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Monitoring & Condition Assessment of large Rotating Machines using latest Partial Discharge Detection and Analysis Techniques

A. El-Rasheed, M. Söller, M. Huzmezan
Megger Limited, Canada

SUMMARY

Most large modern rotating machines use epoxy-mica insulation, which is an electrically stable material that is great for durability. However, it is difficult to identify electrical weaknesses with this type of insulation using basic insulation testing. A partial discharge (PD) test is a highly effective method of assessing the condition of this type of insulation in large rotating machines. A variety of defect mechanisms can be recognized when utilizing the latest analysis techniques.

Partial discharge analysis using phase-resolved discharge patterns serves to identify defect types and their risk potential. Examples of defect types and their typical partial discharge patterns are discussed in this paper using a real-world case study. Considerations such as frequency and capacitance are discussed as well as practical setup. Using the latest analysis techniques provides consistent and reliable data to allow insulation condition assessment.

Finally, in our connected world, the infrastructure is available to easily create a remotely supervised online continuous partial discharge monitoring system for the typical utility. An example of system structure is presented that allows remote measurements to evaluate machine conditions. The structure presented can be upscaled to satisfy the largest of utilities.

KEYWORDS

Rotating Machines, Partial Discharge Measurements, Partial Discharge Pattern Analysis, Insulation Testing, On-line Monitoring, Preventive Maintenance

Ahmed.El-Rasheed@megger.com

Rotating Machines and Partial Discharge

Rotating machines are crucial part of our modern world. These versatile machines can be used for power generation, factory work, and even transportation among many other applications. Therefore, preventative maintenance of these assets is also a crucial job. A common cause of rotating machine faults is the stator winding insulation failure, as shown from research published by IEEE in Figure 1.

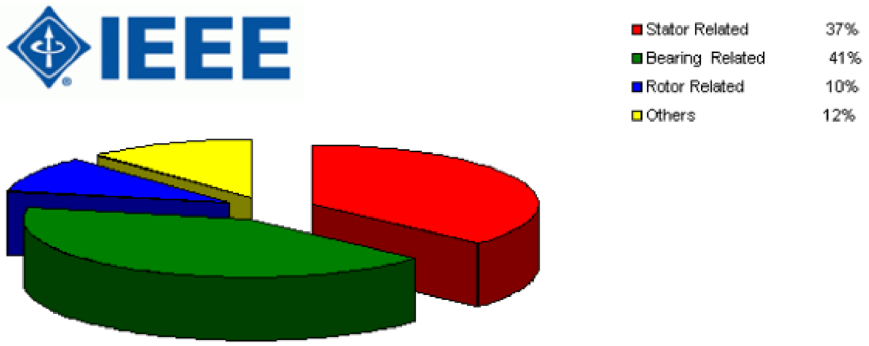


Figure 1: IEEE analysis of 3000 machines (1995)

When the research is further analysed, the impact of stator winding failure is found to be even bigger on large rotating machines as seen in Figure 2. It was found that over 60% of failures were caused by stator windings. The large machines studied were rated at 2 MW or greater.

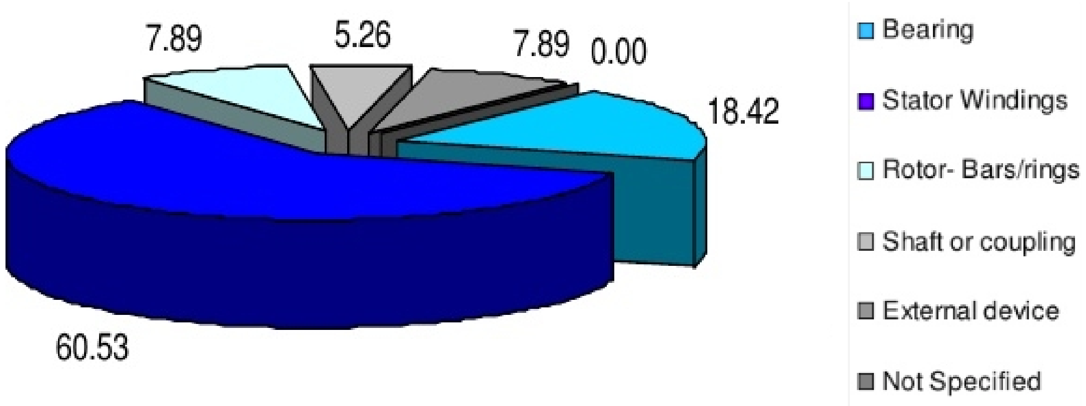


Figure 2: IEEE analysis of > 2 MW machine failures

The latest Partial Discharge (PD) measurement and analysis techniques provide invaluable asset health information regarding stator winding insulation. However, there are currently no standards that define acceptance criteria of PD activity on rotating machines. Therefore, improvement in analysis and abundance of repeatable data is necessary to further this field.

