ANALYSIS OF A PARTIAL DISCHARGE DATABASE TO DETERMINE WHEN STATOR WINDING INSULATION MAINTENANCE IS NEEDED

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Abstract On-line partial discharge testing and monitoring have been widely applied by petrochemical industries on large motors and generators to determine the need for maintenance of the stator winding insulation system. Over the past 20 years, a single consistent method has been used to collect on-line PD data from over 22 000 motors and generators equipped with the required sensors. Of these, PD data from 8500 machines collected to the end of 2021 have been assembled into a single database, along with machine ratings and machine operating data. For each machine, the PD magnitude for each phase from the most recent test when the motor or generator was operating at normal load and stator winding operating temperature was statistically analyzed. The cumulative probability of occurrence for any PD activity level for any particular machine rating, manufacturing method and winding design etc. could then be produced. It has become clear that the probability distributions for different stator winding operating voltages produce statistically significant distributions for machines of various voltage ratings. Over the years, these probability tables have been correlated with visual inspections of hundreds of stator windings as well as off-line test results. This analysis indicates that when the PD magnitude is higher than about 90% of similar machines tested with the same method, then there is a very high probability of significant stator winding aging. This, combined with the evolution of PD over time, can be used to determine when maintenance is advisable.

Index Terms — partial discharge, stator windings, on-line testing, maintenance

I. INTRODUCTION

Partial discharges (PD) are small localized electrical sparks that take place in equipment rated 3 kV and above, which indicates that the electrical insulation is deteriorating, and that equipment failure may occur [1]. Most stator windings 3 kV and above will have some level of PD occurring over its entire life. However, if the PD is high or increasing in stator winding insulation systems, there is a greater risk of motor or generator failure. On-line PD testing has been a tool to determine when stator windings need maintenance or replacement since the 1950s [1, 2]. Today, there are many types of PD sensors and instruments available to measure the stator winding PD activity on-line, either periodically or continuously [1, 3, 4]. The sensors required have been permanently installed on tens of thousands of critical motors and generators [5].

Both IEEE and IEC have created recommended practices, guides and technical specifications, loosely called "standards" here, for the on-line measurement of PD on stator windings [3,4]. These "standards" review the reasons for measuring PD, present a list of available PD sensors (in the case of IEEE 1434) or suggest the most common sensors (in the case of IEC 60034-27-2), discuss the instrumentation and what affects PD results. What these documents do not provide is clear guidance on when stator winding maintenance is needed.

This paper reviews the stator winding insulation problems that on-line PD testing can find and discusses why giving clear interpretation advice is difficult. In addition, for the same winding insulation condition, the PD activity level can be very different for different types of sensors and instruments that are commercially available even with so-called calibration. As a result, establishing what is low and high PD magnitude depends completely on the sensor-instrument system used to measure the PD. This paper describes also how it is possible to overcome this limitation using a large database of on-line PD results collected with one sensor/instrumentation combination.

II. ON-LINE PD BASICS

A. What PD Detects

IEEE 56 presents a summary of the insulation problems that can occur in stator winding due to either manufacturing problems or aging during operation [6]. The most likely causes of PD due to manufacturing problems are:

- Poor impregnation of the windings by epoxy, leading to tiny cavities within the groundwall
- Poorly made or installed PD suppression coatings
- Coils at different voltages that are too close together in the endwinding region of machine windings.

Problems caused by machine operation that can be detected by on-line PD tests include:

- Deterioration of the insulation in all types of windings due to long term operation at high temperatures (greater than about 110 °C)
- Coils that vibrate in the stator slots in non-global vacuum pressure impregnated (non GVPI) machines
- Load cycling of machines
- Contamination of any type of stator winding by dust or dirt combined with oil or moisture, leading to electrical tracking.

More details and repair options for each mechanism are given

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in [7]. Note that loose coils in the stator endwindings, metallic debris and flooding of the motor are less likely to be detected by on-line PD testing. Poor impregnation of multi-turn coils where the voids are only between turns within the copper stack will not produce PD due to the low interturn voltage.

B. PD Detection Methods

On-line PD monitoring requires the installation of one or more sensors on the motor or generator terminals during a short turnaround. The sensors detect the short duration (a few nanoseconds) current pulse which accompanies each partial discharge. The most common sensors used for motors and generators in the petrochemical industry are:

- 80 pF capacitors, usually one per phase in the machine terminal box for motors, and two per phase in the terminal box and outgoing bus duct for generators (IEEE 1434 Table 1, Method 1)
- 1 nF (or so) capacitors, one per phase in the motor or generator terminal box (IEEE 1434 Table 1, Method 14)
- High frequency current transformers (HFCTs) on the connection between surge capacitors (if present) and ground in the motor terminal box (IEEE 1434 Table 1 Method 8).

