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Stator Winding Partial Discharge Activity for Marine Air-Cooled Generators

ABSTRACT

Maintenance personnel need as much advanced notice as possible and ease of reliable data collection when problems develop within the stator winding insulation system of air-cooled generators on marine vessels. Unfortunately, traditional off-line testing does not provide this, as tests are not done under normal circumstances due to mechanical, thermal, ambient and electrical stresses.

Partial discharges (sometimes also known as corona) are known to occur in deteriorated stator winding insulation systems, as well as new systems with manufacturing or installation flaws or shortcomings. Therefore, Partial Discharge (PD) activity is an indicator of the presence of some deterioration mechanisms at work within, or on, the solid insulation of the stator windings of high voltage rotating machines. Although off-line PD has been used for marine vessels, it fails to detect problems related to mechanical, thermal, ambient and even normal electrical stresses. Advances in on-line detection and measurement of partial discharges has resulted in monitoring equipment that provides a knowledgeable user with reliable and repeatable information regarding the behavior of an insulation system while a machine is in operation.

This paper will highlight some of the limitations and benefits of traditional off-line testing and on-line PD testing using case studies and signal analysis from marine vessel applications.

INTRODUCTION

Generators in marine vessels are often multi-turn coils manufactured using a mica-based system and global vacuum-pressure-impregnation (VPI) process. Due to the complexities present during the impregnation process and inadequate acceptance testing, improper impregnation is more probable in global VPI stators than traditional batch VPI or resin-rich tapes. This can occur as the result of inadequate vacuum or pressure, too high resin viscosity, improper temperatures or foreign objects embedded in the tapes. In the presence of voltage stress, partial discharges will occur across these voids and attack the organic resin. This attack may lead to strand or turn shorts if the voids are near the copper conductors, and eventually multi-turn coil failure will occur. If the voids are in the center of the groundwall insulation thickness, they are more benign and, as any discharges that take place within them are of low magnitude, failure due to the presence of voids can take many years. An additional problem from improper impregnation is that the internal voids create a thermal barrier inhibiting the transfer of heat from the copper to the core [1][2].

A typical design for marine generators includes multiple circuits per phase which results in a high number of high voltage coils and turns per coil. Though the overall current output is relatively low, this design presents some unique susceptibility to premature failure mechanisms. In addition, these machines are frequently load-cycled and operated in unique environments, that include wide swings in ambient conditions, exposure to extensive mechanical vibration, and variability of voltage. Because of this, the most common failure processes of the stator winding insulation system in marine generators are: interturn insulation failure, coil movement, and deterioration of the voltage stress coatings. The latter, the stress coatings, is impacted by the variable ambient conditions, but more significantly, the severe harmonic surroundings. Voltage stress coating deterioration does not usually develop into a failure mechanism; however, it can eventually lead to coil movement which can precipitate a failure.

Over 50 years of experience with on-line partial discharge (PD) testing in motors and generators rated 3.3 kV or above has shown that years of warning is often given of possible winding failure [3] [4] [5]. These sparks or discharges occur when voids exist in the insulation, or between the insulation surface and the stator core, or between components of different phases. On-line PD testing at variable operating loads and temperatures and ambient conditions detects most (but not all) of the common manufacturing and deterioration problems, including:

- Poor impregnation with epoxy
- Poorly functioning voltage stress coatings
- Insufficient spacing between high voltage components of different phases or to ground
- Coil movement
- Overheating (long term thermal deterioration)
- Winding contamination
- Load cycling damage of the interturn insulation

TRADITIONAL OFF-LINE TESTING

Off-line tests are often used to locate and determine the severity or risk of failure, and whether repairs are possible. Off-line tests have the advantages of accessibility, noise-free environments, ease of repair, and test variety. The disadvantages are that there are abnormal mechanical, thermal, and electrical stresses, and they require a machine outage which can be time-consuming.

The insulation resistance and polarization index tests [IEEE Std. 43-2000 [6]] are useful indicators of contamination and moisture on the exposed insulation surfaces of a stator winding, especially when there are cracks or fissures in the insulation. The mica in the stator winding insulation system has virtually an infinite DC resistance value, so these tests do not evaluate if the insulation system is well-consolidated or thermally damaged. Therefore, they are ineffective in locating problems with the interturn insulation, thermal damage, phase-to-phase arcing, voltage stress coatings and coil movement.

