# Stator Winding Partial Discharge Activity for Air-Cooled Generators

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*Abstract*— Partial discharge (PD) activity has long been known to be 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.

Specifically, the test can find loose, overheated, and contaminated windings, well before these problems lead to failure. As a result, on-line PD testing has become an important tool for planning motor maintenance. On-line monitoring of partial discharge results is preferred as it provides an indication of the activity while the machine is operating under normal thermal, electrical, ambient and mechanical stresses.

However, when monitoring on-line, the influence of high frequency pulses from sources external to the stator winding must be identified and separated in order to prevent erroneous interpretations. In the past, this has required the use of a human expert. By using results obtained with sophisticated noise separation techniques, 272,000 partial discharge (PD) test results have been analyzed to establish the criteria for comparing results from different machines and the expected PD levels. This paper will highlight some of the benefits of on-line PD testing using these results with case studies and signal analysis from marine vessel applications.

*Index Terms*—Partial discharge, Marine power plants, Marine generators, Ambient humidity, Harmonics

## I. Introduction

Partial discharges (PD) are small sparks that are induced within or on the surface of the insulation systems of high voltage motors and generators. 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 and hence different potentials. The discharges occur when the electrical stress across the void is sufficiently high that under the right conditions, an avalanche of electrons occurs in the form of a spark crossing the void. These sparks generate high frequency signals that can be detected.

Over the past 30 years on-line partial discharge (PD) monitoring has become the most widely applied method to determine the condition of the electrical insulation in motor and generator stator windings rated 3.3 kV or more. Partial discharges (sometimes also referred to as corona) are known to occur in deteriorated stator winding insulation systems, as well as new systems with manufacturing or installation flaws or shortcomings. In general, for machines rated 3.3 kV or above, over 50 years of experience with PD testing in motors and generators has shown that years of warning is often given of possible winding failure [1], [2]. PD testing detects most (but not all) of the common manufacturing and deterioration problems, including:

- Poor impregnation with epoxy
- Poorly made semi-conductive coatings
- Insufficient spacing between high voltage components of different phases or to ground
- Loose coils in the slot
- Overheating (long term thermal deterioration)
- Winding contamination
- Load cycling problems

Initially the detection and use of the information or signals provided by these discharges relied extensively on the expertise of a few individuals and was very subjective in nature. A comparison between different machines, or even between tests taken on the same machine over time, was highly subjective and made firm conclusions or judgments difficult to make.

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.

Power plant generators in marine vessels present a unique challenge in monitoring due to the presence of system harmonics from the POD motors. Additional noise 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 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 noise. The potential consequence is that a good winding is incorrectly assessed as being defective, i.e., a false alarm suggesting that the winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests, and even today, many feel that on-line PD testing is a 'black art' best left to specialists.

Thirty years ago, the Canadian utility industry (via Canadian Electrical Association) sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff with average



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training. The PD test developed emphasized separating PD pulses from electrical noise pulses. The noise separation methods depend on analyzing the shape of individual pulses from 80 pF couplers, one installed per phase. 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. Recently, the test instrument has included sophisticated filtering systems to deal with harmonics and other non-PD pulses that might occur.

Globally, well over 8000 machines have PD sensors, and the test is also used extensively in petrochemical, refineries, and pulp and paper plants. These non-intrusive tests have the capability of providing a wealth of information which can be useful to formulate priorities and develop an appropriate maintenance strategy, especially where many machines are involved. These test methods have enabled utilities to assess the winding condition of their machines utilizing their own staff.

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 the database in order to extract information that can help users to better interpret PD results. The main purpose of this analysis is to help users determine which motors and generators have failing stator insulation, allowing them to plan appropriate maintenance. However, some interesting results have emerged on the differences in PD activity as a function of operating voltage, winding age, and machine manufacturer.