In addition, one supplier installs the HFCT on the connection between the power cable insulation shield and ground at the switchgear [8], rather than at the motor terminal box, although there is controversy on the sensitivity of the method given that the PD pulse will be attenuated and dispersed after travelling through many (if not hundreds) of meters of power cable, in addition to other limitations.

The signals from one or more of these types of sensors are measured by portable instruments or continuous monitors [1, 3, 4]. The instruments in current use for air-cooled machines tend to work in the high frequency (HF, 1-30 MHz) or very high frequency (VHF, 30-300 MHz) range. The selection of frequency range involves a trade-off. HF instruments use less expensive electronics, may be more sensitive to PD occurring remote from the high voltage end of the stator windings, but are more likely to suffer high false positive indication rates due to electrical noise and PD from outside the machine [1, 3, 4]. VHF systems may be less sensitive to PD in coils operating at lower voltage, but have a lower false positive indication rate due to the use of noise suppression techniques of pulse shape analysis and time-of-flight analysis to separate disturbances [1, 3, 4, 9]. Almost all suppliers claim to use “advanced noise suppression techniques” using artificial intelligence (AI)--based pattern recognition or similar pattern recognition tools, although the exact approach is never identified, which makes validation somewhat difficult.

There are two main characteristics of the PD that are measured by the instrumentation. The first is the peak PD magnitude. The PD magnitude tends to be proportional to the size of the defect causing the PD. Simplifying, the larger the defect, then the less good insulation there is between the copper and ground to prevent a winding short circuit. Thus the highest PD pulse measured is an indicator of the biggest defect. In factory testing using IEC 60270-compliant instrumentation, the peak PD magnitude is called the quasi-peak apparent charge Q_{IEC} and measured in pico Coulombs (pC) or nano Coulombs (nC). Q_{IEC} is determined according to the calibration method in IEC 60270 [10]. As discussed in IEC 60270, for technical reasons Q_{IEC} is intended only for capacitive test objects and measurement frequencies below 1 MHz. In this case, the Q_{IEC} should not be used as a gauge of the peak PD magnitude for on-line testing of inductive/capacitive stator windings. More precisely, the PD magnitude measured even on the same stator winding by different IEC 60270-compliant detectors will almost always yield significantly different Q_{IEC} values [11]; that is, Q_{IEC} is not an absolute indicator of peak PD magnitude in windings. When Q_{IEC} is used for on-line measurements, it should be taken as a relative indicator of PD activity. This is why in IEEE 1434 and IEC 60034-27-2, another indicator of peak magnitude is also used. Qm is defined in terms of mV, not pC or nC. This conveys that Qm is still a relative indicator and not an absolute one. Qm is determined digitally and is the PD pulse amplitude at a recommended repetition rate of 10 pulses per second (pps), although other pulse count rates are acceptable. Qm is clearly taken as a relative indicator of peak PD magnitude. Other less common indicators of PD activity are also used, including NQN (Normalized Quantity Number), NQs, total PD current and total PD power, etc. [1, 3, 4]. These tend to represent the average or overall PD activity in the stator winding, rather than the condition at the worst location like the Qm does.

The other main outcome from an on-line PD test is the phase-resolved PD (PRPD) plot (see example in Fig. 1). The PRPD plot is the PD magnitude vs pulse repetition rate vs 50 or 60 Hz ac phase angle. The PRPD plots can help users distinguish between stator winding PD and interference, and sometimes help differentiate between the different root causes of stator winding insulation deteriorations (Section II A). AI tools such as deep learning and training neural networks purport to be able to do this automatically in the absence of an expert, although little blind testing has been done to substantiate this.

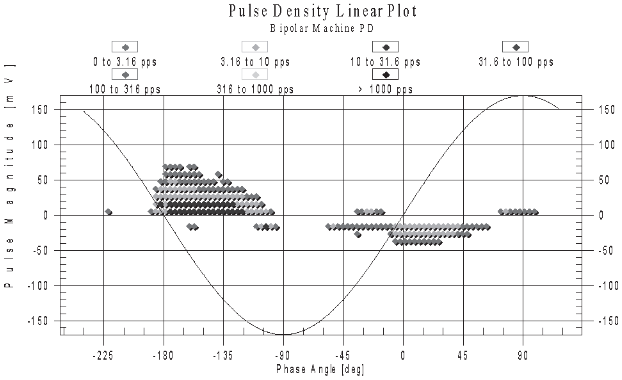

Fig 1: Typical PRPD plot for a PD test on an operating stator winding. The colored dots indicate the pulse repetition rate per second.

