

# CONTINUOUS ON-LINE PARTIAL DISCHARGE MONITORING OF GENERATOR STATOR WINDINGS

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**Abstract:** The use of on-line partial discharge (PD) measurements as an indicator of stator winding insulation condition, is well known. Trending results from on-line PD measurements over time, often allows maintenance personnel to become aware of developing stator insulation problems in motors and generators, and take corrective measures before failure occurs. However, partial discharge measurements on operating rotating machines can be influenced by conditions such as humidity, temperature, terminal voltage, and load. Thus, to provide reliable data which can be trended, it is important to take readings under similar machine operating conditions. In remote plants, or on pump storage units which are frequently cycled, it can be both time consuming and costly to ensure that personnel are available to take PD readings under ideal conditions occur. This paper describes the development of a automatic partial discharge monitoring system which is permanently connected to relevant machine sensors and can be configured to collect PD data when suitable conditions are met. The operating principles of the system are described, and some results are presented from data collected to date on 30 hydrogenerators.

## I. INTRODUCTION

High voltage stator windings often produce partial discharge (PD) as a symptom of many conditions, including loose windings, overheated insulation, and contaminated windings [1-5]. Various methods have been developed to measure the PD activity in a winding. The most popular methods are those which can be implemented during normal operation of the machine, since costly outages can be avoided. In research conducted over the past 20 years, PD measurement methods have been developed which make an on-line PD test easier to perform and interpret, allowing non-specialized plant personnel to reliably perform the test [2,3]. In hydrogenerators, this method depends on high voltage capacitors installed in the winding as well as specialized electronics to eliminate the electrical interference (noise) common to operating machines. Once the PD is separated from the noise, standard electronic pulse counting techniques can be used to accurately determine the magnitude, number and phase position of the PD activity.

The development of instrumentation which can be used by non-specialized plant personnel to reliably perform a PD test, together with recent advances in computer technology, has made it feasible to, develop a system which can be permanently installed in a power plant, and to monitor automatically and continuously the PD activity. Such a

system can be programmed to collect data under various machine conditions, thus providing a series of consistent data points for trending. This paper describes such a system, and presents the results from several generators where it has been used.

## II. NEED FOR AUTOMATED PD MONITORING

Stator winding insulation deterioration is usually a relatively slow process, where the time between when significant PD can be detected and when winding failure may occur, may be several years. Thus measurements which are done once every six months or so, are often adequate for detecting stator winding problems. However, there are several situations where continuous and automated monitoring may be advantageous:

1. There is a trend for hydrogenerator plants to be remotely operated. Since such power plants are often located in remote sites where it is expensive to transport test personnel to the site, an automated PD monitoring system allows measurements to be made, without sending personnel to the plant. This can reduce overall test costs.
2. The stator winding PD activity is often affected by motor/generator operating conditions, including winding temperature, load, voltage, etc. [2]. Although these operating condition-dependent results help in interpreting the type of deterioration occurring, they often make it difficult to trend PD data over time. To obtain trendable data, (which is important for interpretation) the machine must be tested under the same load, temperature and voltage conditions. For critical units which are subject to frequent load cycling, or pumped-storage generating units, it is often difficult for the plant operators to recreate exact operating conditions from test to test. An automated PD monitoring system avoids this problem by continuously measuring the motor/generator operating conditions, and then taking the PD measurement only when the desired operating conditions occur.
3. Collecting PD data at various temperatures and load points can itself be useful in the data interpretation process. For example, if a winding is loose, an increase in generator load (and thus the forces on the stator bars) will cause the PD activity (i.e. slot discharge) to increase dramatically. A continuous PD monitoring system can collect data at specific time intervals, and

under selected operating conditions, thus providing multiple points of compatible trend data. Utilizing such data maintenance engineers have a more complete picture of the winding's condition.

4. Several expert systems are being developed which continuously monitor all the sensors in a generator (for example temperature, vibration, current, voltage, hydrogen gas pressure, etc.) to determine if any problems are occurring in the generator. This provides plant operators, as well as maintenance personnel, with warnings that a problem may be developing, and also gives advice on corrective action. Such expert monitoring systems include the Generator Expert Monitoring System (GEMS) for turbine generators and the Advanced Condition Monitoring System (ACMS) for hydrogenerators [6- 8]. Since partial discharge activity is an important source of information with regards to stator winding insulation, it is desirable that generators equipped with such expert systems have ready access to PD data. An automated PD monitoring system can fulfill this function by making PD data available on a continuous basis to such expert systems.

