A Perspective on On-line Partial Discharge Monitoring to Assess the Insulation Condition of Rotating Machine Stator Winding Insulation

G.C. Stone
Iris Power-Qualitrol
Mississauga, Canada
gstone@qualitrolcorp.com

Abstract— **Partial discharge (PD) monitoring of operating electrical equipment has become, to some extent, an accepted tool to determine the condition of the high voltage electrical insulation in such equipment. More particularly, it is used to determine the need to repair or replace insulation to avoid an in-service failure of the equipment. However, in the past, on-line PD testing did acquire a reputation for being a "black art". Even today, many operators of high voltage equipment are skeptical when on-line PD is proposed. The poor reputation was often deserved due to the high incidence of false positive or false negative alarms, together with the extravagant claims of many researchers and vendors of the efficacy of their favored method. In this paper, a review is made of the technologies that have enabled on-line PD monitoring to overcome (to some extent) this unfavorable reputation, especially with regard to rotating machine stator winding insulation. The requirement to ensure continued gains in the credibility and acceptance of on-line PD monitoring systems is reviewed. Finally, some promising areas of future research are presented.**

Keywords*- partial discharge, on-line, condition assessment, stator winding insulation*

I. INTRODUCTION

Partial discharges are small electrical sparks the can occur in liquid or solid insulation systems in high voltage equipment that can be a cause or a symptom of failure of the equipment [1-3]. PD testing has been used for over 80 years as a factory quality control tool to find manufacturing defects that could eventual lead to equipment failure. We believe that Johnson was the first to measure PD on operating high voltage apparatus in the 1940s [4]. His desire was to find an on-line method to determine if 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 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 on-line, he could indirectly detect that coils were moving, and thus that failure was eventually likely. The measurement had to be made on line, since if the generator was not operating, there were no magnetic forces acting on the coils, and thus the air gaps that are a necessary precursor of PD were not as big, or at best uncertain. Johnson was successful in identifying those generators which were suffering the most from this problem, which was caused by a combination of the introduction of the first thermoset insulation systems and workmanship variations that were magnified by an inadequate method of securing the coils in the stator for the novel insulation system. The success of the Johnson on-line PD measuring system inspired other machine manufacturers and even a few utilities to develop their own methods [5, 6].

The main reason Johnson needed an on-line 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 on-line PD tests – to monitor the condition of the equipment under normal operating electrical, thermal and mechanical stresses. However, with the current emphasis of extending times between maintenance outages and the push to reduce testing costs in general, the main reason now given for on-line PD measurement is to avoid shutdowns of the equipment in order to do an off-line PD or other diagnostic test. Although we believe on-line PD monitoring was first applied to rotating machines, in the past 20 years the same reasons are valid for other electrical apparatus such as oil paper cable joints/terminations, distribution class switchgear, gas-insulated switchgear and power transformers [2, 3].

Given its introduction over 60 years ago, the application of on-line PD monitoring has not been as smooth or as widespread as one would have expected. Various issues, both technical and nontechnical, intervened such that only in the past 20 years has on-line PD monitoring been accepted to some degree as a legitimate, reliable method to assess the stator winding insulation condition. This paper presents an overview of the issues that tended to retard the widespread application of on-line PD. The paper also summarizes the present state of the art, and speculates on what innovations may occur in the future. Although this paper focuses on stator windings, some of the lessons learned in this application may be applicable to other types of electrical equipment where on-line PD may be relevant. Only the electrical measurement of PD is considered in this paper.

II. Initial On-Line Methods

An on-line PD monitoring system must have the following components:

- A sensor to detect the PD 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.
- Software and/or a human being to convert the PD data into information about the condition of the insulation system.

