Partial Discharge Testing of Electrical Equipment: Busting the Myths and Implementing Existing Technologies and Methods

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Myth Busting Criteria:

- Busted – means there is little, if any, truth to the Myth
- Plausible – means that aspects of the Myth may be true, but not the best solution
- Confirmed – means that the Myth is best the solution

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***Abstract* -** Partial discharge technology and equipment – a somewhat newer technology to the electrical power testing and maintenance arena, but it is a technology that provides valuable data in the quest for electrical system reliability and performance. Understanding the various technologies and practical implementation of the technologies in the field can be a daunting task. What really works well? What doesn't work so well? What questions need to be asked before implementing a partial discharge technology on your equipment or systems? Tom Sandri and Vicki Warren will "Bust" through the various myths surrounding PD testing and will provide an overview of the partial discharge technologies along with real world examples of the practical use and application of the many partial discharge options that currently exist.

1 Introduction

Partial discharge or simply PD can be found in all types of medium and high voltage power equipment ranging from switchgear, transformers, cables, splices and terminations, to rotating equipment such as motors and generators.

For more than 50 years, companies have performed partial discharge testing on electrical assets as part of ongoing predictive maintenance programs. Data obtained through partial discharge testing and monitoring has provided critical information on the quality of insulation and its impact on overall equipment health. Since partial discharge activity is often present well in advance of insulation failure, asset managers have the ability to monitor PD activity over time and make informed strategic decisions regarding the repair or replacement of their equipment. Predictive diagnostics resulting from PD testing can assist companies in prioritizing capital and MRO (material, repair and overhaul) investments before an unexpected outage occurs.

1.1 Stationary Equipment:

Once PD starts in stationary equipment it always increases until eventually total insulation failure occurs. According to the National Fire Protection Association (NFPA 70B), the leading cause of electrical failures is insulation breakdown. The National Electrical Code (NEC) states that these partial discharges are the first indicator of insulation deterioration. Research from the IEEE Gold Book, Table 36, indicates that cables, switchgear, and transformers suffer the greatest losses from insulation failures.

Component	**Percentage of insulation failure**
Transformers	84%
Circuit Breakers	21%
Disconnect Switches	15%
Insulated Switchgear Bus	95%
Bus duct	90%
Cable	89%
Cable Joints (splices)	91%

1.2 Rotating Equipment:

Rotating equipment insulation systems for medium and high voltage systems use mica as a dielectric and therefore do not fail the same as solid/liquid dielectrics like in transformers and cables. Mica is resistant to PD damage, so in mica-based insulation systems, PD is a symptom of various failure processes and not the cause. Partial discharges (PD) are the small electrical sparks that occur when voids exist within or on the surface of high voltage insulation of stator windings in medium and high-voltage motors and generators. These voids can occur because of the thermal deterioration, manufacturing/installation processes, winding contamination or stator bar movement during operation and indicate potential damage to the mica dielectric. As the insulation degrades due to thermal, mechanical and electrical stresses, the number and magnitude of PD pulses will increase, but as long as the mica layer is intact failure will not occur – the goal of PD monitoring is to predict and prevent failure of the mica. Although the magnitude of the PD pulses cannot be directly related to the remaining life of the winding, the doubling of PD pulse magnitudes approximately every 6 months indicates rapid deterioration is occurring. If the rate of PD pulse activity increases rapidly, or the PD levels are high compared to other similar machines, this is an indicator that visual inspections and/or other testing methods are needed to confirm the insulation condition [IEEE 1434-2000]. Furthermore, if the PD magnitudes by the same test method from several identical windings are compared, the windings exhibiting higher PD activity are generally closer to failure.

1.3 Myth Busting:

As stated, partial discharge testing offers many diagnostic advantages; however, there are many myths surrounding the technology that lead to it often being misunderstood and/ or misapplied. As we bust through the myths we will learn, partial discharge testing is a powerful tool and when added to other predictive maintenance test methods it will render an effective program for evaluating asset condition and quality.

2 Myth 1: Partial Discharge Testing is Black Magic

The view from many in the electrical community is that partial discharge testing is black magic and an unreliable test rendering inconclusive results. Before we explore this myth let's first define what is partial discharge and what are its effects. As we will see the effects will vary depending on the type of insulating system; stationary equipment with non-mica insulating systems or rotating equipment with mica insulating systems.

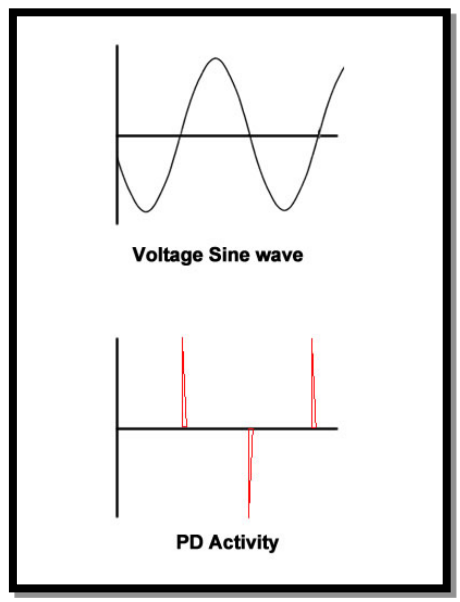

Figure 1. PD Activity - Stationary

A Partial Discharge (PD) is an electrical discharge or spark that bridges a small portion of the insulation between two conducting electrodes. PD activity can occur at any point in the insulation system, where the electric field strength exceeds the breakdown strength of that portion of the insulating material. As stated before, rotating equipment insulation systems for medium and high voltage systems use mica as a dielectric. Mica is resistant to PD damage, so in mica-based insulation systems, PD is a symptom of various failure processes and not the cause.

When partial discharge is initiated, high frequency transient pulses will appear and persist for nanoseconds to a microsecond, then disappear and reappear repeatedly as the voltage sine wave goes through the zero crossing. Since the pulse characteristics are at high frequencies they attenuate quickly as they are transmitted, or pass to ground. In solid dielectric systems, the PD happens near the peak voltage both positive and negative. The severity of the PD is measured by measuring the burst interval between the end of a burst and the beginning of the next burst. As the insulation breakdown worsens, the burst interval will shorten due to the breakdown happening at lower voltages. This burst interval will continue to shorten until a critical point is reached. At this point the discharge is very close to the zero crossing and will fail with a full blown discharge and major failure [Figure 1].

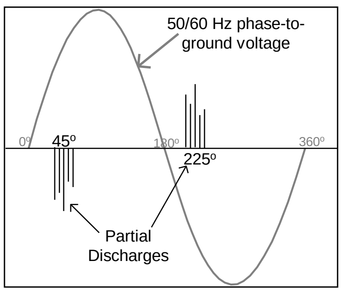

Figure 2. PD Activity - Rotating

In mica-based systems, due to space charge effects, the PD occurs around 45°/225° relative to the AC cycle, that is, confined to the first and third quadrants [Figure 2]. The PD burst creates a current pulse that can be measured in different frequency bands based on the test configuration. Some instruments measure the energy of the current pulse within a low frequency bandwidth, whereas others use a high frequency bandwidth and actually identify the shape and magnitude of the current pulse. As PD is the symptom and not the cause of the failure, it is the progression of PD development that is monitored.

In non-mica based systems, PD activity usually begins within voids, cracks, or inclusions within a solid dielectric; at conductor-dielectric interfaces within solid or liquid dielectrics; or in bubbles within liquid dielectrics. Since these activities are limited to only a portion of the insulation, the discharges only partially bridge the distance between electrodes. PD can also occur along the boundary between different insulating materials.

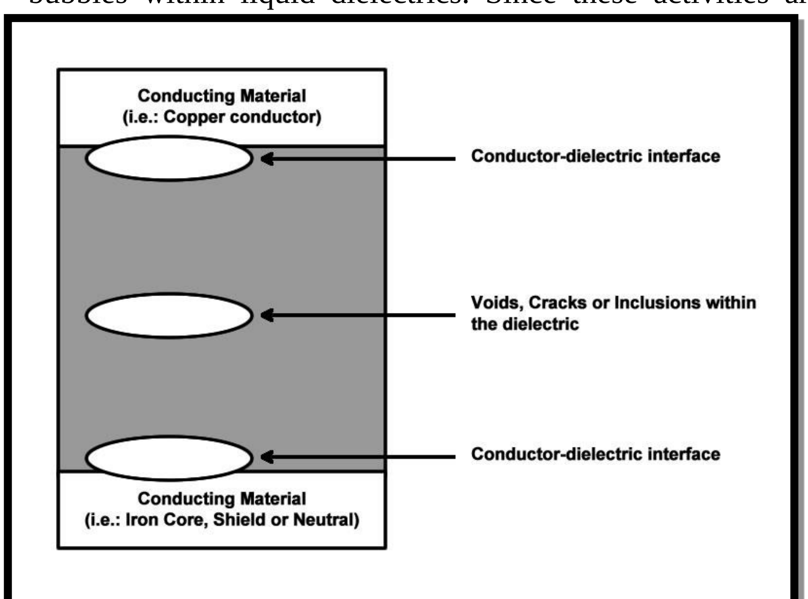

Figure 3. PD within Solid Insulating Systems

Partial discharges within an organic or polymer insulating material are usually initiated within gas-filled voids within the dielectric [Figure 3]. Because the dielectric constant of the void is considerably less than the surrounding dielectric, the electric field across the void is significantly higher than that across an equivalent distance of dielectric. When the applied 50/60Hz increases sinusoidally, the apparent electric stress across the void increases until it reaches 3kV/mm or the equivalent breakdown voltage in the void [Figure 4]. If the voltage stress across the void is increased above the corona inception voltage (CIV) for the gas within the void, PD activity will start within that void. *Over voltage* is the state at which the voltage across a void exceeds the breakdown voltage required for the void size and gas. The larger the over voltage the more intense the space charge effects in the void. Although a void may be in an over voltage state, breakdown will not occur until a free electron (due to cosmic or natural radiation) appears within the gap and starts an avalanche of the electrons. This avalanche is a flow of electrons across the gap which gives rise to a very fast rise-time (a few nanoseconds) current pulse, called a partial discharge (PD). Other issues besides gap length that can affect the electric stress in a void are: diameter, internal gas and pressure, and the nature of the surface in the void. In general, the product of the gap separation and the gas pressure establishes the voltage necessary to lead to a discharge, i.e., breakdown voltage [IEEE 1434-2000].