The need for a continuous and automated PD monitoring system was first recognized in the early 1980's when Ontario Hydro constructed a prototype system to investigate the effect of operating conditions on PD. In the late 1980s other researchers also developed a non-commercial quasi-continuous system [9]. However, the computer technology and computer communication systems available at the time made the earlier systems relatively unreliable and/or relatively expensive and difficult for utility personnel to use. With the advent of superior computer technology, a monitoring system which can be used by non-specialized plant staff has been developed and is described below.

### III. SYSTEM ARCHITECTURE

To measure the machine's operating conditions and to record PD data, each motor or generator monitored requires a Data Acquisition Unit (DAU) to be installed near the machine. The DAU measures the PD activity from all the PD sensors installed on the machine; separates the PD from noise; and counts the number, magnitude, and phase position of the PD. In addition, the DAU has digital and analog inputs to measure the motor/generator operating information such as load, temperature, voltage, and breaker status. The DAU contains a DOS based 80386 computer for control of the PD and analog sensors, and to communicate with a central system controller via an Ethernet Local Area Network (LAN).

Up to eight DAUs in a plant are serviced by one system controller, over a LAN (Figure 1). The System Controller is a PC running a dedicated monitoring application. The System Controller acts as a file server for storing data sent from the DAUs, and is also responsible for configuring and controlling the DAUs. In addition, via the System Controller,

a user defines, for each DAU, the generator operating conditions (i.e. triggers) for which a PD measurement should be made, and how often the measurement is made, assuming the conditions occur for a long time. There is also a facility for continuously measuring the PD activity at each DAU, and for raising an alarm if the PD activity is above a defined threshold. In addition, there is a program for displaying and trending any saved PD data.

The System Controller can be remotely accessed via a Wide Area Network (WAN) or modem. This allows personnel in engineering offices to define or change trigger conditions and alarm levels, as well as to download test results for display on a local computer.

### IV. HARDWARE DESIGN

The electronics used in the DAUs is based on that of portable instruments in use for many years [2,3]. This ensures that PD test results will be trendable no matter which method is used to collect data. The input electronics is based on four single channel pulse height analyzers which can be sequentially scanned through a range of magnitudes to determine the number and magnitude of the input pulses. Four channels are needed to measure simultaneously both polarities from two sensor inputs. Associated logic determines if the incoming pulse is noise or PD, according to the type of sensor used [2,3]. To determine the pulse count, the content of a counter is incremented each time a pulse occurs in the present magnitude window. A counter is associated with PD pulses from each sensor and polarity. Counters are also associated with various noise conditions. Once every one-one hundredth of an ac cycle (167 microseconds for 60 Hz), the contents of the counter are downloaded to the DALTs memory. The computer associates the present ac phase position with pulse count and magnitude. The analog bandwidth is a minimum of 350 MHz.

Most machines are equipped with 6 to 12 sensors, to help locate where in the stator winding the PD is occurring. A multiplexor within the DAU, controlled by the DALTs computer, is used to sequentially scan through all the PD sensor inputs. The multiplexor also has one "open" channel which is used to completely isolate the DAU from the sensors installed in the high voltage winding, to minimize the potential for damage to the electronics during transients. That is, unless the signals from a sensor are actually measured, the sensors are not connected to the electronics. In addition, a test input is permanently attached to one of the multiplexor channels to verify the proper operation of the DAU's PD collection electronics.

Most installations were made in 1996 and 1997, but one installation has been operating since February 1995. After the physical effort of installing the DAUs and LAN, it generally only takes 3 to 4 days at site to commission the system. Figure 3 shows approximately a year's worth of data that has been acquired from one site, collected with the