The insulation resistance is highly dependent on the temperature and humidity of the winding. As described in IEEE Std. 43-2000, the insulation resistance values can be corrected for the winding temperature (as determined from embedded temperature indicators). It is common to correct the measurements to 40°C. If corrected measurements over the years on the same winding reveal gradually decreasing resistance, then the insulation may be deteriorating. However, it is much more probable that the resistance will swing wildly from measurement to measurement due to humidity conditions [6]. Unless the winding is always measured under exactly the same humidity and temperature conditions, it is complex to track the resistance over time. Similarly, in comparisons between two windings, a higher resistance in one does not imply that this winding is in better condition.

After a winding has passed the insulation resistance (IR) and polarization index (PI) test, it is customary to perform a high direct voltage test [IEEE Std. 95-2002 [7]]. A high DC voltage withstand test may provide some assurance that the groundwall may safely be stressed to normal operating voltage. The DC hipot test is **not** a diagnostic test since the outcome is simply pass or fail. As with the IR/PI test the presence of mica within the stator winding insulation means that this test does not evaluate how well the winding is consolidated.

OFF-LINE PD TESTING

Over the past several years, off-line AC tests, specifically PD tests, have been used more often to evaluate the condition of the interturn insulation, quality of impregnation, and the possibility of thermal deterioration in marine generators. The procedures for this test are described in IEC 60034-27 [8]. Both trending and single-shot results of off-line PD may provide information about the condition of the interturn insulation, possibility of thermal delamination, quality of impregnation, and perhaps the deterioration of the voltage stress coatings.

However, when testing off-line, it is not possible to evaluate the power plant under normal operation, that is, while under full load at sea under severe ambient stress. In addition, off-line tests do not enable

- testing at different loads to investigate coil movement,
- testing at different operating temperatures and humidity to confirm deterioration of the voltage stress coatings,
- testing at phase-to-phase electrical stress to investigate discharges between high voltage coils of different phases, and
- evaluation of the impact of ambient conditions to the PD activity.

Case Study 1: Off-line PD

Ship Power Plant:
Rated: 6.6 kV Power: 3.9 MW
Manu: 1996

The measured results during the off-line PD test:

- Partial Discharge Inception Voltage (PDIV): 2.6kV
- Maximum PD levels: 310mV (High)
- Partial Discharge Extinction Voltage (PDEV): 2.3kV

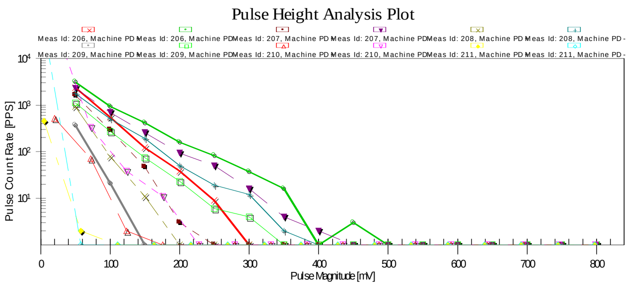


Figure 1. PD at Voltage Increments

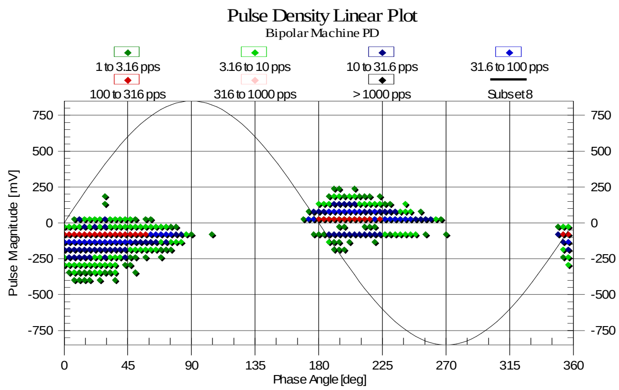


Figure 2. PD Plot (Negative predominant)

Both the inception and extinction voltage were lower than desired, symptomatic of widespread activity, while the maximum PD levels were considered high for a winding of this voltage class (Figure 1). This indicates that this winding has insulation damage. The PD Plot depicts an obvious negative predominance of phase-to-ground activity due to a preponderance of voids within the slot near the copper conductors likely caused by long-term thermal damage due to load cycling (Figure 2). As such, due to the high PD and negative predominance, there was concern about the integrity of the interturn insulation. Because interturn insulation failure is a common occurrence in multi-turn coils for which there is no repair, continuous monitoring was recommended. If the resultant PD trend was upward, a rewind would be necessary.

