Objective Methods to Interpret Partial-Discharge Data on Rotating-Machine Stator Windings

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***Abstract*—Partial-discharge (PD) measurements have long been used to assess the condition of the electrical insulation in motors and generators rated 3.3 kV and above. There are many ways to measure PDs during normal service of the motor or generator. Unfortunately most of the measurement methods mix stator PD with electrical-interference signals from poor electrical connections, power tool operation, corona from transmission lines, etc. The result can be false indications of stator-winding problems, reducing confidence in PD measurements. Another issue with online PD testing is interpretation, i.e., identifying which machines are in good condition and which machines need maintenance. In the past decade, a database of over 60000 test results has been assembled. In hundreds of machines, the condition of the insulation determined by a visual inspection has been compared to the PD levels. The result is a table that provides an objective means of determining the stator-insulation condition relative to other similar machines. An analysis of the results also shows that there are significant differences in PD activity between manufacturers. This paper gives a review of the methods that can reduce the risk of false indications, thus making the measurement less subjective.**

***Index Terms*—Electrical insulation, partial discharge (PD), stator winding.**

I. INTRODUCTION

PARTIAL discharges (PDs), sometimes also known as corona, are small electrical sparks that occur in deteriorated or poorly made stator-winding insulation systems in motors and generators rated 3.3 kV and above. Over the past 15 years, online PD monitoring has become the most widely applied method to determine the condition of the electrical insulation in such machines [l]-[3]. PD testing detects most (but not all) of the common manufacturing and deterioration problems in form-wound stator windings, including the following:

1) poor impregnation with epoxy;
2) poorly made semiconductive coatings;
3) insufficient spacing between coils in the endwinding area;
4) loose coils in the slot;
5) overheating (long-term thermal deterioration);
6) winding contamination by moisture, oil, dirt, etc.;
7) load cycling problems;
8) poor electrical connections (although this is not strictly an insulation problem).

There are many methods available to detect the PD activity in operating motors and generators [1]. The electrical techniques rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. The earliest methods measured the PD pulse currents by means of a high-frequency current transformer at the neutral point [2]. Others have used the leads from RTD temperature sensors to serve as an antenna [4], [5], although organizations such as Electric Power Research Institute (EPRI) and International Council on Large Electric Systems (CIGRE) have expressed reservations about the use of RTDs since the method is controversial and interpretation is extremely subjective [6],[7]. Today, the majority of machines that are routinely PD tested online employ high-voltage capacitors as PD sensors [1].

A key challenge with PD measurements is encountered when the motor or generator is monitored during normal operation. Since the machine is connected to the power system, an electrical interference (noise) is often present. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, arc welder operation, and/or power tool operation. This electrical noise masks the PD pulses and may cause an inexperienced technician to conclude that a stator winding has high levels of PD, when it is actually the noise. The consequence is that a good winding is incorrectly assessed as being defective, meaning that a false alarm is given suggesting that the winding is bad, when it is not.

Such false alarms reduce the credibility of online PD tests; and even today, many feel that online PD testing is a “black art” best left to specialists. This paper briefly describes objective methods that separate a PD from the noise in motors and high-speed generators that are often associated with pulp and paper mills and petrochemical plants.

A large number of PD results using the same test method (and collected in an manner that the noise is suppressed) have been

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In general, for machines rated 3.3 kV and above, over 50 years of experience with PD testing in motors and generators has shown that months, if not years, of warning is often given before a winding failure is likely to happen [I], [3].

accumulated in a single database. Towards the end of 2003, over 60 000 test results have been accumulated; and simple statistical analysis has been applied to the database in order to extract information to better interpret PD results. The main purpose of this analysis is to help test users to objectively determine which motors and generators have deteriorating stator insulation, allowing them to plan appropriate maintenance. However, some interesting results have emerged on the differences in PD activity as a function of winding age, insulation type, and machine manufacturer. This paper also presents these findings.

II. NOISE-SEPARATION METHODS

To enable automated statistical analysis of large quantities of PD data (for example, from 60 000 measurements), one first needs the data to be purely stator PD and not a mixture of a PD and a noise. If the PD and the noise are mixed together, then a human expert is needed to review each test result and subjectively extract the key PD data (for example, the peak PD magnitude—Qm) from the combined noise and PD signals. This clearly would be very time consuming and subject to disagreements among experts.

