A Perspective on Online Partial Discharge Monitoring for Assessment of the Condition of Rotating Machine Stator Winding Insulation

Key words: partial discharge, online, condition assessment, stator winding insulation

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Introduction

Partial discharges (PD) are small electrical sparks that can occur in liquid or solid insulation systems in high-voltage equipment, and can eventually cause failure of the equipment [1]–[3]. Partial discharge testing has been used for more than 80 years as a factory quality control tool to find manufacturing defects that could eventually lead to equipment failure. We believe that Johnson was the first to measure PD on operating high-voltage equipment, in the 1940s [4]. His aim was to find an online method to determine whether stator winding coils or bars were vibrating excessively in the stator magnetic core. These vibrating coils lead to abrasion of the high-voltage electrical insulation and to eventual failure. A symptom of the insulation abrasion process was that PD (or what he referred to as slot discharge) occurred between the surface of the coil and the stator core. By measuring the PD online, he could indirectly detect the movement of coils, which indicated that failure was likely. The measurement had to be made online because, if the generator were not operating, no magnetic forces would be acting on the coils; thus, the air gaps that are a necessary precursor of PD would not be as large. Johnson was successful in identifying those generators that were suffering the most from this problem, which was caused by the introduction of the first thermoset insulation systems and by workmanship variations that were magnified by an inadequate method of securing the coils in the stator slots for the novel insulation system. The success of the Johnson online PD measuring system inspired other machine manufacturers and even a few utilities to develop their own methods [5], [6].

Online partial discharge testing, after a rocky start 60 years ago, has become a widely used method of assessing the condition of high-voltage stator winding insulation.

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The main reason Johnson needed online PD measurement was that loose windings do not produce as much PD when the motor or generator is not operating. Thus one of the important reasons for performing online PD tests is to monitor the condition of the equipment under normal operating electrical, thermal, and mechanical stresses. However, with the current emphasis on extending times between maintenance outages, and the push to reduce testing costs in general, the main reason now given for online PD measurement is to avoid shutdown of the equipment, which would be necessary for an off-line PD test or other diagnostic test. Although we believe online PD monitoring was first applied to rotating machines, the same reasons are valid for other electrical equipment, such as oil paper cable joints or terminations, distribution class switchgear, gas-insulated switchgear, and power transformers [2], [3].

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Given its introduction more than 60 years ago, the application of online PD monitoring has not been as smooth or as widespread as one would have expected. Various issues, both technical and nontechnical, intervened so that only in the past 20 years has online PD monitoring been accepted to some degree as a legitimate, reliable method to assess the condition of stator winding insulation. This paper presents an overview of the problems that tended to retard the widespread application of online PD. It also summarizes the present state of the art and speculates on innovations that may occur in the future. Although the main focus is stator windings, some of the lessons learned in that context may be applicable to other types of electrical equipment for which online PD may be appropriate. Only the electrical measurement of PD is considered in this paper.

Initial Online Methods

An online PD monitoring system must have the following components:

- a sensor to detect the PD current and convert it to a voltage;
- instrumentation to characterize the PD signals, including determining the number of PD events, their magnitude, polarity, and AC phase position (the instrumentation may also help to distinguish PD from electrical noise); and
- software, a human being, or both to convert the PD data into information about the condition of the insulation system.

The first online system developed by Johnson detected the PD signal as a voltage across a neutral grounding resistor at the neutral point of a three-phase stator winding [4]. A narrow band filter and an oscilloscope were then used to display the PD. Looking at the pattern displayed on the oscilloscope, Johnson then used his experience to distinguish between PD and electrical noise. Comparing the PD levels from eight similar machines, he was able to determine the windings showing the highest slot discharge [4].

Shortly after Johnson's paper was published in 1951, other similar test methods were introduced [5], [6]. The use of capacitive sensors at each phase terminal of the stator winding became popular [6]. The advantage of using a capacitor to detect the high-frequency PD signals, while simultaneously blocking the 50- or 60-Hz high voltage, was that the PD signals could be displayed against the 50- or 60-Hz AC cycle. This helped to ensure that the recorded signals were PD and not noise. In addition, the phase with the highest PD could be identified. Regrettably, it was not possible to record the PD accurately by using the technology of the 1950s and 1960s. Even high-speed photographic film could not record the peak magnitude of the very short PD pulses displayed on an oscilloscope screen [5]. The early results were very subjective, not only because judgment was needed to differentiate between electrical noise and PD, but also because the PD magnitudes and repetition rates could be estimated only by the human eye.

