TESTING FOR STATOR WINDINGS

Power Factor Testing and Partial Discharge Monitoring

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ABSTRACT

It has long been known that comparing the partial discharge results obtained from a single machine is a valuable tool enabling companies to observe the gradual deterioration of a machine stator winding and thus plan appropriate maintenance for the machine [4]. This paper discusses two such tests: off-line Power Factor/Tip-up and on-line Partial Discharge monitoring. The theory, applications, interpretation, and limitations for each test setup are addressed. Case studies of each technology and comparisons are included.

INTRODUCTION

The principal function of a stator winding coil or bar is to provide a conductive path for the currents induced in it by the rotating magnetic field. Winding designers have gone to great lengths to make sure they put in as much copper and as little insulation as possible in each coil or bar. The construction chosen depended on the size (at maximum generating efficiency) of the machine and economics. Medium to high-voltage (>2300V) are made with form-wound coils, while lower voltage machines tend to be random-wound.[1] Only form-wound coils will be discussed here.

Failure Mechanisms

Economically produced insulation systems are not expected to last forever. Different thermal, mechanical, electrical, and environmental stresses combine in different ways to yield a wide variety of specific failure mechanisms in stator windings. At some point, the materials will have aged significantly reducing the electrical and mechanical strength of the insulating materials. In such a case, the insulation breaks down or cracks under the normal operating voltages or as a result of a transient electrical (e.g., lightning or switching voltage surges) or mechanical (from motor switch-on in-rush current or current transients from faults in the power system, which cause large magnetic field impulses) situation. If the insulation breakdown occurs in the stator groundwall or turn insulation, this will rapidly lead to high-power-frequency fault currents and circuit-breaker operation.

Stresses can combine to lead to more complicated deterioration mechanisms. For example, in windings that are operated at high temperatures for long periods of time, the insulation delaminates and oxidizes, making it brittle and subject to mechanical failure. Similarly, insulation abrasion can occur as a result of the magnetically induced forces causing the winding to rub against the stator core, until the insulation is thin enough to puncture. Although relatively unusual, pure electrical failure can occur on stators operating above 6kV, since partial discharge (small electrical sparks, sometimes referred to as *corona*) occur, which eventually bore a hole through the organic insulation, causing a short circuit. Finally, partly conductive pollution (for example, oil mixing with dirt) can lead to small currents flowing over the insulation surface in the endwinding, leading to electrical tracking. On-off cycling or load cycling lead to large and sometimes rapid swings in winding temperatures. Such temperature swings can lead to different thermally induced growth among the different winding components, developing shear stresses between the components. With a sufficient number of load cycles, the groundwall may debond away from the conductors, creating an air gap, leading to failure from partial discharges.[2]

Single and multistress interactions, together with load cycling, yield about 20 different identifiable failure processes in stator windings as shown in Table 1. Which process will occur in a specific machine and how quickly the failure will occur will depend on:

- The design stress levels (i.e., operating temperatures, mechanical stress, etc.) and how close these levels are to the insulation material capabilities.
- How well the windings were manufactured and assembled.
- The operating environment – is the machine run at constant load or cycled, is it over-loaded; are oil, moisture, or abrasive particles present.
- How well the winding is maintained – kept clean, kept tight to prevent vibration, etc.

Off-line versus On-line PD Testing

Knowing which deterioration processes are occurring is important, since any winding maintenance to extend winding life should directly address the processes. There are a wide variety of testing procedures available, some conducted when the machine is out-of-service or off-line, and some done when the machine is in-service on-line.[2, 6]

When the predominant problem of an insulation system is due to voids within the groundwall insulation from improper manufacturing, thermal deterioration, load cycling, or slot discharge, off-line partial discharge test results tend to have 2-3 times higher magnitudes than on-line results. This phenomenon occurs because the majority of the coils are subjected to higher electrical stresses off-line than on-line and higher electrical stress leads to higher pulse activity. During normal operation only the line coils will be at phase-to-ground voltage with a graded decline of electrical stress through the winding, whereas during off-line tests all of the coils will be at test voltage levels. [3]

If the predominant problem is due to mechanical stresses, such as loose coils or core-iron arcing, off-line PD results will be significantly lower than on-line ones because there are no mechanical forces during an off-line test. Likewise, if the predominant problem is phase-to-phase PD, it is difficult with a single-phase external power supply to emulate the typical phase-to-phase stresses seen during normal operation; however, in extreme circumstances this may be possible. Because sources of PD can vary due to small changes in ambient or operating condition, caution must be taken that successive tests be done under similar conditions.[3]

Table 1 below shows which methods are detectable via both off-line and on-line methods, neither method, or requires on-line monitoring.

TABLE 1. Common Stator-Winding-Insulation Deterioration Mechanisms

Mechanisms	Description	Root Cause	Relative Speed[1]	Detection[2]
Thermal	Long-term operation at high temperature, leading to embrittle-ment and insulation delamination	Overloading, blocked cooling, unbalanced voltage, frequent starting	Slow	Both
Load cycling	Rapid, frequent on-off cycling leading to de-lamination	0% to 100% load changes in less than 15 min	Moderate	Both
Poor impreg-Nation	Voids in insulation leading to PD	Lack of penetration of mica tapes, by epoxy, or polyester	Moderate	Both
Internal water leaks	Saturation of insulation by water from cracks in hollow copper conductors	Water fittings in direct-water-cooled windings	Slow	Neither
Coil movement	Abrasion of insulation due to movement of coils/bars in slot	Insulation shrinkage over years, oil contamination, poor installation	Fast	On-line
Electrical slot discharge	Partial discharge attack where semiconductive coating is missing or damaged from prolonged movement	Poorly made semiconductive coating or deterioration due to abrasion of insulation	Slow	Both
Contamination	Surface discharges or sparking in end windings due to partly conductive pollution	Poor maintenance	Slow	Both
End-winding vibration	100/120 Hz vibration of coils leading to insulation abrasion, cracking	Poor design, oil contamination	Moderate	Neither
Electrical surges	Puncture of turn insulation by high-voltage pulses	Voltages developed by motor switch-on or inverter-fed drives combined with poor or aged turn insulation	Slow	Neither
Inadequate spacing	Partial discharge attack of groundwall insulation	Insufficient spacing is provided between high voltage components of different phases	Slow	On-line

[1]Relative speed of deterioration
[2]Detection method:

- *Both* off-line and on-line partial discharge testing
- *Neither* off-line or on-line partial discharge testing
- *On-line* partial discharge monitoring only

OFF-LINE POWER FACTOR TESTING

Theory

Power factor testing of rotating machinery is a non-destructive AC test performed off-line at apparatus frequency. When a 60 Hz voltage is impressed across generator stator insulation, the total current that flows is similar to that of any capacitor. The total current has two components: a relatively large capacitive current (i_c) which leads the voltage by 90°; and a smaller resistive current (i_r) which is in-phase with the voltage. The dielectric of this simulated capacitor is the insulation system which is embedded between two electrodes, the high voltage copper conductors and the stator iron core. The power factor is the Cos θ.

$$\cos\theta = \frac{i_r}{i_t} = \frac{E.1_r}{E.1_t} = \frac{W}{E.i_t} = \frac{Watts}{Volts\ x\ Amps}$$

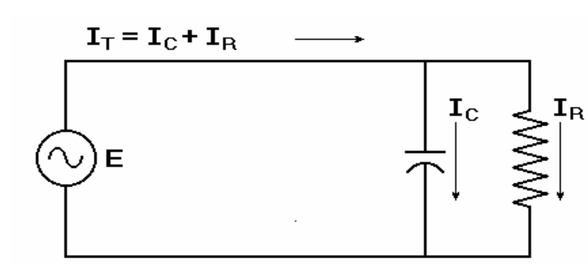


FIGURE 1. Basic Dielectric Circuit

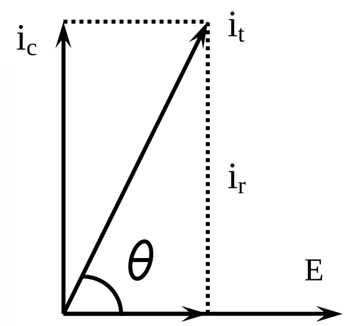
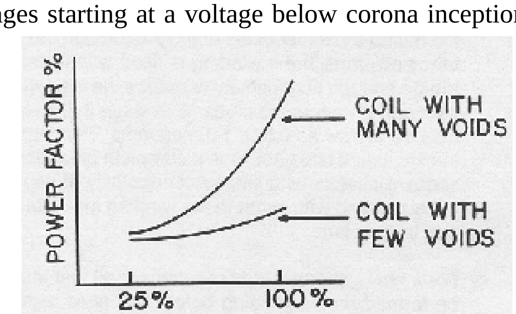


FIGURE 2. Total Charging Current

Power factor is a dimensionless quantity and thus can be compared amongst different volumes of insulation systems. It is a measure of the dielectric losses of the insulation and provides valuable information about the insulation quality.