## II. Offline versus Online

As with most PD measurement systems, the number, magnitude and phase position with respect to the 50/60 Hz ac cycle are recorded, once PD pulses are separated from the noise pulses. Figure 1 shows a typical plot of the PD from one phase of a turbo generator stator winding. The pulse magnitude is measured in the absolute units of millivolts (mV) to be consistent with the relevant IEC standards [5]. From each test, two summary indicators are extracted, representing

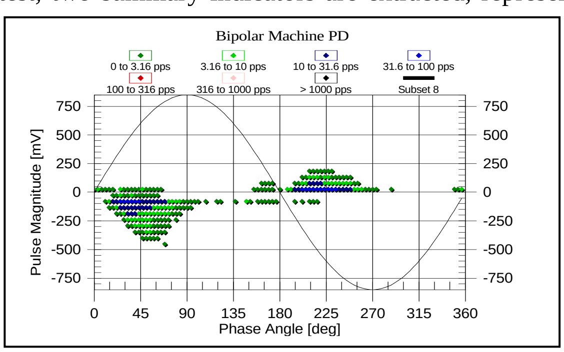



Figure 1. Typical PD Pattern

all the PD pulse data collected. The peak positive and negative PD magnitudes (+Qm and –Qm) represent the highest PD pulses measured in mV with a minimum PD repetition rate of 10 pulses per second. Qm is a reasonable predictor of winding insulation condition. A high Qm measured in a winding compared to a lower Qm in another winding, usually implies that the former winding is more deteriorated.

Testing of PD activity when the generator or motor is offline has been a common method for data collection over the years. However, when testing offline it is not possible to evaluate the power plant under normal operation, that is, while under full load at sea. In addition, offline tests do not enable testing at different loads to investigate coil movement, testing at different operating temperatures to confirm deterioration of the voltage stress coatings, nor evaluating the impact of ambient conditions to the PD activity.

Though trending of offline tests collected at the same operating and ambient conditions may be useful, it is the online test data that can provide the user the most information and be used to compare to the plethora of results from similar machines.

### *A. Case Study 1: Offline versus Online*

A comparison of data collected during offline and online testing was done on one generator. The PD magnitude results, +Qm and –Qm, as shown in Table 1 are clearly different between the two. The Offline results would be considered Moderate, whereas, the Online results would be considered Very High [Table 2]. Please note that Table 2 is based solely on online results and as such should not be used for analysis of offline test data.

Table 1: Offline versus Online

| | kV | MW | +Qm | -Qm | °C (amb) | RH |
|---|---|---|---|---|---|---|
| **Offline** | 6.54 | 0 | 163 | 160 | 26° | 36% |
| **Online** | 6.6 | 3.9 | 858 | 1710 | 26° | 36% |

In addition to differences in the PD magnitudes, the PD patterns from each test configuration also vary greatly as shown below in Fig. 2 and Fig. 3. The reason for this variability can only be attributed to PD sources that are active at the online, such as, phase-to-phase voltage stress, mechanical stresses due to the higher current, and higher thermal stress. In this case, the predominant online source appears to be phase-to-phase activity between two high voltage components of different phases.

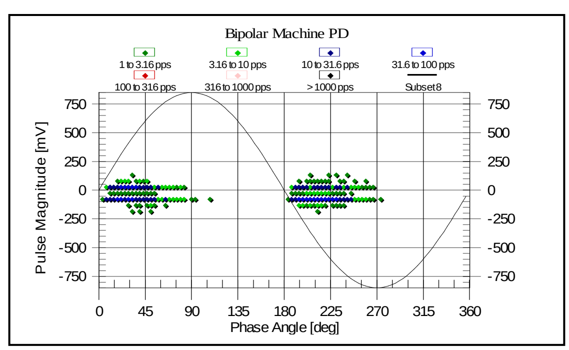



Figure 2. Offline Test Results (50-850mV scale)

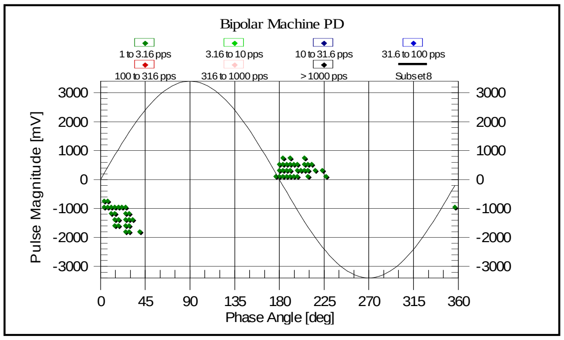



Figure 3. Online Test Results (200-3400mV scale)

## III. Database to the End of 2011

All test results since approximately 1992, have been combined into a single database. This totaled 272,000 tests up to the end of 2011. This database contains many repeat tests on the same machine, 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.