In the 1970s, Bartnikas introduced the pulse magnitude analyzer, which digitally recorded the number of pulses and their magnitudes [7]. Kelen then added the digital recording of the PD pulses with respect to the AC phase, which Fruth later called phase-resolved pulse magnitude analysis (PRPMA or PRPD) [8], [9].

Difficulties caused by electrical noise also began to be addressed in the 1970s. Electrical noise may have many sources, such as poor electrical contacts, substation corona, and power tool operation, among others. The noise signals were often of higher magnitude than stator PD. Until the 1970s, the main methods of separating PD from noise used filters to select a frequency that maximized the PD signal-to-noise ratio, and relied on the skill of the observer looking at the oscilloscope screen. The online PD monitoring systems in use until the mid-1970s were limited to the frequency range from about 5 kHz to a few MHz by the available electronics [5]–[7].

Credibility Issues with Online PD of Stator Windings

Until the end of the 1970s, online PD monitoring was available from only a few major machine manufacturers and was routinely used by only a few utilities, such as Ontario Hydro, the Tennessee Valley Authority, and the Central Electricity Generating Board. There are many reasons why it was not widely used, the main one being that the results lacked credibility; i.e., users were not convinced that an online test would give an accurate indication of the stator winding insulation condition. More specifically, there was a high risk of false positive or false negative indications. False positive means that the test suggests there are insulation problems, but when the winding is visually examined, no problems are found. False negative means that the test suggests there is no insulation problem, when in fact the winding fails because of the insulation, or a serious insulation problem is found when the winding is visually examined. The false indication rate was such that an Electric Power Research Institute project manager suggested in the early 1990s that online PD testing was "black magic." This viewpoint was widely held by many utility maintenance engineers because of bad experiences with the technique. There were many specific reasons for this lack of credibility, as described below.

Noise

Noise has been a vexatious problem for all online PD monitoring, leading to many false positives. As stated above, the early noise reduction methods relied on selection of the best detection frequency, as well as the skill and experience of the person doing the test. Because not all test providers were equally experienced, false positive indications resulted owing to electrical noise being classified as PD. Such false positives are expensive because, after a diagnosis of high online PD activity, a machine is normally shut down for off-line tests and inspections. These are costly, and additional cost is incurred because of lost production. It is no wonder that plant managers were skeptical of the value of online test results. Perhaps the greatest advancement in the application of online PD monitoring came with the development of numerous noise separation methods, as discussed later.

Overclaiming

Another cause of poor credibility was the ambitious claims of effectiveness that many researchers and vendors made for their online PD monitors. It is human nature to claim that a technology is successful when only a few correct diagnoses have been made. However, such diagnoses may have been made under limited circumstances; e.g., the noise in the tested machines may have been relatively benign. The only way to overcome this problem is to ensure that any monitoring system is evaluated on many machines in widely different plants. Blind testing, as mandated for new pharmaceuticals, would also be helpful.

Another cause of overclaiming is that researchers and vendors sometimes give the impression that online PD monitoring can detect all insulation problems. Thus when equipment failure occurs without warning from the PD monitor, users believe that the PD monitoring system is not useful simply because of this false negative. Researchers need to know a) which failure mechanisms are due to PD, b) of which failure mechanisms PD is a symptom, and c) of which failure mechanisms PD is neither a cause nor a symptom. Thus end-winding vibration is an important stator winding failure process that does not produce PD. If a generator fails because of end-winding vibration but the plant manager believes his or her stator is in good condition because the PD level is low, then he may become disillusioned by the online PD monitor unless the vendor has clearly indicated that certain problems will not be detected by the monitor.