To date, PD detectors based on RTDs or radio frequency current transducers (RFCTs) seem to require review by an expert to separate stator PD from all other signals [1]. Thus, the use of automated statistical procedures to analyze vast quantities of PD data from such sensors is not practical. As a result, there are no simple criteria to help motor and generator owners assess if a PD level is high or not when RTDs or RFCTs are used as PD sensors. Even with capacitive PD sensors, noise is sometimes mixed with PD, preventing automated analysis.

Over 20 years ago, the North American utility industry sponsored research to develop an objective online PD test for machines that could be performed and interpreted by plant electrical staff with a few days of training [1]. The PD test that was developed emphasized separating PD pulses from electrical-noise pulses. In fact, the techniques developed during this research depend on the following four separate noise-separation methods—since not one method was found to be completely effective on its own:

1) frequency domain filtering;
2) surge-impedance mismatch;
3) pulse-shape analysis:
4) time of noise and PD pulse arrival from a pair of sensors.

Practically, to reduce the risk of false indications to less than a few percent, at least three of the four methods are implemented simultaneously. In high noise environments, all four are implemented.

A. *Filtering*

As part of the utility research project, surveys were performed of the noise environment in typical plants. It was found that the noise tended to produce the greatest signals at frequencies below 10 MHz or so. In contrast, when measured close to the stator winding, PD produces frequency components up to several hundred megahertz [8]. Thus, the highest PD signal-to-noise ratio (SNR) and thus the lowest risk of false indications occurs if the PD is measured above about 40 MHz. A simple single-pole high-pass filter can be realized with a 50-Ω input oscilloscope or a measurement instrument with a high voltage capacitance of about 80 pf. The capacitor is the same capacitor used for the PD sensor.

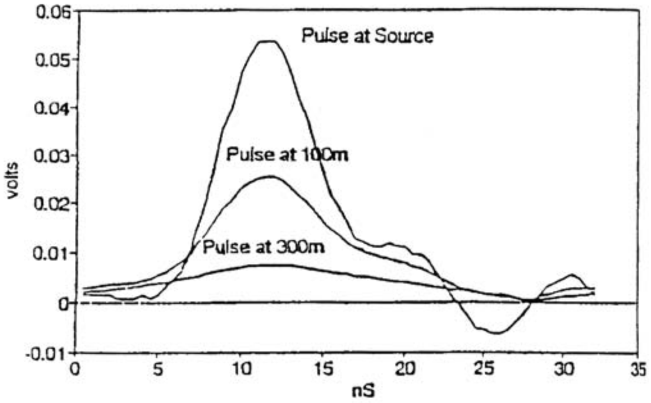

Fig. 1. Attenuation and dispersion of a pulse as it travels along a cross-linked polyethylene power cable of different lengths.

B. *Surge-Impedance Mismatch*

In many cases, a motor or a generator is fed by air-insulated bus or has internal circuit ring buses. In general, such buses have a characteristic (or surge) impedance of about 100 Ω.

In contrast, the surge impedance of a coil in a stator slot is much lower—typically on the order of 30 Ohm. A noise pulse from the power system that travels along the air-insulated bus sees a source impedance of 100 Ohm and then encounters the coil impedance of 30 Ohm. Using the transmission-line theory, the first peak of a fast-rise-time noise pulse is attenuated to about 25% of the original magnitude. A PD pulse originating in the winding has a source impedance of 30 *Ohm,* and then encounters the 100-Ohm impedance of the air-insulated bus. From the transmission-line theory, a reflection and a superposition occur, which results in the first peak of the PD pulse current being amplified by about 50%. The high-speed traveling wave properties of the PD and noise pulses amplify the PD and suppress the external noise, enabling another method of increasing the SNR. To use this method, the noise and PD pulses must be detected with their original rise times of < 5 ns, and the PD sensor must be within 1 m or so of the coils.