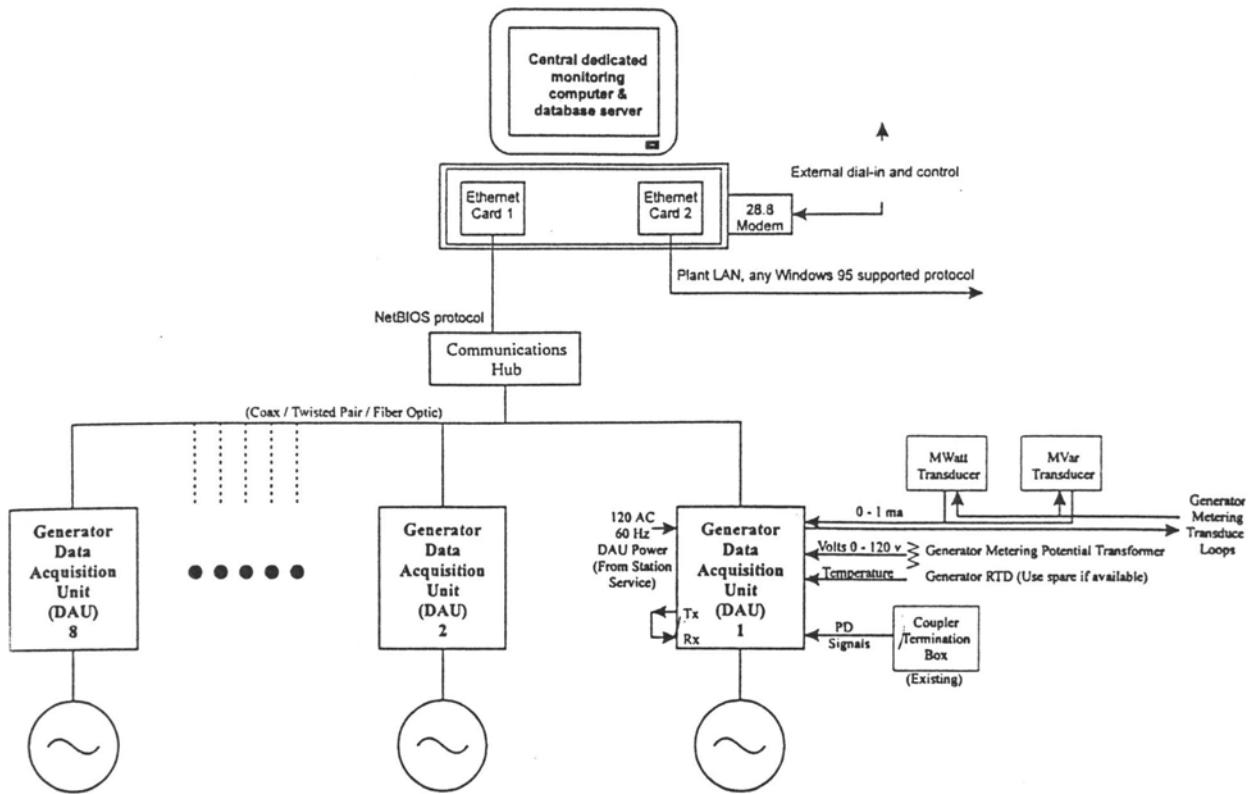


Figure 1 - Monitoring system block diagram.

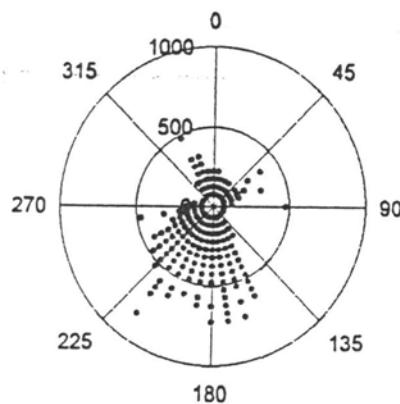


Figure 2 - A polar plot of PD magnitude (mV, radial scale) versus phase angle (polar scale). The data is from a 140 MW, 13.8 kV hydrogenerator.

system in Figure 1. As can be seen from Figure 4, there is a substantial decrease in PD activity with any increase in stator winding temperature. This particular generator has an asphaltic mica insulation system, which is known to be delaminated. This behaviour is expected since the asphalt tends to expand as the temperature increases, closing up the voids and thus reducing the PD activity. This example shows the importance of comparing PD results only when the operating conditions are similar.

In contrast to the temperature sensitivity of the generator

in Figure 3 and 4, the machine in Figure 5 shows little or no temperature dependence of PD. This machine is a large pump storage motor/generator which sees rapid changes in load. Figure 5 shows the two dimensional pulse height analysis for the machine at more or less constant load, but for two very different temperatures. In this case there is little difference in the PD activity.

Figure 6 is an example of a machine which shows very

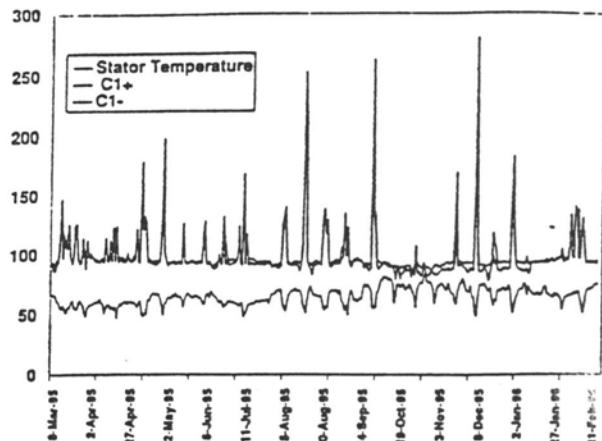


Figure 3 - Positive and negative PD (in mV) recorded over approximately one year on an 80 MW hydrogenerator. Note that the PD activity (upper two lines) increases when the winding temperature (lower line) decreases.