Unreliable "High-PD" Indicators

Most online PD monitoring systems rely on trends in the PD level over time or on tables of what constitutes a high PD level, or both, to determine which stator windings need maintenance. If the interpretation rules are incorrect, false positives or false negatives can result. Note that stator winding insulation is a composite organic and inorganic system. The mica used in most modern stator winding insulation systems provides a high degree of PD resistance. In fact, some PD occurs in almost all stators rated 6 kV or more, but they can endure low-level PD for many decades before failure. This is in contrast to almost all other electrical equipment in which purely organic insulation is used, e.g., oil, paper, epoxy, polyethylene, which is much less resistant to PD. Thus interpretation of PD levels and trends may be completely different for stator windings than for all other types of equipment.

Typically, the trend in PD over time has been the most powerful method of identifying windings with insulation problems [10], [11]. The rule of thumb used for decades was that if the PD magnitude or some other PD quantity [such as integrated charge, quadratic rate, normalized quantity number (NQN), etc.] doubled every year or so, then the winding was at great risk of failure. Regrettably, this simple rule can yield false positives and false negatives. If the PD activity is very low, the doubling rule may yield false positives because a visual examination of the winding may not show any problem or, more correctly, the PD is so low that the cause of the PD cannot be found. Conversely, it is

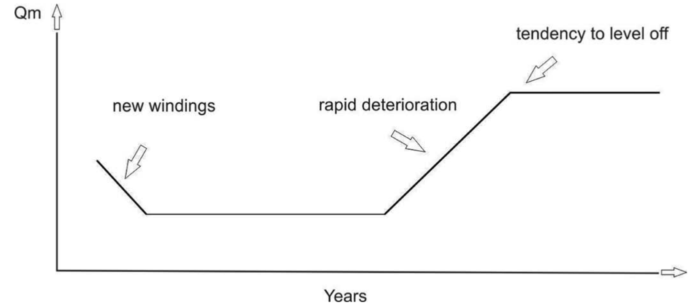

Figure 1. Typical trend in partial discharge (PD) over time for stator windings.

now very clear that PD does not continue to increase until failure occurs in stator windings. Rather, it seems that it increases to a certain point and then levels off (Figure 1). Presumably this leveling off occurs because

- space charge can influence the PD intensity,
- voids do not grow indefinitely in a taped insulation structure,
- mica is very PD resistant, and
- PD is often a symptom of a thermal or mechanical problem with the insulation, not the actual cause of failure.

The result is that even though the PD intensity may be high, it is stable with time. If the plant manager begins monitoring the stator PD once it is in this high but stable mode, he or she may feel the winding is not at risk. If failure then occurs, there is a perception that the monitoring yielded a false negative.

Although high PD levels are not mentioned in any of the IEEE and IEC stator winding PD standards, at least one organization has published them, and many machine manufacturers providing PD test services will indicate when a measurement is high for the relevant insulation system [11], [12]. These high levels are established by comparison and are valid only when the same measuring system is used. Experience has shown that machines of different voltage ratings and different hydrogen pressures will have different high PD level indicators [13]; i.e., one level is not suitable for all stators. The high PD levels also need to be validated by comparison with the actual condition of the winding as determined by a visual examination.

Sensor Reliability

Online PD is performed to prevent stator winding insulation failure. If a PD sensor causes a machine fault, this will certainly lower the credibility of the test. The sensors most likely to cause a machine failure are capacitive couplers, because they are normally connected to the high-voltage machine terminals. Capacitors are, by a very large margin, the most widely applied PD sensors. Vendors have worked hard to produce sensors that are very unlikely to fail in service. The recently published IEC 60034-27-2 standard requires the sensors to be PD free at twice the working voltage, have temperature-stable capacitances and dissipation factors, and pass the same voltage endurance tests as stator windings [11].

Remaining Life

In the past, some researchers, vendors, or both have claimed that, using the measured PD data, the time to failure of a winding can be predicted with some accuracy. No objective evidence exists to support this claim. However, utility managers would like to be able to predict when a motor or generator should come out of service, and therefore would like to believe a vendor who says he or she can predict time to failure. When such predictions prove erroneous, as they inevitably do after several years, the credibility of all researchers and vendors providing PD monitoring is reduced.