The research presented here shows that PD activity in rotating machinery can be accurately measured and trended over time. Additionally, there are various identified patterns that indicate specific types of insulation degradation. Reliable asset health can be quantified with the proper choice of PD decoupling units (CCs) or sensor types, measurement frequency bandwidth, PD pattern resolution, PD polarity recognition, disturbance cancellation and analysis method employed.

Choosing PD Measurement Frequency and Bandwidth

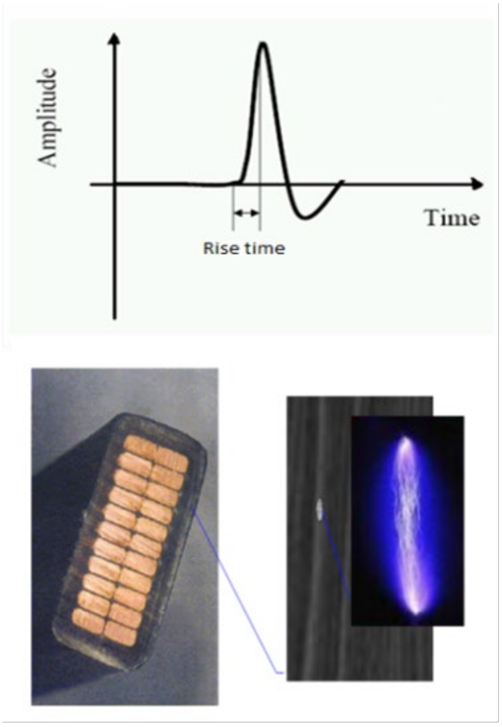
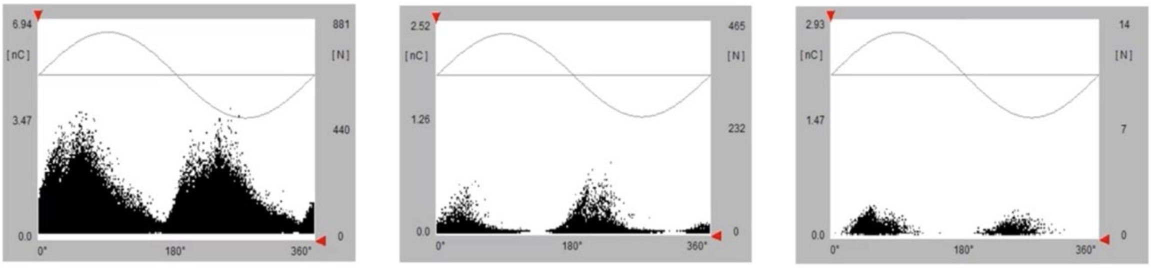


Figure 3: Void in winding insulation

It is critically important to choose a suitable measurement frequency and bandwidth to obtain reliable PD test results. To appreciate this, it is useful to briefly review the phenomenon of PD signals. In most cases, they start as an electric discharge in a void in the insulation, as the electrical field breakdown strength in gases is much lower compared to liquid or solid materials. Degraded insulation is characterised by microscopic voids within it. The electron avalanche that occurs in the insulation void is in effect a high frequency current impulse with a very short rise time.

A gas inclusion containing air, which is mainly nitrogen, has a rise time of typically 1 ns translating into a signal bandwidth up to 350Mhz. This is a partial discharge event at the source, but the characteristics change significantly by the time the current impulse travels to the decoupling sensors and finally to the test instrument terminals. The current pulse is subjected to effects like attenuation, reflection, resonance, dispersion, and radiation. Therefore, there are no easy rules for choosing the best measurement frequency and bandwidth.

Lower frequencies and bandwidths usually provide PD signals with large amplitudes that come from the entire winding, but they are prone to high frequency noise. On the other hand, higher frequencies and bandwidths are less affected by noise but they provide just a partial coverage of the winding. In Figure 4, the effects of using different frequencies and bandwidths is shown.



40-800kHz (IEC60270)
1215697 Counts

2-20MHz
110843 Counts

20-200MHz
2270 Counts

Figure 4: Three PD tests on the same motor at different bandwidths

These tests were done on a 1200 kW – 6600 V asynchronous motor with internal neutral connection. The motor had a new VPI impregnated stator winding and was used in all three tests, but with a different band pass filter each time. The measurement was an off-line PD pattern acquisition using coupling capacitors as the sensors.