The first on-line system developed by Johnson detected the PD signal as a voltage across a neutral grounding resister at the neutral point of a 3-phase stator winding [4]. He then used both a narrow band filter and an oscilloscope to display the PD. For the pattern displayed on the oscilloscope, he used experience to determine what was PD and what was electrical noise. By 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 used [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 high voltage 50 or 60 Hz, was that the PD signals could be displayed against the 50 or 60 Hz AC cycle, which helps to ensure that the recorded signals were PD and not noise. In addition, the phase with the highest PD could be identified. Regrettably, with the technology in the 1950s and 60s, it was not possible to accurately record the PD. Even high speed photographic film could not record the peak magnitude of the very short PD pulses as displayed on an oscilloscope screen [5]. The early results were very subjective, not only because judgment was needed on what was electrical noise and what was PD, but also because the PD magnitudes and repetition rates could only be estimated by the human eye.

In the 1970s two developments occurred which eliminated one problem with PD measurements – the subjective assessment of the number of pulses and their magnitude. Bartnikas introduced the pulse magnitude analyzer to digitally record 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].

The other aspect - electrical noise - also started to be addressed in the 1970s. Electrical noise could come from many sources such as poor electrical contacts, substation corona, power tool operation, etc. The noise signals were often of higher magnitude than stator PD, and thus obscured the stator winding PD. Until the 1970s, the main methods to separate PD from noise was the use of filters, i.e. selecting a frequency that maximized the PD signal to noise ratio, as well as the skill of the observer looking at an oscilloscope screen. Also, electronics limitations tended to mean that the on-line PD monitoring systems in use until the mid 1970s operated from about 5 kHz to a few megaHertz [5-7].

III. Credibility Issues with On-Line PD of Stator Windings

The on-line PD monitoring that was available until the end of the 1970s was available from only a few machine OEMs and routinely used by only a few utilities such as Ontario Hydro, TVA and the CEGB. There were many reasons for this – but the big one was the lack of credibility of the test. That is, users were wary that an on-line test would give an accurate indication of the stator winding insulation condition. More formally, there was a high risk of false positive indications or false negative indications. False positives are where the test suggests there are insulation problems, but when the winding is visually examined, no problems are found. False negatives occur when the on-line PD tests suggests there is no insulation problem, when in fact the winding fails due to the insulation, or when the winding is visually examined, a serious insulation problem is found. The false indication rate was such that an EPRI project manager suggested in the early 1990s that on-line PD testing was “black magic”. This viewpoint was widely held by many utility maintenance engineers because of some bad experience they had had with on-line PD testing. There were many possible specific reasons for this lack of credibility, as described below.

A. Noise

Noise has been a vexatious problem for all on-line PD monitoring, leading to many false positives. The early noise reduction methods relied on selection of the best detection frequency together with the skill and experience of the person doing the test. Since not all test providers have equal experience, false positive indications resulted due to electrical noise being classified as PD. Such false positives are expensive since after diagnosis of high on-line PD, normally the machine must be shut down for off-line tests and inspections – which is costly both because of lost production, and because of the cost of the extra testing. It is no wonder that a plant manager will be skeptical of any future on-line test results where insulation problems are predicted after having previously experienced a false positive. Perhaps the greatest advancement in the application of on-line PD monitoring came with the development of numerous noise separation methods, as discussed later.

B. Over Claiming

Another cause of poor credibility was the ambitious claims of effectiveness that many researchers and vendors made for their on-line PD monitors. It is human nature to claim that a technology is successful when just a few successful diagnoses have been made. But early success may have occurred under narrow circumstances, when perhaps the noise for those machines was relatively benign. The only way to overcome this issue is to ensure that any monitoring system is evaluated on enough machines in widely different plants. Blind testing, as is mandated for new pharmaceuticals, would also be helpful.

Another cause of over claiming is that researchers and vendors sometimes give the impression that on-line PD monitoring can detect all insulation problems. Thus when equipment failure occurs and there was no warning via the PD monitor, users believe that the PD monitoring system is not useful at all due to this false negative. Researchers need to be clear what failure mechanisms PD is the cause or a symptom of, and what mechanisms do not produce PD as a cause or symptom. For example, endwinding vibration is an important stator winding failure process that does not produce PD. If a plant manager has a generator failure caused by endwinding vibration, but believed his stator was in good condition since the PD was low, then the plant manager may become disillusioned by the on-line PD monitor unless the vendor had clearly indicated that certain problems would not be detected.