ON-LINE PD MONITORING

Though trending of off-line tests collected at the same operating and ambient conditions may be useful, it is the on-line trends that can provide the user the most information and be used to compare to results from similar machines. It is preferable to use continuous trending with results at full load while at sea and under variable ambient conditions.

Case Study 2: Off-line PD versus On-line PD

Ship Power Plant:
Rated: 11 kV Power 16.1 MW
Manu: 2002

As shown in Figure 3, surface PD activity from deterioration of the voltage stress coatings (Figure 4) is highly influenced by variable ambient conditions. Therefore, to evaluate the condition of a stator winding based on isolated, off-line test results is ambiguous at best. Caution must taken to consider the influence of ambient conditions when analyzing trend results. More information is provided later in this paper.

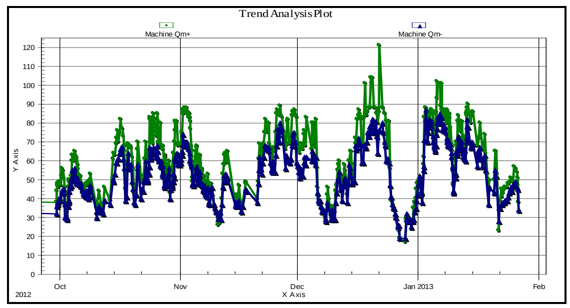


Figure 3. PD Variability with Ambient Conditions - PD ranges 20mV (high humidity) to 122mV (low humidity)

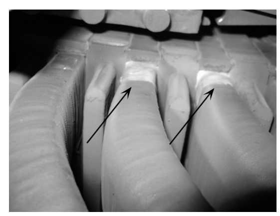


Figure 4. Voltage Stress Coating Deterioration

Case Study 3: Off-line PD versus On-line PD

Ship Power Plant:
Rated: 6.6 kV Power: 3.9 MW
Manu: 1996

A comparison of data collected during off-line (Figure 5) and on-line (Figure 6) testing was done on one generator in a marine vessel. The PD results, the peak magnitudes of each polarity, +Qm and –Qm, as shown in Table 1 are clearly different between the two.

Table 1: Off-line versus On-line

	kV	MW	+Qm	-Qm	°C (amb)	RH
Off-line	6.54	0	156	173	26°	36%
On-line	6.6	3.9	960	1710	26°	36%

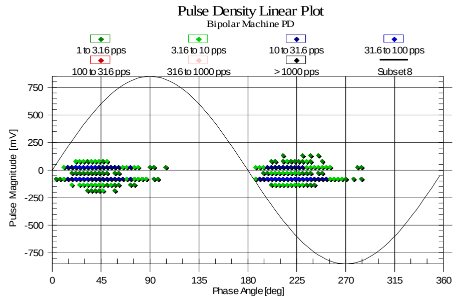


Figure 5. Off-line Test (50-850mV scale)

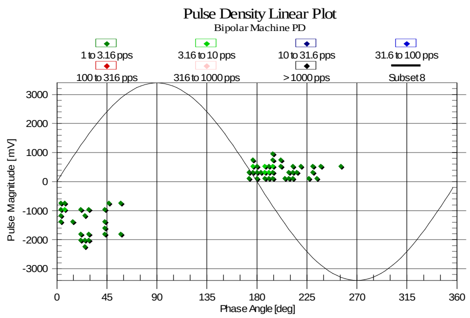


Figure 6. On-line Test (200-3400mV scale)

In addition to differences in the PD magnitudes, the PD patterns from each test configuration also vary greatly as shown in Figure 5 and Figure 6. The predominant on-line source appears to be phase-to-phase activity between two high voltage components of different phases. Off-line test configurations typically do not use phase-to-phase voltage levels as this would be considered an over-potential test, so this problem was not detected during the off-line testing. PD sources that are only active on-line are phase-to-phase voltage stress, mechanical stresses, and higher thermal stress.

EFFECT OF HUMIDITY & LOAD

Perhaps the most influential, yet unpredictable, impacts of ambient conditions to PD are the effects of variances in ambient humidity on air-cooled machines. Humidity can cause the electrical breakdown stress of the air to decrease, and, therefore, cause an increase in surface PD. On the other hand, humidity can also impact the electrical tracking of surface PD, and, therefore, cause a decrease in PD. Present experience indicates that humidity only affects surface activity.