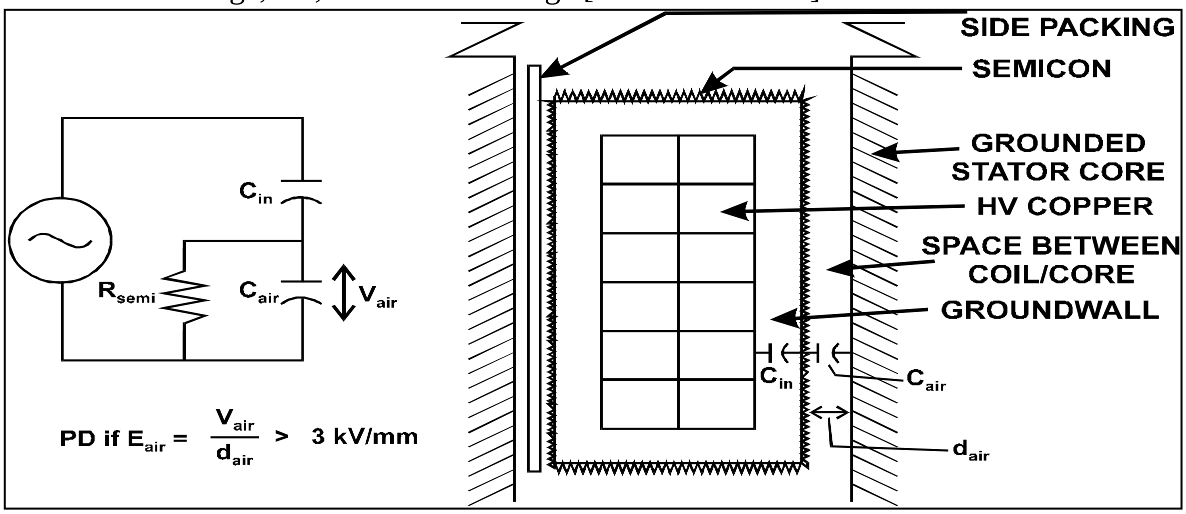

Figure 4. PD on Surface of Mica-based Insulation

Once the breakdown occurs, the voltage across the gap collapses to a voltage level sufficient to sustain the discharge. Some instruments only detect the initial breakdown pulse, whereas others detect the energy dissipated in the breakdown [IEC 60034-27]. No further detectable discharges will occur until the gap voltage has reversed in polarity and another over voltage condition established. Thus, for each pulse position there will be a detectable PD occurring twice in an AC cycle. However, the occurrence, magnitude, and pattern in a void are a complex phenomenon depending on the size, shape, internal gas pressure, and nature of the void surface and will deviate from cycle to cycle due to past space charge trapping.

PD can also occur along the surface of solid insulating materials if the surface tangential electric field is high enough to cause a breakdown along the insulator surface. This phenomenon commonly manifests itself on overhead line insulators, particularly on contaminated insulators during days of high humidity. Overhead line insulators use air as their insulation medium.

A simplified model of an insulating system can be represented by a capacitance and resistance in parallel [Figure 5]. If the insulation is free from defects, like water trees, electrical trees, moisture and air pockets, etc., the insulation approaches the properties of a perfect capacitor. It is very similar to a parallel plate capacitor with the two conductive surfaces being the two plates separated by the insulation material. In a perfect capacitor, the voltage and current are phase shifted 90 degrees and the current through the insulation is capacitive. If there are impurities in the insulation, like those mentioned above, the resistance of the insulation decreases, resulting in an increase in resistive current through the insulation. The insulating system is no longer a perfect capacitor. The current and voltage will no longer be shifted 90 degrees. The shift will be something less than 90 degrees. The extent to which the phase shift is less than 90 degrees is indicative of the level of insulation contamination. This is the concept employed in the use of Tan Delta testing of insulation systems. In the Tan Delta test the tangent of the angle delta is measured. This will indicate the level of resistance in the insulation. By measuring I_R/I_C we can determine the quality of the insulation. In a perfect insulation, the angle would be nearly zero. An increasing angle generally indicates an increase in the resistive current through the insulation, meaning contamination.

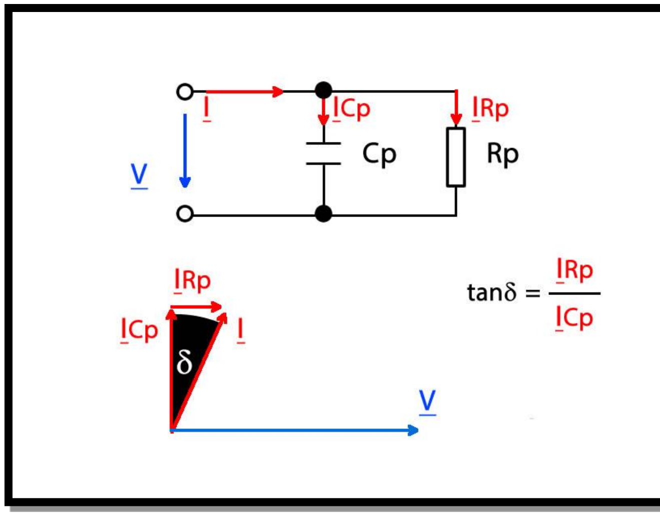

Figure 5. Simplified Insulation Model

Simplified models of voids in insulating systems have been described as consisting of capacitance only. When we review the progressive failure mode of these voids we can also see semiconducting films inside the voids. These films can also consist of carbonization of organic insulation material within the void due to the arching damage caused by partial discharge. Therefore the model of the partial discharge void is similar to that of the insulation medium itself and can be represented as a capacitance and resistance in parallel.

Actual failure modes have indicated a drop in partial discharge intensity shortly prior to complete failure in solid dielectrics. This occurs when the internal arcing had carbonized to the point where the resistive component of the partial discharge void model was low enough to prevent a build-up of voltage across the void. This newly formed low resistive component would allow higher current to flow and additional heating and resultant insulation degradation. The partial discharge void model, including the resistive component correlates to the actual failure mode of a partial discharge void, where the resistive component passes more leakage current as the partial discharges increase with time.

2.1 Stationary Equipment Failure Processes and PD Characteristics:

Figure 6. Trees Caused by PD Activity

The cumulative effect of partial discharges within solid dielectrics is the formation of numerous, branching partially conducting discharge channels, a process called treeing [Figure 6]. Repetitive discharge events cause irreversible mechanical and chemical deterioration of the insulating material. Damage is caused by the energy dissipated by high energy electrons or ions, ultraviolet light from the discharges, ozone attacking the void walls, and cracking as the chemical breakdown processes liberate gases at high pressure.

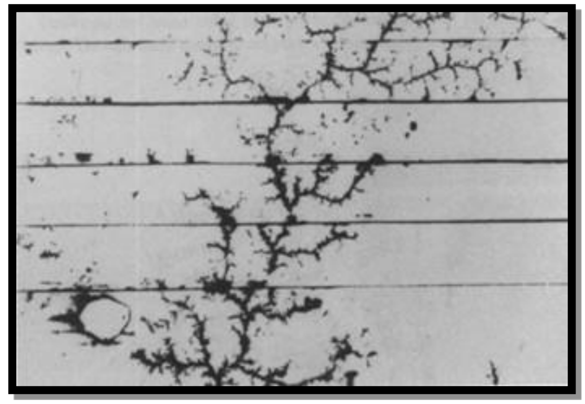

Figure 7. Carbon Tree in PILC Cable

The chemical transformation of the dielectric also tends to increase the electrical conductivity of the dielectric material surrounding the voids. This increases the electrical stress in the unaffected gap region, accelerating the breakdown process. In paper-insulated high-voltage cables, partial discharges begin as small pinholes penetrating the paper windings that are adjacent to the electrical conductor or outer sheath [Figure 7]. As PD activity progresses, the repetitive discharges eventually cause permanent chemical changes within the affected paper layers and impregnating dielectric fluid. Over time, partially conducting carbonized trees are formed. This places greater stress on the remaining insulation, leading to further growth of the damaged region, resistive heating along the tree, and further charring (sometimes called tracking). This eventually culminates in the complete dielectric failure of the cable and, typically, an electrical explosion.

