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ON-LINE PARTIAL DISCHARGE MEASUREMENTS ON TURBINE GENERATORS EXPERIENCE WITH STATOR SLOT AND BUS COUPLER MEASUREMENTS

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Summary

Partial discharge (PD) measurements are increasingly employed by electric utilities as a tool to aid in determining stator winding insulation condition. While off-line techniques have been in use for many years, more recently, the power of measuring PD while the generator is operating normally has been recognized by many organizations worldwide. In a previous CIGRE paper [1] in 1992, preliminary experience in making on-line partial discharge (PD) measurements with a novel partial discharge sensor, known as the stator slot coupler (SSC), was reported. Over the past six years, over 250 installations of these sensors on generators in many countries has taken place. In situations where equipping a generator with SSCs has proved technically or economically unfeasible, an alternative coupler, which is installed in the bus, or on the cable, connecting the generator to the transformer, has been employed.

Data, obtained from on-line measurements in North America and Pacific Rim countries, using these techniques, is presented to illustrate specific cases and to assess their effectiveness. Included in the paper are the results of a study in which the data derived using the above methods is compared with PD information obtained using alternative off-line techniques. The correlation between the on-line PD data and off-line tests and inspections, including PD tests, is also discussed.

Keywords: Generator - Partial Discharge - Insulation - Maintenance - Condition Assessment.

1. INTRODUCTION

Worldwide, electric utilities are under increasing pressure to maximize the reliability and availability of generating equipment. Consequently, over the past decade there has been rapid growth in the introduction and development of diagnostic tools and decision support systems to aid utility maintenance personnel. In particular, over this period, there has been significant global activity in the field of partial discharge (PD) measurements [1 - 5], applied to rotating equipment. Partial discharge data can provide valuable information on stator winding insulation condition in high voltage rotating machines. The benefits of a PD test are maximized when the measurement is performed while the machine is operating normally. In recognition of this fact, Ontario Hydro has been performing periodic on-line PD testing on all generators rated 10 MVA and above since the mid-1950s. Up until the early 1980s, PD testing in all Ontario Hydro generating facilities was accomplished by means of temporarily installing, while the generator was operating, capacitive couplers at the potential transformer (PT) cubicles and observing, via a power frequency filter, the high frequency PD signals. From the early 1980s, PD testing of hydraulic generators was accomplished by means of capacitive couplers permanently installed in the circuit ring bus [6]. These couplers were monitored using an instrument known as the PDA (partial discharge analyzer). The principal benefit of this technology was that plant personnel could now perform the test because a) the live-line aspect of the test was eliminated and b) the method provided a means of rejecting most of the electrical noise associated with a test on an operating

Unfortunately, this technology could not be directly transferred to large steam turbine generators. Therefore, Ontario Hydro, with support from the Canadian Electricity Association, developed two alternative means of coupling PD signals from such machines. These methods have been described in detail elsewhere [7] and are outlined briefly below.

2. ON- LINE PARTIAL DISCHARGE TESTS FOR SMALL GENERATORS

The main difficulty in measuring PD on an operating machine is distinguishing PD originating in the winding from electrical noise. Experience has shown that on motors and small turbine generators, the noise originates principally in the power system, e.g., from corona on transformers and switchgear, from sparking at poor bus connections, and from other operating plant equipment such as power tools, thyristors, etc. Some of this noise is highly irregular and its magnitude can be many times higher than the PD signal from the winding, thus largely obscuring PD readings.

A method was developed for effective separation of such noise from stator winding PD. This technique is based upon permanently installed PD sensors; two high-voltage 80 pF capacitors per phase, six per machine, and a portable instrument known as the TGA-B (turbine generator analyzer - bus) [7]. Alternatively, couplers can be derived from the IPB support insulators by means of isolating the low voltage side of the insulator from the grounded sheath. In either case, the two couplers are located at least two metres apart, ideally with one coupler as close to the generator terminals as possible. Noise can be separated from winding PD by determining in which direction the pulse travels. If a pulse is detected first by the sensor closest to the machine winding, then it is counted as PD. Pulses that arrive at the coupler closer to the unit transformer first are designated noise. Any discharge activity occurring on the bus or cable between the sensors is also identified as noise.

The TGA-B instrument compares the pulse arrival times at the couplers and separates PD from noise on this basis. Plots of the number of positive and negative pulses repetition rate vs. pulse magnitudes for PD and for noise are generated automatically and stored on the instrument's hard drive. The data is available for immediate analysis or can be downloaded for a more detailed review.