Power factor is performed per phase, at incremental voltages starting at a voltage below corona inception and continuing up to the line-ground voltage rating of the machine and possibly 25% over.[8] Power factor Tip-up is defined as the power factor measured at the line-ground voltage minus the low voltage power factor (typically performed at 100% and 25% of the line-ground voltage). Since all dry type insulation systems contain voids, the power factor will increase with an increase in test voltage. The increases in power-factor as a function of voltage are due to the ionization of the gas in the voids of the insulation system. An insulation system with excessive voids will have a higher power factor tip-up (Figure 3). Excessive voids may be due to the aging of the paper tape or of the bonding material in the insulation system. Aging of these materials leads to a reduction of physical strength, and thus the production of voids. Once excessive voids are present, partial discharge will occur which also damages the bonding materials.[13] The degradation of the insulation system may occur internally or on the surface of the coil/bar, due to loose coils within the slot, deterioration of the semicon grading paint and/or inadequate coil spacing.



PF with many and few voids

FIGURE 3

Capacitance and total charging current are also measured and recorded as part of the Doble power factor test. These values provide valuable information about the physical condition of the insulation system. A change in capacitance may occur due to a change in the size, shape or distance between the two conductors. As an insulation system cures or ages, the dielectric constant may change causing a change in the measured capacitance and total charging current.

Applications

The Power Factor test on stator windings is performed off-line with either the rotor in or removed. The test may be performed in air or under sealed hydrogen at near operating pressures. Hydrogen at pressures less than 15 psig have a lower breakdown level than air at atmospheric pressure. Water cooled machines should be tested with the demineralized water flowing through the windings and when the conductivity of the water is less than 0.25 microsiemens per centimeter (micromho per centimeter).[8] The DC losses associated with the water cooling system must be subtracted from the AC losses using a specified test procedure. The test may be performed on low, medium and high voltage machines. The initial test results may be compared with Doble's tabulated data and previous test results should be compared with preceeding results and the tabulated data.

The stator windings must be isolated and the neutral separated so that each phase may be tested individually. Each phase is tested to ground and then to the adjacent phase.

Limitation

The Power Factor test must be performed with the unit off-line and with the stator winding isolated. The test set must be used with a resonating inductor in order to achieve the recommended line to ground test voltage. The resonating inductor extends the total charging current range of the Power Factor test set while minimizing the input current.

On a completed stator, the measured power factor and capacitance results are an average value of the phase under test. Therefore, it may be difficult to determine if a high power factor or tip-up or a change in capacitance is due to an overall condition or an isolated coil or coil set.

Interpretation

Power factor analysis requires knowledge of both test circuits and the parameters which are measured. Each test mode involves a different portion of the insulation system. The phase-to-ground insulation test (GST-Gnd mode) involves mostly the coils/bars located within the slots. The interphase insulation test (UST mode) primarily involves the end-winding insulation because the stator iron core shields the slot sections of the phases.

The parameters that are recorded and analyzed are:

- Total Charging Current
- Watts, Power Factor
- Capacitance
- Power Factor Tip-up or Tip–down.

The power factor and watts values provide information about the quality of the insulation. The power factor measured at low voltage, below corona inception voltage, is an indication of the inherent dielectric losses of the insulation system and its general condition. An acceptable power factor assures that the insulation system was manufactured with low loss materials, processed properly and free of contaminates. The low voltage power factor will also provide information about the moisture content and the degree of overall cleanliness and curing of the insulation. It is common to have an elevated low voltage power factor on a newly rewound insulation system due to uncured materials. It is our experience that typically six months later, the power factor returns to normal. Also, poor contact of the semiconductive slot coating with the core can be detected by an elevated low voltage power factor.[8]

The Power Factor Tip-up (or Tip-down) is a calculated value sensitive to the amount of void content within the insulation system. Thus the power factor tip-up reflects the quality of the construction of the insulating system and the impregnation process. Power factor Tip-up will respond to excessive voids in the slot due to defective or deteriorated semicondictive slot coating. The continuity and condition of the stress control coating is detectable by Power Factor Tip-up or down. Often enough, the interphase test will exhibit a negative power factor as the voltage is increased. This is referred to as Tip-down and typically appears when the stress gradient paint or tape is applied on the windings as part of the insulation system. The Power Factor Tip-down is considered normal and should be compared with previous tests to monitor the condition of the stress gradient paint. Power Factor Tip-up is also sensitive to delamination of the insulation due to thermal stresses, and partial discharge damage.[8]

In low loss specimens (less than 20% power factor), the total charging current is nearly equal to the capacitive current. As a result, when the measured capacitance changes, the total charging current will change proportionally. Therefore, total charging current and capacitance provide valuable information about mechanical or physical changes in the insulation system. A change in capacitance with increasing test voltage (i.e. the standard Doble test procedure) of 5% or more or when compared to a previous test, may indicate deterioration of the semiconducting paint or tape used to ground the coils in the slots. [13,14]

Measured power factor, capacitance and power factor tip-up should be compared amongst the phases and with previous test results. For insulation in good condition, the per phase results should be similar.

PF Case Study I: Slot Discharge

- Turbine generator: 13.8kV, 15.4MVA, Mfr. 1985, Epoxy-mica
- Power Factor: Initially very high, improved some after repairs, normal after rewind
- Power Factor Tip-up: Initially very high, normal after rewind
- Capacitance: Increase w/test voltage of approximately 8% before rewind
- Analysis: Severe slot discharge, deterioration of semiconductive coating and stress gradient paint with overall contamination

Note: Machine re-wound November, 1995

FIGURE 4. Insulation to Ground Power Factor Trend, Phase A

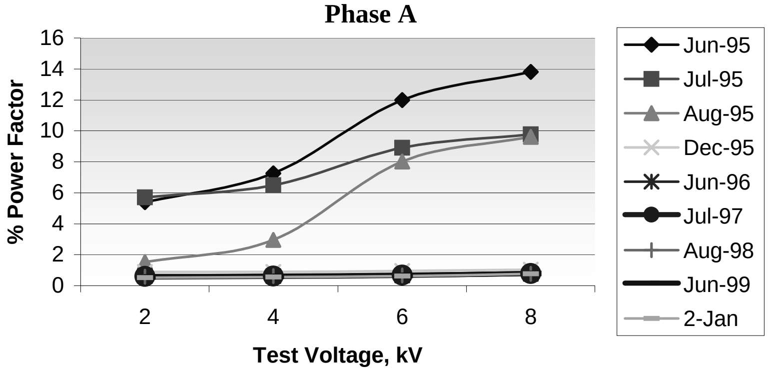
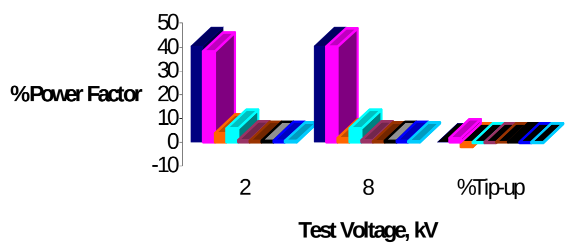
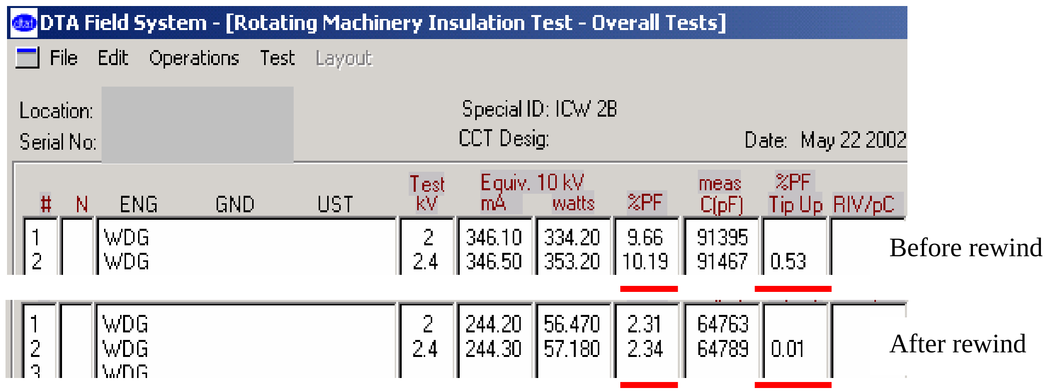


FIGURE 5. Interphase Insulation Power Factor & Tip-up Trend, Phase A



PF Case Study II: Insulation Delamination

- Induction Motor: 4.16 kV, 600 HP, Mfr. ≈1980
- Initial Power Factor: High
- Initial Power Factor Tip-up: High
- After Rewind Power Factor: Normal
- After Rewind Power Factor Tip-up: Normal
- Analysis: Overall winding deterioration and insulation delamination due to thermal stress or poor impregnation.



