ASSESSMENT OF STATOR WINDING INSULATION CONDITION BASED ON ABSOLUTE PARTIAL DISCHARGE MAGNITUDE

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INTRODUCTION

Partial discharge (PD) measurement is widely used for all types of high voltage equipment for both factory quality assurance and insulation system condition assessment. For the latter, the PD may be measured off-line or on-line. For motor and generator stator windings in particular, on-line PD testing has been implemented on tens of thousands of machines using a wide variety of methods. How to perform such on-line tests is described in IEC and IEEE standards [1,2]. The usefulness of on-line testing has been described in many case study papers, and in particular, reference [3] summarizes the results of about 200 PD case studies presented by machine owners where stator failures were anticipated by the test, or where the findings of the on-line PD results were confirmed by visual inspections, therefore allowing proactive maintenance.

Despite this success, there are many issues surrounding the interpretation of on-line stator winding PD data. The main standards are clear that the trend in PD activity on a particular machine over time is an important indicator of when winding maintenance may be prudent [1, 2]. However, there are caveats when using the trend to determine when maintenance is prudent:

- The same PD measurement technology and the same frequency range must be used to build up the data points for the trend [1,2,4].
- It is recognized that while PD activity increases when significant aging occurs, the trend stabilizes (and sometimes even decreases) at some point and does not increase further even though aging continues with elevated risk of failure. In other words, the trend may be misleading if the monitoring of the asset starts at an advanced stage of insulation deterioration.
- The trend is only valid if the data is collected at about the same operating voltage, load, winding temperature and ambient humidity, otherwise any change in PD may be due to the effect of these factors on the PD activity.
- Fluctuation and seasonal variation are the results of such influences.
- If the PD level is very low (to be discussed later), even a doubling of the PD activity does not imply that failure is imminent.
- The PD activity must be free of the influence of electrical noise and PD from other equipment, that is, the stator PD must be higher than the interference level.

Both IEEE 1434 and IEC 60034-27-2 state that the absolute level of “high” PD activity cannot be generally and objectively defined for stator windings. The magnitude of PD activity is usually taken to mean the Q_{IEC} or Qm, value, which are both approximate indicators for the peak PD magnitude. Q_{IEC} is the quasi-peak apparent charge (in Coulombs) measured according to IEC 60270 [5], whereas Qm is defined in IEEE 1434 and IEC 60034-27-2 as the PD magnitude (in any units, but normally mV) at a pulse repetition rate of (usually) 10 PD pulses per second. It must be noted that the apparent charge in Coulombs should not be employed for stator windings. The reasons have been known since the 1960s (for example see [6]), and are reiterated below. Despite this, some vendors of PD systems have published levels for “high” apparent charge for motor windings [7]. Even more importantly, high PD activity levels have made it into at least one IEEE motor protection and control standard, where a level of 15-25 nC of PD indicates disassembly and inspection is needed, and the winding is unreliable if the PD activity is over 25 nC [8]. As indicated by one set of researchers [9], the use of such PD levels may lead to the unnecessary rejection of a new stator winding or unnecessary maintenance.

This paper is another contribution on the care needed in applying PD activity limits, no matter which units are used. It discusses the technical issues surrounding the use of absolute PD quantities when applied to stator windings, and presents some new data that confirms the earlier work that such absolute levels can be fallible.

ORGANIC VERSUS INORGANIC INSULATION SYSTEMS

Power cables, transformers and switchgear use predominantly organic insulation to separate and/or support conductors away from one another. If PD occurs in such equipment during operation, PD will degrade the organic insulation (polyethylene, oil, paper, epoxy) relatively rapidly and cause breakdown of the insulation by either electrical treeing (within the bulk insulation) or electrical tracking (over insulation surfaces) [10]. Thus, factory quality assurance tests require the equipment to have no PD at the expected operating voltage, or at an even higher voltage as a safety factor. The PD is usually required to be measured by an IEC 60270-compliant detector, which limits the PD test frequency to 1 MHz. The calibration process stipulated in IEC 60270 is used to measure the background noise in terms of an apparent change in pC, and the voltage at which PD is observed above the electrical noise “floor” is defined as the PD inception voltage (PDIV). The main issue in factory tests is the noise level in apparent charge. This depends on a combination of the typical noise floors found in factories, and the sensitivity needed to detect flaws that may result in failure during service at the required PDIV. The sensitivity in pC is different for different test objects (GIS and power cables seem to require the most sensitivity, whereas air-insulated switchgear and power transformers seem to require less sensitivity [10]). In any event, most standards for cables, switchgear and transformers specify sensitivities in the range from 1 pC up to about 100 pC.