Bus couplers have now been installed on over 600 machines worldwide, and the data base is expanding rapidly. It is now possible to collate the data in histograms of measured PD levels for various classes of machines. This information can be made available for comparisons and ranking of machines within a group of similar motors or generators.

3. STATOR SLOT COUPLERS (SSCs) FOR LARGE TURBINE GENERATORS

Large turbine generators, rated above approximately 100 MW and operating in hydrogen gas at elevated pressures, have significantly different noise sources. Measurements have shown that large amounts of PD-like pulses are generated within the stator core or enter the stator winding via the rotor circuit. Bouncing of the stator core on the keybars, back of core burning and inter-laminar short circuits produce pulses which are very similar to the winding PD. Brush sparking at rotor sliprings, or at the grounding brushes, and commutation transients from thyristor exciters or diode bridges, introduces high frequency noise to the stator winding via the rotor circuit. Experiments have shown [8] that it was not always possible to separate the stator winding insulation partial discharges from this noise by bus couplers installed in the buses which are outside the zone of internal noise sources. In addition, the hydrogen gas environment at elevated pressures largely reduces the magnitude of discharges in insulation voids. This reduces the signal-to-noise ratio and makes the separation of PD from noise even more difficult.

These considerations led to the development of a new sensor and a different method of PD detection [9]. The sensor, known as the stator slot coupler (SSC), is an ultrawide band antenna, installed on top of the stator winding bars, under the wedges, at the ends of core slots. This antenna detects any electrical signal in the frequency range of 10 MHz to 1000 MHz. From tests on operating generators, it has been determined that the winding PD pulses close to their origin are 2 to 6 ns wide and have a 1 to 2 ns risetime from this sensor. The noise pulses, having a similar shape and frequency at their origin, must travel some distance through the circuit ring, the endwinding, along the laminated core or through the rotor circuit. This relatively long propagation path broadens the width of these pulses beyond those of the winding PD occurring in the vicinity of the antennae. This difference in pulse width between PD and noise at the sensor locations, is the basis for separation of PD from internal and external noise sources.

A variant of the TGA instrument, known as the TGA-S, was developed to acquire the signals from the SSCs, determine their width, and count them as PD or noise. The SSCs have outputs from both ends, thus, the direction the pulse travels can also be determined by counting the pulse arrival times at each end. This permits separation of PD occurring in the slot section of bars from the surface discharges in the endwindings.

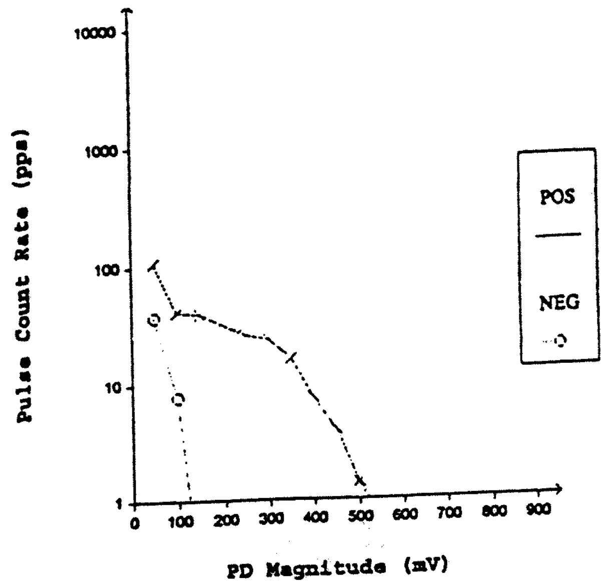
4 OVERVIEW OF UTILITY EXPERIENCE

4.1 Ontario Hydro

Commencing with a prototype installation on a 22 kV, 500 MW turbine generator in 1989, over 20 such machines have been equipped with SSCs to date. In addition, capacitive bus couplers were installed on four 22 kV, 1000 MW machines. Generally, each of these machines is tested once per year, although the frequency of test is increased if problems are suspected. The majority of generators tested within Ontario Hydro do not exhibit high levels of PD activity. On average, at any one time, only one, or two, machines, display PD levels which may cause concern. Hence, in this situation PD testing is beneficial because of the avoided costs associated with not performing unnecessary maintenance.