C. *Pulse-Shape Analysis*

A third method of separating a PD from a noise depends on the time-domain characteristics of the PD and noise pulses. Short rise-time current pulses, no matter what their source, are modified as they travel along a power cable. There are two types of modification: attenuation and dispersion, where the latter refers to the frequency dependent attenuation of the pulse. The longer the distance the pulse must travel, the greater is the attenuation and dispersion encountered. Fig. 1 shows the effect of these two properties as a voltage pulse propagates along a power cable. As the pulse propagates farther, the magnitude of the pulse decreases due to attenuation, and the rise time of the pulse lengthens due to dispersion.

If a PD sensor is installed very close to the stator winding (say less than 1 m), then any PD pulses from the stator winding will undergo negligible attenuation and dispersion as the PD pulse travels to the sensor. However, if a noise pulse from the power system first has to propagate through many meters of power cable,

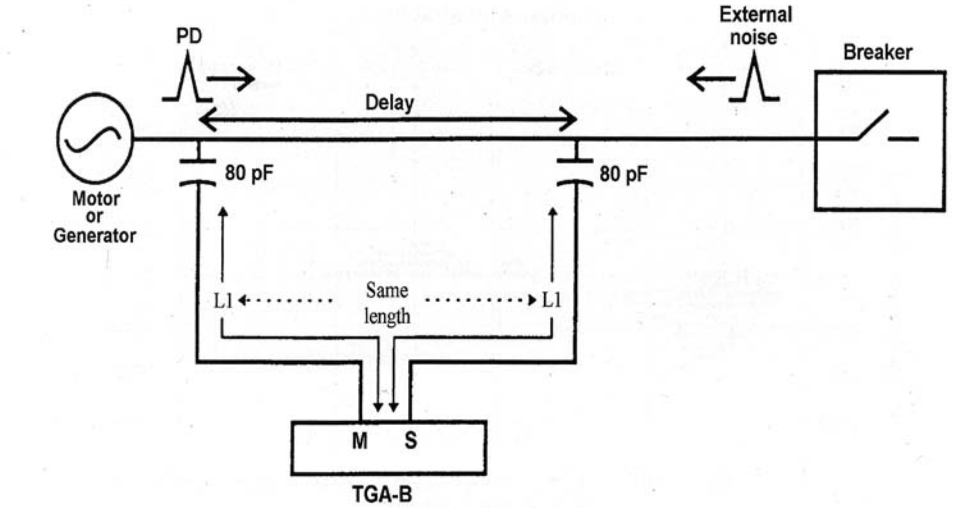

Fig 2. Use of two capacitors per phase to separate a PD and a power-system noise based on the direction of pulse travel. Two sensors are only needed if there is approximately less than 30 m of power cable between the switchgear and the motor.

then the noise pulse will be significantly reduced in magnitude and will have a longer rise time. By digitally measuring the rise time, the PD can be separated from a noise on a pulse-by-pulse basis using rise time or pulse width [9]. Although intended to separate the PD from the noise that must travel along a power cable, pulse-shape analysis is also effective in separating sparking sources on the machine rotor (for example, sparking from shaft ground brushes or slip-ring sparking in synchronous machines), since such a noise tends to have a slower rise time when coupled to the stator winding.

D. Pulse Time of Arrival

Where the connection to the power system is via air-insulated bus or very short power cables and thus the pulse shape is not sufficiently different between a noise and a PD, an additional noise-separation method based on using two sensors per phase has been implemented (Fig. 2). If the sensors are at least two meters apart, a pulse from the power system will arrive at the "S" sensor before they are detected by the "M" sensor. Similarly, if the pulse is due to stater-winding PD, the pulse will first arrive at the "M" sensor before it arrives at the "S" sensor. With fast responding digital logic, the pulses can be classified as a noise or a PD, based on which sensor detects the signal first.

III. PD DATA

The noise-separation methods mentioned above, with the practical implementation using 80-pF capacitors and appropriate digital instrumentation, has been permanently installed on more than 6000 motors and generators around the world. Some of the installations were made over 20 years ago. As a result, a very large body of data has been collected where the PD is essentially noise free. Once the PD is separated from the noise, electronic instruments record the number, the magnitude, and the phase position with respect to the 60-Hz ac cycle. Fig. 3 shows a typical plot of the PD from one phase of a motor stator winding. Consistent with international standards for PD testing of inductive apparatus (IEEE 1434 and IEC 60270), the pulse magnitude is measured in the absolute units of millivolts (mV). From each test, two summary indicators are extracted, representing all the PD pulse data collected.