C. Unreliable "High PD" Indicators

Most on-line PD monitoring systems either rely on trending the PD over time, or use tables of what constitutes a high PD level, or both, to determine which stator windings need maintenance. If the interpretation rules are incorrect, either 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 almost all stators rated 6 kV or more have at least some PD occurring, and can endure low level PD for many decades before failure. This contrasts to almost all other electrical equipment where 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 between stator windings and all other types of equipment.

Typically, the trend in PD over time was the most powerful method of identifying windings with insulation problems [10, 11]. For example, the rule of thumb used for decades is that if the PD magnitude or some other PD quantity (such as integrated charge, quadratic rate, 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, then in fact the doubling rule may yield false positives, since 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 now very clear that PD does not increase until failure occurs in stator windings. Rather, it seems that PD increases to a certain point and then levels off. Presumably, this leveling off occurs because of:

- space charge effects,
- the fact that voids do not grow indefinitely in a taped insulation structure,
- since 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 may be high, it is stable with time. If one begins monitoring the stator PD once it is in this high but stable mode, then the plant manager may feel the winding is not at risk. If failure then occurs, there is a perception that it is a false negative.

Although there is no "high PD" level 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 insulation system [11, 12]. These "high PD" levels are established by comparison, and are only valid 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" indicators [13], i.e., there is not one level that is suitable for all stators. The high PD levels also need to be validated by comparing levels with the actual condition of the winding as determined by a visual examination.

D. Sensor Reliability

On-line PD is put in place 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, since 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 requires the sensors to be PD free at twice working voltage, have a stable capacitance and dissipation factor with temperature, and be able to pass the same voltage endurance tests as stator windings [11].

E. Remaining Life

In the past, some researchers and/or vendors have claimed that by measuring the PD, the time to failure of a winding can be predicted with some accuracy. There is no objective evidence to support this claim. But utility managers would like to predict when a motor or generator should come out of service, and would like to believe a vendor who says they can predict life. When such life predictions prove erroneous, as they inevitably do after several years, the credibility of all researchers and vendors providing PD monitoring is reduced.

F. Identifying the Wrong Failure Mechanism

Stator windings have a dozen different failure processes where PD is a symptom or a cause [10, 11]. For 30 years, PD testing has been used to help identify what the cause of a stator winding might be [10, 11, 14]. Knowing the failure mechanism is useful since it defines what the repair options are, and may yield an indication of time line available for corrective repairs (some failure processes are fast and some are slow). As discussed later, many methods have been developed to identify the failure mechanism based on PRPD patterns and/or the effect of machine operating conditions on PD activity. Regretfully, sometimes a winding is correctly assessed as having insulation problems due to the PD level or rate of increase, but the wrong mechanism is identified. This means the wrong repairs may be planned for. Plant management tends to regard such false indications as unreliability of the on-line PD monitor.

IV. Present Status

From the initial development of on-line PD methods for rotating machines to the present, the credibility of on-line PD testing has increased. Now more than 12,000 motors and generators employ routine on-line PD testing to provide early warning of developing insulation problems. In North America, >75% of utility generators (rated >20 MVA) employ this technology. Thus on-line PD has become a mainstream condition based maintenance tool for stator winding predictive maintenance. The innovations that have lead 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 processes.

A. *Noise Suppression*

Finding an optimum PD detection frequency is the most popular method to reduce the impact of electrical noise. As for transformers and GIS, there is general recognition that the VHF (30-300 MHz) or UHF (300-3000 MHz) frequency range provides more noise suppression [11, 15, 16]. However, it is noted that detecting PD in these frequency ranges will mean that there is less sensitivity to PD 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 risetimes and ringing characteristics, are more likely to be PD than noise [11, 12, 17].
- Time frequency maps [11, 18] where noise and PD may appear as clusters of pulses in different regions of plot of pulse time domain versus pulse frequency domain.
- Signal processing using the wavelet "denoising" method [19].