If IEEE 3004.8 (and the accompanying caveats) is ignored, there are no PDIV or sensitivity requirements for factory acceptance tests on conventional rotating machine stator windings in the relevant IEEE and IEC standards [1, 2]. The lack of standards for machines is partly for commercial reasons. OEMs tend to discourage any pass/fail criteria for equipment that is unlikely to fail (due to, for example, PD) during the warranty period. However, there are also sound technical reasons. Almost all stator windings rated 3.3 kV and above use mica that is bonded together with epoxy within the high voltage groundwall insulation. Mica is exceptionally resistant to PD, and electrical treeing in particular. The authors are aware of stator windings that have “moderate” (to be defined below) PD activity level for over 50 years and have not yet failed. Furthermore, almost all new windings have PD at voltages below the operating voltage. Hence an argument can be made that PD itself is irrelevant to the long-term operation of a stator winding insulation system. On-line PD testing of machines has become popular not because PD is necessarily all that bad, but because considerable experience shows that significant and increasing PD is correlated with the onset of thermal, thermo-mechanical, mechanical or contamination-induced aging of the insulation [11, 12].

THE MEANING OF APPARENT CHARGE

IEC 60270 outlines the PD measuring methods and provides a procedure to calibrate the quasi-peak pulses measured in mV or mA into apparent charged expressed in Coulombs. A careful reading of IEC 60270 [5], together with a CIGRE technical brochure describing its use [13], indicates the following:

- Apparent charge is measured since there is no way to analytically connect the actual flow of charge in a PD event within a void in the test object (i.e. how many electrons and ions are damaging the organic materials as they hit the insulation) to the measured signal at the terminals of the test object.
- The mV signals that are almost always used by vendors to detect PD pulses are converted to a current that is integrated by an analog circuit (or nowadays with a low pass digital filter) to obtain a measured value with the unit of electric charge.
- The integrator (or low pass filter) must have a low-pass cutoff frequency of 1 MHz or less (i.e. work in the low frequency or LF range) to integrate the current to the estimated charge correctly. Technical experts in the working group that is currently revising IEC 60270 were even unwilling to increase the cutoff frequency from 1 MHz to 3 MHz (which would eliminate the frequency gap between IEC 60270 and IEC 62478 [14]).
- The test object must be capacitive in nature or be a simple transmission line like a power cable. The calibration process is not applicable to inductive-capacitive test objects [5, 14].

In spite of the above limitations, many PD measurement system vendors produce so-called 60270-compliant detectors which work up to 10 MHz or so (the HF range, in addition to the LF range) that output results of quasi-peak apparent charge in pC and nC.

Stator windings have a very complex impedance, especially near 1 MHz. A stator winding has the following inductive and capacitive components, many of which interact:

- Inductance of the end winding and slot areas of the coil
- Capacitance to ground at the endwinding and slot areas of the coil
- Mutual inductance and capacitance between coils at their endwinding
- Mutual inductance between coils in the slots

- Mutual inductance and capacitance between turns (for multiturn coils) in the slot and at the endwinding.

The result is a complex LC network with many natural frequencies (Figure 1), which can vary widely between stators of different designs. The IEC 60270 calibration procedure cannot compensate for the resonances caused by such natural frequencies. As a result, various IEC 60270-compliant PD detectors operating in slightly different frequency ranges below 1 MHz produce as much as 30 to 1 difference in apparent charge even on the same stator winding [6]. Kemp found similar results, which also included the effect of the detection impedance [16]. Clearly calibration into apparent change in pC or nC is not effective on windings. As a result, any advice on "high" PD in terms of apparent charge cannot be "absolute", or meaningful and applicable to all IEC 600270 compliant detectors.