From the results, it is clear to see that the lower bandwidth, of 40-800 kHz provides far more data to work with. Furthermore, since PD measurements are relative then calibration is essential to compensate for attenuation and other characteristics of the test circuit. Strictly according to IEC60270, which provides guidance on PD testing, it is only valid to calibrate using a bandpass filter up to 1 MHz on lumped components between 100kHz up to 1MHz. In fact the IEC60270 is not applicable on stator windings, however a "calibrated" measurement according to this standard provides a very good assessment of the condition of the insulation system.

Insulation Failure Causes

Using the best measurement frequency and bandwidth along with high quality sensors provides reliable data with limited noise interference. The results of such measurements have produced recognisable patterns that indicated types of faults. The most common types of faults are shown in Figure 5.

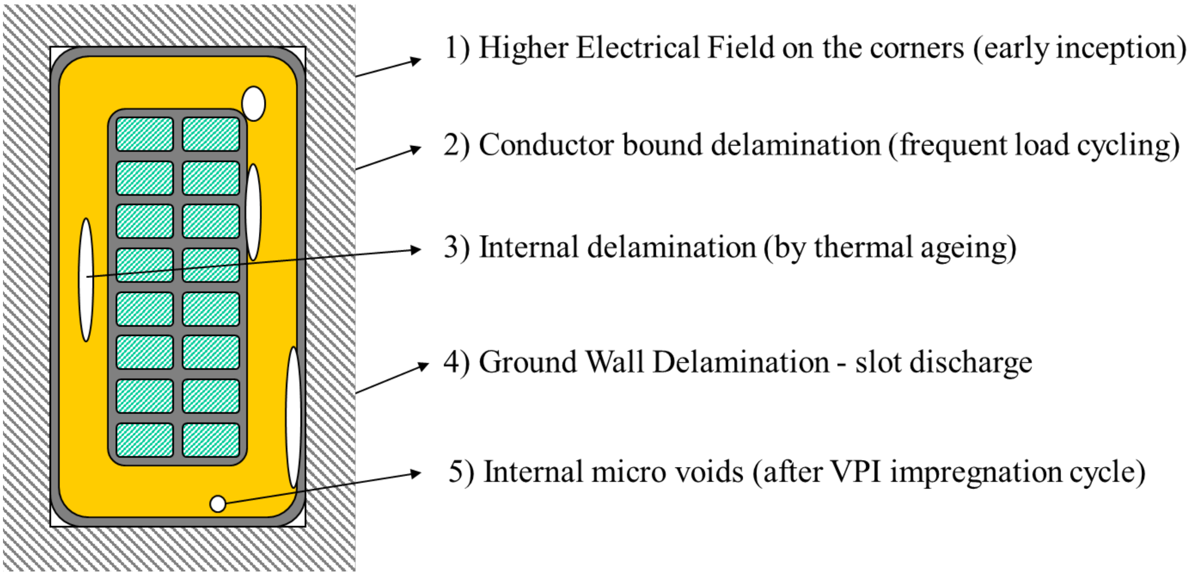


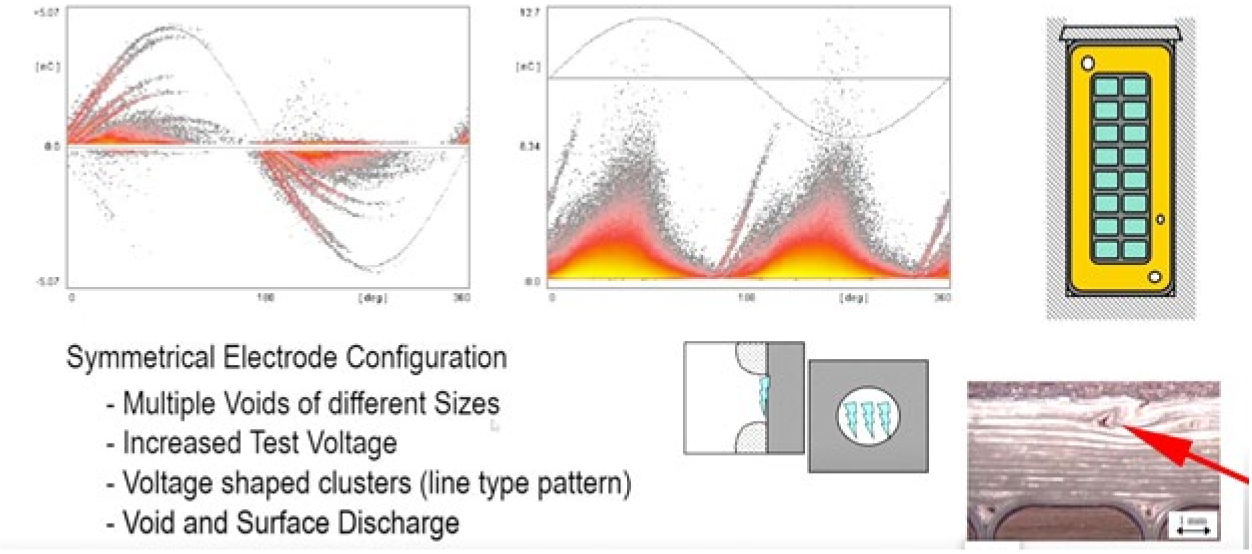
Figure 5: Defect locations on stator bars