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

B. *Identifying Deteriorated Winding Insulation*

For many decades PD was measured in pC, as was common for laboratory or factory testing using what is now known as a low frequency PD detector that integrates the PD pulse currents into pC and calibrated according to ASTM D1868 or IEC 60270. Since this calibration procedure is strictly valid for capacitive test objects, it was found that the pC could be widely variable depending on resonances between the stator inductance and the stator capacitance [20]. Thus, although pC is still used for on-line PD measurement of stator windings, the standards point out that it is really just a relative indicator amongst similar machines [11]. Due to this possible confusion, other researchers prefer PD measurement units of mV, mA, etc, which are less likely to be viewed as absolute quantities [11, 12].

The recognition of the comparative nature of PD in stator winding, implies that researchers have to define what constitutes a "similar" winding. Most often machine manufacturers have many stators of the same basic design (number of parallels, coil surge impedance or capacitance, voltage and power rating) that enables them to compare PD levels amongst them and correlate the levels to the actual stator winding insulation condition. Regrettably, the high PD levels from such databases are not published.

Warren has published high PD levels based on a database of >225,000 on-line PD results collected by the same method on many thousands of machines [13]. Since the surge impedance of different windings is relatively constant in the VHF frequency range, compared to the very high diversity of winding capacitances in the LF range, it seems reasonably robust when the levels are compared to the actual insulation condition [21]. The "high PD" levels are most affected by measurement method, voltage class (which affects the surge impedance), and hydrogen pressure (if relevant). Machine power rating, insulation class or type (motor, hydro, etc) seem much less important. Publishing of these levels, together with taking account of the trend in PD, seems to have reduced the risk of both false positives and false negatives.

C. *Identifying Failure Processes*

Misidentification of the failure processes was pointed out as one of the causes of reduced credibility. In the past 20 years the advent of superior signal processing techniques, together with the clarification of the impact of load, temperature and humidity has greatly reduced the risk of misidentification of the root cause of any high PD [11, 14]. For example, it is clear now that humidity tends to only strongly affect PD due to problems in the stator endwinding. Thus, if a humidity effect on PD activity is noted, then it is likely to be due to tracking (contamination) or insufficient space between coils in the endwinding. Similarly, PRPD patterns (PD phase position, polarity effects) can help identify the cause. However two issues still exist:

- When two or more deterioration mechanisms are occurring simultaneously, which is not uncommon in older windings, then even human experts disagree on the what is occurring based only on PD results.
- Perhaps because of this, pattern recognition techniques (neural networks, statistical manipulation, T-W maps, etc [2]) have not been shown in blind testing to accurately identify multiple processes.

V. Opportunities to Improve Reliability

Although much progress has been made in the acceptance of on-line PD monitoring, at least for rotating machines, more improvement and more research is needed. Some suggestions include:

- 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, with wider application of software based methods. New pattern recognition methods are constantly being developed and need to be independently evaluated.
- The reliable, automatic identification of failure processes, especially in the case of a winding experiencing multiple simultaneous deterioration processes. These new methods need to be validated by blind testing and correlation to the actual winding condition.
- It is clear that some failure processes, such as where the slot conductive coating and silicon carbide coating interface deteriorates, produce a very high PD that does not pose much of a risk of stator failure. Yet other processes, such as thermal aging next to the turn insulation in a multi-turn coil, can produce relatively rapid failure even though the PD is not as high. This argues that "high PD" levels need to be established for each failure process. This will of course take a lot of case studies with correlation to visual examinations of the windings. It will also be aided if the individual failure processes can automatically be identified, as discussed above.
- Development of PD quantities other than those used in the past (Qm, NQN, integrated charge, etc) which better correlate to the risk of winding failure.

VI. Opportunities to Improve Reliability

Tremendous progress has been made in making on-line partial discharge monitoring technology a viable method to assess the condition of motor and generator stator winding insulation. More than 12,000 machines have now been equipped for on-line 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 needed to reduce the risk of false negative and false positive "alarms". Even more widespread acceptance is achievable, but further improvements in technology are needed.

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