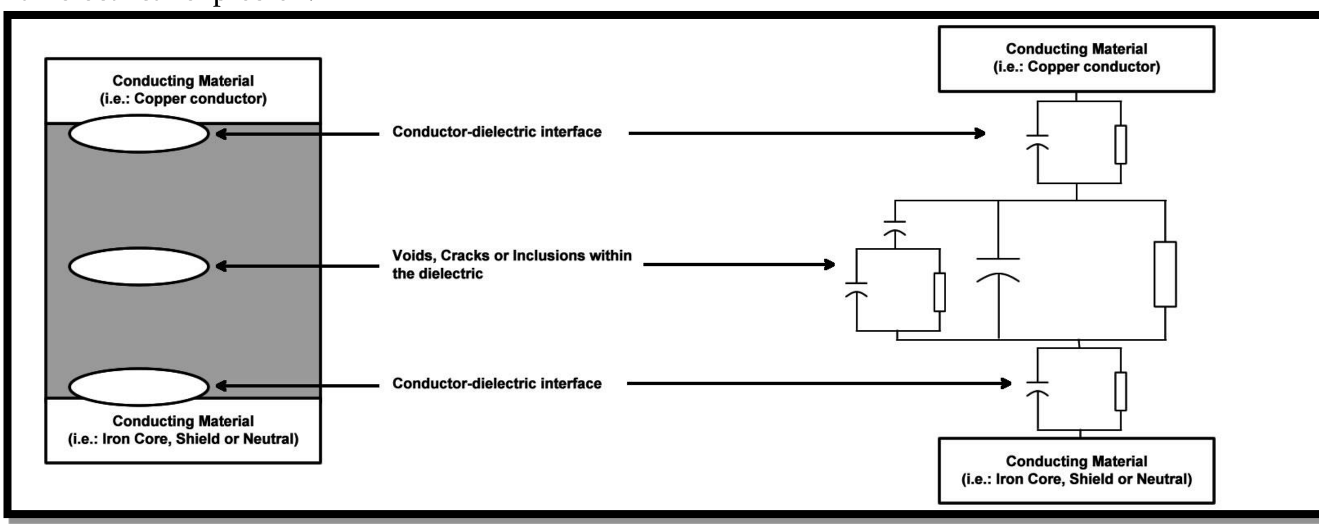

Figure 8. Insulation System Partial Discharge Model for Solid Insulation

Once we understand the simplified models for insulation and voids, we can illustrate a complete model of the various insulation system discharges represented in **Error! Reference source not found.**and thus a better understanding of partial discharge activity.

There are many causes of degradation to insulating systems in stationary equipment. Among the causes are:

Manufacturing Defects:	These defects can be voids in solid insulation often caused during manufacturing process.
Electrical Stress:	Insulation is designed for a particular application. Over-voltages and under-voltages cause abnormal stresses within the insulation, which can lead to cracking or delamination of the insulation.
Mechanical Stress:	Mechanical damage such as hitting a cable while digging a trench is a fairly obvious form of mechanical stress but

	mechanical stresses can also occur from running a machine out of balance. Frequent stops and starts on rotating equipment also induce mechanical stress. The resulting vibration from machine operation may cause defects within the insulation.
Chemical Attack:	While you would expect insulation to be affected by corrosive vapors, dirt, water and oil can also operate to reduce the effectiveness of insulation.
Thermal Stress:	Exposure to excessively hot or cold conditions will cause over expansion or contraction of the insulation which might result in cracks and failures. However, thermal stresses are also at hot spots along conductive surfaces due to poor contact resistance.
Environmental Contamination:	Environmental contamination covers a multitude of agents ranging from moisture from processes, to humidity on a muggy day, and even to attack by rodents that gnaw their way into the insulation.

2.2 Rotating Equipment Failure Processes and PD Characteristics:

Machines that have *not been properly impregnated* or that have been operating for several years at *high temperatures* tend to develop voids within the groundwall insulation. If both sides of the void have similar insulation materials then the charge distribution will be equal during the positive and negative cycles. In theory, there will be two observable PD pulses in each AC cycle of *equal magnitude* and opposite polarity per void within the bulk of the insulation [Figure 2]. These pulses clump at the classic positions for phase-to-ground dependent pulses, that is, *negative pulses at 45°* and the *positive pulses at 225°* with reference to the 50/60Hz phase-to-ground voltage [Figure 9].

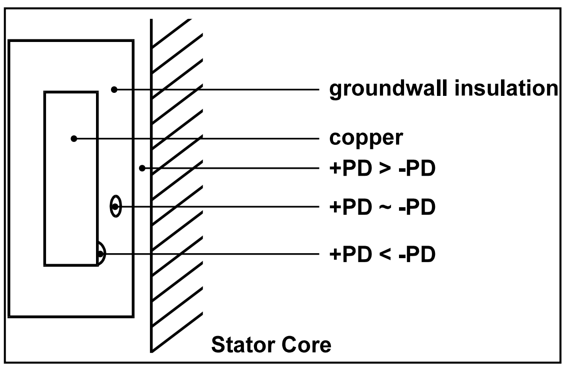

Figure 9. Polarity Predominance

A machine that is frequently *load cycled* or *severely overheated* develops voids near the copper conductors. A void bounded by the copper conductor and insulation, exhibits a different phenomenon than those within the bulk of the insulation. Though the basic breakdown mechanisms are the same, because the electrodes are of dissimilar materials, polarity predominance occurs. The mobility of the positive ions on the insulation surface is much lower than the negative ions on the conductor surface. The result is a predominance of negative ions migrating through the gap to the positive insulation surface. In this case, there will usually be an observable *predominance of negative PD* pulses clumped at 45° during the positive AC cycle [Figure 2].

Loose coils, poor semi-conductive coatings, and problems with the *grading/semicon interface* can all lead to surface discharge between the stator bar and the grounded core iron, called slot discharges. As with those near the copper conductors, these discharges occur between electrodes made of different materials. Here, the immobile positive charges on the insulation and mobile negative charges on the grounded metallic electrode lead to pulses occurring during the negative

AC cycle. Because the metallic electrode is grounded, the observable PD pulses will be *predominantly positive clumped at 225°* [Figure 2].

Contamination and/or *Phase to Phase Discharges* in the end arm area, on ring busses, or motor leads can lead to partial discharge activity in these areas. Unlike the previously described pulses that are phase-to-ground voltage dependent, these pulses are based on phase-to-phase voltages. Though these pulses tend to be very erratic, it is sometimes possible to distinguish these pulses from others by observing their location with reference to the phase-to-ground voltage. Typically, because of the *phase-to-phase* voltage dependency there is a *30° phase shift* from the classic phase positions associated with pulses that are phase-to-ground voltage dependence as shown in Figure 10. Phase-to-phase pulses tend to clump at 15°, 75°, 195°, and 255°, based on the location of the pulses and the phase rotation of the machine. Sometimes, it is possible to determine which two phases are involved, but often it is difficult to extract that information accurately from the quantity of pulses detected.

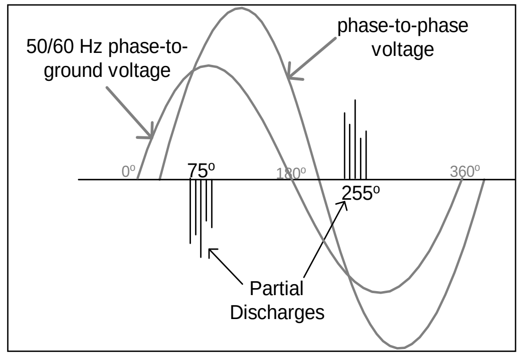

Figure 10. Phase-to-phase Discharges

2.3 PD Development

Regardless of how partial discharge activity begins; once begun, PD activity causes progressive deterioration of insulating materials, ultimately leading to the cause of electrical breakdown in stationary equipment using organic and polymer dielectrics. Inorganic dielectrics, including glass, porcelain, and mica, are significantly more resistant to PD damage than organic and polymer dielectrics.

When PD activity is present the partial discharges emit energy in several ways, as:

- Electromagnetic emissions, in the form of radio waves, light and heat,
- Current pulses
- Acoustic emissions, in the audible and ultrasonic ranges, or as
- Ozone and nitrous oxide gases.

These various emissions allow us to detect, locate, measure and analyze PD activity so that we can identify defects before they contribute to or result in failures as will be discussed later.