C. When is Maintenance Needed?

The main purpose of on-line PD testing of machines is to help asset managers determine when stator winding maintenance would be prudent to avoid an in-service failure. The only practical advice on this in the standards is based on the change in Qm over time. Clause 11.5 in IEEE 1434-2014 suggests “doubling of the Qm in 6 to 12 months may indicate rapid aging-insulation condition change”. However, this advice come with limitations.

The normal variation in PD activity from minute to minute in on-line tests seems to be around +/- 25% [1, 3, 4, 5]. In addition, when there is considerable aging present in a winding, the PD activity tends to stabilize and no longer increases, even though aging is continuing [5]. Thus if a PD monitoring system is installed after the deterioration has already reached an advanced stage, the apparently flat trend over time would erroneously imply that machine owners do not have to worry about imminent failure. Furthermore, this trend guidance implies that if the activity doubles from initially very low levels, then maintenance activity is warranted when in fact it is not. Clearly the "doubling" rule is only useful when the activity is above some threshold. Lastly, if there is only one on-line test result, no guidance is given in the standards on the winding insulation condition, since all the indicators are relative.

Section 11.1 of IEEE 1434-2014 does state that these limitations of the PD activity trend can be overcome if there is a database of "tests on particular insulation systems and winding configurations, by means of a common detection system", then establishing what is high and low PD may be possible. This paper presents such an analysis of a very large database of results on air-cooled motors and generators, of which the PD is measured by the same method. Statistical analysis is used to determine what machine ratings constitute "similar" windings, and what the normal range of PD activity is.

III. ON-LINE MEASURMENT METHOD

Over 22 000 motors and generators have been equipped with one method of on-line PD detection. Although there have been many changes in software and hardware over the years, the basic detection technology and signal separation method have remained the same since 1993. The system is based on 80 pF capacitive sensors installed at the machine terminals and either a portable instrument or continuous monitor operating in the VHF range, and using pulse shape analysis, time of pulse arrival or both to separate stator winding and terminal box PD from power system noise and external interference. Further details are given in [1, 9]. The suppression of noise from stator PD ensures the false positive indication rate is below about 1.5%, which enables the statistical analysis to be completed without humans vetting each test result. Then the Qm analyzed in Section IV represents actual stator PD, rather than external electrical noise or PD from outside equipment. The method does exhibit some false negative indications [5], but these are on the order of about 10 machines (out of all tests reported per year.

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IV. PD DATABASE

The database collected to the end of 2021 consists of over 750,000 on-line PD tests from 8500 motors and generators. The tests in the database are gathered mostly from on-line periodic tests, usually collected every 6 months, using a portable instrument. The data was mainly collected by the owners/operators of the motors and generators. Most data came from generation utility machines, with about 20% from petrochemical industry motors and generators. About 2700 of the machines in the database are motors. That data was collected on machines from around the world, but most of the data comes from Europe and North America.

At this time, the data from over 5500 continuous PD monitors using the same basic measurement principles was not included to ease database assembly. Each continuous on-line monitor produces a lot of data, and for the most part that data was not shared with us, but side-by-side studies show they have the same characteristics as data from periodic testing.

The analysis was performed on a reduced "dataset" culled from the database. The following data was included in the statistical analysis:

- Only the most recent test result from each phase of each machine was used. Previous results are related to the most recent test (unless the machine was rewound or repaired), and thus are not statistically independent.
- Only test results where the motor or generator was operating at or close to normal operating load and normal operating temperature are included. That is, off-line PD tests or data collected at low load were excluded from the analysis. This is because load and winding temperature can affect the PD test results, and therefore would contribute to additional data variability [1, 3, 4].
- Only data from air-cooled motors and generators are included. A separate study [12] shows that the hydrogen gas pressure in large turbine generators results in much lower Qm levels, everything else being equal.

As a result of these exclusions, the dataset was reduced to 27 000 independent tests. For the purposes of this paper, hydrogen-cooled turbine generators and low-speed hydro generators are excluded from the analysis, but analyzed separately.