Therefore the database was carefully reduced such that:

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

Once these criteria were applied, about 16,700 statistically independent test results were analyzed.

## IV. Database Results

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

- Operating voltage of the stator winding
- Winding age
- 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 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 an 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% of similar machines, significant stator winding insulation deterioration was always observed [4].

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 a 13.8 kV stator should not be confused with those from a 6.9 kV stator.

Similar tables have also been prepared for those with other types of PD sensors [3]. With these tables, it is possible for motor and generator owners to determine if the stator winding insulation has a problem with only an initial test. If the PD is 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.

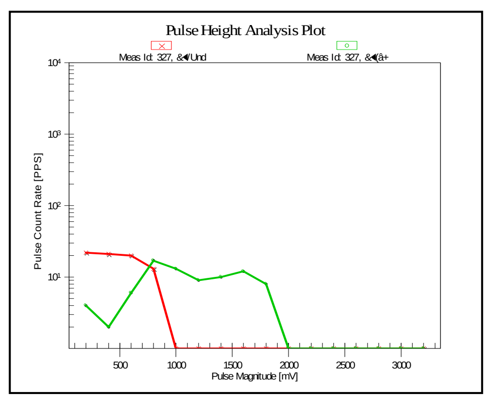
### *A. Case Study2 - PD Magnitudes*

Ship Power Plant: 1 of 5 generators

Rated: 6.6kV Power: 3.9MW
+Qm: 858mV -Qm: 1710mV
Manu: 1996

### *B. Analysis:*

As shown in Case Study 2, based on the Iris Database, the 95% for 6-9kV machines is 433mV; therefore, the levels observed for this generator were excessive. The primary source of the activity was assessed to be phase-to-phase PD between high-voltage components of different phases [Fig. 4] combined with a likely compromised interturn insulation. Reportedly, this winding was replaced.




Case Study 2. PD Magnitudes (6.6kV)

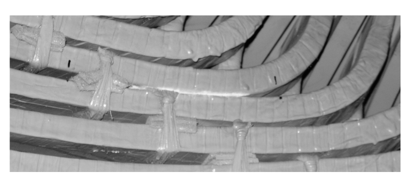


Figure 4. Example of Phase-to-phase PD



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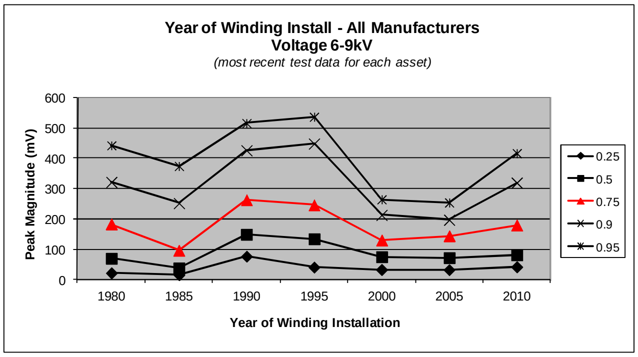



Figure 5. Effect of Age

## V. Effect of Winding Age

An analysis of the statistical distribution of PD for several manufacturers was also performed. Figure 5 depicts the 25th, 50th, 75th, 90th and 95th percentiles for all manufacturers based on date of winding installation (<1981, 1981-1985, 1986-1990, 1991-1995, 1996-2000, 2001-2005, and 2006-2010). Note that only the most recent test data is displayed, that is, even if a winding was installed in 1986, only the PD results from the 2011 tests are included. In this presentation, it is expected that due to aging, the older machines in the 2011 test results would have higher PD results than the newer ones. That is, there should be a noticeable downward trend from those manufactured before 1981 to those installed in 2006-2010.

However, it is apparent that this is not the case. Instead, the newer windings manufactured from 2006-2010 actually have higher PD for the 75th, 90th and 95th percentiles than the previous decade of 1996-2005. This suggests that across the industry for this voltage class that some of the newer windings have PD sources that were not present in the past decade, but perhaps was present in earlier machines.