Busted - Stationary　　Busted - Rotating

3 Myth 2: The Measurement of Partial Discharge Requires an Outage

For partial discharge to occur, a sufficient voltage must be applied to the system under test to meet the minimum voltage required to start partial discharge activity. This is known as the partial discharge inception voltage (PDIV).Once the PDIV has been reached, voltage may be lowered and PD will remain present at the lower voltages until finally they extinguish at what is referred to as the partial discharge extinction voltage (PDEV). The PDEV is therefore less than the PDIV [IEC 60034-27]. If the PDEV voltage level is lower than the system operating voltage (phase to ground) this implies that an over voltage surge on the insulating system could initiate PD, and then even when the system voltage returns to normal, the PD activity may continue. Partial discharge activity that can continue at operating voltage is therefore more likely to result in an insulation failure than PD that extinguishes above normal operating voltage. Provided that PD activity occurs at the operating voltage level it can be detected and/or measured through online detection methods and therefore testing for partial discharge activity can be performed either online at operating voltage levels or offline.

3.1 Stationary Equipment:

Online PD testing has the obvious advantage in that it does not require disconnecting or an outage. The main disadvantage when testing stationary equipment is that the test is only performed at the operating voltage level and cannot be adjusted. Obviously if the applied voltage is fixed and cannot be changed the PDIV and PDEV voltages cannot be determined and therefore, in comparison to offline testing, where voltages can be adjusted to simulate transients or other over voltage conditions, a lower percentage of defects in stationary equipment can be detected through online methods.

As stated earlier; for partial discharge to occur, a sufficient voltage must be applied to the system under test to meet the minimum voltage required to start partial discharge activity. When testing stationary equipment the online testing approach uses the system voltage of a constant fixed magnitude. In an offline approach a temporary voltage source will be required. Considerations for an offline voltage source should include:

- The applied voltage should cause partial discharges in the insulating system under test that have characteristics close, if not identical, to those that occur when the insulating system is in service.
- The temporary voltage source should cause no appreciable damage to the insulating system during the time required to perform the measurements.
- The temporary voltage source should have a variable voltage output so that PDIV and PDEV tests can be performed.
- The size and weight of the equipment required to produce the voltage levels required for testing various assets needs to be considered. Is the equipment to be used in a fixed location or used in a field application?

Voltage sources that are used for commercially available field partial discharge measurement systems will fall into the general categories of power frequency and alternative voltage sources such as Very Low Frequency (VLF).

Depending on the type of defect, VLF voltage sources, usually 0.1 Hz, for extruded dielectric systems may require a higher test voltage to generate the same partial discharge level compared with tests performed with power-frequency voltages. For example, the conductivity of the surface of a cavity that has been exposed to PD increases, which allows any charges deposited on the surface by PD to leak away and thus lowers the electric field in the cavity. As more charge can leak away between polarity reversals at VLF than at power frequency, the PDIV at VLF will be larger than that at power frequency. If there has been no previous PD activity to increase the conductivity of the cavity surface, the PDIV at VLF and power frequency will be similar [IEEE Std. 400.3].

Another consideration that needs to be reviewed when comparing online and offline measurements is noise effect on the measurement. In the offline approach the detection equipment can be calibrated at the time of the test by injecting a known PD pulse level into the specimen under test. This is not possible in the online approach. Further, assets can be isolated during offline testing.

When detecting PD activity using online methods further analysis will typically be necessary to ensure that the suspect activity was not caused by external noise. It will also be advantageous to locate the source of the partial discharge activity and to quantify and assess the severity of the problem. This can be accomplished by measuring and analyzing activity over time to detect deterioration and to raise an alarm or call-to-action if PD activity reaches a critical level. As an example, if PD activity that is intermittent or possibly influenced by environmental conditions (changing temperature, humidity, vibration or electrical noise) is found, temporary installed multi-sensor systems that automatically monitor your plant can be utilized.

Online approach versus offline approach as applied to stationary systems using organic or polymer insulating systems:

Online Approach	**Offline Approach**
Advantages:	**Advantages:**
• No outage or downtime required. • Many circuits and gear can be tested in one day. • Less expensive approach and serves well as an initial survey and help to target offline testing.	• Not affected by noise. Detection equipment can be calibrated at time of test. • Able to determine PDIV and PDEV levels. • Since voltage can be controlled a higher percentage of defects can be uncovered.
Disadvantage:	**Disadvantage:**
• Can be affected by noise. • When testing cables, requires access to cable shield and non-insulated cable glands. • Bonding methods can limit testing.	• Outage is required. • Time consuming.

Plausible - Stationary

3.2 Rotating Equipment:

For rotating machines, online testing has proven to be the preferred method as it allows for investigation of the impact of thermal and mechanical stresses by testing at variable operating conditions. In addition, the results are more realistic as to what potential failure mechanisms are developing of which PD would be a symptom, such as coil/bar movement, phase-to-phase discharges, or discharges impacted by ambient conditions. Testing PD online poses a problem due to the presence of system noise and disturbances. The test configuration utilized must address these problems to ensure repeatable and accurate results [IEC 60034-27-2].

Testing large rotating machines offline in the field is often impractical due to the size of the AC power supply necessary to energize the winding. In addition, the tests are normally done when the winding is at ambient temperature and therefore highly impacted by variability of ambient conditions. This makes trending of offline results ambiguous. The primary advantage of offline tests is to locate isolated PD activity that has been indicated by the online results, or to verify quality for new or rewound equipment.

Online Approach	Offline Approach
Advantages:	**Advantages:**
• No outage or downtime required. • Test under normal operating and ambient conditions to evaluate most of the failure mechanisms associated with rotating machines. • Many machines can be tested in one day, or even continuously monitored. • Less expensive approach overall.	• Not affected by noise. • Able to determine PDIV and PDEV levels. • Wide variety of sensors/tests available.
Disadvantage:	**Disadvantage:**
• Can be affected by noise. • Requires installed sensors	• Outage is required. • Time consuming. • Ineffective in evaluating many problems associated with stator windings.

Busted - Rotating

4 Myth 3: All Insulation Testing finds the same problems as Partial Discharge

4.1 Tests Performed on Stationary Equipment:

Over the years there have been several methods and/or philosophies regarding the testing of insulating systems in stationary equipment. The range of tests methods or philosophies can be divided into two fundamental categories, pass/fail or diagnostic.

Pass/Fail tests are intended to detect defects in the insulation system in order to improve the service reliability after the defective part is removed and appropriate repairs are performed. These tests are usually achieved by application of moderately increased voltages across the insulation for a prescribed duration of time. *Diagnostic* tests are intended to provide indications that the insulation system has deteriorated, hence, are termed “diagnostic.”

	Test	Test Type	Status	Myth	Problem Detected
0	Insulation Resistance (IR)	Pass/Fail	Offline	Plausible	General Degradation and contamination
4.1.2	Time-Resistance Methods (DA or PI)	Diagnostic	Offline	Plausible	Contamination
4.1.3	Dielectric Discharge (DD)	Diagnostic	Offline	Plausible	Contamination and defects in multi-layered insulation.
4.1.4	High Potential Testing (DC)	Pass/Fail	Offline	Busted	Withstand strength, major defects. May actually cause increased degradation.
4.1.5	High Potential Testing (PF)	Pass/Fail	Offline	Plausible	Withstand strength, major defects.
4.1.6	High Potential Testing (VLF)	Pass/Fail	Offline	Plausible	Withstand strength, major defects.
4.1.7	Power Factor	Diagnostic	Offline	Plausible	Contamination, Ionization
4.1.7	Dissipation Factor (Tan Delta)	Diagnostic	Offline	Plausible	Contamination, Ionization
4.1.8.1	Capacitive/InductiveD ecoupling (PD)	Diagnostic	Online	Plausible	PD activity
4.1.8.2	Transient Earth Voltage	Diagnostic	Online	Plausible	PD activity
4.1.8.3	Ultrasonic	Diagnostic	Online	Plausible	PD activity
4.1.9	Partial Discharge	Diagnostic	Offline	Confirmed	PDIV, PDEV, PD mapping

4.1.1 Insulation Resistance (Spot Reading)

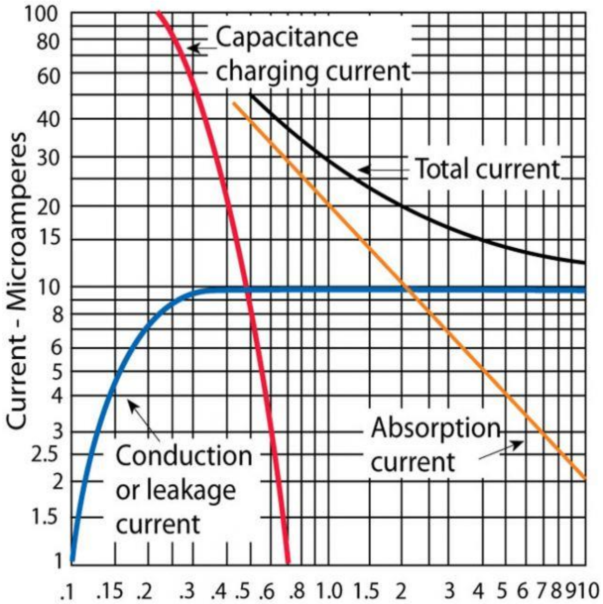

Figure 11. Components of Test Current

Insulation resistance is measured with an insulation resistance test set commonly referred to as a Megohmmeter. The Megohmmeter places a known DC voltage potential across the dielectric under test. If we apply a test voltage across a piece of insulation, then by measuring the resultant current and applying Ohm's Law (R=V/I), we can calculate the resistance of the insulation. Unfortunately, more than one current flows, which tends to complicate matters [Figure 11]. The total current that flows during an insulation resistance test is made up of three main components:

Capacitive Charging Current

The current required to charge the capacitance of the insulation being tested. This current is initially large but relatively short lived, dropping exponentially to a value close to zero as the item under test is charged. Insulating material becomes charged in the same way as a dielectric in a capacitor.