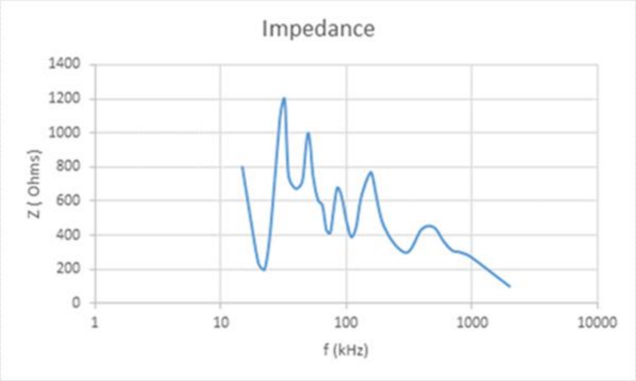

Figure 1 Natural frequencies for one phase of a 13.2 kV, 7000 HP motor stator winding measured with an impedance analyzer. From [15].

IEC 62478 was specifically developed to complement IEC 60270, in that it describes measurements in the HF, VHF and UHF ranges (3-30 MHz, 30-300 MHz and 0.3-3 GHz ranges, respectively), as well as being valid for any type of test object: lumped capacitors, transmission lines or inductive-capacitive windings. IEC 62478 simply points out that "the PD magnitude as apparent charge cannot be evaluated directly as a calibrated value".

□ INFLUENCE OF MACHINE RATINGS ON PD ACTIVITY

When a high PD activity level is given by a PD system (for example in [7]), or indeed that which appears in the IEEE 3004.8 standard, it seems to be independent of the rated voltage of the winding (as long as it is above 10 kV), and the "high" level is apparently independent of the PD measuring system [8]. As discussed above, the PD measurement system has a big influence on what is considered high PD, and activity results from different instruments should not be compared. Other work has already indicated that some aspects of machine design also need to be taken into account for PD measurements in the LF and HF range [9]. This seems reasonable given our experience with the analysis of a very large PD database measured in the VHF range.

A database of more than 750,000 on-line VHF PD test results from stator windings collected up to the end of 2021 has been statistically analyzed. The results are from about 8500 motors and generators. The PD was measured with either one or two 80 pF capacitors connected per phase at the machine terminals and a short distance away (the second sensor helps to separate disturbances [1, 2, 10]), or UHF antennae called SSCs installed within the windings of large hydrogen-cooled turbine generators. An early analysis for data collected before 2014 is in [11]. A significant portion of the data was discarded because:

- many results were repeat tests on the same machine (only the most recent test result was used),
- since it is well known that PD activity may be strongly influenced by voltage, load and winding temperature [1, 2, 10], only data collected near normal full load, operating voltage and high winding temperature is selected for the analysis, and
- all off-line tests were discarded.

27,000 statistically independent results were left and analyzed.

For each test on each phase, the Qm (and an integrated PD activity indicator called NQN [1,2]) was evaluated. The Qm levels were organized from the smallest to the largest to create a cumulative probability distribution for the entire data set. In addition, the cumulative distributions of Qm were created for any desired subset of data, for example: voltage rating, power rating, hydrogen pressure (if applicable), machine OEM, machine age, insulation thermal class, epoxy impregnation method, machine type (motors, hydro generators or turbine generators) or any combination of these [11]. The cumulative distributions for a given set of factors were observed to check if changes in that factor (or combination of factors) resulted in different cumulative probability distributions. When the distributions were close, statistical tests were done to ascertain the significance of any difference. In particular, a regression line was calculated for each cumulative distribution and standard statistical tests were calculated to determine if significant differences were present on the mean or the 90th percentile.

The results of the analysis on data collected to the end of 2021 show that the following factors had a significant impact on the cumulative distributions of Qm:

- Type of PD sensors (80 pF capacitor vs SSC)
- Rated voltage of the stator
- Operating hydrogen pressure of the turbo generator (if applicable)
- Manufacturer and age of the machine

The factors that did not have a significant impact on the Qm distribution are:

- Rated power of the machine
- Type of machine (motor or generator)
- Manufacturing method (GVPI vs non-GVPI), at most voltage ratings, but not all.

These results are similar to those found on a much smaller database in 2014 [11].

Table 1 Distribution of Qm for Air-Cooled Stator Windings with 80 pF Sensors at Terminals. The cells contain the Qm (in mV) that have the indicated cumulative probability of occurrence.