Case Study 4: Humidity

Power plants on ships often travel where there can be significant variability in the absolute humidity due to changes in ambient air temperatures and moisture content. Since surface PD due to deterioration of the voltage stress coatings is a common occurrence on stator windings, it is imperative that the ambient humidity and temperature be recorded at the same time as PD magnitudes. Since each scenario is different, trends must be properly evaluated and decisions not made about upward trends that occur because of humidity effects as opposed to changes in winding condition. As shown in Case Study 2 and here, the PD Magnitudes (Qm values) of surface PD are often inversely correlated with the absolute humidity.

Ship Power Plant:
Rated: 11 kV Power: 16.1 MW
+Qm: 37 mV high humidity
(113 mV at low humidity)
-Qm: 31 mV high humidity
(81 mV at low humidity)
Manu: 2002

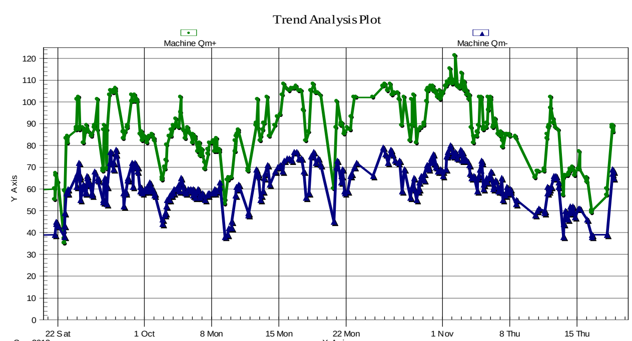


Figure 7. On-line trend – Inverse- Humidity Effect

Figure 8. Surface PD Activity – Voltage Stress Coating Deterioration

The overall levels are considered "Typical" when at low absolute humidity and "Low" at high humidity, in other words an inverse correlation between PD and humidity (Figure 7). This, along with the positive predominance, suggests the predominance of surface activity due to deterioration of the voltage stress coatings (Figure 8). Recommended action is to test at different loads as the next stage in failure mechanism development will be coil movement. Also, as clearly shown in Figure 9, the PD increased at a higher load indicating the onset of coil movement in addition to the stress coating deterioration. Careful inspection of the wedging system revealed that some of the wedges appear to have moved slightly (Figure 10). Though deterioration of the voltage stress coatings is considered a slow-acting failure mechanism, the onset of coil movement changes the diagnosis, as coil movement is considered a fast-acting failure mechanism.

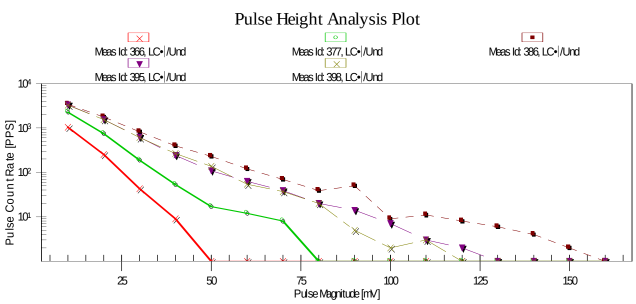


Figure 9. PD Increasing with Load

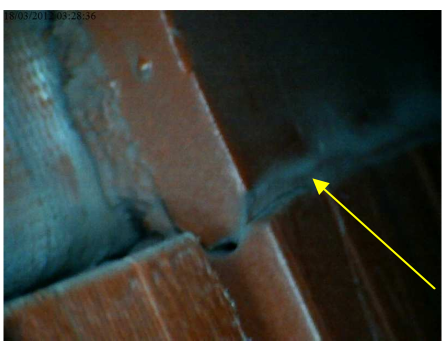


Figure 10. Indication of Wedge Movement

SIGNAL FILTERING – ON-LINE PD

An on-line system needs to provide the user with reliable and repeatable results that are easy to interpret. Most companies prefer a PD test that can be performed by their staff during normal machine operation. Due to the variable operating and ambient conditions and their impact to the PD results, a continuous PD on-line system is preferred.