V. STATISICAL ANALYSIS APPROACH

The Qm data (and sometimes the NQN) from each test result were ordered from smallest to largest and the cumulative probability of occurrence of particular Qm levels were determined. Then the dataset was parsed to determine the cumulative probability distribution for several different factors. The parsing factors were:

- Operating voltage of the machine (which is normally closely related to the rated voltage)
- Maximum operating load in MW or HP (closely associated with the rated load)
- Machine type (motor, turbogenerator)
- Nameplate year of manufacture
- Stator winding manufacturing method (GVPI vs non-GVPI)

Other factors such as the effect of hydrogen pressure in turbogenerators and the difference between turbo and hydro generators was also analyzed [12], but not reported here.

In most cases the cumulative probability distributions were simply compared to see if different factors resulted in different distributions. When the simple comparison was not conclusive, a line was fit to the Qm vs factor curve, the R^2 was calculated, and the factor significance value was calculated [13]. The factor significance is the likelihood that the results would occur by chance. For example a 5% significance factor means that there is a 1 in 20 possibility the results would have occurred by chance. The lower the significance level, the more dependent the results are on the factor or combination of factors.

VI. ANALYSIS RESULTS

A. Effect of Voltage

Table 1 shows a table of the Qm distribution collected up to the end of 2021 for air-cooled motors and turbo generators as a function of operating voltage, while ignoring the winding age, manufacturing method or power rating of the machine. For example Table 1 shows that for a 6.6 kV stator winding, 25% of machines have a Qm <21 mV, 50% of stator windings have a Qm <55 mV, 75% of 6.6 kV machines have a Qm <141 mV, etc. It is clear from Table 1 that the median (cumulative 50% probability) increases as the voltage increases from 4 kV machines until 15 kV. However for machines rated 16 kV and above, which are almost always turbo generators in generating utilities, the medians are significantly lower. The other percentiles of the distributions show the same trend for rated voltage, and the differences between voltages is significantly different with a very high level of confidence, due to the large amount of data.

Data has also been analyzed for data collected at different year ends (i.e. ignoring later years). Fig. 2 shows the trend in cumulative percentiles over the past 25 years for 11 kV stators. Except for the early years when there were relatively few test results in the dataset, the Qm at different percentiles have been essentially stable over the years.

TABLE I.
DISTRIBUTION OF Qm FOR AIR-COOLED STATORS WITH 80 pF SENSORS ON THE TERMINALS
The cells contain the Qm (in mV) that have the indicated cumulative probability of occurrence

Cumulative Probability	**Operating voltage (kV)**					
	2 - <6kV	**≥6 <10kV**	**≥10 <13kV**	**≥13 <16kV**	**≥16 <19kV**	**≥ 19kV**
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

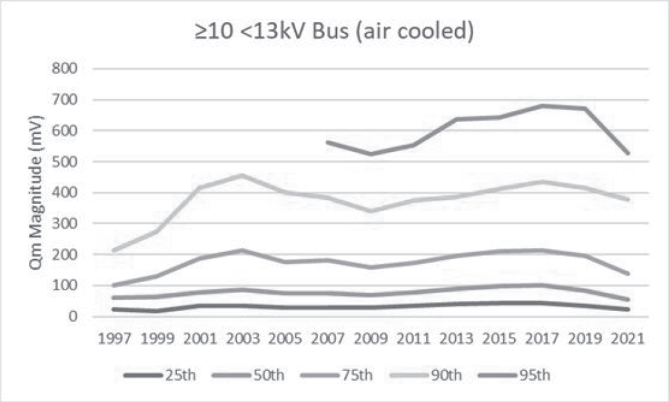

Fig. 2 Trend in cumulative probability percentiles versus year for 10-12 kV rated machines collected up until 2021. Similar trends were found for 6.6 and 13.8 kV machines.

Over the years visual inspections of the stators, usually by the machine owners or their service shops, have been correlated with the PD test results. In a 2006 summary paper of over 200 machine inspections and/or failures by end users [14], there was a significant correlation with the 90th percentile values in Table 1 and the independently confirmed actual condition of the stator winding. Many dozens of more recent case studies have confirmed this initial result. Thus it seems that for any particular rated voltage, machine owners can treat the 90th percentile as an "alert" that stator winding insulation aging may be occurring. The Qm values in Table 1 are only valid for the particular PD measurement system used in the dataset. However the 90% levels go some way toward answering the question of what is low and what is high PD activity. A utility independently did their own statistical analysis of hydro generators using the same sensor and VHF instrumentation and found the Qm percentiles were very close to those shown in Table 1 [15].