DTA Field System - [Rotating Machinery Insulation Test - Overall Tests]

File Edit Operations Test Layout

Location:
Serial No:
Special ID: ICW 2B
CCT Desig:
Date: May 22 2002

#	N	ENG	GND	UST	Test kV	Equiv. 10 kV mA	Equiv. 10 kV watts	%PF	meas C(pF)	%PF Tip Up	RIV/pC
1		WDG			2	346.10	334.20	9.66	91395		
2		WDG			2.4	346.50	353.20	10.19	91467	0.53	

Before rewind

#	N	ENG	GND	UST	Test kV	Equiv. 10 kV mA	Equiv. 10 kV watts	%PF	meas C(pF)	%PF Tip Up	RIV/pC
1		WDG			2	244.20	56.470	2.31	64763		
2		WDG			2.4	244.30	57.180	2.34	64789	0.01	
3		WDG									

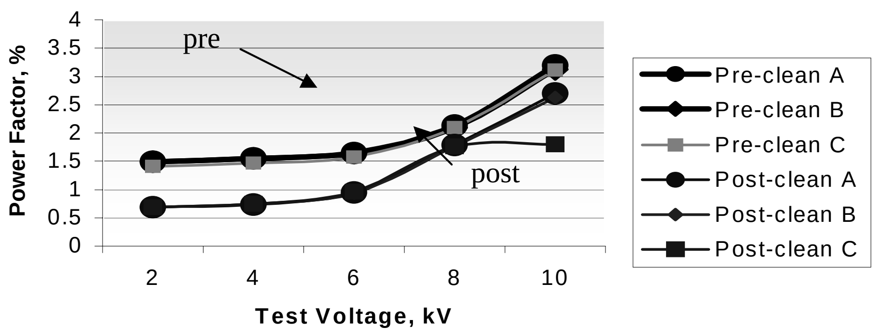
After rewind

FIGURE 6. Power Factor and Tip-Up Results Before and After Repairs

PF Case Study III: Effects of Maintenance

- Turbine generator: 13.8kV, 46.5MW, Mfr. 1972, Epoxy-mica
- %PF @ 2kV Before Clean: Slightly High
- % Tip-up Before Clean: Normal
- %PF @ 2kV Tabulated: Less than 1.0%
- Analysis: Contaminated insulation
- %PF @ 2kV After Clean: Normal
- %Tip-up After Clean: Normal, but higher
- %Tip-up Tabulated: Less than 1.0%

FIGURE 7. Insulation to Ground Power Factor Before And After Cleaning



ON-LINE PARTIAL DISCHARGE MONITORING

Theory

Partial discharge (PD) is a symptom of several stator-winding problems caused by electrical, thermal, mechanical, and enviromental stresses. Monitoring PD can be a useful addition to any company's tests and inspection procedure. Not only is PD a symptom, it is also damaging to the organic resins used in insulation materials. Fortunately, since most stator winding insulation systems for machines rated greater than 2300V contain a discharge-resistant material called mica, degradation of the groundwall is usually slow. It is because of this relatively slow aging process that periodic monitoring of the PD activity makes sense.

When the applied 50/60Hz increases sinusoidally, the apparent electric stress across a problem site (void) increases until a condition of over voltage occurs (see Figure 8). Over voltage is the state at which the voltage across a void exceeds the electrical breakdown voltage required for the void size and gas. The larger the over voltage achieved, the more intense the space charge effects in the void. Once the breakdown occurs, the voltage across the gap collapses to a voltage level sufficient to sustain the discharge. Most partial discaharge monitoring instruments only detect the initial breakdown pulse.[4] Periodic detection of the quantity, magnitude, polarity and relative phase position of the PD activity can be used to monitor the aging progression as well as determine the most likely failure mechamisms and provide maintenance personnel with guidance as to when and what maintenance might be required. As shown in the Table 1, on-line PD monitoring is capable of identifying problems due to thermal deterioration, load cycling, poor impregnation, coil movement, electrical slot discharge, contamination and inadequate spacing.

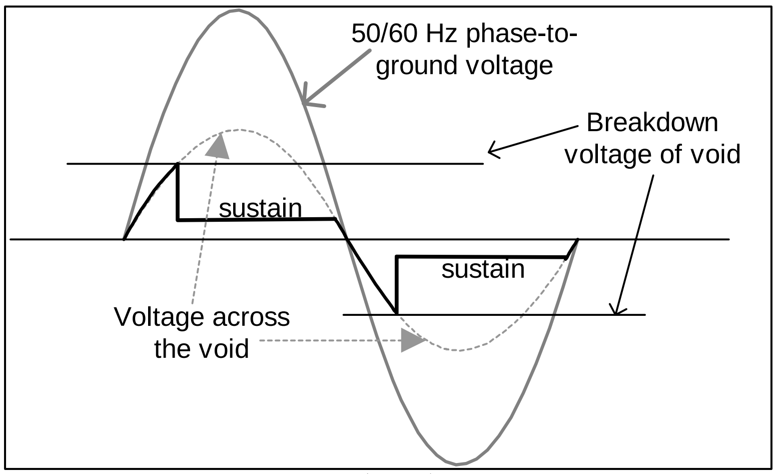


FIGURE 8. Partial Discharge Occurrence

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Electrical noise from power tool operation, corona from the switchgear, RF sources, etc., is easily confused with PD from the machine windings. This confusion can lead to healthy windings being misdiagnosed as deteriorated, which lowers confidence in the test results. An improved on-line PD test was developed which can significantly reduce the influence of noise, leading to a more reliable indication of machine insulation condition.[5]

Applications

On-line PD monitoring can be done on any stator winding with a voltage rating above 3kV. As the test is done on-line, it requires sensors to be permanently mounted within the machine housing or at the machine's terminals, see Figures 9 and 10. Permanently mounted PD sensors block the AC power signal, but pass the high frequency PD pulses. During normal operation, a PD monitoring instrument connected to the sensors separates noise and properly classifies the PD. The type of sensor installation and test instrument depends on the machine or equipment being monitored.

Data is then collected either periodically with a portable instrument or continuously monitored. The collection of data should be repeated at least every six months for machines rated 6kV and up. If a problem develops, then the frequency of collection may need to be increased. Due to the short-time frame between detection and failure for motors rated less than 4kV, it is recommended that PD testing be done more frequently, best if continous, on these machines. By using the summary variables, trending of data is straightforward and useful. Collection of data at different operating parameters may also help in determining the condition of the stator winding. [5]

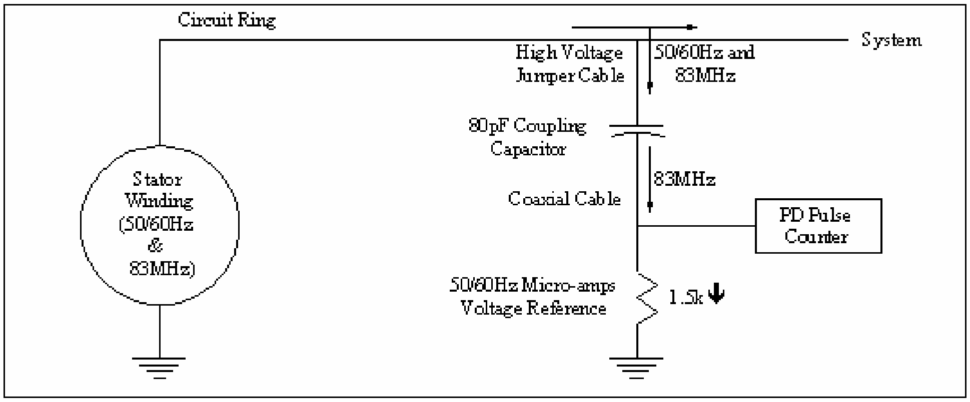


FIGURE 9. 80pF Capacitive Sensors used in Motors, Hydrogenerators and Small Turbine generators