Power plant generators in marine vessels present a unique challenge in on-line PD monitoring due to the presence of system harmonics from the POD motors. Additional noise/disturbance sources include such things as corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, and/or power tool operation. This noise or disturbance can obscure the PD pulses, and may cause the technician to conclude that a stator winding has high levels of PD, when it is actually not high. Therefore, a dependable continuous on-line PD test should significantly reduce the influence of noise and disturbances, leading to a more reliable indication of insulation condition [10].

"*Noise* is defined to be non-stator winding signals that clearly are not pulses." "*Disturbances* are electrical pulses of relatively short duration that may have many of the characteristics of stator winding PD pulses – but in fact are not stator winding PD" [10].

One common method of noise separation depends on analyzing the shape of individual pulses from 80 pF couplers, one installed per phase (Figure 11). These sensors are most sensitive to detecting the PD at frequencies greater than 40 MHz to maximize the signal-to-noise ratio, and thus further reduce the risk of false indications. In some cases, disturbance separation requires sophisticated filtering systems to deal with harmonics to discern the zero crossings and isolate non-PD pulses that might occur within the PD measuring bandwidth.

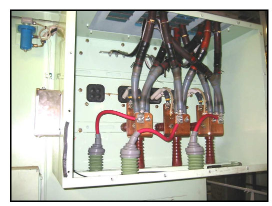


Figure 11. 80pF PD Sensors on an 11kV Generator

While at dock there is a relatively clean signal, so collecting on-line PD data is straightforward using common noise/disturbance separation based on measuring bandwidth and pulse share recognition (Figure 12).

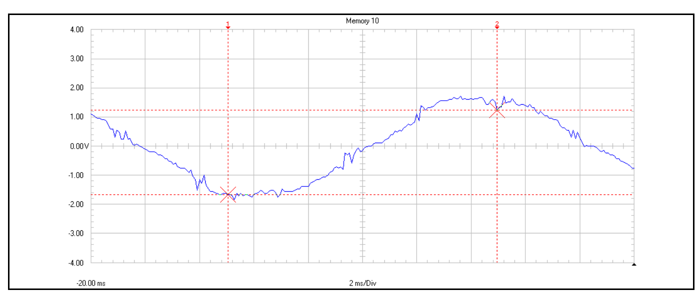


Figure 12. PD Waveform at Dock (time domain)

When the vessel is at sea under full load, the signal is significantly different [9]. While at sea there are significant harmonics from the PODs and other load sources that generate disturbance peaks of up to 7V.

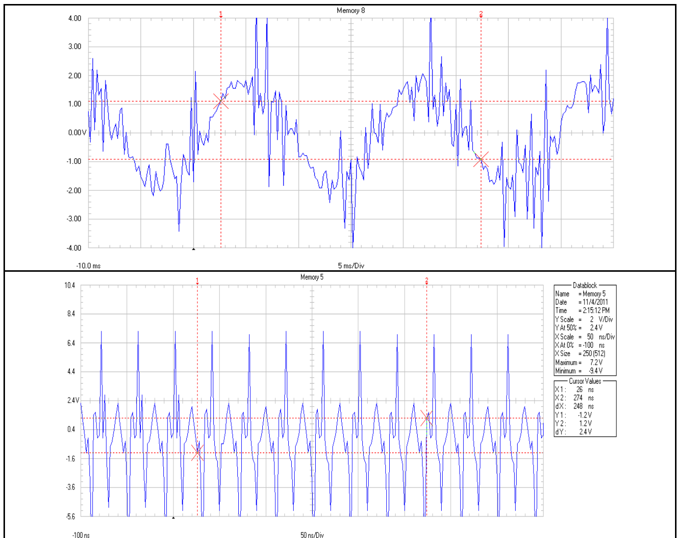
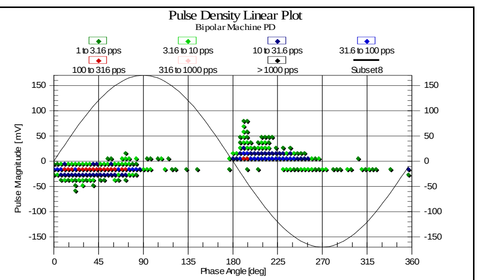
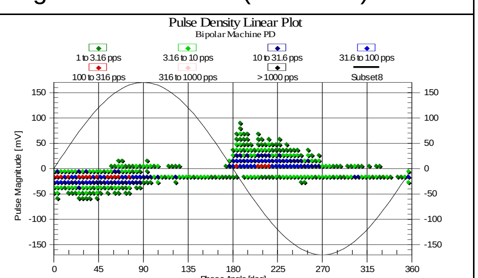


