TWENTY-FIVE YEARS OF EXPERIENCE WITH ON-LINE PARTIAL DISCHARGE TESTING OF STATOR WINDINGS

G.C. Stone, M. Sasic

Iris Power-Qualitrol, Canada

INTRODUCTION

Partial discharge (PD) testing has been used for many decades as a quality control test for the electrical insulation in high voltage electrical apparatus such as cables, switchgear, transformers and rotating machine stator windings. PD testing is also used on-site (i.e., at the plant where the HV equipment has been installed) as an off-line test to determine if insulation problems are developing in this equipment during service. Now it is becoming more common for on-line PD monitoring to detect insulation deterioration due to ageing in service [1].

On-line PD monitoring was perhaps first applied to motor and generator stator windings when Johnson used high frequency current transformers (HFCTs) and capacitive couplers to detect the PD during normal generator operation in the late 1940s [2]. Shortly after, some large OEMs and a few utilities introduced their own version of the on-line PD test for rotating machines [3, 4]. These tests seemed to be particularly good at detecting problems, such as loose coils in the stator slots (which lead to groundwall insulation abrasion) and delamination of the insulation caused by long duration operation at high temperatures. The early versions of the on-line PD test for stator windings required significant skill on the part of the test technician to distinguish stator winding PD from other pulse-like signals due to interference. Such interference may be caused by power line corona, electrostatic precipitators, poor electrical connections elsewhere in the plant, power tool operation, variable speed drives, etc. Of course, if this interference is misdiagnosed as stator PD by the technician, a false indication of the condition of the stator insulation may result.

In 1976, the Canadian Electrical Association (CEA) initiated a research contract to develop an on-line PD test for stator windings that was less subjective than the tests existing at the time. This led to what are now called the PDA and TGA tests, which have been deployed on more than 12,000 motors and generators around the world since the commercial introduction of the PDA in 1986. This paper reviews the basic principles of these on-line tests and discusses its advantages and limitations. Recent progress in on-line PD test result interpretation is also presented.

HISTORY OF THE UTILITY RESEARCH PROJECT FOR ON-LINE PD DETECTION

The CEA, representing most electric generating companies in Canada, decided in 1976 to fund a research project to develop an on-line PD test for hydrogenerator stators that could be performed and interpreted by utility personnel. The motivation was to reduce test costs since utility personnel would do the tests instead of external experts. In addition, the utilities could determine the PD activity free of any perceived conflict of interest that some test service providers may have attributed to the severity of the PD. The Research Division of Ontario Hydro (the largest utility in North America at the time) submitted a proposal to do the research based on finding ways to separate the stator PD from all other signals (noise). A contract was awarded, with Mr. Mo Kurtz as project leader. Dr. Ray Bartnikas (Hydro Quebec), Mr. Richard Huber (BC Hydro) and Mr. Bill McDermid (Manitoba Hydro) were the external advisors. As discussed later, key outcomes from the research were:

- a low capacitance PD sensor (or coupler) made from a short length of power cable that is permanently connected to the stator winding (Figure 1);
- a differential method to separate PD from noise; and
- analog/digital instrumentation (called the Partial Discharge Analyzer or PDA) to record the PD pulse magnitude and repetition rate.

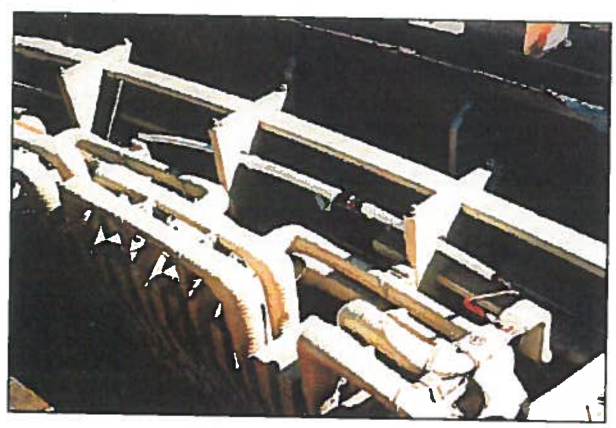

Figure 1 A photograph of an 80 pF "cable-type" coupler (in the process of being installed) that was widely used in the 1980s to detect the PD on hydrogenerators.