load dependent behavior that can be automatically detected by the continuous monitoring system. This machine is a large pump storage generator which is suffering from slot discharge. In this case, the PD monitor has collected data at no load, while the machine is still hot, and again at full load, at approximately the same temperature. The significant difference in PD between the no load and full load condition is usually a result of the change in bar forces with load and indicates that the bars may be loose in the slot.

Conventional analog to digital converters are incorporated in each DAU to measure the generator/motor voltage, power, and stator winding temperatures. The electronics can be configured to measure any type of analog signal (from transducers, current loops, RTDs and/or thermocouples) and to yield digital data for the DAU computer. Calibrated,

a complete scan of the PD sensors. For example, a PD measurement on a generator may be taken once every 3 months when the load is above 225 MW and the stator winding temperature is above 85° C and once every 3 months when the load is above 225 MW and the stator winding temperature is between 50° C and 55° C. Utilizing such a trigger, the effect of temperature on the PD can be investigated.

- a module to control communication over the LAN to each of the DAUs connected to the System Controller, as well as to a remote computer.

A proprietary NetBIOS-based remote procedure call (RPC) protocol was developed to provide communication between the DAU and System Controller. This protocol allows for 3 distinct communication channels with the DAU: a command channel for sending command and configuration data to the DAU; a data channel to allow the DAU to send PD data records to the System Controller; and an emergency command channel to allow the controller to gain a DAU's attention, while a PD test is in process. An Ethernet communication protocol is used to ensure future compatibility to proposed IEEE standards for generator station monitoring system communication [8].

The DAU software is a DOS based application. The software accepts commands from the System Controller via the RPC protocol described above. Once a configuration has been loaded into a DAU, it will run autonomously - monitoring the machine sensors for appropriate trigger conditions and only communicating again with the System Controller when PD data has been collected. This reduces network traffic and allows one System Controller to service many DAUs

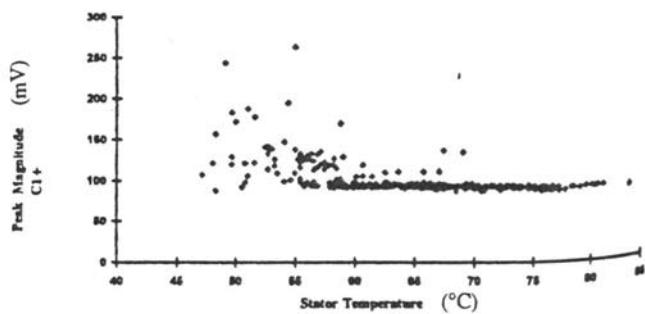


Figure 4 - A plot derived from the data in Figure 3 showing that the PD activity is stabilized at a lower level when the stator winding operates above about 60°C.

Temperature compensated reference voltages are used to detect any drift in the A/D electronics.

## V. SOFTWARE DESIGN

The System Controller has most of the critical software to run the monitoring system. The software modules are written in the C++ programming language and are 16 bit Windows applications. Because each successful PD test of 6 coupler pairs results in over 800kB of data, the PD test result data is compressed and stored in binary large object fields of a Paradox™ database.

The controller consists of several distinct software modules:

- a supervisory program to configure and accept data from the DAUs
- a module to control the sensitivity of the PD measurements in each DAU, as well as the time to scan the PD sensors.
- a module to allow the user to input the particular operating conditions of the motor or generator which cause each individual DAU under what operating condition ranges

## VI. HYDROGENERATOR EXPERIENCE

The operating conditions and PD data can be displayed on any network computer. The display module has a wide variety of possible output graphs including:

- conventional pulse height analysis plots with families of curves based on sensor identifier, time of test, pulse polarity, machine load, etc.
- conventional 3 dimensional pulse phase analysis plots of the number of pulses per second versus magnitude and phase position of the 50/60 Hz voltage
- pulse phase analysis graphs which plot the pulse magnitude versus the phase position (either linear or polar mode) on a 2 dimensional graph, with the pulse repetition rate encoded as the color of a data point (Figure 2)
- trend plots of PD activity indicators (such as the peak PD magnitude or the total discharge activity, NQN) versus time, for a user-defined set of machine operating conditions (Figure 3)
- trend plots of PD and generator operating conditions versus time

Since a tremendous amount of data can be acquired in theory, it is critical for powerful display techniques to be available for the user, to reduce the data to meaningful results. A variety of "filters," based on date and machine operating conditions have been developed. Multiple operating conditions can be ANDed to interactively provide selectable data access patterns to extract meaningful results.