Absorption or Polarization Current

Absorption current, is the current that is being drawn into the insulation by the polarizing of the electrons; its value is initially high but drops over time (at a rate slower than the charging current).

Conduction or Leakage Current

The conduction or leakage current, which is the small, steady state current that divides into two parts:

a. The conduction path through the insulation.
b. The current flowing over the surface of the insulation.

With modern insulating materials there is little, if any, difference in the reading obtained, regardless of which way the terminals of the test set are connected. However, it is industry standard to connect the positive (+) lead to ground. The reason for this is that on older insulation, a little known phenomenon called electroendosmosis (iʹlek•trō¦en•däsʹmō•səs) causes a lower insulation reading to be obtained with the positive terminal connected to the grounded side of the insulation being tested. Since insulation testing is typically concerned with safety, maintenance and /or troubleshooting the worst case reading would be the one which yields the most relevant information. Also negative polarity is preferred since water molecules are positive polarity and are attracted to the negative voltage which gives a more comprehensive picture of insulation condition.

If the insulation resistance reading obtained during the spot reading test was high and if it increased or remained steady during the test, the insulation is good. If the insulation resistance reading decreased during the test, the insulation of the cable is probably wet or otherwise in bad condition.If the final value is low, the insulation of the cable is poor.

The insulation resistance test provides a simple and convenient method of obtaining a general condition assessment of the insulating system. The test is useful in uncovering contamination or general imperfections. Tests are performed at voltages under the rating of the insulation under test and therefore, the test is considered to be a non-destructive test. Since DC voltages are used and applied at low levels the test offers little to no value in identifying the existence of PD.Insulation resistance readings are also influenced by temperature and must be corrected for temperature, particularly if trending is to be performed.

Plausible - Stationary

4.1.2 Time-Resistance Methods (Dielectric Absorption or Polarization Index)

A valuable property of insulation, but one that must be understood, is that it “charges” during the course of a test. The polar DC field applied by the test set causes re-alignment of the insulating material on the molecular level, as dipoles orient themselves with the field. This movement of charge constitutes, of course, a current. Its value as a diagnostic indicator is based on two opposing factors: the current dies away as the structure reaches its final orientation, while “leakage” promoted by deterioration passes a comparatively large, constant current. The net result is that, with “good” insulation, leakage current is relatively small, and resistance rises dramatically as charging goes to completion. This changing resistance is exactly what an experienced technician wants to see. Deteriorated insulation will pass relatively large amounts of leakage current at a constant rate for the applied voltage. This will “flood out” the charging effect.

Time-Resistance Methods, as they are known, take advantage of this charging effect. Graphing the resistance reading at time intervals from initiation of the test yields a smooth rising curve for “good” insulation, but a “flat” graph for deteriorated equipment. The ultimate simplification of this technique is represented by the popular Polarization Index (PI) and Dielectric Absorption tests, which requires only two readings and a simple division. Performing the PI test the one-minute reading is divided into the ten-minute reading to provide a ratio. In Dielectric Absorption the time values are typically 30 seconds and 60 seconds. Obviously, a low ratio indicates little change, hence poor insulation, while a high ratio indicates the opposite.

References to typical PI values are common in the literature, which makes this test very easy and readily employed. Note that resistance readings alone are difficult to work with, as they may range from enormous values in new equipment down to a few megohms just before removal from service. Tests like the PI and DA are particularly useful because theyyield a self-contained evaluation based on relative readings rather than absolute values.

These tests are useful in uncovering contamination or general imperfections, but since fixed DC voltages are used these tests provide little to no assistance in detecting PD. The test can, however, give a clue to the severity of contamination and thus the insulating systems ability to withstand higher voltage testing.

4.1.3 Dielectric Discharge

An example of a still more specialized test, developed by EdF, France’s national power utility, is the “Dielectric Discharge Test” (DD). This test measures the current that flows during discharge of the test sample. It is especially applicable to multi-layered insulation. The test item is first charged until full absorption has taken place (10 to 30 minutes). At this time, capacitance is fully charged and the alignment of dipoles (absorption) is essentially complete. Only leakage current continues to flow. Then when the external voltage field ceases, molecules will “relax” and return to their original random configuration, constituting a re-absorption current. This discharge current is measured 60 seconds after the insulation test is finished. At this time, capacitance is discharged and voltage has collapsed, so that the charge stored in the dipoles can be viewed independently of the “masking” currents, such as leakage current that is dominant during an insulation test. A high re-absorption current indicates that the insulation has been contaminated, while a low current indicates that it is relatively clean. The precise definition of Dielectric Discharge is:

$$\frac{\textit{Current flowing after 1 minute (nA)}}{\textit{Test Voltage (V) x Capacitance (uF)}}$$

This calculation provides a figure of merit that indicates the condition of the insulation. In multi-layered insulation, each layer is meant to share the voltage stress equally. Upon discharge, each layer’s charge will decrease equally until no voltage remains. When a layer is faulty between good layers, its leakage resistance will decrease while capacitance is likely to remain the same. A standard insulation test will be determined by the good layers, and not likely to reveal this condition. But during dielectric discharge, the time constant of the faulty layer will mismatch the others to yield a higher DD value. A low DD value indicates that re-absorption current is decaying quickly, and the time constant of each layer is similar. A high value indicates that re-absorption exhibits long relaxation times, which may point to a problem.

These tests are useful in uncovering contamination or general imperfections, but since fixed DC voltages are used these tests provide little to no assistance in detecting PD.

4.1.4 High Potential Testing – Direct Current

For years, high-voltage DC testing has been the traditionally accepted method for judging the serviceability of medium-voltage cables. DC high- potential tests have worked well as a withstand and condition assessment test for paper insulated, lead covered (PILC) cable. When plastic insulated cables were first introduced in the 1960’s DC was still the preferred method.

As time moved on plastic insulated cables became more abundant and began showing effects of service age. DC continued to be the dominate test, but concerns began to grow over the effectiveness of this test. In the early 1990's reports started to surface indicating that DC high potential testing could be the blame for latent damage experienced by extruded medium voltage cable insulation (XLPE and EPR). After receiving these reports the Electrical Power Research Institute (EPRI) funded two studies relating to XLPE and EPR cables. These studies (EPRI reports TR-101245 and EL-6902) yielded several conclusions regarding XLPE cable:

- DC high potential testing of field-aged cable reduces the life of the cable.

- DC high potential testing of field-aged cable generally increases electrical tree growth.

- DC high potential testing before energizing new medium voltage cable doesn't cause any reduction in cable life.

The current versions of most industry standards no longer include DC high potential testing of extruded cables (XLPE and EPR) as a maintenance test. Of those that still do, all have reduced the recommended test duration from 15 minutes to only 5 minutes. None endorses DC high potential testing as a factory test for extruded cables, but most continue to include DC high potential testing as an acceptance test on newly installed extruded cable. These industry standards also no longer endorse DC high potential testing as a maintenance test for extruded cables that have been in service for more than five years.

If deemed appropriate for the insulation system under test, DC high potentialserves as a pass/fail test and gives information about the dielectric strength of the insulation and can be used to find cracks or sever defects. The test looks at the total leakage current in the insulating system. High leakage current readings due to contamination in the insulating system may not produce partial discharge. Also, PD activity can be present and not observed in the high potential test.

Busted - Stationary

4.1.5 High Potential Testing – Power Frequency

When used by itself, power frequency high potential testing is a pass/fail test and useful in testing dielectric strength and uncovering cracks and sever defects in the insulation. Power frequency offers benefit over DC in that it stresses the insulation more uniformly and uncovers a wider range of defects such as dry cavity defects. Unfortunately, PD activity can be present and not observed since the nature of the test is pass or fail. High potential testing at power frequency can be used as a method of pre-stressing prior to performing a partial discharge measurement.

Plausible - Stationary

4.1.6 High Potential Testing – Very Low Frequency (VLF)

High potential testing at very low frequency is similar to power frequency testing and will uncover the same defects. If used alone, VLF testing is also considered a pass/fail test.

VLF high potential test sets are commonly used as alternative power supplies in testing large capacitive loads in field applications. The major limitation of power frequency is the need for large transformers when referring to the capacitance of the load being tested. Capacitive Reactance (X_c) changes as a function of frequency as seen in formula $X_c = 1/2\pi fC$. Therefore, if we are testing a 15 kV cable of approximately 10,000 feet the capacitance would be around 1uF. Based on the formula the capacitive reactance at 60 Hz would be 2650 ohms. To apply the IEEE recommended 22 kV test voltage, it would require a power supply rated for 8.3 amps, or 183 kVA.