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The method depended on the sensors and instrumentation working in what is now called the very high frequency (VHF) range, 30 to 300 MHz, which was radically different from the low frequency range (up to 3 MHz) which was typical of IEC 60270 style PD detectors in common use at the time. The research project resulted in prototype instruments that were used in the early 1980s by several Canadian utilities who installed the necessary capacitive couplers. In 1986, the technology was formally licensed by Ontario Hydro and CEA to FES International, a fore-runner of Adwel, which later merged with Iris Power Engineering.

After the initial development of the on-line test for hydrogenerator stators, CEA extended the research contract to develop a less-subjective PD test for motors and turbine generators (TGs). The method developed for hydrogenerators was not directly applicable to motors and TGs since there was insufficient space within the stator for the sensors, and also because the minimum required circuit ring bus lengths (see below) were not present in most motors and TGs. This lead to the development of the "directional bus coupler" method using sensors installed exterior to the machine, and an instrument that was called a turbine generator analyzer or TGA.

Extensive evaluation of this method with many dozens of installations in the 1980s showed that this approach was flawed for large hydrogen-cooled TGs. Specifically, if there was contact sparking within the generator, for example from an untorqued, oxidized bolt on the flexible connections at the generator bushing, which is generally harmless, it could be misdiagnosed as stator insulation PD. This lead to the development of a special antenna called the stator slot coupler (SSC) that worked in the VHF and UHF range. The TGA instrument together with capacitive "bus" couplers and the SSCs were commercialized via a new company called Iris Power Engineering in 1990.

Several developments occurred in the 1990s. One was the creation of the "epoxy mica coupler" or EMC as an alternative to the cable-type coupler. With partial sponsorship from the New York Power Authority (NYPA) and the Electric Power Research Institute (EPRI), continuous PD monitoring systems were introduced in 1994.

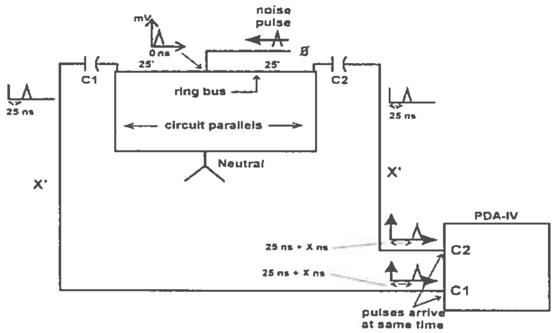
By 2011, 25 years after the first commercialization of the PDA technology, the test has been implemented by utility owners around the world. Canada and the USA were earlier adopters but so were Brazil and the UK. Now most developed countries are using PDA or TGA.

HYDROGENERATOR PD TESTING AND MONITORING

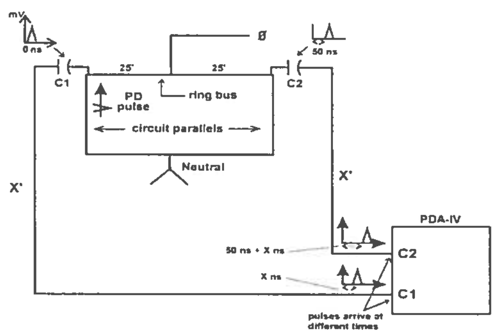
As mentioned previously, there were three key technical developments that occurred to make the PDA test for hydrogenerators practical. The following discusses the most important developments (and ignores many less critical details and "dead ends" that were not used in the long run).