Incorrect Failure Mechanism Identification

Stator windings have a dozen different failure mechanisms of which PD is a symptom or a cause [10], [11]. For 30 years, PD testing has been used to help identify the cause of a stator winding failure [10], [11], [14]. Knowing the failure mechanism is useful because it defines the repair options and may also yield an indication of the time available for corrective repairs (some failure processes are fast and others are slow). As discussed later, many methods have been developed to identify the failure mechanism based on PRPD patterns or the effect of machine operating conditions on PD activity, or both. It is regretful that sometimes a winding is correctly assessed as having insulation problems because of the PD level or its rate of increase, but the wrong mechanism is identified. This means the wrong repairs may be scheduled. Plant managers tend to regard such incorrect identifications as proof of the unreliability of the online PD monitor.

Present Status

The credibility of online PD testing has steadily increased from its initial development for rotating machines up to the present day. Routine online PD testing is now carried out on more than 12,000 motors and generators, to provide early warning of developing insulation problems. In North America, we estimate >75% of utility generators (rated >20 MVA) are tested in this way. Thus online PD has become a mainstream condition-based maintenance tool for stator windings. The innovations that have led to a high level of acceptance include better noise suppression methods, more reliable means for determining the severity of the PD, and better methods for identifying failure mechanisms.

Noise Suppression

Selecting the optimal PD detection frequency is the most popular method used to reduce the impact of electrical noise. As is the case for transformers and gas insulated switchgear, the VHF (30- to 300-MHz) and UHF (300- to 3000-MHz) frequency bands provide greater noise suppression [11], [15], [16]. However, the use of these frequency ranges results in less sensitivity to PD sources located far from the PD sensors. Other methods of noise suppression include

- time of PD and noise pulse travel between a pair of PD sensors [10]–[12];
- pulse shape analysis; i.e., pulses having certain rise times and ringing characteristics are more likely to be due to PD than to noise [11], [12], [17];
- time-frequency plots [11], [18], in which noise and PD may appear as clusters of pulses in different regions of plots of pulse time versus pulse frequency; and
- signal processing using the wavelet “denoising” method [19].

Although a single noise suppression technique is unlikely to suppress all sparking or discharging noise, two or more may reduce the false positive indication rate to levels such that loss of confidence is not severe. One vendor claims a false positive rate of 1.5% for concurrent use of the VHF frequency range, pulse shape analysis, and the time-of-flight method [12].

Identifying Deteriorated Winding Insulation

For many decades, laboratory or factory PD measurements were expressed in picocoulomb (pC) units, using what is now known as a low-frequency PD detector, which integrates the PD pulse currents and is calibrated according to ASTM D1868 or IEC 60270. This calibration procedure is valid only for capacitive test objects, strictly speaking, so the measured pC quantity may vary widely because of resonances between the stator inductance and the stator capacitance [20]. Thus although the pC unit is still used for online PD measurement of stator windings, the standards point out that it is really only a relative indicator among similar machines [11]. Consequently, some researchers prefer PD measurement units of millivolts or milliamps, which are less likely to be viewed as absolute quantities [11], [12].

Recognition of the comparative nature of PD measurements in stator windings implies that researchers need to define what constitutes a “similar” winding. Machine manufacturers frequently use many stators of the same basic design (number of parallels, coil surge impedance or capacitance, voltage and power rating), which enables them to compare PD levels between machines and correlate the levels with the actual stator winding insulation condition. It is regrettable that the “high PD levels” in the resulting databases are not published.

Warren has published high PD levels based on a database that now includes more than 275,000 online PD results, collected by applying the same method to many thousands of machines [13]. Because the surge impedance of different windings is relatively constant in the VHF frequency range, compared with the wide variation in the low-frequency range owing to widely varying capacitances and inductances, it seems reasonably safe to correlate the PD levels with the actual insulation condition [21]. The high PD levels are mainly affected by measurement method, voltage class (which affects the surge impedance), and hydrogen pressure (if relevant). Machine power rating and insulation class or type (motor, hydro, etc.) seem much less important. Publishing these high levels and taking account of the trend in levels seem to have reduced the risk of false positives and false negatives.