In some cases, capacitive couplers were temporarily installed at the PT terminals, facilitating comparison with SSC and bus coupler derived data. The former method, in use for 45 years, has proven effective and is used as a benchmark for other PD measurement tools. The results of this comparative testing have shown good correlation between the two on-line techniques. An example of data derived from SSCs installed on a twenty year old, 2 pole, 3600 r.p.m., 24 kV, 555.5 MVA machine with a liquid cooled stator and gas cooled rotor is illustrated in Figure 1. For brevity only the data for red phase are supplied. Significant PD is evident in the slot portion of the stator winding. The ratio of positive and negative PD pulses indicates some slot discharge activity. Winding slackness in the slots is a possible reason. Further investigation will be required to determine if the trend is increasing. Partial discharge magnitudes, recorded using the conventional method, indicate only moderate activity, however, because of the location of these couplers some attenuation of the high frequency PD signals will have occurred. Further, the high frequency characteristics of the SSCs render them very location sensitive. Consequently, the high magnitude, high frequency, signals observed in this particular slot will likely be heavily attenuated prior to being detected at the PT terminals of the machine.

Similar experiments were performed on four generators in a nuclear station. equipped with capacitive bus couplers. An example of the type of data obtained from these experiments is illustrated in Figure 2 and Table 2. For brevity, only red phase information is shown in Figure 2. For the particular data shown, the generators was operating at 21.3 kV, 917 MVA. This machine has been in operation for approximately five years and operates at a hydrogen gas pressure of 40 kPA. Consequently, the low, to non-existent, levels of PD recorded are not surprising.



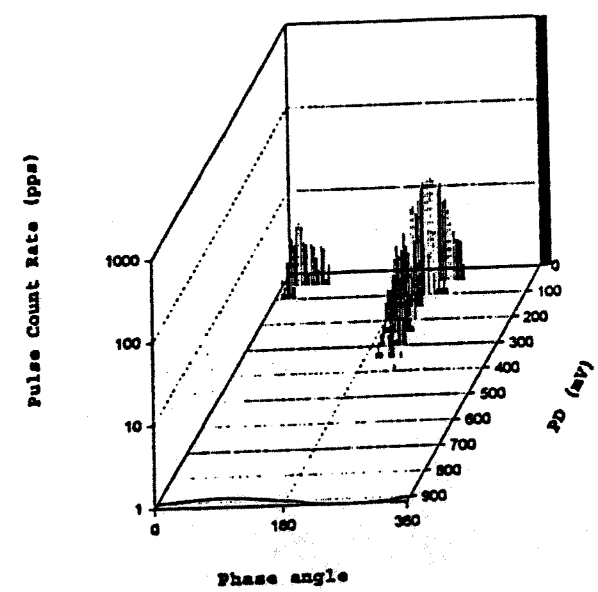
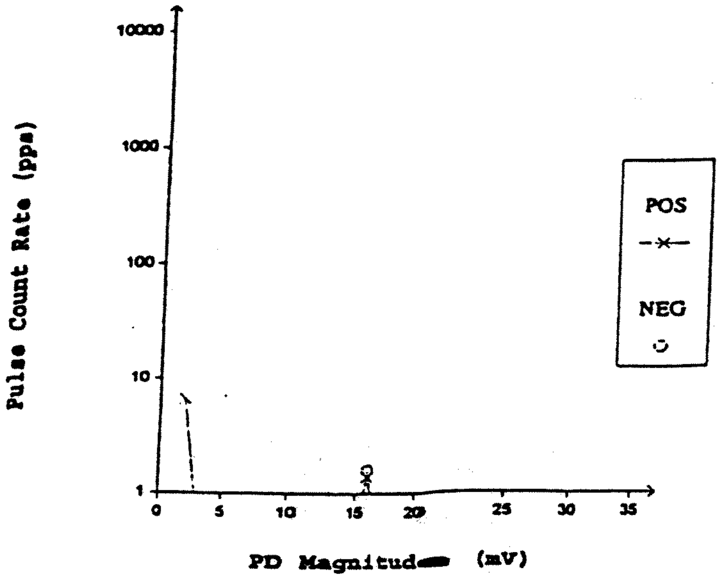


Figure 1: Pulse height and pulse phase plots obtained on a thermal generator operating at 24.7 kV, 509 MW, 136 MVAr. The winding exhibits PD behaviour which could be indicative of slot discharge.