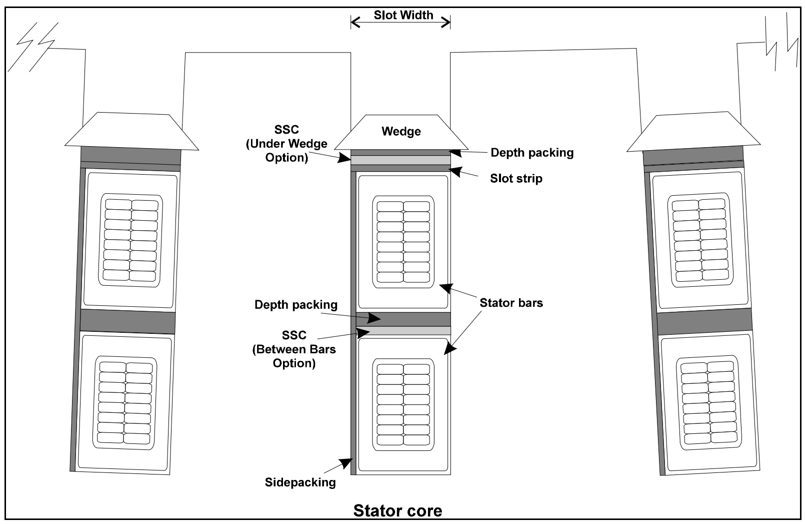


FIGURE 10. Stator Slot Couplers used in high-speed Turbine generators

Limitation

Sensors must be permanently mounted within the winding during an outage. These sensors should be connected to the high voltage bars or coils of the winding, that is, the areas with the highest electrical stress and therefore the most susceptible to failure. Because high frequency PD signals will disperse and attenuate as they travel, this test configuration is not responsive to isolated problems located away from the high voltage areas, but is responsive to the most common aging mechanisms and failure stresses within windings.

Interpretation

PD detection involves measuring four characteristics of the PD patterns:

- PD magnitude ⇒ relates to the size or volume of the voids
- PD pulse count rate ⇒ relates to the quantity of voids
- PD polarity ⇒ relates to the location of voids within insulation bulk
- PD position relative to the phase-to-ground voltage ⇒ relates to the location of defects either in the slot or from interphasal activity, often in the endwinding

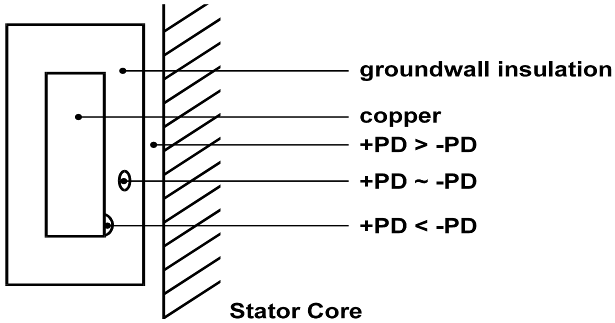


FIGURE 11. Pulse Polarity Based on Void Location

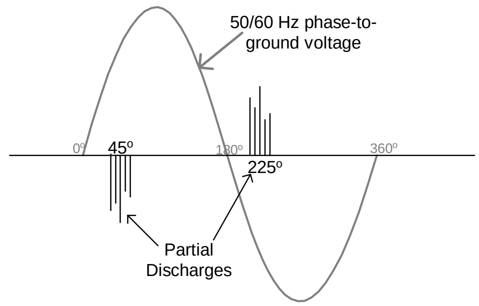


FIGURE 12. Voids in the Bulk of the Insulation

For ease of interpretation, the PD monitoring instruments calculate the quantities Q_m and NQN based on the entire Pulse Height Analysis (PHA) plot. The NQN, or Normalized Quantity Number, is a partial discharge quantity that is proportional to the total partial discharge measured by a PD sensor. The negative NQN refers to the total activity from negative PD pulses, while positive NQN refers to the total PD activity from positive PD pulses. NQN is an indicator of the average condition of the stator winding insulation. Q_m, or Peak Magnitude, is the magnitude of the pulses for one fundamental (directory measured) pulse category that has a repetition rate of 10 pulses per second, and corresponds to the peak PD activity. Q_m is an indicator of how severe the PD is at the most deteriorated part of the winding. Positive and negative Q_m refers to the peak PD activity from the positive and negative PD pulses, respectively.[4]

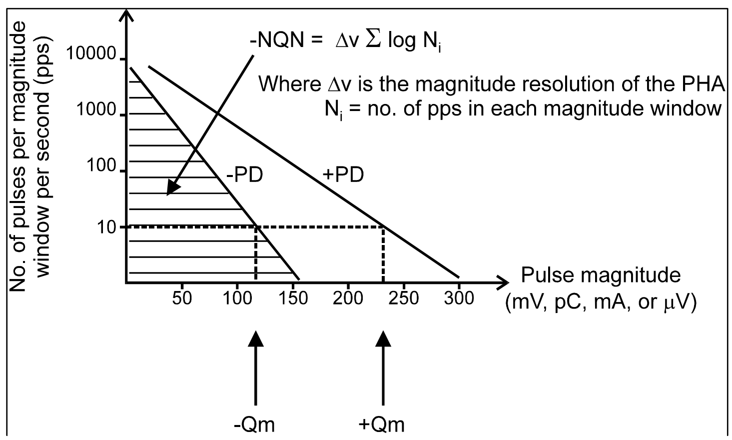


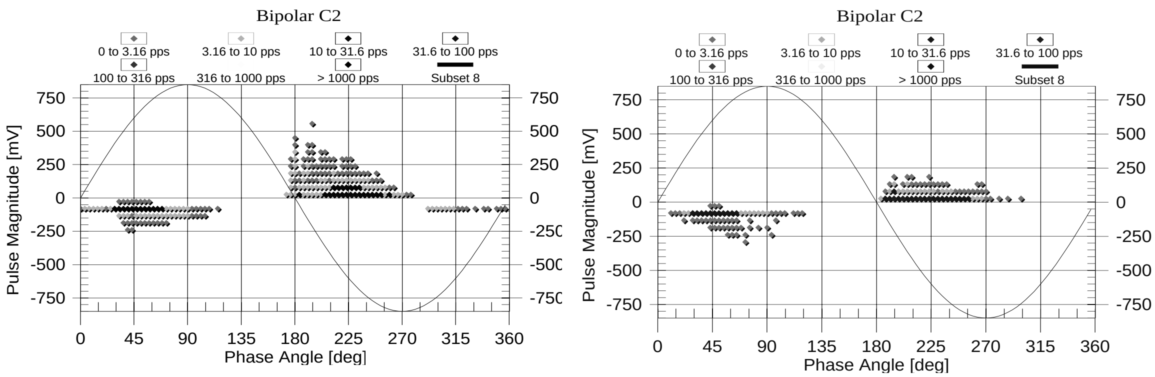
FIGURE 13. Partial Discharge Summary Variables

There are four steps in interpretation to determine the aging progression and likely failure mechanisms:

- Trend of Q_m and NQN – progression of *aging* mechanism
- Statistical comparison of Q_m and NQN – relative *severity* of the PD activity [7]
- Pulse distribution – identification of the *nature* and *relative location* of different PD sources
    - Polarity – negative predominance indicates voids near the conductors while positive predominance indicates surface activity
    - Classic PD – PD clusted at positions of 45° and 225° relative to the phase-to-ground voltage originate from voids within the slot section of the winding
    - Non-classic PD – PD clustered at positions other than the classic positions are from sources external to the slot section of the bars
    - Distribution – normal from internal voids or wideband from surface activity
- Effects of operating parameters – PD pattern changes dependent on operating parameters identify the *cause* of the PD activity

PD Case Study I: Operating Load Effects

- Hydrogenerator: 13.8kV, 66MW, Mfr. 2002, Polyester-mica, PDA-IV portable instrument
- Trend: Stable
- Statistical Qm levels: Moderate
- Pulse distribution: Wideband at classic positions with positive predominance
- Load dependent: Positive PD increases with load
- Analysis: Combination of internal and surface voids with indications of the onset of coil looseness, but as of yet no severe problems



High Load Low Load

FIGURE 14. Load Effect for a Hydro Generator

PD Case Study II: Trend

- Turbine generator: 13.8kV, 24MW, Mfr. 1992, Epoxy-mica, BusTrac continuous monitor
- Trend: Stable
- Statistical Qm levels: Low
- Analysis: No indications of any problems, though the PD in October was erratic