The NQN values (which are an indicator of the total PD activity in the that phase of the stator winding) were analyzed in the past. There seemed to be little correlation between high NQN and the observed condition of the winding. Perhaps this is because even though many coils may have PD contributing to a high NQN, in a visual observation one tends to look at the areas of most severe deterioration.

B. Effect of Power Rating

It seems reasonable to assume that machines with different power (MW or HP) ratings would have different statistical distributions of Qm, since the winding designs are different and have different capacitances and inductances. But in fact this was not found to be the case. In the analysis, the operating load is taken to be an indicator of the rated load of the machine, since only data from machines operating at or near rated load are included in the dataset. Figure 3 shows the different Qm at various percentiles for air-cooled machines with different (rated) loads. Also shown in the dark blue bars is the percentiles including machines of all load and voltage ratings. It seems that there is no consistent pattern vs load. Thus unlike rated voltage, there is no consistent relationship between "high PD" and the load. We infer that as long as the voltage rating is the same, the power rating does not make a difference to what is high or low PD. Note however that Figure 3 shows a very high standard deviation on the mean, which makes proving statistical significance more complex.

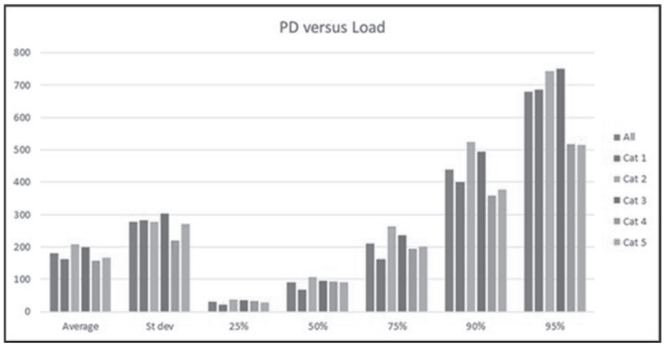

Fig. 3 Effect of generator load on the different cumulative percentiles of Qm. The categories are 1: 0-3 MW, 2: 3-5 MW, 3: 6-20 MW, 4: 21-50 MW, 5:>51 MW. "All" is the Qm at the indicated percentile for all machine loads.

C. *GVPI vs. Non GVPI*

Over the decades there have been endless debates about which stator manufacturing technology is superior. For mainly economic reasons, the GVPI process of impregnating complete stators with epoxy is used by virtually every motor OEM. However, generator stators continue to be made with both the GVPI process, as well as individual coil impregnation process using either the resin rich (including variants called press cure or B stage processes) or the single-coil VPI process. Since some air-cooled turbine generator manufacturers are known to prefer the GVPI process beginning about 1990, the OEM was used as an indicator of manufacturing process. This will sometimes be in error (and increase the standard deviation) since not all of an OEM's plants change their manufacturing process at the same time. Fig. 4 shows results for 11 kV and 13.8 kV generators, which are the most common voltages for such machines in petrochemical applications. 13.8 kV is more widely used in North America. There appears to be little difference between processes for 13.8 kV machines, but 11 kV machines made with the GVPI process clearly have higher Qm, everything else being equal. This points toward 11 kV GVPI stators having more voids within the groundwall insulation. One can only speculate what the reason for this is.

Regrettably the database does not capture information about the single coil impregnation process, so that the PD database analysis yields no information on the relative PD levels of resin rich and VPI coil impregnation processes.

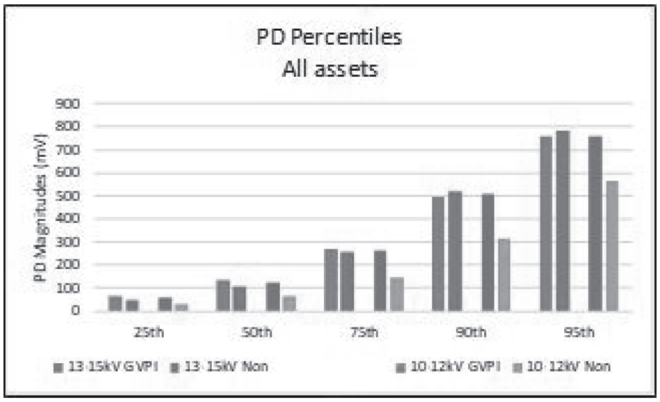

Fig. 4 Cumulative probability distributions for Qm when comparing GVPI and non-GVPI epoxy impregnation processes.