Phase	PD Magnitude (mV)
Red	+70/-60
White	+60/-50
Blue	+70/-60

Table 1: On-line PD levels recorded on a thermal generator using conventional method



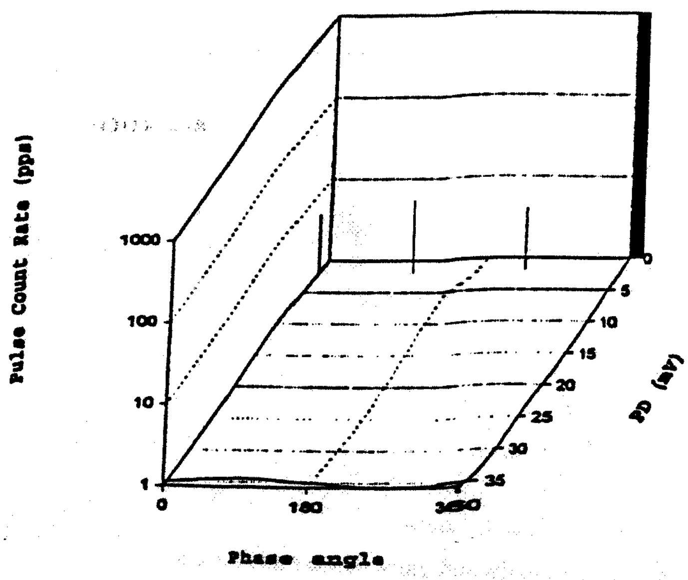


Figure 2: Pulse height (top) and pulse phase (bottom) PD plots obtained on a nuclear generator operating at 21.3 kV, 917 MW, -18 MVAr.

Phase	PD Magnitude (mV)
Red	±5
White	±5
Blue	+5/–10

Table 2: On-line PD levels recorded on a nuclear generator using conventional method

4.2 Kansas City Power & Light

In 1990, Kansas City Power & Light (KCPL) started a life assessment and management program with the assistance of an external body. This organization recommended rewind of a stator on the basis of tests indicating high winding resistance and low insulation resistance. The 170 MW generator was constructed in 1958 and the winding was insulated with an asphaltic-mica system. Further, in 1991 the OEM recommended rewind in 18 months, based on the winding failing a DC insulation resistance test. Consequently, a stator rewind was budgeted for 1999. In 1993 KCPL installed a PD monitoring system, based on SSCs. On the basis of a consistently low rate of PD and an acceptable DC insulation resistance test result in 1994, the stator rewind was removed from the budget.

A 1960s vintage generator of the same design and rating as the above generator in the same plant, was also recommended for a stator rewind in 2003, for the same reasons. Based on outage testing, which included an AC high potential test and on-line partial discharge measurements, plans to rewind this stator were cancelled. In addition, the generator maintenance outage was postponed for 3 years (from 1997 to 2000), based on winding diagnostic tests, including the on-line partial discharge test.

Favourable partial discharge test results led to a decision not to remove the rotor, and not to perform a high potential test on another generator in the same station during a 1996 unit outage.

In another KCPL generating facility, a 25 year old generator, rated at 700 MW, failed the AC high potential test, making it necessary to rewind a portion of one phase. This failure was found to be the result of slot discharge, since stator bar insulation had been abraded in the slot area. The damaged bars were removed, refurbished and re-installed. At this time, SSCs were installed in the stator winding for on-line PD monitoring. The post outage partial discharge tests indicated that the stator was in good condition and that there was little concern for the windings in the other two phases.

4.3 Florida Power & Light

In 1993 six SSCs were installed, two per phase, on the highest voltage bars at the exciter end of a 20 kV, 365MVA machine, placed in service in 1963. The stator insulation system is comprised of epoxy-mica blend. At the time of installation a thorough visual inspection of the generator stator was performed. The inspection revealed some greasing in the slot area migrating from under the wedge system. The first set of PD readings were taken one month after the unit returned to service. Two of the SSCs indicated very high levels of PD activity. Peak PD magnitudes were in the 3200 mV range. Investigation of the data and subsequent testing confirmed the high levels of PD. Florida Power & Light is considering several different options to reduce the PD level.

4.4 Pacific Power

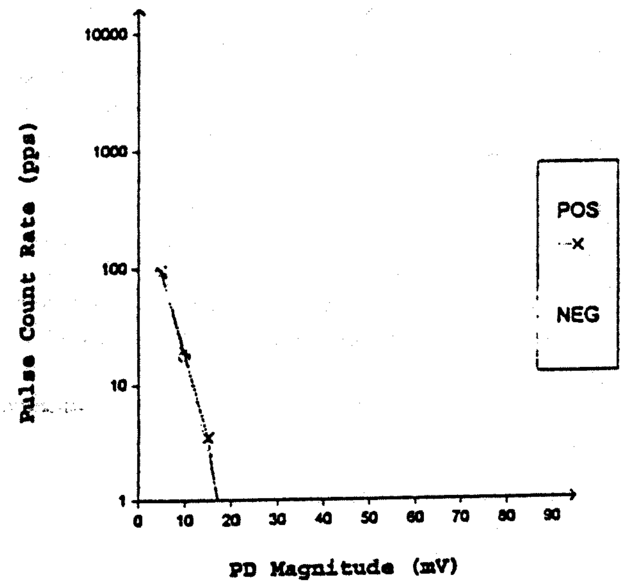
Stator slot couplers were installed on two 22 kV, 500 MW turbine generators in 1996. Both units have liquid-cooled stators and hydrogen-cooled rotors. However, one generator is four years older than the other with an asphaltic insulation system. The other unit possesses a hybrid epoxy-asphalt stator insulation. One of the generators is suffering from back of core burning. On this unit conventional off-line PD tests were made using a resonant transformer as a HV power source and an integrating-type discharge detector. Both terminals of the winding ,line and neutral end, under test were connected to the HV source while the other phases were grounded. The PD readings obtained were very high. However, because of the possibility that the high readings may be due to the voltage distribution in the winding [10] or resonances [11] and thus may not occur under normal operating conditions, the unit continued in service. Measurements subsequently made using the SSCs showed that, in operation, the PD activity was low and gave some confidence in the integrity of the insulation system.