The PD patterns of typical stator insulation failures are shown in the next section. The typical causes of most failures in stator insulation are:

- Internal discharge activity, caused by micro voids, delamination, and thermal aging.
- End winding (overhang) discharge, causes by surface contamination and vibration
- Slot discharge, caused by wedge problems and inadequate impregnation
- Slot-exit discharge caused by field grading issues

PD Pattern for Voids

The gas molecules in a typical void, indicated by the red arrow in Figure 6, are ionized by cosmic photons and the free electrons can produce internal discharge pulses due to the electrical field exceeding the breakdown level leading to PD impulses. When these pulses are measured, "fresh" voids on new machines show up in a distinct line pattern. The screen image in Figure 6 shows the captured PD activity, which indicates seven individual voids. Over time, the discharge in the void will create increased carbonisation, which then increases PD activity. This leads to a more distributed pattern over time. The carbonisation provides more free electrons in the voids and this creates the more distributed pattern.

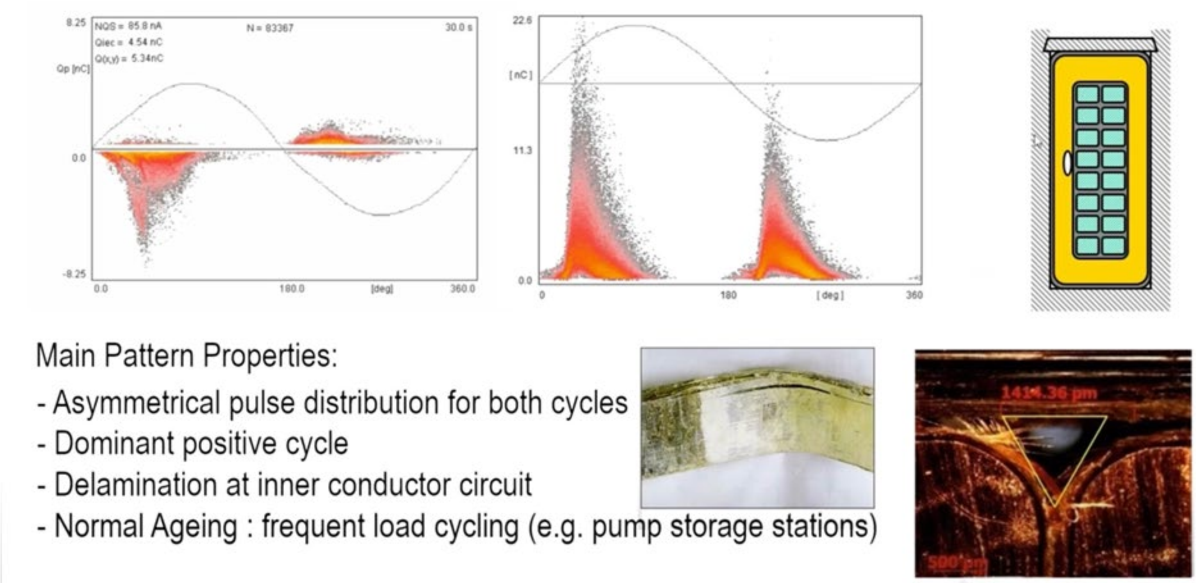


Symmetrical Electrode Configuration
- Multiple Voids of different Sizes
- Increased Test Voltage
- Voltage shaped clusters (line type pattern)
- Void and Surface Discharge

Figure 6: PD pattern from voids in the insulation

PD Pattern for Conductor Binding Delamination

Delamination close to the inner conductor produces an asymmetrical partial discharge pattern, as seen in Figure 7. In bipolar mode (left hand screen image), the PD activity of the first half cycle is shown below the x-axis. While in unipolar mode (right hand screen image) shows activity in the same relative phase position but entirely above the x-axis. This pattern of high PD activity in the positive half cycle and lower activity in the negative half cycle is typical for conductor binding delamination issues.