Until the development of the PDA test, the most common sensors used to detect PD in stator windings were either HFCTs on the connection between the stator neutral and the neutral grounding transformer or a capacitor on the output terminals, typically in the 1000 pF range. These systems worked in what is now called the low frequency (LF) range, usually <1 MHz. The availability of 100 MHz, single shot analog storage scopes, such as the Tektronix 466, in the mid 1970s led to the realization that PD pulse risetimes in air at atmospheric pressure were only a few nanoseconds, and thus had Fourier frequency components >100 MHz. In addition, using RF radio receivers, it was found that most of the RF "noise" in the hydro plants due to static exciters, power line carrier, power tool operation, etc. produced frequencies <10 MHz. Thus to optimize the PD signal to power station noise ratio (SNR) and hence to reduce the risk of false indications, the decision was made to use a measurement frequency range of about 40 MHz and above. This had the advantage that the capacitance of a coupler at the high voltage terminal could be small, which meant a physically smaller capacitor. After experimentation using the centre conductor of a power cable as the high voltage plate of a capacitor and the cable shield as the low voltage plate, an 80 pF coupler was settled upon. When feeding a 50Ω coaxial cable, this resulted in a lower cutoff frequency of 40 MHz. Measuring frequencies >40 MHz was very unusual at the time. As discussed in IEEE 1434 and IEC 60034-27-2, the use of the very high frequency (VHF) range for PD detection has a limitation however, since it means that PD occurring far from the machine terminals, where the PD sensor is located, may not be detected [5].

Another innovation was to separate PD from power system noise using two sensors per phase and the fact that pulses take time to travel in the winding. To use this "time of flight" noise separation method, the couplers are installed normally at the end of the stator circuit ring bus, where the bus is connected to a parallel circuit of coils (Figure 2). The velocity of electrical pulse propagation along the circuit ring bus is close to the speed of light, 300,000 km/second. The basic concept is that if an electrical noise pulse is coming from the power system (Figure 2a), it will enter the circuit ring bus, split at the bus and propagate in both directions. If the circuit ring bus is the same length both to the left and to the right of the terminals (which is actually rarely the case), the noise pulse will arrive at the C1 and C2 couplers at the same time and, if the coaxial cables are the same length, the noise pulse will appear at the two PDA instrument inputs at the same time. In older PDAs, there was an analog differential circuit that subtracted the signals from one another. Since the pulses arrive at the same time and have the same magnitude, the output of the differential circuit would be zero, and the noise would not be counted. Conversely, if PD was occurring in a coil close to the C1 coupler (Figure 2b), the PD pulse would first arrive at the C1 coupler, but would take some time (50 ns in the example) to travel along the circuit ring bus to C2. Thus there would be a net output from the PDA differential circuit, since the pulse arrives at C1 well before it arrives at C2. Early technical papers on this method of noise separation are in references [6-8].



(a)



(b)

Figure 2 Schematic showing one phase of the stator winding which has two parallels (of several coils connected in series). (a) shows the response due to noise and (b) the response due to PD in a coil located in parallel 1.

The time of flight method only suppressed noise from the power system. It did not suppress noise that may come from the rotor winding. Specifically, many rotors obtain their DC current via slip rings and it is common for the carbon brushes to have sparking to the slip ring. This sparking signal can cross-couple from the rotor to the stator winding and be confused with stator PD. This problem was circumvented by noting that the slip ring sparking signal, once it is coupled into the stator, has a very slow risetime, usually much longer than 10 ns. Using the concept of pulse shape analysis, if the pulse risetime detected at the coupler was too long, the pulse is classed as being from noise [9].

The final innovation was to record the PD signals digitally rather than on an oscilloscope, using a pulse magnitude analyzer. This followed the development of similar circuitry by Bartnikas for research applications [10].

After the initial developments resulted in a commercial test, additional work was carried out over subsequent years to further improve the practicality of the test. Some of these developments included:

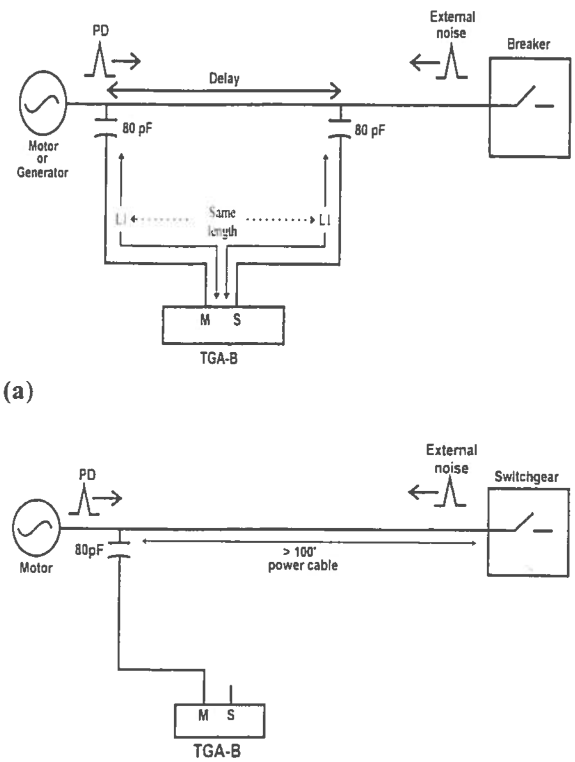
- Replacing the analog differential circuit with digital circuitry that only required the noise pulses to arrive at the same time yet allow for significant mismatches in magnitude and ringing characteristics.
- The introduction of phase resolved pulse magnitude analysis, sometimes also called pulse phase analysis, following on the work by Kelen in research applications [11]. This enabled PD to be displayed with respect to the 50 or 60 Hz AC cycle. As discussed later, this display method can sometimes be used to identify the root cause of the PD, and hence the failure process.
- The use of mica splittings as the dielectric in the PD sensor, as opposed to XLPE cable insulation. Such epoxy mica PD sensors were much more compact and easier to install than the cable-type variety.
- The application of modern computer and communications technology to enable continuous monitoring of the PD. This facilitated observing the PD remotely. This has turned out to be especially useful for hydro plants that are remotely operated or located far from utility engineering offices [12].

MOTOR AND TURBINE GENERATOR PD TESTING AND MONITORING

Since capacitive couplers could usually not be installed within a turbine generator or motor, the sensors were installed at the terminals [13]. To separate stator PD from external noise pulses, two couplers per phase were installed on turbine generators (Figure 3a). Pulses from the power system arrive at the S sensor before traveling to the M sensor. Conversely, stator PD arrives at the M sensor before it arrives at the S sensor. A digital decoder then identifies the source of the signal based on the difference in travel time along the bus. Since the risetime of the PD pulse is a few nanoseconds, the two sensors must be separated by more than 2 m (or 6 ns) in order to ensure reliable identification of which pulse arrived first.

Early attempts to use this approach with motors revealed that it was often possible to discard the second sensor, as long as the motor was connected to the power system by a PD-free power cable longer than 30m. Short risetime noise pulses propagating through a sufficiently long power cable undergo dispersion, which effectively lengthens the pulse risetime. An instrument that measures the risetime of each pulse can thus discriminate between power system noise and the stator PD, which does not see significant dispersion [9].

As mentioned above, the use of capacitive sensors led to false positive indications of stator PD in large hydrogen-cooled TGs. Sparking from electrical contacts either in the stator core or from an oxidized bolt at the gas seal bushing would come from the stator and have the necessary short risetime to be classed (erroneously) as stator PD. This lead to the SSC which is installed in stator slots that contain stator bars operating at or near terminal voltage. A bar in a stator slot has a well-defined characteristic (surge) impedance (20 to 30ohms) and PD within the same slot is detected as a symmetrical, non-oscillating pulse with a risetime of 1 ns or less (PD in high pressure gas tends to have a shorter risetime than PD at atmospheric pressure). Noise, due to sparking from the stator terminals, travels through a complex path with many impedance mismatches, which results in pulses that have a longer risetime and/or are oscillatory due to many reflections. Thus a customized instrument called the TGA-S separates stator bar PD from noise based on the pulse shape [13]. Note that PD from a different slot also sees many impedance mismatches, which causes reflections as it propagates to a slot with the SSC. Thus PD in other slots is classified (erroneously) as noise. Stator PD is only correctly identified as PD if it is in the same slot that contains an SSC. SSCs have been installed on over 1000 large hydrogen-cooled TGs due to their immunity to all types of noise.



(a)

(b)

Figure 3 (a) Separation of PD from external noise using two sensors per phase and the time of flight. (b) shows the use of a single sensor per phase to separate PD from external noise if the stator is separated from the power system by 30 m or more of power cable.