Cumulative Probability	Operating voltage (kV)					
	2 - <6 kV	≥6 - <10 kV	≥10 - <13 kV	≥13 - <16 kV	≥16 - <19 kV	≥ 19 kV
25%	7	21	32	45	42	45
50%	24	55	78	111	85	90
75%	71	141	175	239	186	191
90%	208	308	368	488	346	507
95%	393	476	587	730	506	798

Table 1 shows an example of the differences in the cumulative percentiles as a function of stator voltage for air-cooled motors and turbine generators measured in the VHF range with 80 pF sensors at the machine terminals. The cell entries are the Qm in mV at different cumulative distribution percentiles as a function of the voltage rating. For example, 25% of such stators rated 11 kV have a Qm below 32 mV, 50% have a Qm less than 175 mV and 90% have a Qm up to 368 mV. Perusal of the table shows the median (50th percentile) Qm increases as the rated voltage increases, except for machines rated 16 kV and above which are almost always large generators. The differences in Qm at any percentile against the rated voltage is highly significant (< 0.01% being due to chance). The significance of Table 1 is that a Qm for a 3.3 kV motor should not be compared with the Qm for a 13.2 kV motor. As discussed in [11], the results in this table have been correlated with visual inspection of hundreds of stator windings that have significant insulation deterioration, or had failed. It seems that when the Qm for a particular rated voltage is at the 90th percentile or higher, there is a very high likelihood of serious insulation deterioration. Thus the 90th percentile is defined as an “Alert” or “high” PD level.

These Alert levels are valid for the measurement system using 80 pF sensors at the machine terminals only, a VHF instrument with inherent pulse-by-pulse signal identification based on time-of-flight and pulse shape analysis [1,2,4,10], and the Qm calculation method in IEEE 1434 and IEC 60034-27-2. The table is not valid for any other types of sensors, sensor location, LF or HF instrumentation, and where there is not an automatic means of noise separation (i.e. a human intervention is required to distinguish between PD and other signals by defining clusters or filter settings). It is also clear that the voltage rating needs to be considered (at least for VHF detection). Thus, 11 kV and 13.2 kV motors should not be bundled together and use the same “Alert” level, as proposed in [7, 8].

In contrast, the cumulative probabilities of Qm do not seem to depend on the power rating of the machine. Figure 2 shows a chart of the Qm at different percentile as a function of air-cooled turbine generator power rating. The power rating categories in Figure 2 are 1: 0-3 MW, 2: 3-5 MW, 3: 6-20 MW, 4: 21-50 MW, and 5: over 51 MW. “All” is the Qm at the indicated percentile for all machine power ratings.

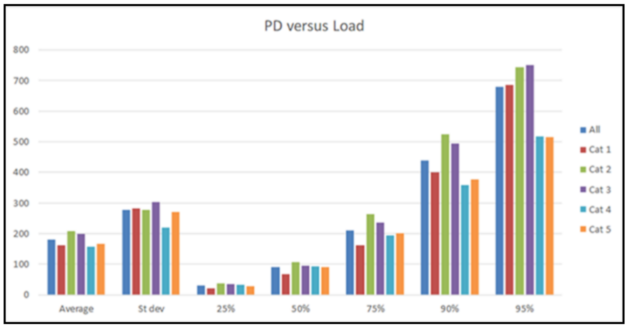

Figure 2 Effect of generator load on the different cumulative percentiles of Qm.

CONCLUSIONS

Although some PD measurement system vendors and at least one standard suggest that stator winding inspection is required if the PD level is 15-25 nC, and the winding is unreliable if the PD activity is higher than 25 nC, such guidance should be used with extreme caution. The reasons for this caution are:

1. Considerable theory indicates that apparent charge, using the calibration procedure in IEC 60270, is only valid for PD measurement frequencies below 1 MHz. Furthermore, the calibration procedure will not yield the same apparent charge for different IEC 60270 instruments used on inductive-capacitive test objects such as stator windings. The concept of adopting apparent charge as an absolute and universal indicator for stator winding PD magnitudes is therefore not theoretically valid. Apparent charge is only useful as a relative indicator of PD activity provided that the tests are carried out on the same design of stator winding, using the same model of PD detector with the same frequency settings. This is consistent with the findings in [9] for a LF/HF PD detector.
2. For a VHF detection system, the stator winding behaves more as a surge (characteristic) impedance, rather than a complex lumped LC network. The power rating of the machine does not have much effect on what is considered “high” PD. However, the rated voltage does have an important impact on what is considered “high” PD. Thus the use of a single level to represent high PD for all stator windings is not valid for PD measurements in any frequency range.
3. A single PD activity to indicate which stator windings are at risk should be deleted from IEEE 3004.8. If any level is given, it must be made clear that that it is valid for which specific measurement system/vendor used, and the restricted range of machines.

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