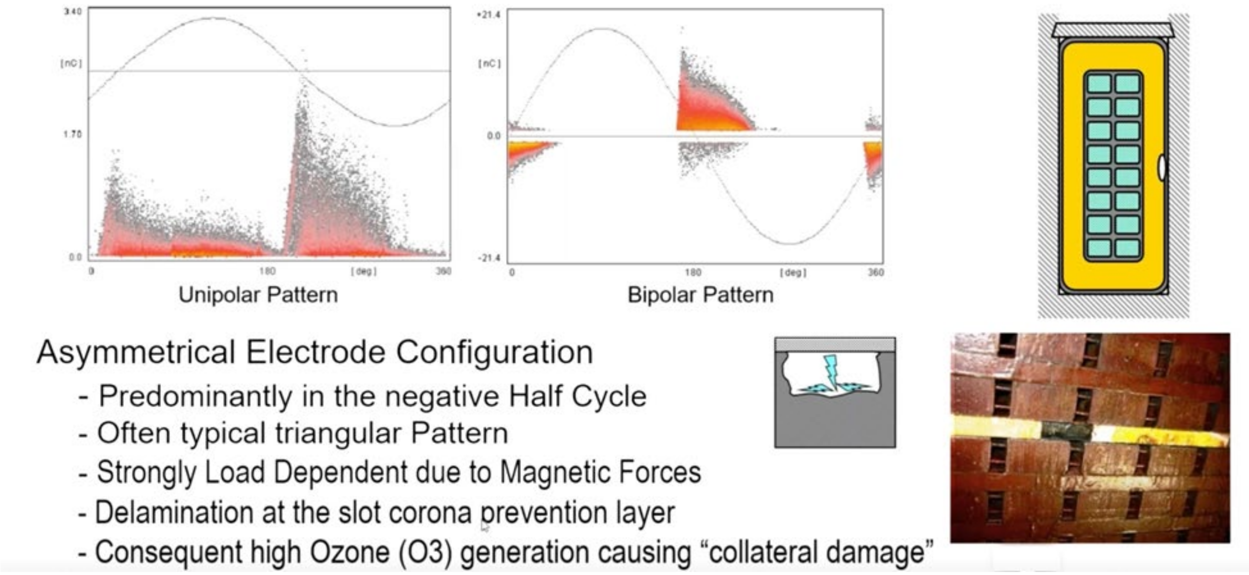
Main Pattern Properties:
- Asymmetrical pulse distribution for both cycles
- Dominant positive cycle
- Delamination at inner conductor circuit
- Normal Ageing : frequent load cycling (e.g. pump storage stations)

Figure 7: PD pattern from conductor binding delamination

PD Pattern for Slot Discharge at Machine Bars

Insulation defects at the outer area cause the reverse PD pattern seen with conductor binding delamination. Figure 8 shows PD activity at its highest in the negative half cycle, while it is less than half the amplitude in the positive half cycle. The bipolar pattern, which is on the right in Figure 8, shows the PD in the negative half cycle starts close to zero and crosses the applied voltage forming a triangular shape.

To make this type of determination, it is critical that the phase relationship between the applied voltage and the pattern display is correct. Therefore, the synchronisation signal from the coupler is as important as the PD signal. This type of PD activity produces ozone from the epoxy-mica insulation. Ozone causes a lot of damage and the longer this PD activity continues the worse it will get.



Unipolar Pattern

Bipolar Pattern

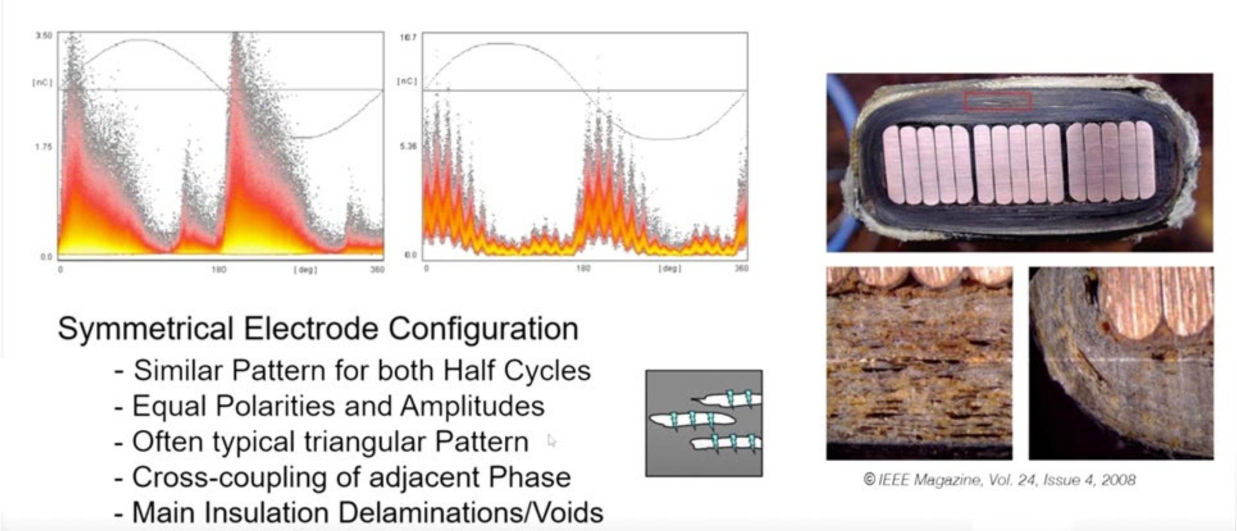
Asymmetrical Electrode Configuration

- Predominantly in the negative Half Cycle
- Often typical triangular Pattern
- Strongly Load Dependent due to Magnetic Forces
- Delamination at the slot corona prevention layer
- Consequent high Ozone (O3) generation causing "collateral damage"