## VI. Effect of Manufacturer

Figure 6 depicts the 25th, 50th, 75th, 90th and 95th percentiles for each and all of the manufacturers. It is apparent by the chart that for manufacturers D and F, the PD values are higher than typical (ALL), especially for the machines with measured PD levels in the 90th and 95th percentiles. This indicates that for these two manufacturers, the highly PD-active machines are substantially more active than similar machines from other manufacturers. Since it is the higher percentiles (75% and 90%) that deviate, it is possible that the variability is due to quality control.

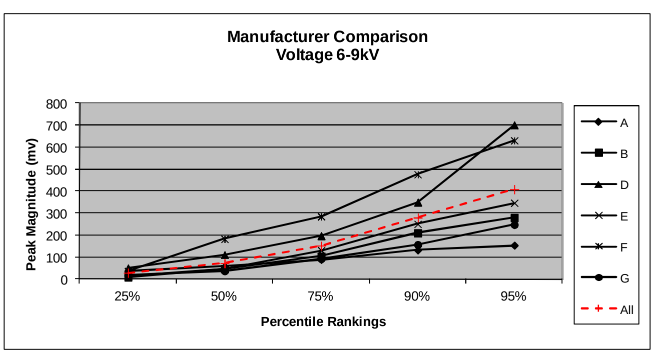



Figure 6. Effect of Manufacturer

## VII. Effect of Humidity

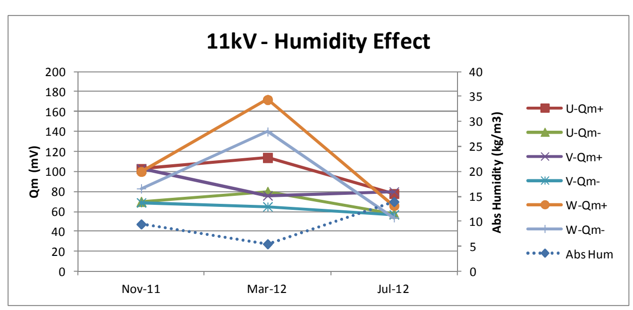
Environmental conditions may have a very noticeable impact, especially if the surface contamination becomes partly conductive when damp, so it should be recorded from one test to the next. It is appreciated that at times it may be very difficult to duplicate test conditions, particularly temperatures; however, the emphasis should always be on trying to achieve as uniform conditions as possible. This means taking tests when units are hot and the temperature has stabilized, while accurately recording both the operating and ambient conditions.

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. Thus, in some circumstances, the PD may go up (*direct effect*), while in others it would go down *(inverse effect)* with increases in relative humidity. In some circumstances, the humidity effect has been known to cause the PD to fluctuate by as much as 300%. Since each scenario is different, it is extremely important the ambient humidity be recorded at test time so trends can be properly evaluated and decisions are not made about upward trends that occur because of humidity effects and not changes in winding condition. Present experience indicates humidity only affects surface activity.

### *A. Case Study 3 – Humidity*

Though power plants on ships are often located in high humidity environments, there can be significant variability in the absolute humidity due to changes in ambient air temperatures. Since surface PD 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. As shown in Case Study 3, the PD Magnitudes (Qm values) are inversely correlated with the absolute humidity.

Ship Power Plant: 1 of 4 generators
Rated: 11kV Power: 12.1MW
+Qm: 66mV low humidity (172mV at high humidity)
-Qm: 54mV low humidity (140mV at high humidity)
Manu: 2002




Case Study 3 - Effect of Humidity

Figure 7. Damage to Voltage Stress Coating

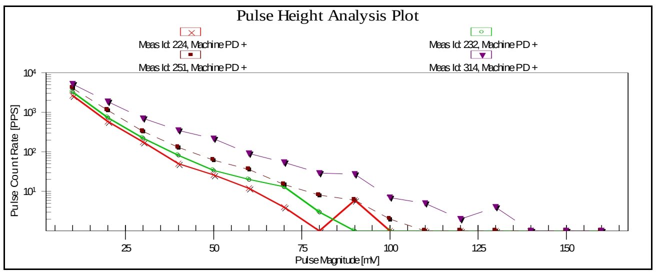



Figure 8. Tests at Different Loads

*B. Analysis:*

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. This along with the positive predominance suggests the predominance of surface activity due to deterioration of the voltage stress coatings [Fig. 7]. Recommended action is to test at different loads as the next stage in failure mechanism development will be coil movement. And as clearly shown in Fig. 8, the PD increased at a higher load indicating the onset of coil movement in addition to the stress coating deterioration.