The peak positive and negative PD pulse magnitudes (+Qm and -Qm) represent the highest PD pulses measured in mV with a minimum PD repetition rate of ten pulses per second. Qm is a reasonable predictor of insulation condition at the most deteriorated location in the winding. A high Qm measured in a winding compared to a lower Qm in another winding, usually implies that the former winding is more deteriorated.

A. Database to the end of 2003

Since 1992, test results from portable test instruments were combined into a single database. This totaled to 60342 tests until the end of 2003 [10]. The database contains many repeat tests, sometimes performed over many years. Also, many of the tests were done at different operating conditions. Machine operating conditions can affect the PD activity and thus add additional variability to the analysis [1]. Therefore, the database was carefully reduced such that the following applied.

1) Only online PD readings obtained when the machine was operating at or near full load at normal operating temperature are included.
2) There is only one test result collected per sensor, thus, only the latest reading is extracted.
3) Tests were discarded where there was reason to believe the measurement was mislabeled.

The result of this culling is that to the end of 2003, there were 4828, 3953, and 2211 statistically

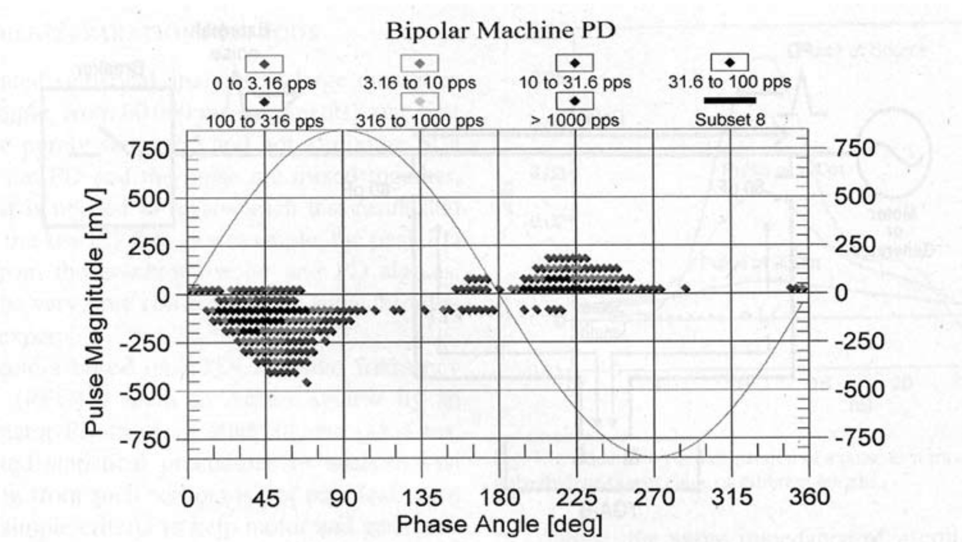

Fig. 3. Typical PD data from one phase are plotted with respect to the 60-Hz ac cycle. The vertical scale is the positive and negative PD magnitude in millivolts. The color represents how many discharges are occurring per second at this magnitude and phase position. The higher the PD, the larger is the defect within the insulation. The peak PD magnitude (Qm) for this phase is —400 mV and +200 mV.

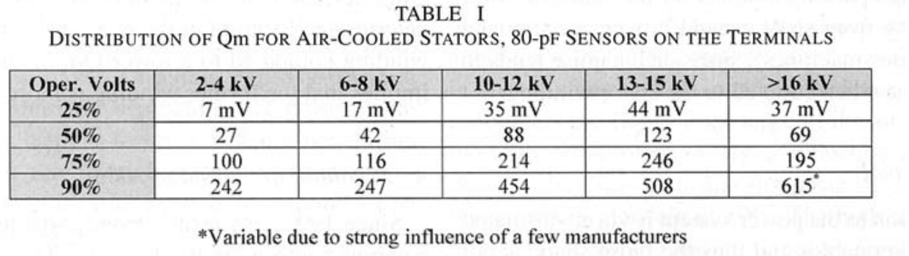

TABLE I

DISTRIBUTION OF Qm FOR AIR-COOLED STATORS, 80-pF SENSORS ON THE TERMINALS

Oper. Volts	2-4 kV	6-8 kV	10-12 kV	13-15 kV	>16 kV
25%	7 mV	17 mV	35 mV	44 mV	37 mV
50%	27	42	88	123	69
75%	100	116	214	246	195
90%	242	247	454	508	615*

*Variable due to strong influence of a few manufacturers

independent test results for hydrogenerators, turbo generators, and motors, respectively, in the database.