Figure 8: PD pattern for slot discharge at machine bars

PD Pattern for Thermally Aged Insulation

Figure 9 shows the results from thermally aged insulation. Thermal aging tends to produce gaps in the middle of insulation layers. Consequently, the PD pattern of thermally aged insulation is symmetrical. The level of PD activity and number of pulses is markedly the same in the positive and negative half cycles. The right-hand screen image in Figure 9 determines how useful high-resolution measurements can be, because it exposes how harmonics have a strong influence on PD patterns. In this case the harmonics produced vertical striations.



Symmetrical Electrode Configuration

- Similar Pattern for both Half Cycles
- Equal Polarities and Amplitudes
- Often typical triangular Pattern
- Cross-coupling of adjacent Phase
- Main Insulation Delaminations/Voids

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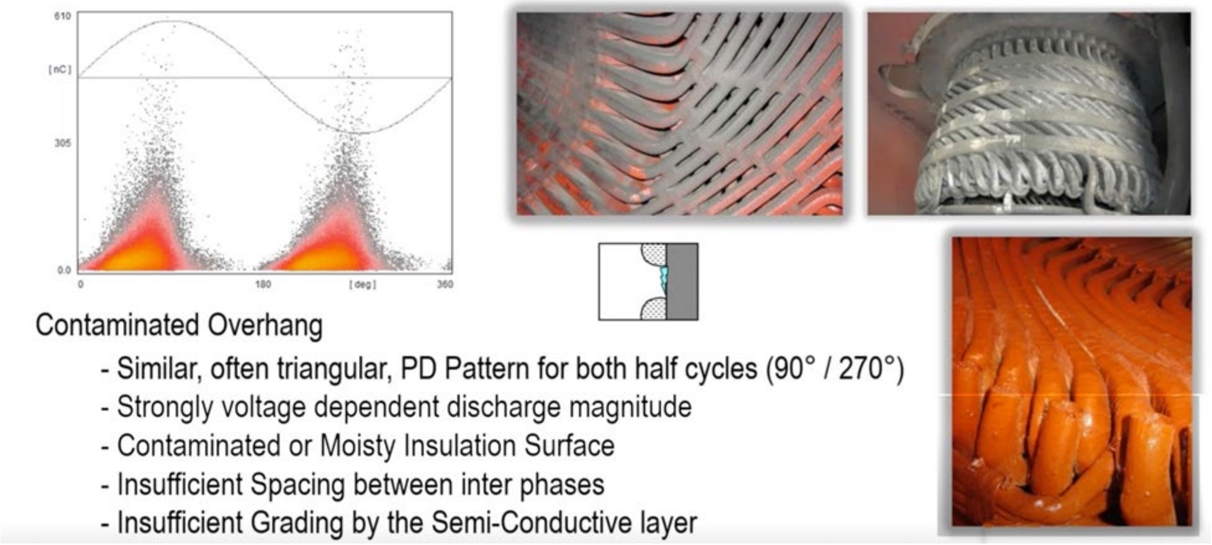
Figure 9: PD pattern for thermally aged insulation

PD Pattern for End Winding Surface Discharge

The white powder seen in the photographs of Figure 10 are a result of ozone action, which leads to surface discharge. Dust and other contaminants can also cause end winding surface discharge. The PD pattern here reveals that the maximum PD activity coincides with the maximum applied voltage. Surface discharge is strongly dependent on applied voltage, which creates the observed pattern. Also, proximity of surfaces because of insufficient spacing can cause surface discharge.