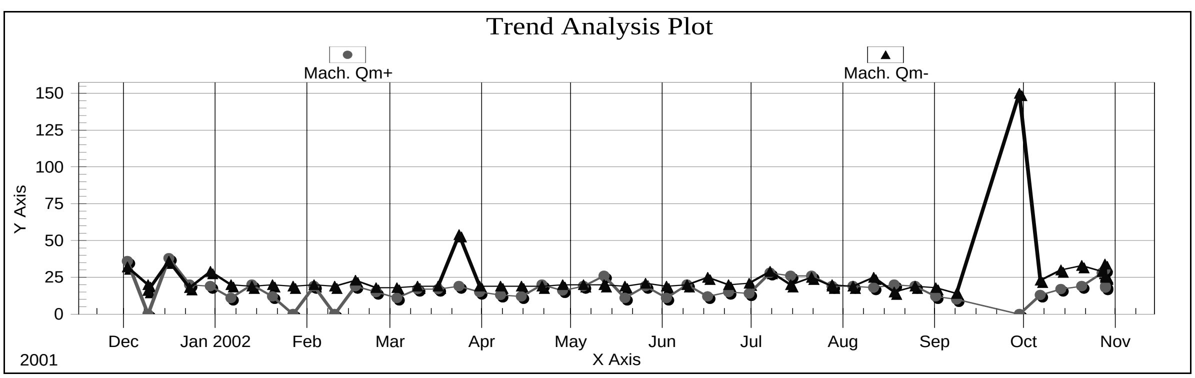


FIGURE 15. Qm Trend

PD Case Study III: Operating Hydrogen Effects

- Turbine generator: 13.8kV, 60MW, Mfr. 2000, Epoxy-mica, TGA-B portable instrument
- Trend: Fluctuates with operating pressure, but stable at constant pressure
- Statistical Qm levels: Very high at low pressure
- Pulse distribution: Non-classic interphasal arcing from A to B at 18psi
- Hydrogen dependent: Extremely sensitive to hydrogen pressure
- Analysis: Inadequate spacing between high voltage components in the endwinding

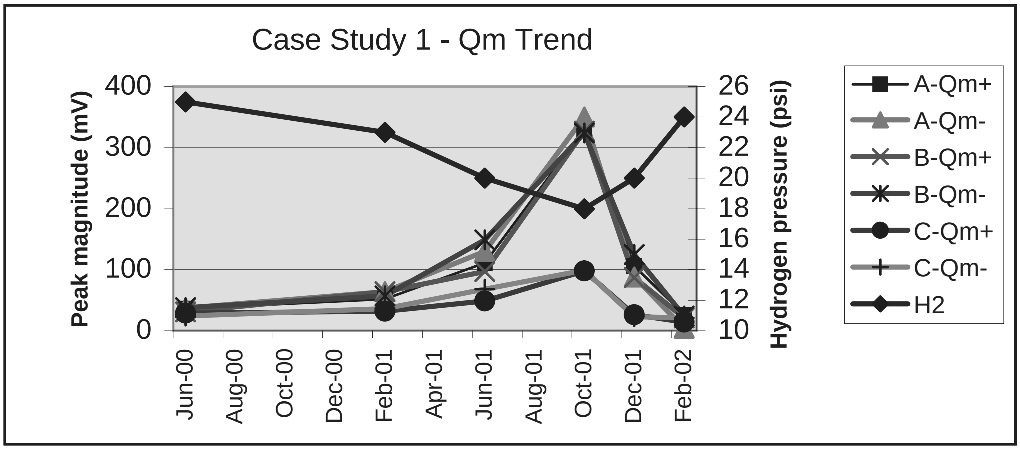


FIGURE 16. Trend at different H2 pressure

COMPARATIVE CASE STUDIES

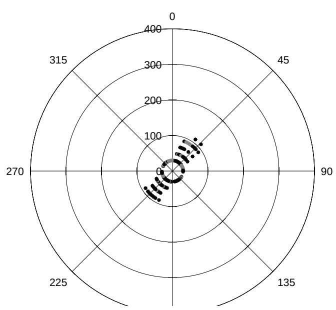


FIGURE 17. Classic PD at 45° and 225°

Case Study I: Turbine Generator

- Turbine generator: 13.8kV, 70MVA, TGA-B portable instrument, Thermalastic, Mfr. 1988, air cooled
- Statistical Qm levels: Low
- PD distribution: Classic at the 45° and 225° positions due to small internal voids
- Power factor results: Normal
- Tip-up results: Normal
- Analysis: Internal voids due to normal thermal and electrical aging stresses
- Detection: By both test methods

FIGURE 18. Insulation to Ground Power Factors
Avg % Tip-up 0.24%

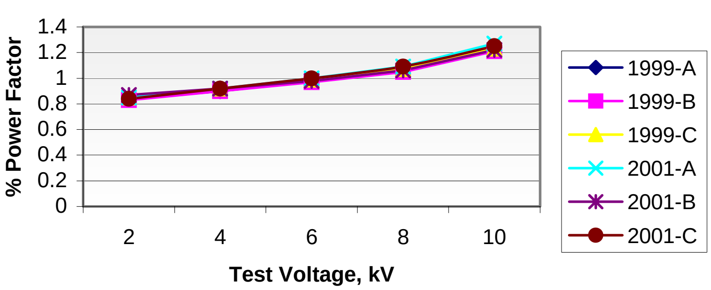
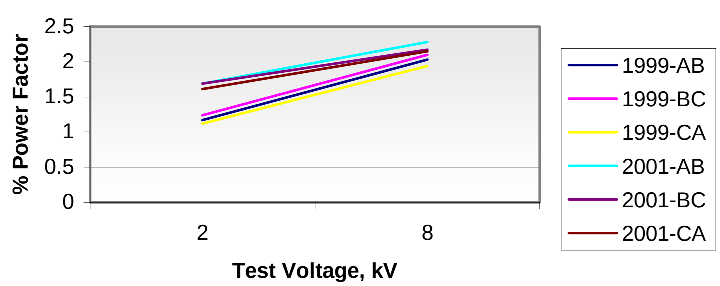


FIGURE 19. Interphase Insulation Power Factors
Avg % Tip-up 0.69%



Case Study II: Hydrogenerator

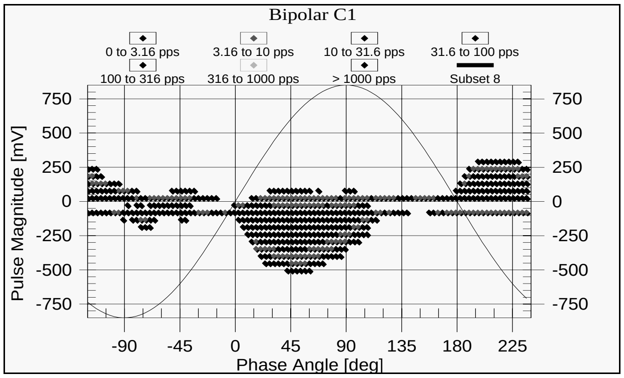


FIGURE 20. High Negative PD Predominance

- Hydroelectric generator: 13.8kV, 108/122MVA, Mfr. 1967, Thermalastic, air cooled
- Statistical Qm levels: High
- PD distribution: Normal distribution at 45° with negative predominance
- Power Factor: Normal [Fig. 22]
- Power Factor Tip-up: Normal, B phase elevated after repairs, slightly high after rewind [Fig. 21]
- Analysis: Evidence of internal voids near the conductors caused by thermal stresses
- Detection: On-line PD

Note: 1998 & 2001 tests prior to failure. Mar-02 test after repairs, Oct-02 test with new winding

FIGURE 21. Insulation to Ground Power Factor Tip-up

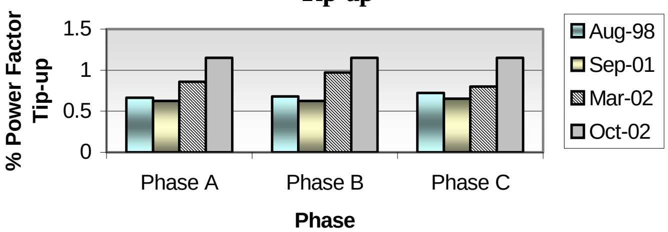
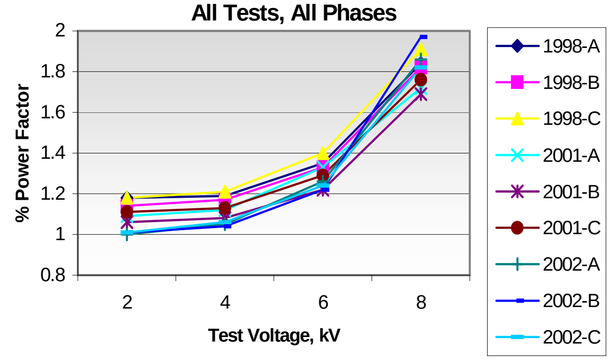