KEY DEVELOPMENTS FOR PD INTERPRETATION

Perhaps the biggest challenge in on-line PD testing of machines is to extract useful and reliable information from an on-line PD test to facilitate meaningful stator winding maintenance decisions. It is now clear that there are two distinct steps to PD interpretation: determining which stators have insulation problems and then, for those machines with issues, what is the root cause. The latter step determines how fast action must be taken (since some failure processes are slow and some are fast), as well as determining what the repair options are (for example, cleaning vs. rewedging vs. rewinding).

For the first step, even the earliest users of on-line PD testing, employed the trend over time as a basis for deciding what machines need maintenance. A machine where the PD was doubling in magnitude every year or so was most in need of maintenance. However, this simple rule is sometimes flawed, since it seems that after a dramatic increase, a significantly aged stator winding will no longer produce increases in PD magnitude, even though aging continues and eventually machine failure ensues. That is, the PD may level off or sometimes even decrease (Figure 4). There are several possible explanations for this leveling off, including:

- Accumulated space charge in voids which make void surfaces conductive enough that it reduces the electric field within the void to suppress subsequent PD;
- PD attack of the organic binder may produce enough conductive material within groundwall voids that the internal field suppresses future PD activity;
- Voids do not grow indefinitely in size due to the taped structure of the groundwall and the use of mica;
- In coils and bars that are loose in the slot, the abrasion of the graphite together with oil may reduce the electric field between the bar/coil and the stator core enough to suppress PD, even though erosion of the bar/coil continues;
- Endwindings may become conductive enough due to contamination that grades the electric field sufficiently to suppress PD.

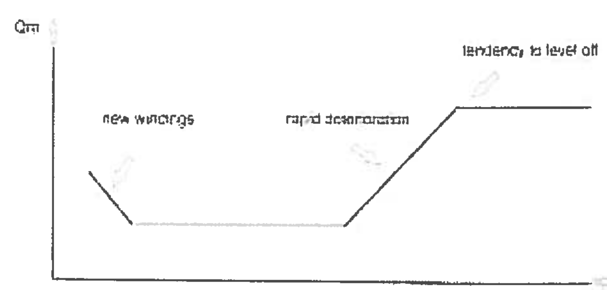


Figure 4 Typical trend in stator PD over a stator's lifetime.

To overcome the limitation in PD trending, Warren published another method to rank the need for stator maintenance [14, 15]. She assembled all the PD data collected using the PDA and TGA methods into a single database, found the statistical distribution of the peak PD magnitudes (mean and standard deviation), and determined which parameters had a statistically significant influence on the distribution. The operating voltage and the hydrogen pressure (if relevant) of the machine had the most profound effect on the PD distribution, whereas power rating and insulation type (i.e. asphalt, polyester or epoxy resin) had almost no effect. When the statistical distributions for each voltage class were compared with the actual condition of the stator windings as determined by a visual examination of the winding, if the PD was higher than 90% of other machines, then there was a very high probability that a significant insulation problem would be found. The result is a table of "high PD" or "Alert" levels, depending on operating voltage. The latest example is shown in Table 1 for hydrogenerator windings, which is based on data from thousands of machines and over 270,000 test results using portable instruments.

TABLE 1 High PD levels (Qm) for hydrogenerators using 80 pF couplers mounted within the stator windings. Qm is the IEC standard term for peak PD magnitude at a PD pulse repetition rate of 10 pps.

Voltage Class (kV)	PD Magnitude (mV)
6-9	236
10-12	229
13-15	372
16-18	588

Progress has been made in identifying the cause of PD. Some of the advancements that have been made include:

- Recognition that the well-known polarity effect, which can help determine if the PD is on the coil surface or within the groundwall, is only effective if the PD is occurring in the slot [16].
- Confirmation that the effect of load and temperature on the PD can be used to identify loose windings, stress relief coating deterioration and thermal aging, as long as only one process is occurring [7]. This has been augmented by the humidity effect, where PD occurring on the surface of endwindings will increase as the humidity decreases [17].
- Development of three-phase plots that are phase shifted from one-another by 120 degrees (Figure 5) to determine what PD is driven by the phase to ground voltage (in the slot) or caused by PD in the endwinding resulting from phase to phase stress [15].