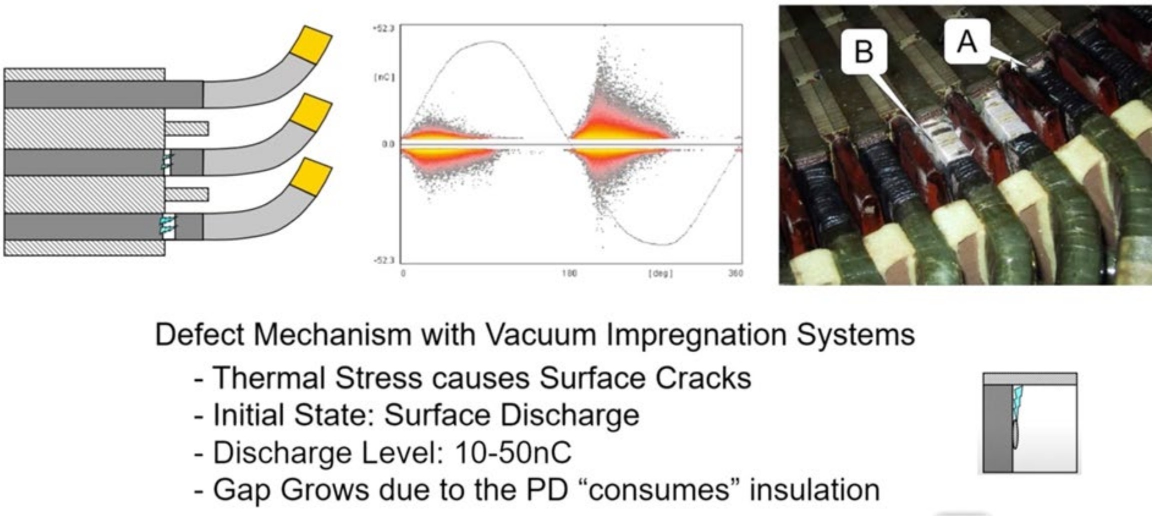
Contaminated Overhang

- Similar, often triangular, PD Pattern for both half cycles (90° / 270°)
- Strongly voltage dependent discharge magnitude
- Contaminated or Moisty Insulation Surface
- Insufficient Spacing between inter phases
- Insufficient Grading by the Semi-Conductive layer

Figure 10: PD pattern for end winding surface discharge

PD Pattern for Slot-exit Discharge

The last patten example to show is for slot-exit activity, as seen in Figure 11. The photograph shows where the PD activity started at the point marked A. The semiconductor tape is partially destroyed, while the PD plot displays an asymmetrical pattern with higher activity in the negative half cycle. Eventually, the damage to the tape will result in surface discharge.

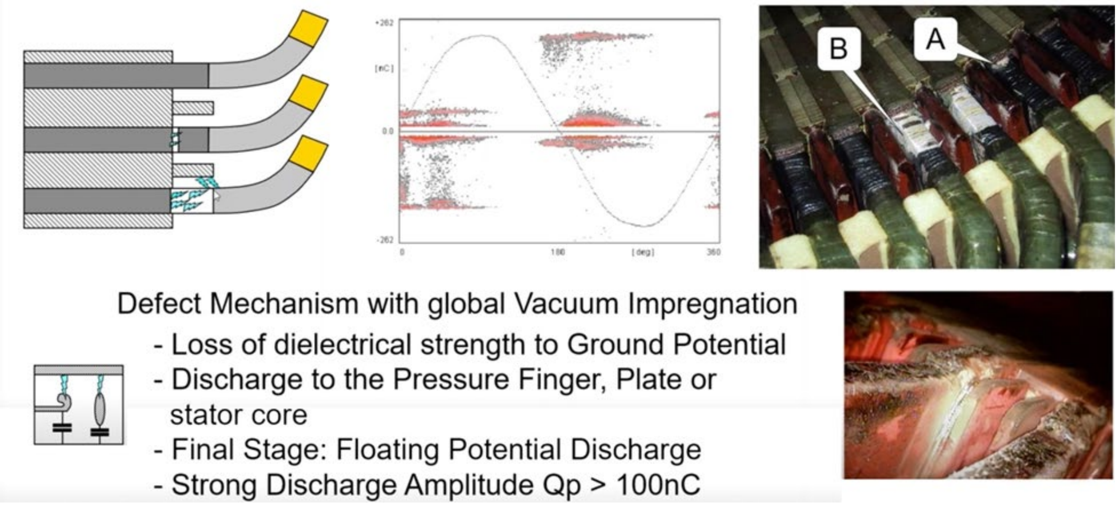


Defect Mechanism with Vacuum Impregnation Systems

- Thermal Stress causes Surface Cracks
- Initial State: Surface Discharge
- Discharge Level: 10-50nC
- Gap Grows due to the PD “consumes” insulation

Figure 11: PD pattern for slot-exit discharge at early stage

A few months later, the situation with the slot-exit discharge had deteriorated to the point shown in Figure 12. The PD pattern is different because of floating potentials. The pattern is flatter with a much greater amplitude than at the early stage.