If the frequency, however, is dropped to 0.1 Hz, the capacitive reactance becomes 1.6 megohms. The same 22 kV would only draw 14 mA or 0.303 kVA. Therefore, the size, weight and portability of the power supply become convenient for field use.

Plausible - Stationary

4.1.7 Power Factor (cos θ), Dissipation Factor (Tan δ)

The power factor and dissipation factor (tan δ) test are diagnostic test that allow an evaluation of the insulation system at operating or at test voltage levels. The tests are conducted at power frequency or at VLF frequencies. If the insulation of the system under test is free from defects, like water trees, electrical trees, moisture and air pockets, etc., the insulating system approaches the properties of a perfect capacitor. It is very similar to a parallel plate capacitor with the conductive surfaces being the two plates separated by the insulation material.

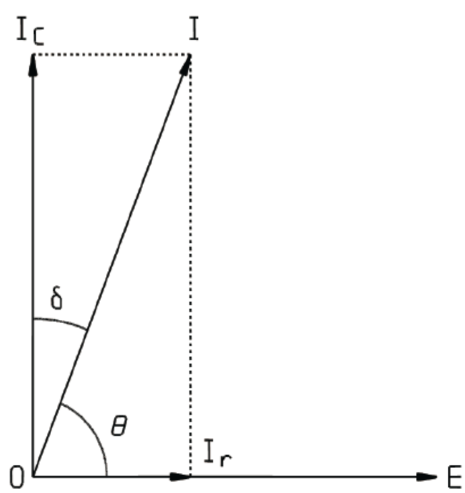

Figure 12 Vector diagram insulation system

In a perfect capacitor, the voltage and current are phase shifted 90 degrees and the current through the insulation is capacitive. If there are impurities in the insulation, like those mentioned prior, the resistance of the insulation decreases, resulting in an increase in resistive current through the insulation. It is no longer a perfect capacitor. The extent to which the phase shift is less than 90 degrees is indicative of the level of insulation contamination in the insulating system [Figure 12]. This "Loss Angle" is measured and analyzed. These tests do not "locate" defects in the insulation system; they simply give an indication of the insulation quality and level of contamination.

The dissipation factor (tan δ) test is typically performed at multiple voltages ranging from 0.5 V_o to 2.0 V_o. If the insulation is perfect, the tan δ will change little as the applied voltage is increased. The capacitance and loss will be similar for all applied voltages. If there is contamination changing the capacitive/resistive nature of the insulation, then the tan δwill be higher at higher test voltages.

Similar to the dissipation factor (tan δ) the power factor(cos θ) test is looking for any changes in the insulation system. The test is normally done at a specific applied voltage that makes it possible for comparing the results to other like assets.

Plausible - Stationary

4.1.8 Online Partial Discharge Testing

Online partial discharge tests are performed at the fixed operating voltage level. To perform online tests, suitable partial discharge decoupling methods are required. Over the years different sensors have been developed to detect PD events. The online decoupling methods at switchgears can include:

- Capacitive decoupling via pre-installed, insulation coordinated coupling capacitors
- Capacitive decoupling via already existing taps at current transformer, bushings (capacitive interface for voltage sensing / voltage detection system)
- Inductive decoupling using Radio Frequency Current Transducers (RFCT)
- Transient Earth Voltage Sensor (TEV)
- Ultrasonic

4.1.8.1 Capacitive and Inductive Decoupling

As stated earlier, partial discharge transient pulses, both voltage and current, caused by electromagnetic emissions of energy tend to be of short duration and have rise-times in the nanosecond realm. On an oscilloscope, the discharges appear as evenly spaced burst events that occur at the peak of the sine wave [Figure 13]. Random events are arcing or sparking. Since these transients can be captured, their magnitude can also be measured. The usual way of quantifying partial discharge magnitude is in Picocoulomb (pC). The intensity of partial discharge is displayed versus time.

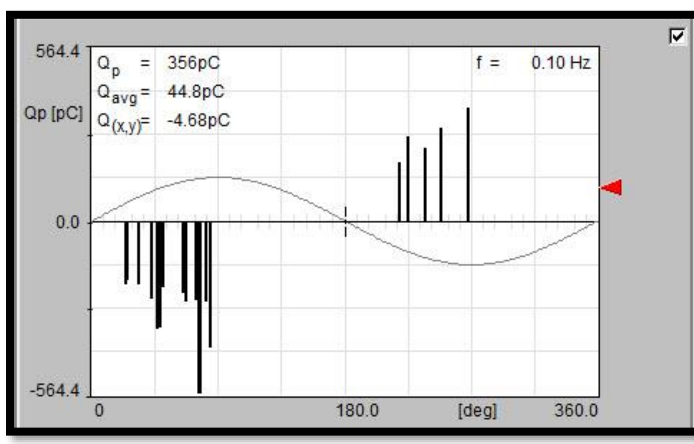

Figure 13 PD Activity as seen on an oscilloscope

Reviewing the simplified insulation model seen in Figure 3, we can see that a capacitance in parallel with a resistance also serves as an attenuator circuit. This concept of the insulation system being an effective attenuator gives rise to several critical issues regarding the detection and measurement of partial discharge activity in various assets. Since sensors, either radio frequency current transducers (RFCTs) or capacitors, will need to be used to capture the transient pulses, the location and sensitivity of the sensors must be considered for practical application on various electrical assets. In the testing environment there will ultimately be other sources of electromagnetic emissions, therefore detection, filtering and/or elimination of unwanted noise must also be considered.

4.1.8.2 Transient Earth Voltage (TEV)

When partial discharge activity occurs within medium voltage switchgear, electromagnetic waves in the radio frequency range are emitted. These waves escape from the inside of the switchgear through openings in the metal casing. When the electromagnetic wave propagates on the outside of the switchgear they also impinge on the metal cladding generating a transient earth voltage on the metal surface. The Transient Earth Voltage (TEV) has a nanosecond rise time and amplitude which varies widely from millivolts to volts. The TEV is measured (in dBmV) with a capacitive probe placed on the grounded or earthed metalwork of the switchgear.

TEVs are a very convenient phenomenon for measuring and detecting partial discharges as they can be detected without making an electrical connection or removing any panels from the switchgear. While this method may be useful to detect some issues in switchgear and surface tracking on internal components, the sensitivity is not likely to be sufficient to detect issues within all assets such as solid dielectric cable systems.

4.1.8.3 Ultrasonic

Partial discharge also emits energy in the form of acoustic emission, in the audible and ultrasonic range. Acoustic emission from PD activity occurs over the whole acoustic spectrum. Audible detection is possible in some situations, but depends on the hearing ability of the individual and the level of background interfering noise. Using an instrument to detect the ultrasonic part of the acoustic spectrum will have several advantages. Measuring instruments are more sensitive than the human ear and are not dependent on the operator's hearing. Since measuring instruments can operate above the audible frequency, they are also more directional. One of the most sensitive methods of detection is using an airborne ultrasonic microphone with a center frequency set around 40 kHz. This method is very successful at detecting partial discharge activity provided there is an air passage between the PD source and the microphone. Ultrasonic measurement relies on the fact that the partial discharge will emit sound waves. The frequency for emissions is "white" noise in nature and therefore produces ultrasonic structure waves through the solid or liquid filled electrical component. Using a structure borne ultrasonic sensor on the exterior of the item under examination (i.e.: switchgear panels), internal partial discharge can often be detected and located when the sensor is placed closest to the source of the PD activity.

Since online partial discharge tests are conducted at operating level, PD activity may not be detected if the PDIV has not been initiated. This does not necessarily mean that the insulation does not have issues and that PD activity will not appear during overvoltage events such as lightning strikes or switching events. Contaminations such as water trees, also will not product PD and will not be detected. Since spot tests only look at conditions during that particular test period, online testing renders better results if monitored over time.

4.1.9 Offline Partial Discharge Testing

The most basic test performed is the partial discharge inception and extinction voltage test (PDIV/PDEV). This test is performed by applying a voltage well below the expected inception voltage of the test object and then gradually increasing the test voltage until discharges develop, or exceed, a specified low magnitude. The test voltage at this specified magnitude is the partial discharge inception voltage. The test voltage is then increased to a specified voltage level and thereafter gradually reduced to a value at which the discharges become less than the same specified magnitude. The test voltage at this discharge limit is the partial discharge extinction voltage. It should be noted that the value of PDIV can be affected by the rate of rise of voltage, and PDEV can be affected by the amplitude and duration of voltage application and also by the rate of decrease of voltage. Offline testing uncovers a greater number of defects since the applied voltage can be adjusted simulating overvoltage or stressed conditions.

Confirmed - Stationary

4.2 Tests Performed on Rotating Equipment:

As with stationary equipment, for centuries there have been several methods and/or philosophies regarding the testing of stator winding insulating systems in rotating equipment. 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 [IEEE 1434].