B. Statistical Distribution of PD Data

The database was analyzed to determine the effect on Qm of several different factors, including the following:

1) operating voltage of the stator winding;
2) winding age:
3) winding manufacturer.

The range in Qm from all the tests for the particular operating voltage was established for each set of the above factors. A cumulative version of the statistical distribution is shown in Table I. For example, for a 13.8-kV stator: 25% of tests had a Qm below 44 mV; 50% (the median) of the tests had a Qm below 123 mV; 75% -were below 246 mV; and 90% of tests yielded a Qm below 508 mV. Thus, if a Qm of 500 mV is obtained on a 13.8-kV motor, then it is likely that this stator will be deteriorated, since it has PD levels higher than 90% of similar machines. In fact, in over 200 machines where a stator was visually examined after registering a PD level greater than 90% of similar machines, significant stator-winding-insulation deterioration was always observed [11].

The effect of a particular factor on Qm was determined by comparing 90 percentile levels between the two data sets composed of, for example, 13.8-kV machines. It was concluded that this factor is important in interpreting results if there was a significant difference in the average and 90% distribution levels of Qm for the two sets. From Table I, it is interesting to note that as the operating voltage of a motor or generator increases, the 90% level also increases. Clearly, PD results from a 13.8-kV stator should not be confused with those from a 6.9-kV stator. Statistical analysis (assuming the normal distribution) indicates that there is < 0.01 % chance that the voltage rating is not a key factor influencing the Qm levels.

With this table, it is now possible for motor and generator owners to determine if the stator-winding insulation has a problem with only an initial test. In addition, with some limitations, motor and generator manufacturers can use this information as an indicator of the relative quality of a new winding. If the PDs were higher than that found on 90% of similar machines, then off-line tests and/ or a visual inspection would be prudent. Continuous PD monitors would have their alarm levels set to the 90% level.

C. Effect of Winding Age and Manufacturer

An analysis of the statistical distribution of PDs for several manufacturers was also performed. Fig. 4 shows the results for 13-15-kV stators from 11 different original equipment manufacturers (OEMs) based around the world. Note that the data covers all ages of machines and all insulation systems made by these manufacturers over the years. Clearly, there are differences between the manufacturers. For example, OEMs D, E, H, and J have relatively low PDs on average, whereas manufacturer B has a relatively high PD for its fleet of machines. The cause of the differences between manufacturers is unknown, but it may be due to different manufacturing processes, electric-stress design levels, and assembly methods.

One surprising result from the statistical analysis of the database

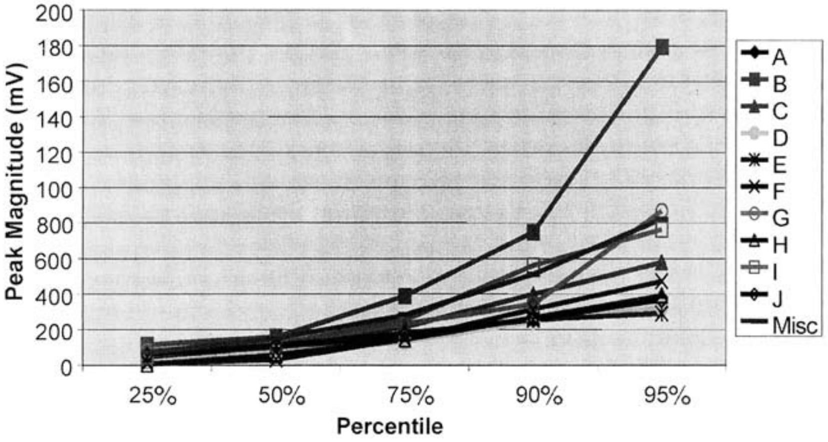

Fig. 5. PD activity for nine motor and generator manufacturers as a function of the year the stator winding was built or rewound. The PD tests were done in 2003. For some manufacturers, the PD activity for machines made in the past ten years is higher than machines they made more than ten years ago. 75th percentile of PD results by manufacturer and year of installation (13-15-kV air-cooled machines with 80-pF sensors).