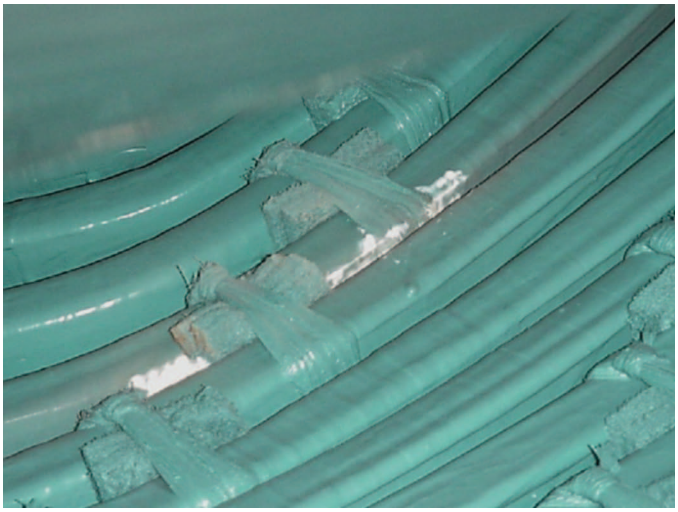

Figure 2. Phase-to-phase partial discharge (PD) occurring in an end-winding because of inadequate space between the stator bars.

Better Identification of Failure Processes

It was stated above that incorrect identification of the failure processes was one of the causes of the reduced credibility of online PD monitoring. In the past 20 years, the advent of superior signal-processing techniques and clarification of the impact of load, temperature, and humidity on PD activity have greatly reduced the risk of incorrect identification of the root cause of any high PD levels [11], [14]. Thus it is now clear that humidity tends to have a strong effect only on PD that originates in the stator end-winding. If no dependence of PD activity on humidity is noted, then it is likely that the activity is due to tracking (contamination) or insufficient space between coils in the end-winding. Similarly, PRPD patterns (PD phase position, polarity effects) can help identify the cause. Two examples of PD in stator bars are shown in Figures 2 and 3.

It should be noted that when two or more deterioration mechanisms occur simultaneously (not uncommon in older windings),

- even experts disagree on what is occurring when only PD data are available; and
- pattern recognition techniques (neural networks, statistical manipulation, T-F maps, etc.) have not always been capable of correct mechanism identification in blind testing.

Opportunities to Improve Reliability

Although the acceptance of online PD monitoring has greatly increased, at least for rotating machines, more research is needed. Some suggestions include the following:

- Research is needed on the development of cost-effective sensors that are not galvanically coupled to the high-voltage terminals, yet have the same sensitivity to PD from all the likely parts of the stator to experience PD.
- Continued improvement in noise suppression requires further research, with wider application of software-based methods. New pattern recognition methods are constantly being developed, and need to be independently evaluated.
- Research on reliable, automatic identification of failure processes, especially for windings experiencing multiple simultaneous deterioration processes, is needed. New methods need to be validated by blind testing and correlation with the actual winding condition.
- It is clear that some failure processes, such as those in which the interface between the slot conductive coating and the silicon carbide coating deteriorates, produce very high PD, which nevertheless does not pose a significant stator failure risk. However, other processes, such as thermal aging next to the turn insulation in a multiturn coil, can produce relatively rapid failure even though the PD level is not as high. This suggests that high PD levels need to be established for each failure process. This will, of course, require many case studies and correlation with the results of visual examination of the windings. It would also help if the individual failure processes could be identified automatically, as discussed above.

Figure 3. Powder deposit attributable to partial discharge (PD) occurring between a motor stator core pressure finger and a coil.

- Research is needed on the definition and development of PD quantities other than those used in the past [peak PD magnitude (Q_m), NQN, integrated charge, etc.], which correlate better with the risk of winding failure.

Conclusions

Tremendous progress has been made in making online PD monitoring technology a viable method for assessing the condition of motor and generator stator winding insulation. More than 12,000 machines have now been equipped for online monitoring by various vendors. To gain this acceptance, earlier skepticism of the usefulness and effectiveness of the technology had to be overcome. Specifically, better noise separation and interpretation methods were developed to reduce the risk of false negative and false positive "alarms." Even more widespread acceptance is achievable, but this will require further improvements in technology.

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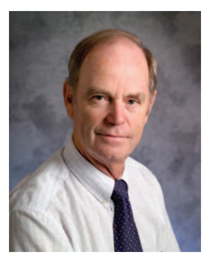

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