Table 1. Summary of Common Failure Mechanisms

Manufacturing Defects	Thermal Cycling (Excessive starts)
Voltage Stress Coating Failure	Contamination
Coil Movement	Phase to Phase discharges
Internal Delamination	

Over the years there have been several methods and/or philosophies regarding the testing of stator winding insulating systems in rotating equipment. The range of tests methods or philosophies can be divided into two fundamental categories, pass/fail or diagnostic. Do these tests adequately measure the common winding problems, like PD does?

	Test	Test Type	Status	Myth	Problem Detected
4.2.1	Insulation Resistance& PI	Pass/Fail	Offline	Plausible	Contamination
4.2.2	High Potential Testing (DC)	Pass/Fail	Offline	Busted	Cracks
4.2.3	High Potential Testing (PF)	Pass/Fail	Offline	Busted	Cracks
4.2.4	Capacitance Testing	Diagnostic	Offline	Plausible	Internal delamination/ Manufacturing Defects/ Stress Coating
4.2.5	Power Factor	Diagnostic	Offline	Plausible	
4.2.6	Dissipation Factor (Tan	Diagnostic	Offline	Plausible	

	Delta)				
4.2.7	Surge Testing	Diagnostic	Offline	Plausible	Thermal Cycling
4.2.8	Ozone Monitoring	Diagnostic	Offline	Plausible	Stress Coating
4.2.9	LF PD Testing	Diagnostic	Online	Busted	Noise interference
4.2.9	HF PD Testing	Diagnostic	Online	Confirmed	All FM above
4.2.9	VHF PD Testing	Diagnostic	Online	Confirmed	All FM above
4.2.9	EHF PD Testing	Diagnostic	Online	Plausible	Isolated activity
4.2.10	Electrical Pulse Sensing	Diagnostic	Offline/Online	Plausible/Confirmed	No movement or phase-to-phase for offline
4.2.10	RF Radiation Sensing	Diagnostic	Offline/Online	Plausible/Confirmed	
4.2.10	Energy/integrated charge transfer	Diagnostic	Offline	Plausible	
4.2.10	Acoustic & Ultrasonic	Diagnostic	Offline	Plausible	Isolated activity
4.2.10	Black out	Diagnostic	Offline	Plausible	Only surface PD

4.2.1 Insulation Resistance & Polarization Index

This test is primarily used to determine whether or not a winding is suitable for return to service or subsequent high potential testing. It involves application of a relatively moderate direct voltage to the test specimen for a period of 10 minutes while monitoring the current flow. Because the test uses DC, no PD is initiated. Some have proposed that doing a Polarization-Depolarization Index test has provided insight regarding the measure of the condition of consolidated insulation systems. Though perhaps some merit has been found for solid insulation systems, there is little evidence that this is beneficial for mica-based systems.

✎ IEEE Std 43 - *Recommended Practice for Testing Insulation Resistance of Rotating Machinery*

Plausible - Rotating

4.2.2 Direct High Voltage Testing

After a winding has passed the IR/PI test and deemed suitable for high potential testing, you may want to perform a high direct voltage test. This involves subjecting the winding to a high direct voltage to see if it will survive over-voltage stress. The hope is that if there is a crack or weak spot in the insulation it will "pop" during the test where there is substantial energy stored in the winding capacitance but little "follow" current from the test supply and therefore minimal damage. It will also "fail" during a scheduled outage when repairs are easier to perform. There are two general procedures for high potential testing: a proof test used for a new winding or after major repairs and a maintenance test used for routine testing. This test does not provide information about how well the insulation is consolidated, only if it is already cracked.

✎ IEEE Std 95: *Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct-Voltage*

Busted - Rotating

4.2.3 Alternating Voltage High potential

Like the direct voltage High potential test, this test is a go or no-go test. It is strictly a test to determine if the winding will survive an over-voltage stress typical of a bus fault, or is sealed from moisture ingress. It is a destructive test by design in that if a failure occurs the machine is not suitable for return to service until the failure is repaired. The ac high potential stresses the endwinding similarly to that induced during normal operation. This test does not provide information about how well the insulation is consolidated, only if it is already cracked.

> ✐ IEEE Std 432: *Guide for Insulation Maintenance for Rotating Electrical Machinery (5 hp to less than 10,000 hp)*

Busted - Rotating

4.2.4 Capacitance Testing

As an insulation system ages, some of the organic resin is replaced with a void that fills with air and thus changes the dielectric constant of the insulation system. In older, pre-1970, machines the change in the dielectric constant was often significant enough that it was possible to detect the effects of aging by measuring the total capacitance of a winding. Though still possible on severely deteriorated newer windings, the change in capacitance is usually so subtle that until the winding is nearing failure it is difficult to observe any changes. Therefore, on new windings, the capacitance test is less effective in a condition-based maintenance program. It does, however, have some merit for determining the extent of moisture Contamination and delamination on the older windings.

> ✐ Capacitance testing monitors the change in the dielectric constant of the insulation.
>
> 👓 $C = \varepsilon A / d$

- delamination ⇒ capacitance decreases (1% change)
- moisture Contamination ⇒ capacitance increases (5% change)

The capacitance can be measured at a low voltage and best done with a bridge that will eliminate the effect of the stray capacitance of the test supply.

A variation on the capacitance test is the capacitance tip-up test, which is performed on complete windings or preferably individual winding phases, and measures the void content in the groundwall of the stator coils. It is based on the fact that at a relatively high voltage of say phase-to-ground voltage, if there are voids in the groundwall insulation, the gas in the void ionizes to produce sufficiently high conductivity to short the void out causing PD. This produces an increase in capacitance between low and high line-to-ground voltage. Normally this test is performed on each phase of a winding with an accurate capacitance bridge. The capacitance C_{lv} is measured at 0.2E where E is the rated phase-to-phase voltage and also C_{hv} is measured at line to ground voltage which is about 0.58E. The capacitance tip-up is:

$$\Delta C = (C_{hv} - C_{lv})/C_{lv}$$

The higher ΔC is, the more voids there are in the winding groundwall. For a well bonded groundwall insulation:

$\Delta C < 1\%$ for modern epoxy mica insulation $\Delta C < 3$ or 4% for older asphaltic mica windings

It should be noted that if the coils have semi-conducting and grading voltage stress control layers, these influence the results of this test. At the higher voltage, the grading layers of silicon carbide material conduct to increase the effective surface area and thus the capacitance of the sections of winding being tested, and so may give a false indication of high void content. However if the results are trended against time an increase in ΔC may give a true indication of increased void content in the groundwall insulation.

Plausible - Rotating

4.2.5 Dissipation Factor

Like the capacitance test, the dissipation factor test also looks for any changes in the insulation system of the winding. This test, however, is done at high voltage steps that increase from zero to normal line-to-ground voltage. The intention of the test is to observe the increase in real power loss due to the presence of voids in a delaminated insulation ($\Delta\tan\delta$). As the applied test voltage increases so will the partial discharge activity in the voids and thus an increase in mW or real power loss. The absolute value of the dissipation factor is also useful in determining the extent of curing in a new insulation system.

$$DF = \tan\delta = mW / mVar = I_R / I_C$$

delamination $\Rightarrow \Delta\tan\delta$ increases, whereas, moisture Contamination $\Rightarrow \tan\delta$ increases

Typically the DF for epoxy mica windings is about 0.5% and for asphaltic mica windings it is 3 to 5%. Trending the results against time makes the best use of this test. As with the Δ capacitance test, voltage stress coatings can lead to ambiguous results obtained at high voltage.

Plausible - Rotating

4.2.6 Power Factor (cos θ)

Similar to the dissipation factor ($\tan\delta$) the power factor test is looking for any changes in the insulation system of the winding. The test is normally done at a specific applied voltage that makes it possible for comparing the results to other machines. This is a valuable test for determining the extent of curing in new coils or winding. Because the presence of the voltage stress control in a complete winding greatly affects the results, tests on complete windings can be ambiguous.

> ✎ IEEE Std 286: *Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation*

$$PF = \cos\theta = mW / mVA = I_L / I_{total}$$

- delamination $\Rightarrow \Delta\cos\theta$ increases
- moisture Contamination $\Rightarrow \cos\theta$ increases

$PF_{polyethylene} = 0.01\%$
$PF_{epoxy} = 0.5\%$
$PF_{asphalt} = 3 - 5\%$

The tip-up test ($\Delta\cos\theta$) is done at two voltages, one below the inception of partial discharge activity (25% line-to-ground) and one at line-to-ground voltage. As with the $\Delta\tan\delta$ test, the difference in the power factors at these two voltages can be attributed to the energy loss due to partial discharges. The increase in energy required to produce PD indicates the quality of the bond within the insulating resin.Therefore, this value trended over time may be helpful in determining the development of partial discharge activity in a winding. However, as with the capacitance tip-up test the results of this test are influenced by the presence of voltage stress coatings on the coils, since at high line-to-ground voltage currents flow through it to produce additional power losses. Because this test method measures total energy it is only sensitive to how widespread the PD is and not how close the winding is to failure (worst spot).

Tip-up = PF_{high} -PF_{low} (typical results: 0.5% for epoxy)

High at 100% line-to-ground rated voltage (above PDIV)

Low at 25% line-to-ground rated voltage (below PDIV)

This test is widely used by manufacturers of resin rich and individual VPI coils as a quality check. In this type of testing the grading layer on high voltage coils are "guarded out" by applying aluminum foil over it.