Figure 13. PD Waveform at Sea (time domain)

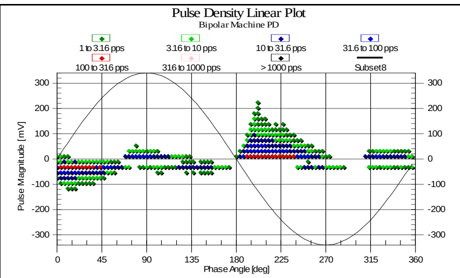
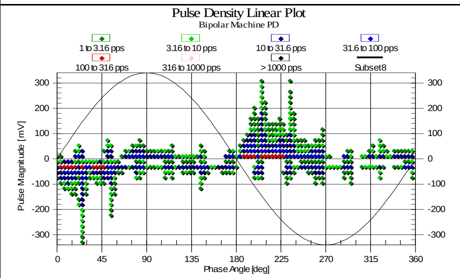
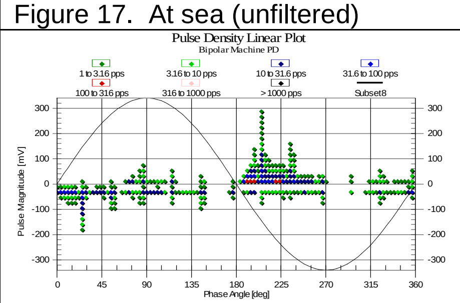
On-line PD monitoring experience has determined that the efficacy of the system is impacted by whether the ship's harmonics are filtered on the high-voltage side or the low-voltage side.

Case Study 5: High-voltage Side Harmonic Filtering

Load: 10.5 MW Load: 5.7MVa Voltage: 11 kV Ambient: 25°C, Humidity: 34% Temp: 62°C Peak magnitude (Qm): 58 mV	 Figure 14. At dock (unfiltered)
Load: 12 MW Load: 7.5MVa Voltage: 11 kV Ambient: 28°C, Humidity: 51% Temp: 72°C Peak magnitude (Qm): 78 mV	 Figure 15. At sea (unfiltered)

When the ship's harmonic filters are on the high-voltage side, then, with the exception of the increase in PD with load or temperature, the PD patterns at dock (Figure 14) and those at sea (Figure 15) are almost identical. Therefore, for ships with the filtering on the high-voltage side, no additional filtering beyond common noise/disturbance separation is required for continuous on-line PD monitoring.

Case Study 6: Low-voltage Side Harmonic Filtering

Load: 2.6 MW Load: 1.7MVa Voltage: 6.6 kV Ambient: 29°C, Humidity: 32% Temp: 74°C Peak magnitude (Qm): 176 mV	 Figure 16. At dock (unfiltered)
Load: 2.9 MW Voltage 6.6 kV Ambient: 29°C, Humidity: 31% Temp 86°C Peak magnitude (Qm): 262 mV	 Figure 17. At sea (unfiltered)
Load: 3.8 MW Voltage: 6.6 kV Ambient: 29°C, Humidity: 40% Temp: 87°C Peak magnitude (Qm): 160 mV	 Figure 18. At sea (filtered)

When the ship's harmonic filters are located on the low-voltage side, then it is likely that the harmonics shown in Figure 13 will produce periodic spikes across the AC cycle of the PD plot as shown in Figure 17. Though these spikes are easily discernible by shape and location in the PD plot, because their presence affects the Qm trend values for continuous on-line monitoring, it is necessary to filter the signals. At dock, the PD values are 176mV, whereas at sea the levels are 262mV, an increase of 49%.

For reliable and repeatable values, Qm values are expected to be within ±25%. Filters were installed that suppressed the spikes from the harmonics, while ensuring that the overall PD levels were within 25% of the expected values. In this case, the levels were within 10% of the "at dock" values.

COMPARISON TO SIMILAR MACHINES

Globally, well over 8000 machines have PD sensors that use this configuration of noise separation and disturbance identification, and the test is also used extensively in petrochemical, refineries, and pulp and paper plants. A large number of test results have been accumulated from thousands of machines in a single database with the widespread application of the same on-line test method. To the end of 2011, over 272,000 test results have been accumulated in a single database, and simple statistical analysis has been applied to help users determine which motors and generators have failing stator insulation, allowing them to plan appropriate maintenance [3]. With the advance of filtering for marine vessel applications, these database results have proven suitable for analysis in the marine environment.