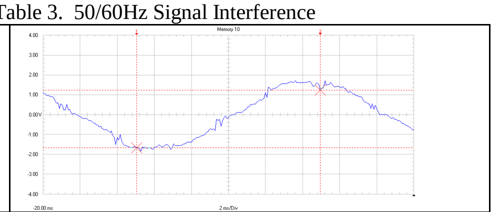
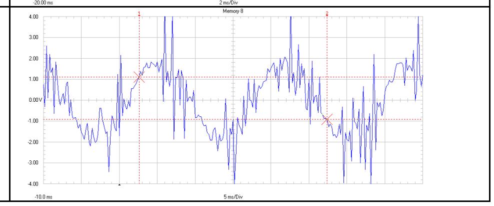
## VIII. Effect of Harmonics

Since the electrical system on a cruise ship is isolated and has loads that include VSD motors, there is concern that the system harmonics and noise will make PD monitoring difficult. There are three aspects of monitoring the PD activity that can be heavily influenced by noise:

a. Identification of the 50/60Hz signal so that the location of the PD pulses can be evaluated based on their occurrence relative to the AC phase to ground voltage.
b. Noise signals that have frequency characteristics which are outside the PD system measuring bandwidth.
c. Noise signals that have frequency characteristics which are within the typical PD bandwidth of 50-250+MHz.

*A. 50/60Hz Signal*

Table 3. 50/60Hz Signal Interference

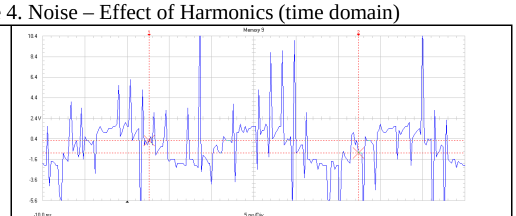
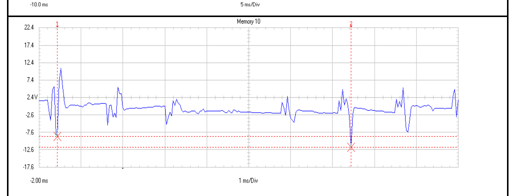
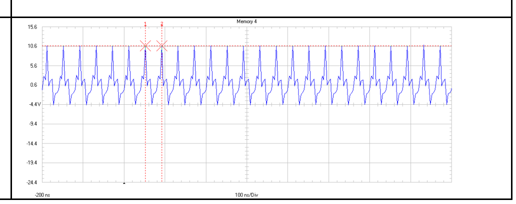
| | |
|---|---|
| While at dock there is a clean 50/60Hz signal |  |
| While at sea there are significant harmonics |  |

As shown in Table 3, offline PD testing and testing with only the station service while at the dock, the 50/60Hz poses no problem to most monitoring systems. However, tests under these circumstances do not fully evaluate the generators under maximum load and temperature. Therefore, tests should also be done while underway at sea. In this case, the measuring system needs to either properly filter the 50/60Hz signal or be able to supply a steady external reference signal that can be used to evaluate the position of the PD activity in order to properly display the phase-resolved data and to calculate the peak (Qm) values per IEC60034-27 [5] and IEEE 1434 [5].

*B. PD System Measuring Bandwidth*

The PD system measuring bandwidth is dependent upon the sensor and the test instrument. Noise sources are primarily from the system harmonics and pulses from the VSD propulsion motors [Table 4].