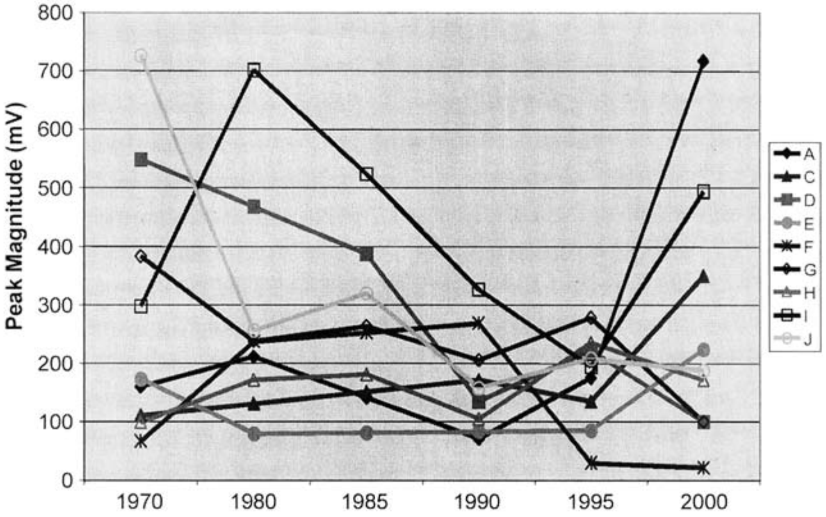

Fig. 4. Plot of PD magnitude versus cumulative probability of occurrence for 11 major motor and generator manufacturers. Manufacturer B has higher PD than most other manufacturers of 13.8-kV motor and generator stator.

was the distribution of Qm as a function of winding, age. Fig. 5 illustrates the PD results in the database from machines that were one-year old to greater than 30 years old. There is no consistent trend—which is surprising since one would normally assume that older windings would be more deteriorated and thus have higher PD levels. Fig. 5 implies that both older windings and new windings can have about the same high PD activity. In fact, four brands of air-cooled windings manufactured in the past 10 years seem to have higher PD activity than older machines. This may reflect the fact that modem windings tend to operate at higher thermal and electrical stresses than older machines [12], [13]. Other explanations for the inconsistent pattern of PD versus winding age may include the observation that manufacturers of machines have a learning curve to climb as they adopt new designs and manufacturing techniques or that machine operators are continuously oscillating between proactive and breakdown maintenance strategies, depending on current management policies.

IV. CONCLUSION

1) With thousands of machines monitored for as long as 15 years with the same method, online PD testing has become a recognized proven too] to help maintenance engineers identify which stator windings need off-line testing, inspections, and/ or repairs.

2) Objective separation of a PD and a noise is crucial if one is to automate the analysis of the huge volumes of data that can come from online PD tests. Four complimentary methods are described and were used for the data reported in this paper.

3) With over 60 000 test results acquired with the same test methods, what constitutes a winding with low, moderate, or high PD has been defined. Table I enables test users to objectively identify, with some certainty and without the need of an expert, which stators are likely to suffer from groundwall insulation deterioration.

4) The practical importance of Table I is that if one applies PD sensors to a machine and one obtains a Qm that exceeds the 90 percentile of the relevant Qm distribution in the first measurement, then one should be concerned enough at the high PD level to take action such as more frequent testing and/or off-line tests and inspections at the next convenient machine shutdown.

5) Some machines made in the past decade exhibit higher PD activity than machines that are considerably older. Newer

machines do not necessarily have more reliable insulation, implying that time-based maintenance practices may not be optimal for large machines.

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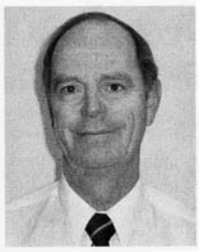

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