The range in peak magnitude (Qm) from all the tests for the particular operating voltage was established. A cumulative version of the statistical distribution is shown in Table 2. For example, for a 6.6 kV stator, 25% of tests had a Qm below 29 mV, 50% (the median) of the tests had a Qm below 70 mV, 75% were below 149 mV and 90% of tests yielded a Qm below 288 mV. Thus if a Qm of 300 mV is obtained on a 6.6 kV motor or generator, then it is likely that this stator will be deteriorated, since it has PD levels higher than 90% of similar machines. In fact, in many dozens of cases where a machine was visually examined after registering a PD level >90%, significant stator winding insulation deterioration was always observed [11].

Table 2: Distribution of Qm for Air-Cooled Stators, 80 pF Sensors at the Terminals

Oper. kV	2-4	6-9	10-12	13-15	16-18	> 19
25%	8	29	34	50	41	40
50%	20	70	77	113	77	85
75%	63	149	172	239	151	136
90%	228	288	376	469	292	497
95%	398	433	552	723	582	722

From Table 2, it is clear that overall; as the rated voltage increases the 90% level also increases. Clearly, results from an 11 kV stator should not be confused with those from a 6.6 kV stator. PD is a symptom of problems when the insulation system uses mica as the dielectric, so though PD provides a method of trending, as problems develop, it is the source of the PD that determines what and when maintenance activity should be done. High PD, therefore, is an indicator of a potential problem and should be diagnosed to determine the cause before further action is taken.

Case Study 7: PD Magnitudes

Ship Power Plant:

Rated: 6.6 kV Power: 3.9 MW
+Qm: 912 mV -Qm: 906 mV
Manu: 1996

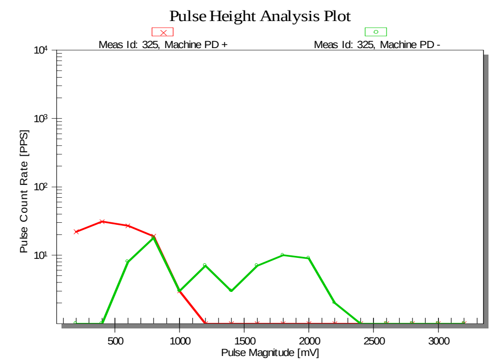


Figure 19. High PD Magnitudes (6.6kV)

As shown in Table 2, the 95% for 6-9 kV machines is 433 mV; therefore, the levels of 906mV observed for this generator of Case Study 7 were excessive (Figure 19). The primary source of the activity was assessed to be phase-to-phase PD between high-voltage components of different phases (Figure 20) combined with a likely compromised interturn insulation. Reportedly, this winding was replaced.

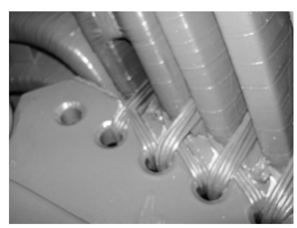


Figure 20. Example of Phase-to-Phase PD

CONCLUSIONS

1. Unique operating requirements for generators in marine vessels make it difficult to properly test and monitor the condition of the stator winding insulation Traditional testing using insulation resistance, DC High potential or the more recent practice of off-line AC testing do not adequately discern the most common problems of turn-to-turn damage, coil movement and deterioration of the

stress coatings. Continuous on-line PD monitoring has proven to be effective.

2. An effective on-line PD monitoring system must adequately filter out the impact of noise and disturbances in order to provide valid results. Noise and disturbances from the power system and harmonics can influence the quality of the PD signals.
3. Absolute Humidity should be included in all trend analysis, especially if surface PD (positive predominance) is present. Tests under variable load conditions, including full load at sea, are required to detect coil movement.
4. With thousands of machines monitored for as long as 30 years with the same method of noise and disturbance separation, on-line partial discharge testing has become a recognized, proven tool to help maintenance engineers identify which stator windings need off-line testing, inspections and/or repairs. Based on these 272,000 test results acquired with the same test methods, test users can easily identify with some certainty which stators are likely to suffer from groundwall insulation deterioration, with only a single measurement on a machine.

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