During generator life extension work, with the rotor removed, some damage to the windings was found due to molten pellets of steel ,about 4-5 mm diameter, originating from back of core burning. The damage was close to the neutral end of the winding and thus were not detected by on-line TGA-S tests. Minor repairs to the insulation were carried out and no further off-line tests were made to date.

4.5 Hong Kong Electric Company

From 1994 to 1997, Hong Kong Electric installed SSCs on the generators in a thermal generating station. Five steam turbine generators and one gas turbine generator were equipped with SSCs. All the generators were manufactured by a Japanese OEM, except one which was manufactured in the UK. The ages of these generators range from 2 to 16 years. Partial discharge monitoring of the generators has been carried out every six months with the machines operating at full load. For the five hydrogen inner-cooled generators, the PD levels detected were basically very low. These results indicate that the stator insulation of these generators including the 16 year old winding is in good condition. This is consistent with the results of detailed visual inspection performed during a major maintenance

The direct liquid-cooled stator winding was carefully inspected at the time of SSC installation and no abnormalities were observed. at which time off-line PD tests were carried out Both off and on-line, Figure 3, tests indicated that minimal levels of PD activity were present in the winding. Overall, on-line PD tests indicated low levels of PD activity on these generators. These findings are consistent with other tests and inspections carried out on these stator windings. However, the data collected, so far, are limited and further monitoring is required. Additional off-line PD tests are planned to confirm the on-line PD measurements.



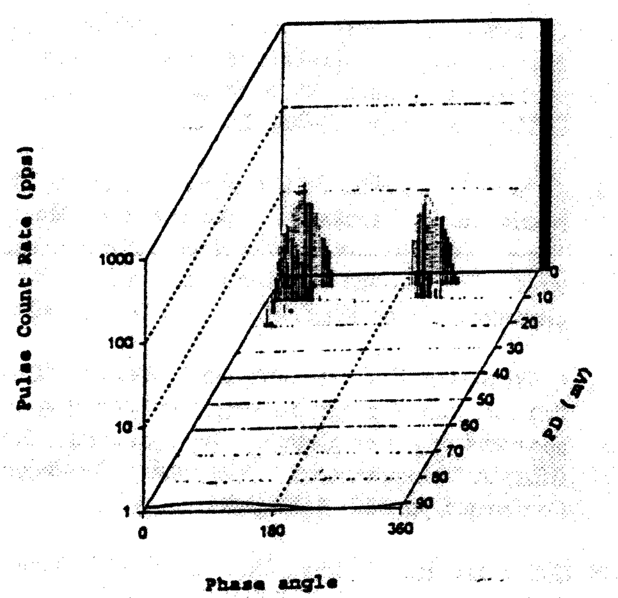


Figure 3: Pulse height (top) and pulse phase PD plots obtained on a thermal generator operating at 18.5 kV, 318 MW, 28 MVAr.

5 CONCLUSIONS

On-line partial discharge testing is a valuable tool for the assessment of the stator winding insulation condition in large generators and motors. The gradual aging of the insulation and most failure mechanisms can be identified early in their development for timely maintenance and repairs. Winding maintenance outages can be scheduled only on those machines which require it and when it is required.

Sensors and instruments are now available for on-line PD tests to be performed by plant personnel, at their convenience and without interruption of unit production. The data processing and results interpretation has been automated to the degree where very little specialist help may be required.

Users of such PD testing technology can derive significant maintenance cost savings. Winding replacements can be delayed or avoided, times between inspections and tests can be extended. Increasing confidence in the interpretation of PD results is helping users to justify the transition from preventive maintenance to lower cost condition-based maintenance.

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