Defect Mechanism with global Vacuum Impregnation
- Loss of dielectrical strength to Ground Potential
- Discharge to the Pressure Finger, Plate or stator core
- Final Stage: Floating Potential Discharge
- Strong Discharge Amplitude Qp > 100nC

Figure 12: PD pattern for slot-exit discharge at final stage

Online PD Monitoring Case Study

Understanding of the PD patterns allows fast analysis of data, which is necessary for online PD monitoring of rotating machines. This is demonstrated in the case study of online PD measurements on an 85 MVA, 12.5 kV steam turbine generator.

The generator was monitored during normal operation using 145 pF coupling capacitors that were installed during a scheduled maintenance break. These sensors were installed on the bus duct using curved washers. The coupler signals were carried to a termination box, and the PD activity was recorded and analysed using a portable set of PD instruments.

Measurements and calibration were done at a frequency band below 1MHz, and it produced valuable results. The registered discharge activity was determined to originate from a large defect in Phase C. General weaknesses were observed in Phase A, with the least activity in Phase B. The patterns indicated slot-exit degradation due to field grading issues.

- **An 85MVA, 12.5kV steam turbine generator**
- **145pF coupling capacitors installed on busbar duct using curved washers**
- **Frequency band below 1MHz used for calibration and measurements, following IEC60270**
- **PD pattern determined a large defect in the field grading at slot-exit of phase C. General weakness indicated in the field grading of phase A, while phase B had the lowest activity**

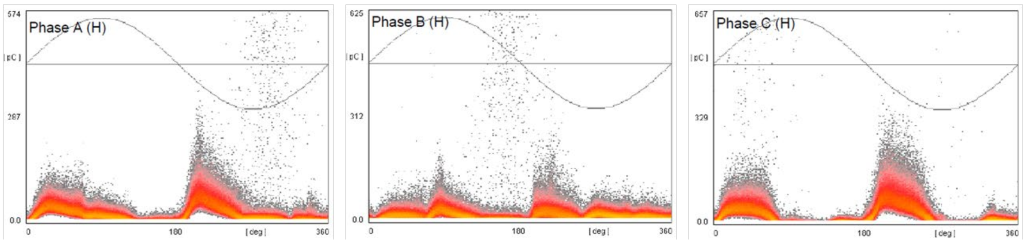


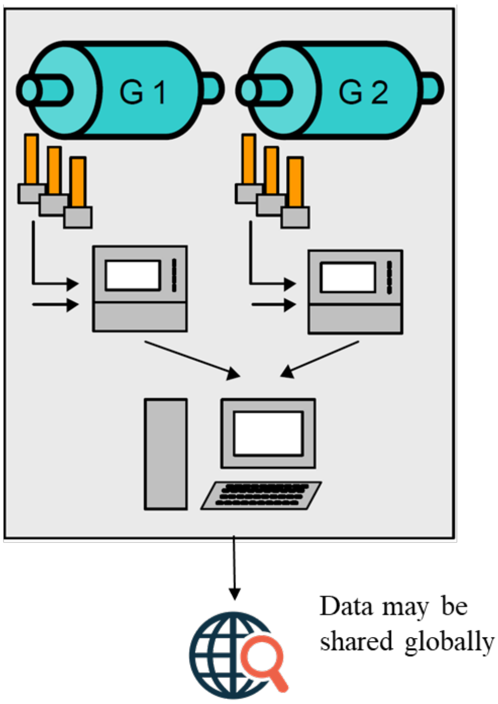
Figure 13: Results from online PD monitoring of steam turbine during operation

Accordingly, it was recommended to clean, carefully inspect, and re-varnish the slot-exit area. Explicitly, Phase C shall be inspected for traces of sparking type discharge to avoid damage.

Structure of Online PD Monitoring System

An online PD monitoring system is the effective method for preventative maintenance. As demonstrated in the case study, sensors are installed on the rotating machines and their signals provided to the PD instruments. A system is created when multiple assets are monitored, and the PD measurements transmitted to a central server. There are software suites available that can perform analysis and automatically alert whenever conditions deteriorate beyond a set point.

As seen in Figure 14, a utility can create a monitoring system with PD instruments collecting signals and feeding a central server where further analysis of trends can be done. This structure is scalable, allowing use on all the high value rotating machines at a site. Furthermore, monitoring of various sites can be done when linking the local servers to a central server. Valuable live data is viewed and up to the minute health assessments can be automatically done.



Data may be shared globally

Figure 14: Monitoring system

Conclusions

Partial Discharge is a valuable tool, when used correctly, to provide asset health assessment and preventative maintenance. Phase resolved partial discharge pattern analysis provides identification of a wide variety of defects on epoxy-mica insulation among other materials.

Offline PD measurements are valuable for determining specific repairs needed. However, online monitoring provides a constant “pulse” of the large rotating machine. Together an effective system for asset maintenance is created.

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