About 30 DAUs have been installed to date in utilities around the world, mostly on hydrogenerators.

## VII. CONCLUSION

A practical, automatic, continuous, PD monitoring system has been developed to measure, store, and display the PD activity in generator stator windings. Since the first installation on a generator more than two years ago, the system has been proven to be robust and reliable. From the data collected thus far, several interesting features of PD, as a function of machine operating conditions, have been found. It is expected that as more data is collected on more machines, and correlated with machine condition, as determined by visual inspection, other relationships may be established.

## VIII. BIOGRAPHY

**Dr. Greg Stone** obtained his degrees in Electrical Engineering from the University of Waterloo, Canada. From 1975 to 1990 he worked primarily at the research Division of Ontario Hydro where he contributed to the development of on-line partial discharge tests.

He joined Iris Power Engineering in 1990, and is currently Vice President of Global Education Services. He has won several IEEE awards for the development of on-line PD tests, has chaired a number of IEEE standards working groups, represents Canada on EEC 2J and 15E, and is a past President of the IEEE Dielectrics and Electrical Insulation Society. He is a Fellow of the IEEE and a registered professional engineer in Ontario, Canada.

**Mr. Blake Lloyd** graduated in Electrical Engineering from the University of Waterloo, Canada. From 1985 to 1991, he was employed in the Electrical Research Division of Ontario Hydro where he was responsible for developing software for advanced measurement, testing, and diagnostic monitoring equipment for rotating machines. He joined Iris Power Engineering in 1991, and is the Vice President of Research and Development. His responsibilities include new product development and design, and he has been an architect of several on-line monitoring products. He has been an TREE member since 1985.

**Mr. Steve Campbell** graduated from Sheridan College, Toronto in 1981, specialising as an Electronics Technologist. After graduation Mr. Campbell worked with Ontario Hydro Research Division, where he was responsible for design

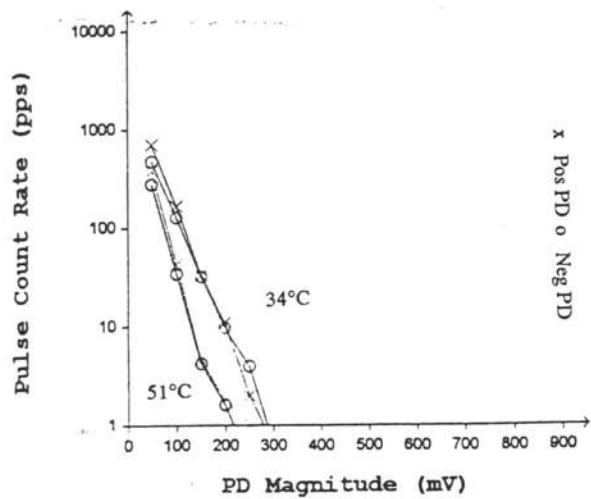


Figure 5 - A plot comparing the behavior of a 333 MVA pump storage generator at 34°C and 51°C, and approximately the same load.

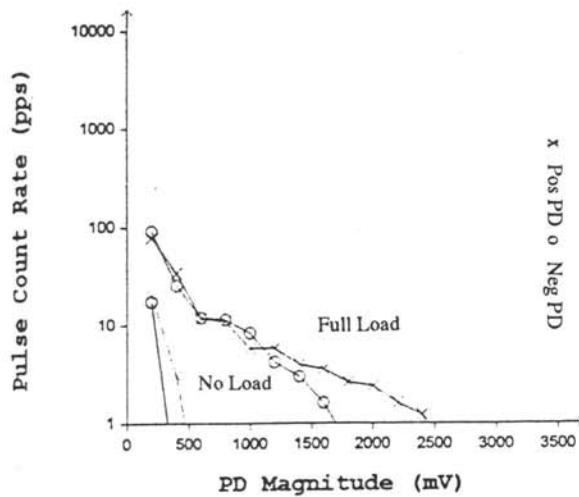


Figure 6 - No load hot and full load hot plots for a 350 MVA pump storage generator.

and construction of high speed trigger circuits, system design of computer-controlled, high speed digitizers and measurements of high speed, high voltage pulses in large motors and generators. He is presently Vice President of Strategic Planning for Iris Power Engineering.

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