D. *Type of Machine and Owner*

One might expect that whether the stator is from a motor or a turbo generator may have an impact on the statistical distributions. In fact this was not the case. The calculated significance factor (see Section V) for type of machine is 64%, which implies the factor is not significant (or would occur 64% of the time by chance).

The situation is more interesting if one compares machines in generating stations with those used in industry. For 6.6 kV motors, industrial motors have higher Qm than utility machines, everything else being equal (Fig. 5a). Yet for 13.2 and 13.8 kV machines there is no significant differences between utilities and industry (Fig. 5b). The reasons are unknown.

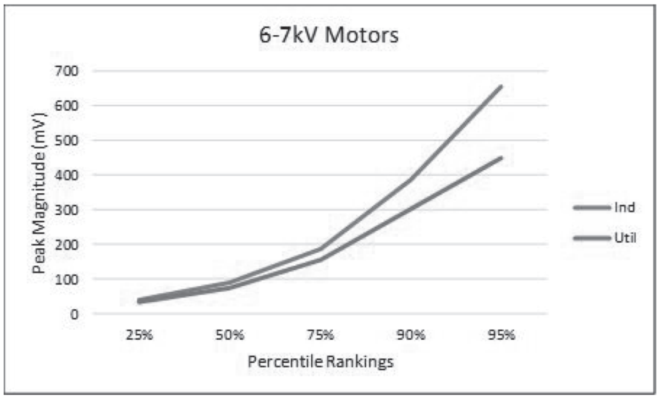

Fig. 5a Cumulative Qm distributions for 6.6 kV machines.

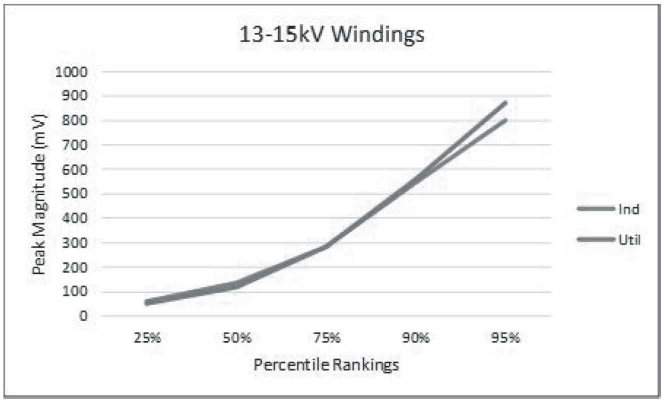

Fig. 5b Cumulative Qm distributions for 13.2/13.8 kV machines.

E. *Summary of the Factors of Influence*

The operating voltage of the stator windings must be considered when establishing if the Qm from a machine is low or high. That is, the results from a 4.1 kV machine and a 13.8 kV machine cannot be directly compared. However most other factors including machine power rating, whether a machine is a motor or generator, and in most cases whether a stator winding is made by a GVPI or non-GVPI process, has no influence on the statistical distribution of Qm, and thus whether a particular Qm reading is high or low.

Note that Table 1 is only valid for the measurement system used. PD sensors of other types or capacitances will not produce the same statistical distributions. The table is also only valid if noise and disturbance have a negligible influence on the Qm for each machine.

VII. CASE STUDY

A refinery located in British Columbia, processes 55 000 barrels a day of sweet crude, Transmix and renewable co-processing. The refinery operates a fluid catalytic cracking unit (FCC). The main air blower (MAB) is a large axial compressor with a low compression ratio to blow regeneration air into the FCC regenerator. The MAB is driven by an induction motor through a speed increasing gear via couplings. The compressor is connected to the high-speed end of the gear, and the motor is horizontally connected to the low-speed end of the gear. The

MAB induction motor is rated 5500 hp, 1800 RPM, 3 phase 60 Hz, 12 kV, and with TEWAC enclosure and forced lubricated sleeve bearings. The stator insulation is a Class F global VPI epoxy-mica system designed for an 80 °C temperature rise at full load.