FIGURE 22. Insulation to Ground Power Factor All Tests, All Phases



Case Study III: Turbine Generator

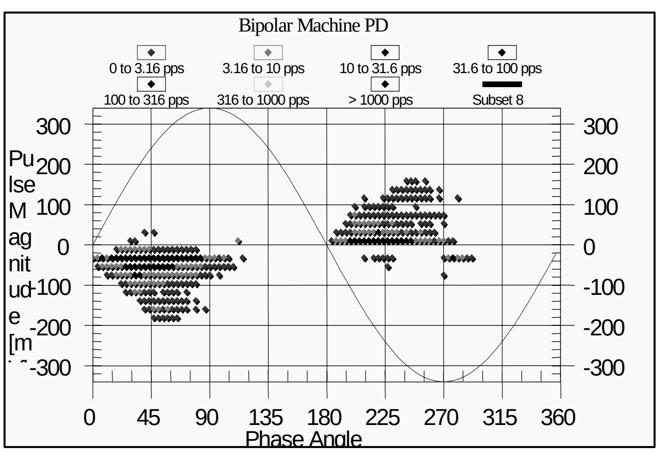


FIGURE 23. Classic & Interphasal Activity

- Turbine generator: 13.8kV, 37MW, TGA-B portable instrument, Epoxy-mica, Mfr. 1989, air cooled
- Statistical Qm levels: Typical
- PD distribution: Classic at the 45° and 225° positions due to small internal voids and higher PD 30° shifted due to interphasal arcing [Fig. 16]
- Power factor results: High interphase, normal ground [Fig. 25]
- Tip-up results: Normal [Fig. 24]
- Analysis: Internal voids due to normal thermal and electrical aging stresses combined with some interphasal arcing involving high voltage components of A and C-phases
- Detection: By both methods

FIGURE 24. Insulation to Ground Power Factors
Avg %Tip-up 0.27

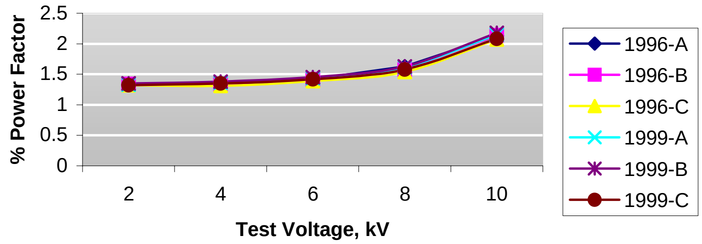
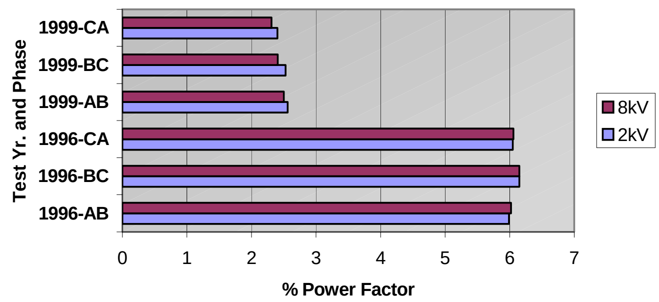


FIGURE 25. Interphase Insulation Power Factors



Case Study IV: Hydrogenerator

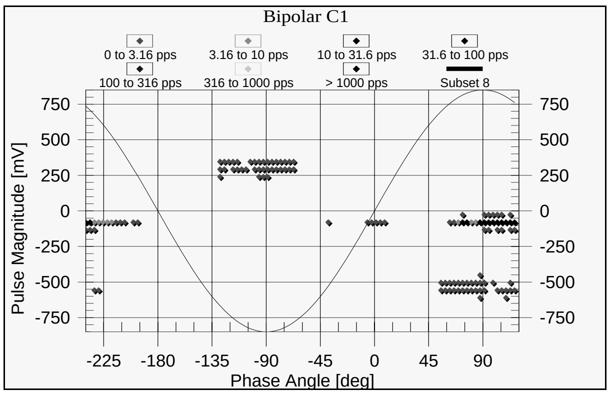


FIGURE 26. Interphasal Activity

- Hydroelectric generator: 13.8kV, 108/122MVA, Mfr. 1967, Thermalastic, air cooled
- Statistical Qm levels: Negligible for classic PD and high for interphasal activity
- PD distribution: Non-classic PD at 75-90° and 255-270° from interphasal activity
- Power Factor: Insulation-ground power factor high for new insulation system [Fig. 27]
- Power Factor Tip-up: Phase-gnd normal, interphase inconsistent across phases on new insulation system [Fig. 28]
- Analysis: Questionable quality of the new insulation system materials, impregnation process and/or uniformity of stress gradient application
- Detection: Off-line power factor for quality of insulation system and both methods for interphasal activity

Note : Unit was rewound in summer 1999

FIGURE 28. Interphase Insulation Power Factor
Tip-Down

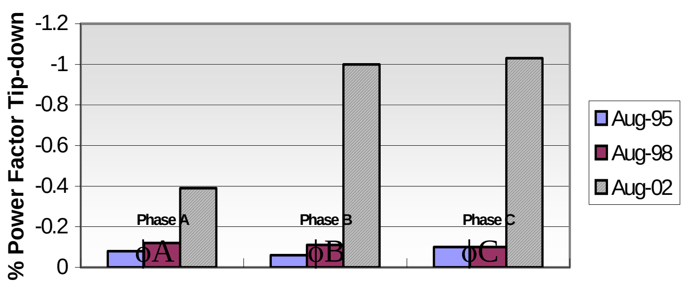
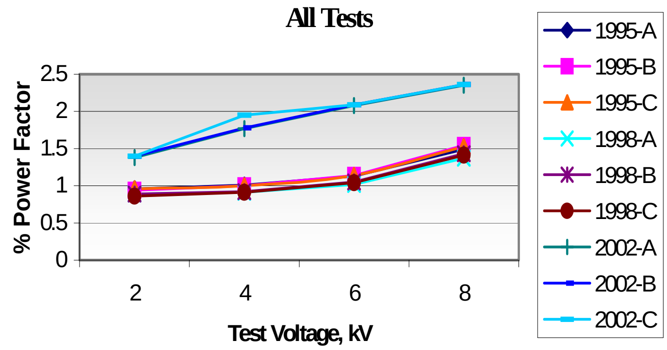


FIGURE 27. Insulation to Ground Power Factor
All Tests



Case Study V: Hydrogenerator

Hydroelectric Generator, 14.4 kV, 62.2MVA, Thermalastic, air cooled
Statistical Qm Levels: Moderate

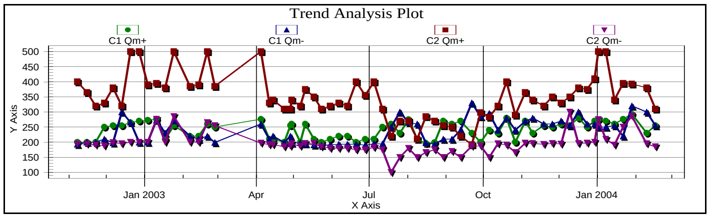


FIGURE 29. Continuous PD Monitoring

Continuous PD Monitoring: One phase exhibits persistent positive predominance on C2 that is not obvious on the other phases Though all three phases have similar levels of classic PD, the positive predominance evidence of surface PD warrants concern about the onset of coil movement.

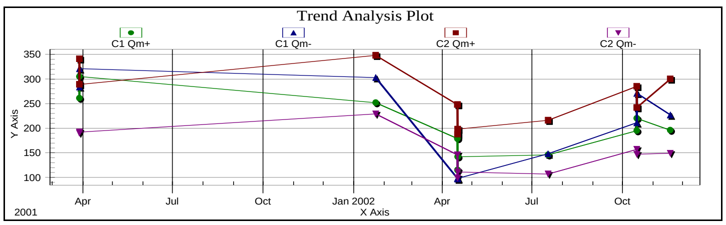


FIGURE 30. Periodic On-Line PD Testing

On-line PD Testing: The periodic on-line PD test results have been relatively consistent over the past 2 years. There was a noticeable drop in April 2002 following the outage, but the levels have steadily returned to what would be considered moderate.

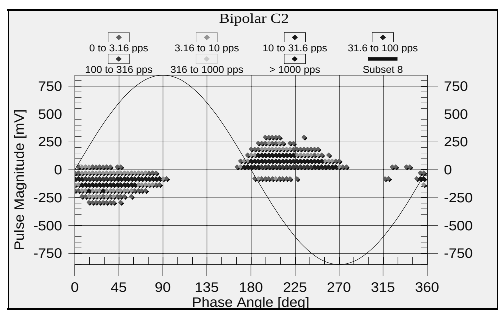


FIGURE 31. PD Pulse Distribution

PD distribution: Classic at the 45° and 225° positions due to small internal voids and higher PD 30° shifted due to interphasal arcing. Similar patterns occur on all 3 phases.