Table 4. Noise – Effect of Harmonics (time domain)

| | |
|---|---|
| Typical harmonic ranges: $3^{rd}$, $7^{th}$, $10^{th}$, $11^{th}$, $12^{th}$, $13^{th}$, $23^{rd}$, $24^{th}$, $25^{th}$ up to the $100^{th}$ (6MHz) |   |
| Background noise: 40ns period 25MHz $10.8V_{pk}$ |  |

An online PD measuring system must have methods of isolating the high magnitude noise harmonics from the true, erratic PD patterns. A system must provide a maximum signal-to-noise ratio. This can only be done with sensors, such

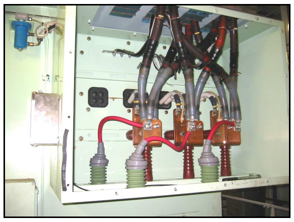


Figure 9. 80pF Capacitors installed on a ship's generator (11kV)

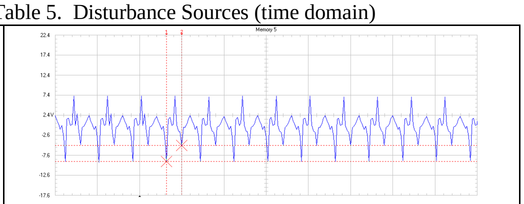
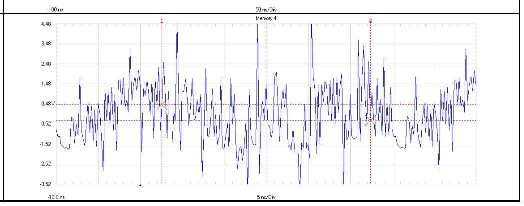
as the 80pF capacitors, that have minimal attenuation of the PD signal frequency bandwidth while attenuating very high frequency pulses [Fig. 9]. The air-cored Rogowski coil has significant attenuation of both PD and noise. The ferrite core RFCT is impacted by the impedance of the (surge) capacitor and the cable it surrounds, so it also attenuates both signals. If both are attenuated it is difficult to discriminate true PD from noise. Typical measuring bandwidths for various setups are:

- RFCT ferrite core -- 100kHz to 30 MHz [1]
- Rogowski Coils – variable bandwidths 0.1-10MHz
- 80pF Capacitors – higher than 40MHz

### *C. Disturbance Sources within PD bandwidth of 50-250MHz*

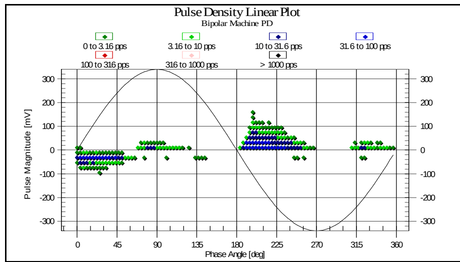
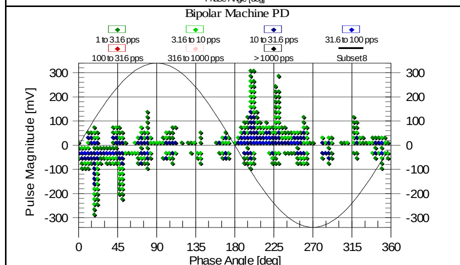
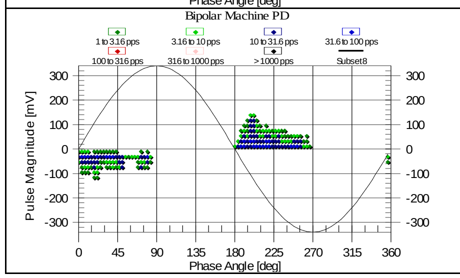
PD pulses have unique pulse shapes, and as such, a PD monitoring system must be able to isolate the PD pulse from the recurring background disturbance signals that are within the PD frequency bandwidth [Table 5]. This separation can be done by pulse-shape recognition or by filtering of the disturbance-like signals so that the PD signals are detectable "above" the disturbance [1].

Table 5. Disturbance Sources (time domain)

| | |
|---|---|
| Background disturbance: 18ns period 55MHz $-9.4V_{pk}$ |  |
| Background disturbance: Variable high frequencies up to 5V spikes |  |

### *D. Case Study 4: Effect of Harmonics*

As shown in Case Study 4 with proper filtering of the harmonics, the PD results at sea will properly represent the data collected at dock. This makes it possible to properly monitor the condition of a stator winding while at normal loading, thermal and ambient stresses. This additional filtering may not be necessary in certain cases.