The refinery has two motors for this critical application. The original motor (FC6638) was manufactured in 1984 and ran from 1984 -2000. This motor was replaced with a new build from the same manufacturer in 2000 (FC7940). The old motor was put into storage as an emergency spare. Both motors have chronic lubricating oil leaks due to the absence of labyrinth seals in the bearing housing, which contaminated the stator winding. In normal operation, this unit is expected to operate continuously for a 5-year interval. The asset maintenance strategy has been removing the motor from service every 10 years for overhaul at a local motor shop. The stator is steam cleaned, oven dried and varnish treated. In 2015, the motor lead insulation was found having cracked and exposing the conductor, due to oil impregnation and swelling. The leads were re-taped with guideline self-vulcanizing tape, mica mat tape and 25 kV shrink sleeving. Stator maintenance tests in the motor shop included insulation resistance (IR), polarization index (PI), winding resistance and surge voltage tests. Offline motor circuit analysis was conducted on site opportunistically or at a 5-year interval to trend the IR to ground, capacitance to ground, phase-to-phase resistance, phase-to-phase inductance, PI and dielectric absorption. On-line motor circuit analysis is conducted annually for monitoring on power quality, rotor bars and air gap eccentricity. The motor is consistently operated at a steady load of approximately 75% rated. The six stator RTDs show a temperature of about 72 °C throughout its operation. Summer ambient temperatures typically do not exceed 25 °C.

Based on the findings in 2015, the motor was removed from service again in 2020 for inspection and testing, with the above tests being conducted. The motor was deemed suitable for operation and returned to service.

In March 2020, a continuous online PD monitor was installed with 80 pF epoxy-mica capacitive PD sensors on each phase to enhance the condition monitoring on this asset. Initial results were considered very high, but the commissioning report noted that potentially the very high magnitudes were possibly due to ineffective maintenance in the recent outage and further analysis in six months was strongly recommended. PD magnitudes were trended over an 18-month period. Qm+ values of 900-1000 mV were recorded from Phases A and C. (Figure 6), nearly three times higher than the highest Qm of a similar 12 kV asset.

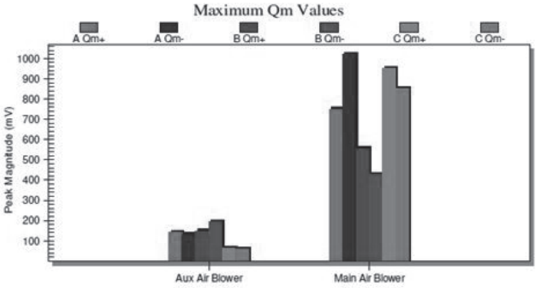

Fig. 6 September 2021 Qm+ and Qm- values for each phase for the “new” MAB motor FC7940, as well as another 12 kV motor in the refinery also equipped for continuous PD monitoring which has much lower PD activity.

These PD magnitudes indicate that the PD levels in the FC7940 are higher than 95% of 12 kV motors measured with the same PD system (Table 1), where if an upward trend persists, further investigation is warranted.

Given the criticality of this motor to the overall operation and the requirement to run continuously, the maintenance decision was made in October 2021 to remove FC7940 from service and swap it with the old motor (FC6638) in storage, outside of its normal turnaround cycle. This decision was based on elevated and increasing PD magnitudes observed in data trending when compared to the statistical database for similar machines. (Figure 7). A phase-resolved PD plot of the PD activity in C phase (Figure 8) indicated a classic PD pattern with respect to the ac cycle, attributing the PD in the stator winding ground wall insulation [1, 3, 7].

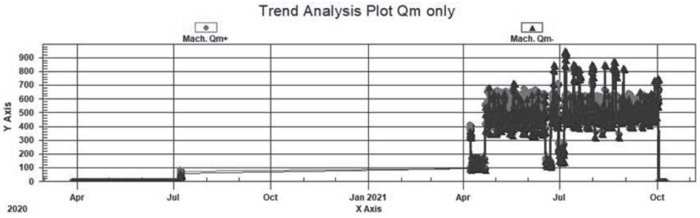

Fig. 7 PD trend plot for C phase in FC7940 from Apr 2020 – Oct 2021. The monitoring instrument was out of service from July 2020 to April 2021.

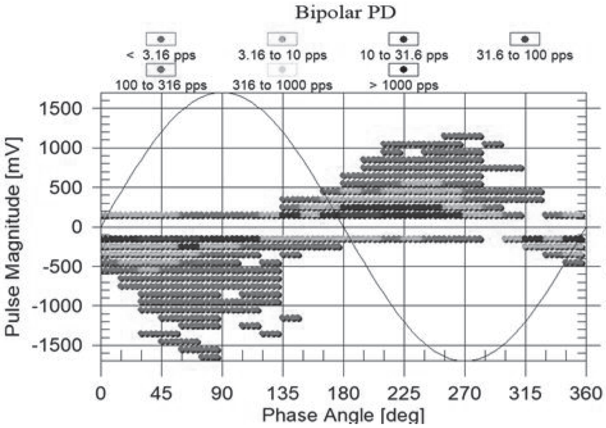

Fig. 8 Phase resolved PD plot of PD activity versus 60 Hz ac cycle for the C-phase of FC7940 measured on October 1, 2021, just before removal from service.