Power Factor: Steady increase in insulation-ground pf. Improvement after spike in 1984. Slight elevation of low voltage pf in 2001 tests, more significant as test voltage is increased. Interphase insulation high in 1984 and 2001. Shift in capacitance, steeper at higher voltages.

Power Factor Tip-up: Steady increase in pf tip-up till 2001. Improvement after spike in 1984. 2001 tip-up high. Figure [32]
Analysis: Excessive contamination in 1984. Increase in void content within the bars in slot and deterioration of stress gradient coating (2001). Moderate, but stable PD levels since 2001 with noticeable surface activity on one phase, but only small internal voids within the insulation.
Detection: By both methods

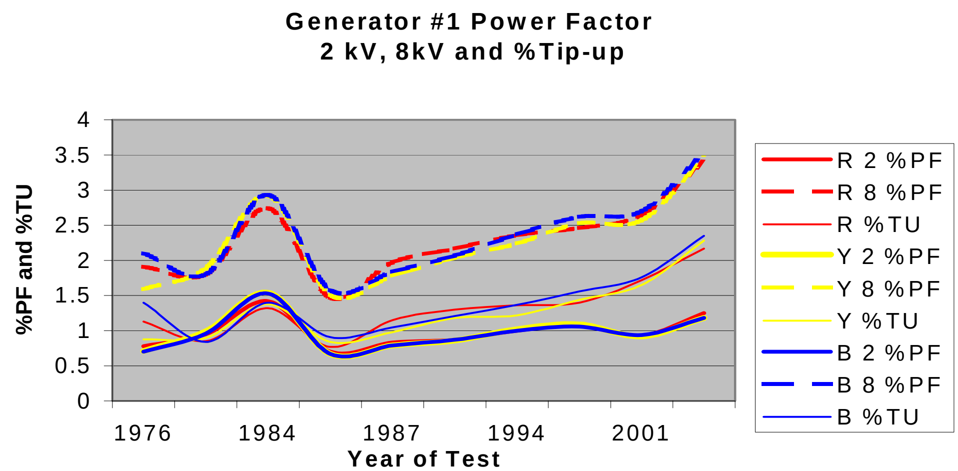


Figure 32. Power Factor Trend

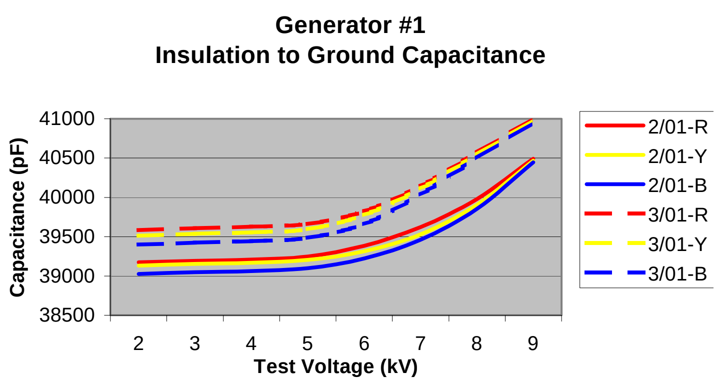


Figure 33. Capacitance Trend

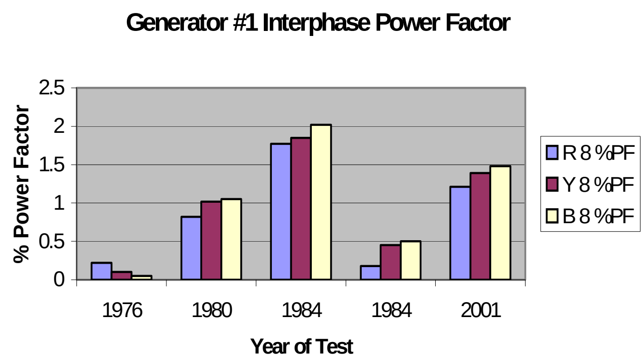


Figure 34. Interphase Trend

Case Study VI: Hydrogenerator

Hydroelectric Generator, 14.4 kV, 62.2MVA, Thermalastic, air cooled
Statistical Qm Levels: Moderate, but with intermittent extremely high PD

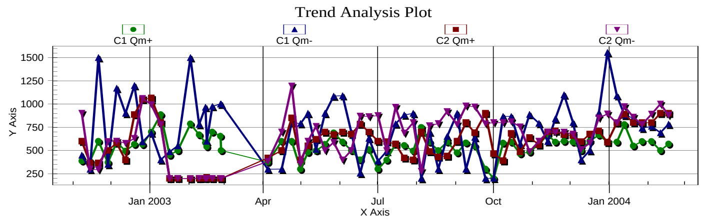


FIGURE 35. Continuous PD Monitoring

Continuous PD Monitoring: One phase has extremely high, but erratic PD. The classic PD from within the winding is stable, moderate and uniformly distributed throughout the winding.

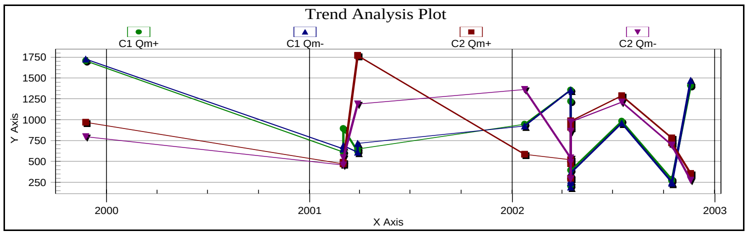


FIGURE 36. Periodic On-line PD Testing

On-line PD Testing: The periodic on-line PD test results have also been erratic over the past 2 years. Off-line PD results in Oct 2002 indicated the sources of the non-classic PD were on the circuit ring between the two sensors, and not internal to the winding.

PD distribution: Classic at the 45° and 225° positions due to small internal voids and higher PD at the non-classic positions skewing back towards 0° and 180°. This non-classic PD is originating outside of the groundwall insulation from sources on the circuit ring. Similar patterns of much less magnitude occur on all 3 phases.

Power Factor: Insulation-ground pf consistent and acceptable, slight increase in 2002. Interphase insulation high in 2002. Figures [38,39,40]

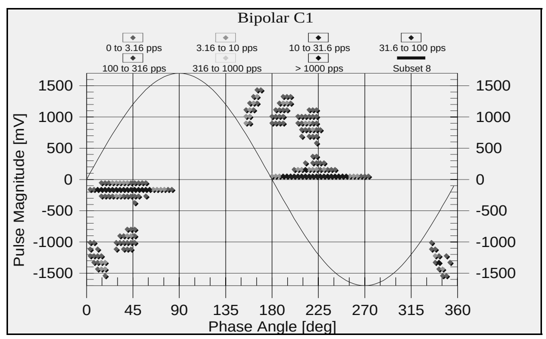
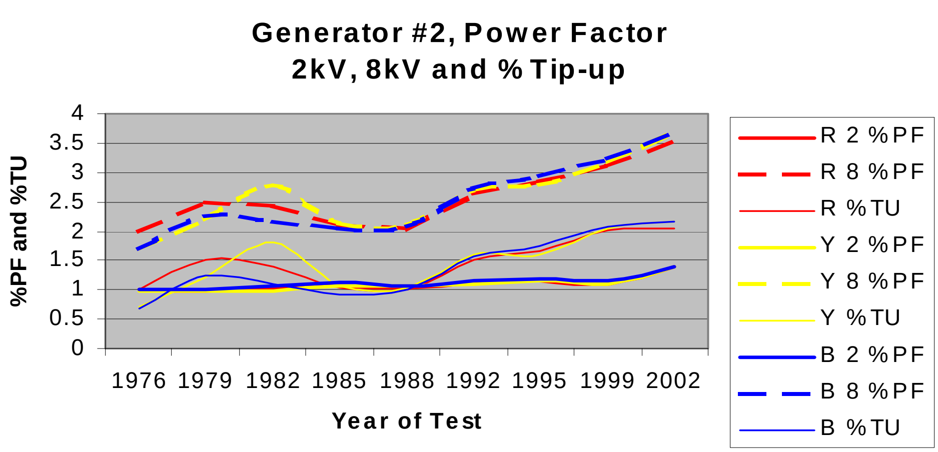


FIGURE 37. PD Pulse Distribution

Power Factor Tip-up: Steady increase in pf tip-up. Improvement after spike in 1982 on Yellow Phase.
Analysis: Increase in void content within the bars in the slot, Yellow Phase severe in 1982.
Contaminated endwindings in 2002. Erratic very high PD on one phase from sources external to the slots, while the groundwall insulation appears to be in good condition.
Detection: Both methods

