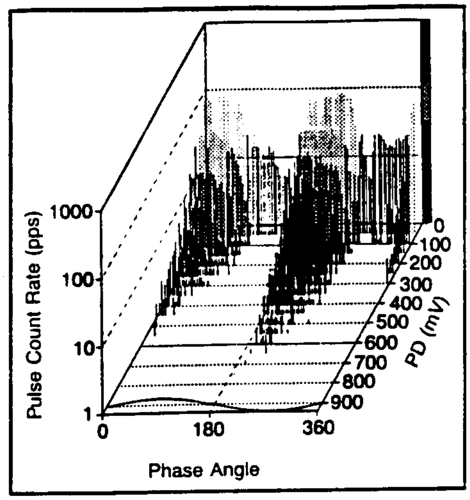


Figure 3: This three-dimensional "pulse phase analysis" plot of the partial discharge activity shows where the partial discharges are occurring with respect to the AC phase angle. This is one of the charts that can be generated with the PDA-IV instrument. Such plots may be useful to maintenance personnel in more precisely determining the cause of any winding problems.

Summary

The PDA test has become a widely used method for evaluating the condition of the high voltage insulation in stator windings in hydro generators larger than 20 MW. The PDA test allows hydro plant maintenance personnel to measure the partial discharge activity in the stator during normal hydro generator operation, rather than requiring an outside specialist. Partial discharges are a symptom of most types of insulation deterioration. Therefore, by trending the PDA data over the years, the onset of many types of winding problems can be detected and maintenance planned to prevent catastrophic winding failure.

Recent improvements in the test hardware, as well as software for interpreting test results, make it easier for users to diagnose specific winding problems. The test also is becoming applicable to a wider range of hydro generators. □

Messrs. Lyles and Goodeve may be contacted at Ontario Hydro, 5775 Yonge St., North York, Ontario M2M 4J7; (416) 590-2646 or (416) 590-2647. Mr. Stone may be contacted at Iris Power Engineering Inc., 6380 Tomken Road, Unit 1, Mississauga, Ontario L5T 1Y4; (416) 564-4977.

Notes:

[1] Evans, D.L., "IEEE Working Group Report of Problems with Hydrogenerator Thermoset Stator Windings: Part I," *IEEE Transactions*, PAS-100, July 1981, page 3284.

[2] Franklin, D.E., B.C. Pollock, and J. Laasko, "Hydroelectric Machine Condition Monitoring: A Technical Proposal and Business Argument," Paper to be presented at the Waterpower '93 Conference, Nashville, Tennessee, August 10-13, 1993.

[3] Anders, George, et. al., *Motor and Generator Life Estimation*, Report TR-100185, Volume 1, Electric Power Research Institute, Palo Alto, California, January 1992.

[4] Kurtz, M., and J.F. Lyles, "'Generator Insulation Diagnostic Testing," *IEEE Transactions* PAS-98, September 1979, page 1596.

[5] McDermid, W., "Utility Program for Monitoring the Condition of Large Generator Stator Insulation Systems," Proceedings of 15th IEEE Electrical/Electronics Insulation Conference, Chicago, Illinois, 1981, page 41.

[6] Lyles, J.F., G.C. Stone, and M. Kurtz, "Experience with PDA Diagnostic Testing on Hydraulic Generators," *IEEE Transactions* EC, December 1988, p. 824.

[7] Stone, G.C., and S.R. Campbell, *Digital Methods of Eliminating Noise in On-Line Generator Partial Discharge Measurements,* IEEE Winter Power Meeting, Publication 92-THO-425-9-PWR, February 1992.