For comparison purposes, when FC6638 was returned to service after being in storage for 20 years, the recorded PD magnitude was significantly lower than the newer FC7940 motor (Figure 9). Clearly it has much lower PD activity than the new motor, which is well below the 90% Alert level of similar machines (Table 1).

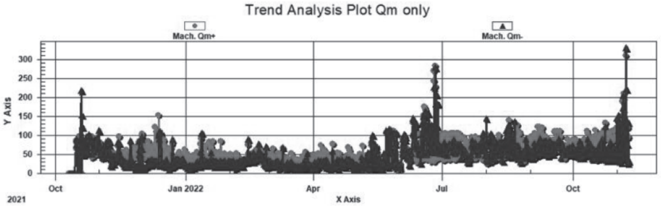

Fig. 9 PD Trend plot for A phase of FC 6638 from October 2021 when it was re-installed, until November 2022. The other phases had lower activity.

After FC7940 was removed from service, the stator was again steam cleaned and oven dried, and the motor was re-leaded with medium voltage high temperature flexible cable that is oil resistant. An off-line power factor (PF) tip-up test was performed with results that were overall consistent among the three phases for the various test voltages for both PF and capacitance measurements. The tip-up results may be considered high at 2%, but there were no prior tests for comparison, nor a similar machine with which to compare the results. This triggered another set of off-line tests to evaluate the health of the insulation system by a third party. These tests included:

- Polarization – depolarization current analysis (PDCA)
- Tan delta & capacitance analyses (TDCA)
- Non-linear insulation behavior analysis (NLIBA)
- Offline PD analysis

PD source(s) were suspected by the third-party tester to be internal voids and possible surface discharge activity, consistent with the on-line PD results. All three phases reveal characteristic clusters of pulse activity at 45°/225° phase positions. This pattern of uniform distribution of negative and positive pulses typically indicates the presence of micro-voids forming within the slot section of the coils due to thermal aging, and possibly with voids present from manufacturing [1, 3, 7]. The TDCA analysis by the third-party tester indicated that the discharge void volume content (%) is two times greater than the normal range of 0.5%. The offline partial discharge analysis confirmed that there is evidence of discharging of voids or delamination within the insulation from the partial discharge patterns recorded, with the internal discharge seen to be the most dominant discharge pattern. The overall result of this testing confirmed what was suspected from the recorded online partial discharge magnitudes. The stator winding insulation can be described as weak, and so the winding is not suitable for long term reliable service in a critical application.

Since FC7940 was stocked as a contingency spare, the refinery has time to evaluate repair or replacement options for the motor. The options that exist include:

- Consider operating after exchanging the line and neutral connections, with the theory being that the degradation by PD has not occurred evenly throughout the winding, instead occurring mainly at the line ends. The assumption is that the aging is not entirely related to thermal aging since the stator maximum operating temperature has been much lower than its allowable temperature rise.
- Rewind the existing stator and modify the bearing housing with seals to address chronic oil leak
- Purchase a new motor

This case study highlights the benefit of online partial discharge monitoring as an effective condition monitoring tool. PD trends, combined with guidance provided from statistical database has enabled this facility to make a planned maintenance decision, preventing costly, and in this instance, catastrophic production losses with an unplanned failure on the stator winding.

VIII. CONCLUSION

1. Statistically significant differences in the Qm probability distributions occur for different voltage ratings. One should avoid comparing PD levels from stators with different voltage ratings, even when the PD sensors and instrumentation are the same.
2. The power rating of the motor or generator does not result in different distributions, and the manufacturing method (VPI, resin rich, GVPI) has only a minor impact.
3. By comparing the statistical distributions with visual inspections of the stator windings, it seems when the Qm is higher than about 90% of the Qm of similar windings, significant winding problems are almost always apparent. The 90% Qm level has therefore become the “Alert” level for when further tests or maintenance is advisable.
4. The Alert levels for most machine ratings has essentially been stable for 20 years. However some types of machines or PD sensors that are not well represented in the database are less stable.
5. PD levels can be assessed in comparison to the database and the Qm Alert levels depend on the voltage rating of the stator winding.
6. A case study of an air compressor motor has shown that both the trend and the level of the PD can help guide maintenance alternatives.

IX. ACKNOWLEDGEMENTS

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