Figure 38



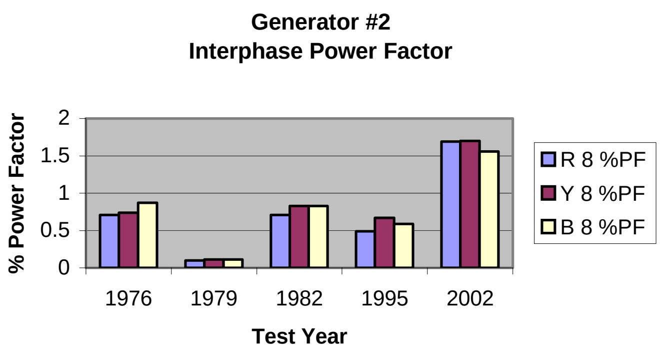


Figure 39. Interphase Trend

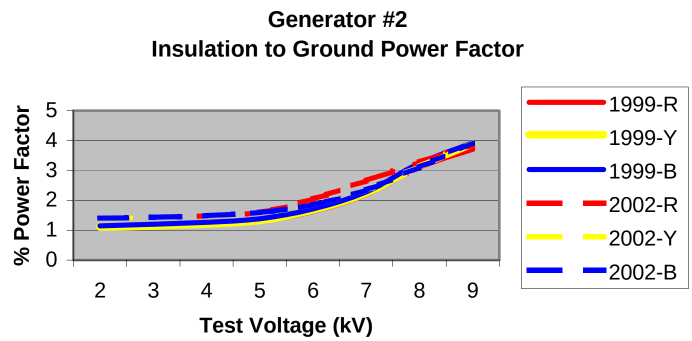


Figure 40. Power Factor Trend

Case Study VII: Hydrogenerator

Hydroelectric Generator, 14.4 kV, 62.2MVA, Thermalastic, air cooled
Statistical Qm Levels: High, but with intermittent extremely high PD

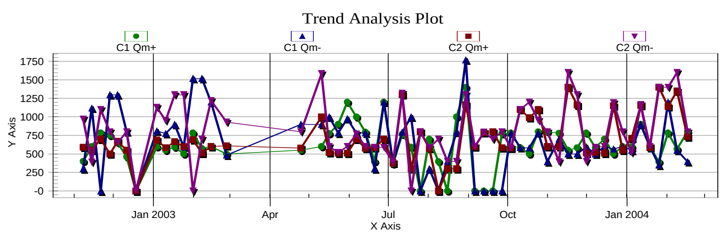


FIGURE 41. Continuous PD Monitoring

Continuous PD Monitoring: One phase has extremely high, but erratic PD. The pattern is non-classic and indicates problems along the circuit ring.

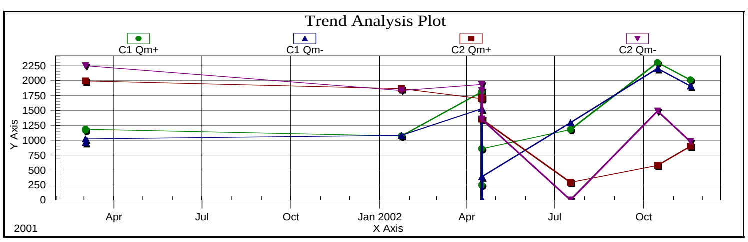


FIGURE 42. Periodic On-line PD Testing

On-line PD Testing: Following the outage in April 2002, the PD levels on one phase have returned to what would be considered extremely high. The classic PD from within the winding is stable, moderate and uniformly distributed throughout the winding.

PD distribution: Nominal classic PD at the 45° and 225° positions due to small internal voids and much higher PD at the non-classic positions skewing back towards 0° and 180°. The pattern indicates the non-classic PD is originating outside of the groundwall insulation from sources on the circuit ring.. The PD on the other phases is much lower, but similar.

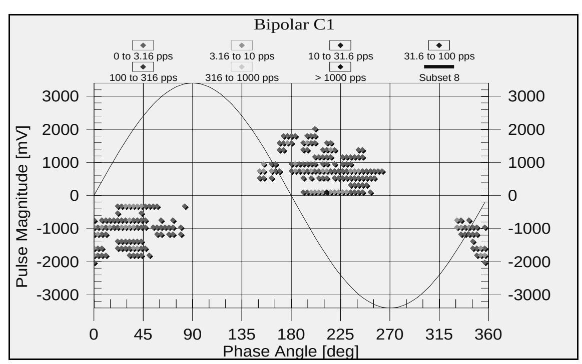


FIGURE 43. PD Pulse Distribution

Power Factor: Insulation-ground pf shows sudden increase in Red phase at 7 kV (2000). Interphase insulation high in 1979 and 2003. Figures [44, 45, 46]

Power Factor Tip-up: Erratic pf tip-up trend. Red Phase showing highest changes.
Analysis: Increase in void content within the bars in the slot, Red phase excessive. Contaminated endwindings. (1979, 2003). Erratic very high PD on one phase from sources external to the slots, while the groundwall insulation appears to be in good condition. Detection: Both methods

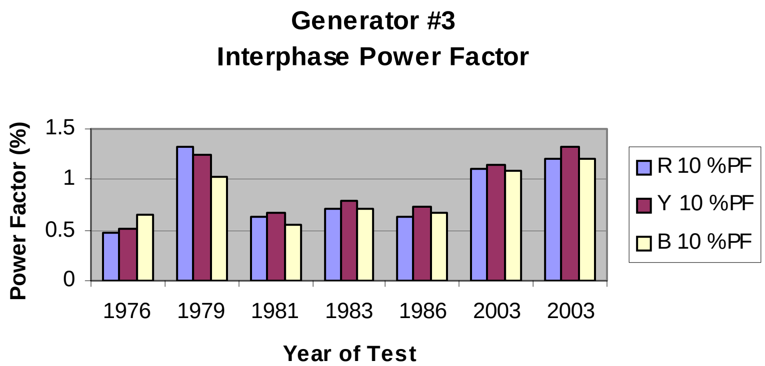


Figure 44. Interphase Trend

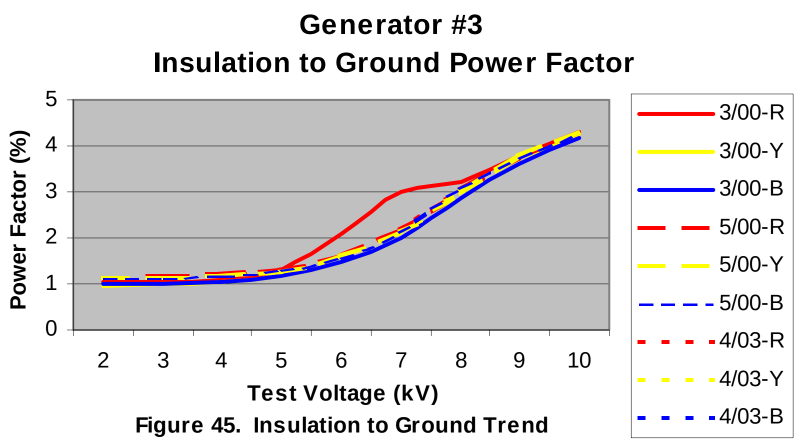


Figure 45. Insulation to Ground Trend

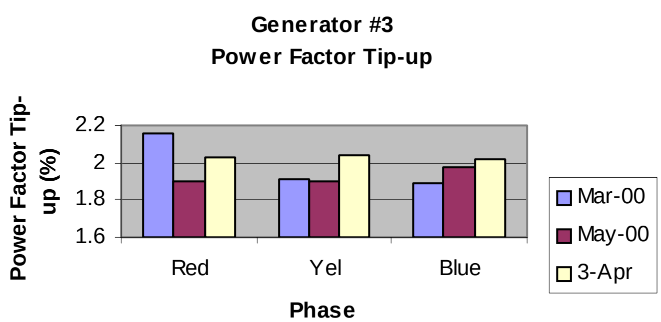


Figure 46. Tip-up Trend

CONCLUSION

Both power factor/capacitance and partial discharge are valuable condition assessment techniques. Both can pick-up significant number or aging mechanisms occurring in the stator insulation of rotating machines. Each has its own particular advantages and disadvantages, and consequently each has a role in the overall assessment of a machine.

Power factor and capacitance is particularly good at detecting defects that are global in the winding. Examples are poor quality of insulation after a rewind, contamination, or global delamination. The test also provides information about the quality of the semicon and stress gradient coatings**.**

Partial discharge, particularly when done on-line, is more effective in detecting localized damage and factors that are best revealed when the machine is operating under normal conditions of stress, stress distribution, temperature and vibration. Examples are coil movement, thermal deterioration, interphasal arcing, and electrical slot discharge. Additionally, the results can be made without disrupting the operating regime.

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