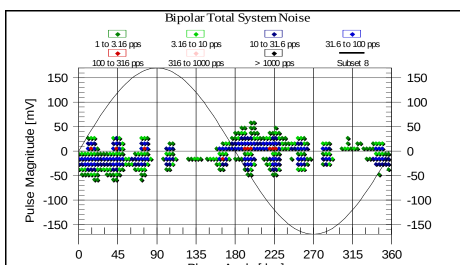
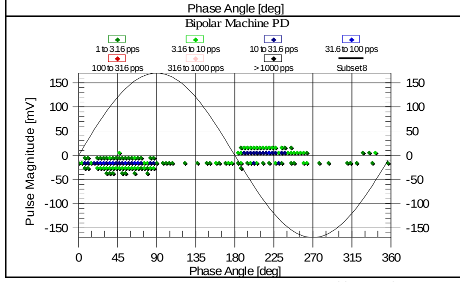
| | |
|---|---|
|  | At dock (unfiltered)<br><br>Oper load: 2.4 MW<br>Oper Voltage 6.6kV<br>Amb Temp 32 deg C,<br>Amb Humidity: 33 %<br>Oper. Temp 78 C |
|  | At sea (unfiltered)<br><br>Oper load: 3.4 MW<br>Oper Voltage 6.6kV<br>Amb Temp 30 deg C,<br>Amb Humidity: 31 %<br>Oper. Temp 78 C |
|  | At sea (filtered)<br><br>Oper load: 3.4 MW<br>Oper Voltage 6.6kV<br>Amb Temp 30 deg C,<br>Amb Humidity: 31 %<br>Oper. Temp 78 C |

Case Study 4. Effect of Harmonics (Filtering)

### *E. Case Study 5: Effect of Harmonics*

Based on experience to date, it appears that when a ship's harmonic filtering is located on the high-voltage side, there are negligible disturbance signals within the PD pattern. However, if the harmonic filters are located on the low-voltage side then disturbances may be an issue.

In these cases, the harmonic filtering on the high voltage side significantly attenuates the harmonic interference to levels that do not obscure the PD patterns. As the stator winding ages, the PD patterns will emerge above the disturbances, as shown in Case Study 5.

| | |
|---|---|
|  | At sea (unfiltered)<br><br>Oper load: 8.3 MW<br>Oper Voltage 11kV<br>Amb Temp 20 deg C,<br>Amb Humidity: 32 %<br>Oper. Temp 59C<br><br>Baseline test |
|  | At sea (unfiltered)<br><br>Oper load: 12 MW<br>Oper Voltage 11kV<br>Amb Temp 28 deg C,<br>Amb Humidity: 51 %<br>Oper. Temp 70C<br><br>Third test series |

Case Study 5. Effect of Harmonics

## IX. Conclusions

1. With thousands of machines monitored for as long as 30 years with the same method of PD measurement, 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.

2. With over 270,000 test results acquired with the same test methods, the different magnitudes of discharge activity that identifies a winding with low, moderate or high PD has been defined. Table 2 enables test users to easily identify with some certainty which stators are likely to suffer from groundwall insulation deterioration, with only a single measurement on a machine.

3. The practical importance of Table 2 is that if one applies PD sensors to a machine, and in the first measurement one obtains a Qm that exceeds the $90^{th}$ percentile of the relevant Qm distribution, then one should be concerned enough at the PD level to take action such as more frequent testing and/or off-line tests and inspections at the next convenient machine shutdown.

4. Some machines made in the past decade exhibit higher PD activity than machines that are considerably older. Therefore, newer machines do not necessarily have more reliable insulation; however, this appears to be limited to only a few OEMs.

5. PD Trends are different for different manufacturers perhaps due to variability in quality control.

6. Absolute Humidity should be included in all trend analysis, especially if surface PD (positive predominance) is present.

7. Noise and disturbances from the power system and harmonics can influence the 50/60Hz reference signal and also the quality of the PD signals. If present, the PD monitoring system needs to filter out the impact in order to provide valid results.

## X. References


[1] G.C. Stone, E.A. Boulter, I. Culbert, and H. Dhirani, *"Electrical Insulation for Rotating Machines"*, Wiley Interscience, 2004.

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