Reliably identifying the cause of any high PD can still be frustrating, especially on older machines where multiple deterioration processes may be occurring.

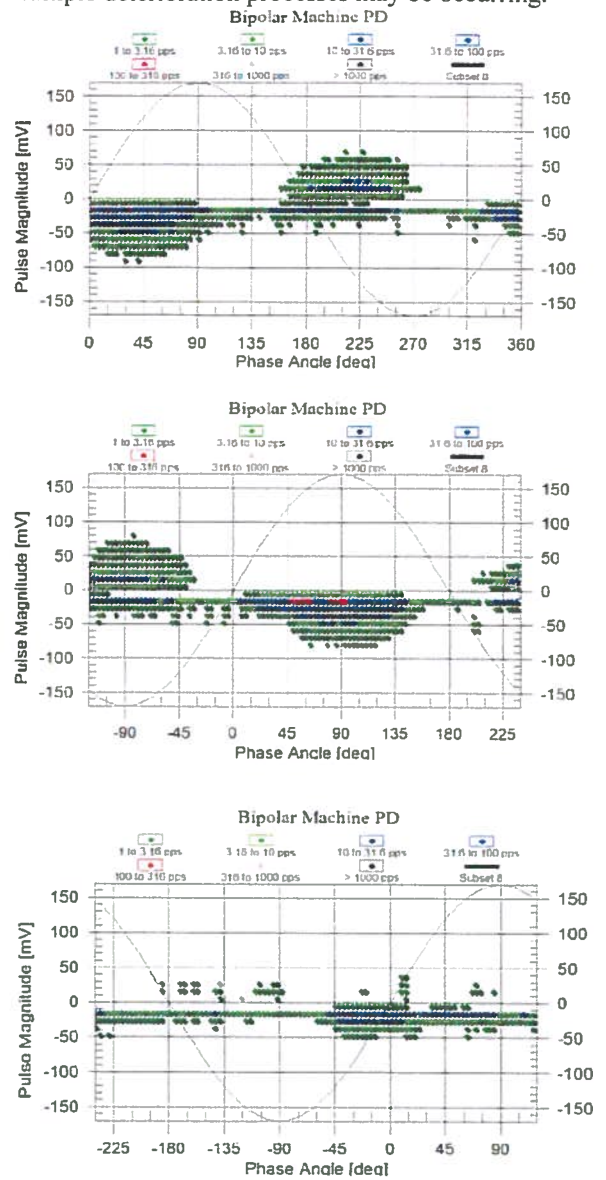


Figure 5 Plot of PD in each phase, with each phase displaced from each other by +/-120 degrees. Thus a vertical line drawn between the three plots indicate activity at the same time. The plots show the PD in phases A and B (top and middle plots) are due to A phase to B phase PD in the endwinding [16]. The activity on C phase (bottom plot) is cross-coupled from phases A and B. The vertical scale is the PD activity in mV and the horizontal scale is the 60 Hz AC phase angle.

CONCLUSIONS

All diagnostic technologies have weaknesses, and on-line PDA and TGA testing is no exception. The following are some limitations of the test that have been found over the past 25 years:

- On-line PD testing cannot provide an estimate of the remaining life of the stator winding insulation. It merely identifies which machines have serious insulation problems, and sometimes what the mechanism is. A careful visual examination of the stator by a knowledgeable expert is needed to assess the risk of winding failure.

- False indications will still occur due to noise, no matter how sophisticated the noise separation method. Even with the three noise separation methods described above, the false positive indication rate of the test is about 1.5%. Achieving this low rate depends on the optimum installation of the couplers to reduce the effect of noise.
- If multiple failure processes are simultaneously occurring on the same winding, even experts will disagree on which is the most important (life limiting) process.
- If there is a significant insulation problem on a coil that is not operating at or near high voltage, then such problems may not cause PD (since the operating voltage at that point may be too low), even though a voltage transient can still cause that point to fail.

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