4.2.7 Surge Test

Most of the insulation testing described thus far has been for testing the integrity of the groundwall insulation. Because of the high frequency surges that exist when a generator is started, the turn insulation of the line end coil can be subjected to extremely high electric stress. During the manufacturing process a surge test is often used to locate defects prior to impregnation. Some companies also use the test as a maintenance tool. The test procedure is to apply a high-frequency surge to two similar specimens and compare the results or to observe the surge waveform for changes in frequency as the applied voltage is increased. At high frequency, the majority of the surge will be dropped across the capacitance of the insulation between the first and second turns. A noticeable difference between the resultant waveforms would be an indication of a problem. Any misconnection affecting the magnetic field patterns within the winding, such as a coil reversal, phase-to-phase short, or coil-to-coil short, would cause large irregularities. Not as observable because of the small change in frequency, < 0.1%, are turn-to-turn shorts. Since it is difficult to detect turn-to-turn shorts, only people truly familiar with the patterns of the generator being tested should be relied upon for interpretation.

> IEEE Std 522: *Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines*

The surge test is essentially a go/no-go test similar to a high potential test of the turn insulation.

For new windings the test is normally performed at the peak voltage value calculated from the above figure and with a rise time of 0.1 to 0.2 μs. For a 11 kV motor this would be:

$\sqrt{2}/\sqrt{3}*11*3.5 = 31$ kV

For motors that have been in service, a surge with the same rise time, but with a peak value of 75% of that for a new winding is normally used, i.e., for a 6.6 kV motor this would be 23.25 kV

Plausible - Rotating

4.2.8 Ozone Monitoring

An easy method for determining the extent of surface partial discharges in an air-cooled machine is to periodically test the cooling air for ozone concentration. This can be done using "draeger" tubes or sophisticated electronic sensors. Ozone is a by-product of electrical discharges in an oxygen-rich environment and may be sensitive to severe insulation degradation from grading coating deterioration, electrical slot discharges, coil/bar movement, or phase to phase discharges between high voltage components.

0.1 ppm indicates significant PD (OSHA - personnel exposure are 0.1 ppm for 8 hours)

1 ppm indicates severe PD

Plausible - Rotating

4.2.9 Online Partial Discharge Testing

Online PD testing of rotating machines is complicated by the presence of noise and disturbances from non-stator winding signals; therefore, a reliable measuring configuration must make it easy to adequately separate the PD from these external signals. According to IEC 60034-27-2, for PD on-line measurements on rotating machines the following typical frequency ranges are used:

a) In the **low frequency (LF) range** a typical bandwidth of about 1 MHz, or 100 kHz and upper cut-off frequencies usually below 3 MHz. Since the upper cut-off frequency of the detection bandpass is significantly lower than the upper cut-off frequency of the pulse frequency response, the detected PD pulses are directly proportional to the apparent charge of the PD current pulse (principle of "*quasi-integration*"). Since the original shape of the PD pulse arriving at the sensor location is lost when using low frequency bandpass systems, a separation of disturbance signals that are highly prevalent during online testing by pulse shape analysis or time domain separation is limited; therefore special procedures for noise and disturbance separation are needed.

Busted - Rotating

b) In the **high frequency (HF) range** a typical bandwidth of 3-30 MHz is used. PD detection in the high frequency range is less susceptible to noise and disturbance and can be efficiently used to characterize the PD pulses arriving at the PD sensor by their individual pulse shape and thus being able to discriminate between different PD sources according to their signal shape. PD results in the high frequency range are usually expressed in terms of voltage [mV].

Confirmed - Rotating

c) In the **very high frequency (VHF) range** a typical bandwidth 30 MHz to 300 MHz range. The very high frequency range also provides a good signal to noise ratio and is therefore less susceptible to noise and disturbance. PD results in the very high frequency range are usually expressed in terms of voltage [mV]. Efficient methods of time and frequency domain disturbance separation such as time-of-pulse arrival, and pulse shape analysis can be applied

Confirmed - Rotating

d) In the **ultra high frequency (UHF) range** typically 300 MHz up to 3 GHz are used. PD sensors working in that frequency range are antennae, which detect electromagnetically radiated pulse signals. The signal energy detected by these sensors and thus the sensitivity of PD detection mainly depends on the specific location of the antenna, the distance between the antenna and the PD source and the bandwidth of the detection system.

Plausible - Rotating

4.2.10 Offline Partial Discharge Testing

Similar to the online test, the offline partial discharge test is sensitive to delamination and semicon/grading coating problems. Tests are usually taken at line-to-ground voltage. Because the voltage stress is higher than normal on the majority of the coils there is no direct comparison between offline and online testing. It is often possible with offline testing to identify the exact problem spot and therefore repair it. When used offline mechanical is absent and electrical stress is abnormal, so no evaluation can be made about movement or phase-to-phase stresses. The following are test procedures described in IEEE Std. 1434-2010 that can be used both online and offline:

- **Electrical Pulse Sensing** – using high-voltage capacitors or current transformer to detect the current pulse created by the occurrence of PD (frequency range options are similar to the online measurements described in Section 4.2.9).
- **RF Radiation Sensing** – using antennas to detect the electromagnetic frequencies of 100kHz to several hundreds of MHz generated by the PD (can also be used online)
- **Energy/integrated Charge Transfer** - the PD activity is calculated from measurements of capacitance and dissipation factor obtained using a conventional high-voltage capacitance bridge
- **Acoustic and Ultrasonic Detection** - Each PD creates a small "shock wave" caused by a rapid increase in temperature of the gas in the immediate vicinity of the PD. This small shock wave in turn creates acoustical noise.
- **Black-out Test** - A common means of determining the presence and location of surface discharges is to energize the coil/bar or winding under conditions of complete darkness and conduct a visual inspection from a safe distance

Plausible - Rotating

5 Myth 4: A Partial Discharge Program is a One Step Process

5.1 Stationary Equipment:

As we had seen there are numerous insulation tests to assist in assessing the quality and condition of insulation systems. The pass/fail tests provide the means of identifying gross defects while the diagnostic tests provide us with an understanding of the severity of degradation or the extent of contamination in the insulation. Since certain contaminations such as water trees, a defect known to many extruded dielectrics, do not produce partial discharge these tests do not positively indicate if PD activity is present.

5.1.1 Partial Discharge Fault Detection

Detection of PDrelated faults is based on the principle of determining whether PD activity is at a critical level.Low levels of partial discharge activity are often present in assets at levels which may be considered acceptable i.e. non-critical, or unlikely to develop into failures in the short to medium term.

Faults are detected by testing to establish whether PD activity exceeds critical thresholds:

Threshold 1 - PD activity is not present or at sub-critical levels. Results provide assurance that PD-related faults are unlikely to be developing at present.

Threshold 2 - PD activity is at a level which indicates that a fault is developing and requires further investigation or monitoring.

Threshold 3 - Partial Discharge activity is at a level which indicates that a fault is at an advanced stage of development. The fault is likely to cause imminent failure – and the asset may be energized to an extent that is a danger to personnel. This level of PD activity indicates the need for immediate investigation and intervention.

5.1.2 Partial Discharge Condition Data Gathering

Partial discharge testing is a useful technique for assessing the condition of individual assets, but it is of far greater value when applied to groups of assets – for example a substation or an entire network.

Offline testing of equipment is a good start in establishing inception and extinctions levels. This can be done atany time during the life of the asset or as part of the acceptance testing process when the asset is new. Establishing diagnostictest values like dissipation factor at time of acceptance will also provide a good benchmark for moving forward on a predictive maintenance program. This can be viewed as a Level 0 survey, benchmark.

After the equipment has been put into service periodic online checks can be performed to determine if PD activity is taking place at operating voltage levels. To determine if PD activity is present at operating voltage levels a simple Level 1 survey can be conducted. The purpose of a Level 1 survey is to conduct a basic first pass assessment of assets and to check for the presence of PD activity. This is a quick and efficient check that can rule out good equipment in an economic manner. In most cases nearly 90% of a facility's equipment will be "good." The other 10% will need further investigation and will advance onto a Level 2 survey. The Level 1 survey typically utilizes ultrasonic and TEV measurements.

A Level 2 survey is conducted while the equipment is online and is designed to locate and quantify PD activity in order to produce a detailed asset health report. Once a potential insulation issue has been uncovered in Level 1 further analysis will be necessary to ensure that the suspect activity was not caused by external noise. It is also advantageous to locate the source of the partial discharge activity and to quantify and assess the severity of the problem. During this process multiple ultrasonic, TEV and RFCTs can be deployed for a more detailed survey. Depending on severity either a Level 3 survey or an outage may be scheduled to conduct a more detailed assessment.

During a Level 3 survey PD activity is measured and analyzed over time to detect deterioration and to raise an alarm or call-to-action if PD activity reaches a critical level. As an example, if PD activity that is intermittent or possibly influenced by environmental conditions (changing temperature, humidity, vibration or electrical noise) is found, temporary installed multi-sensor systems that automatically monitor your plant can be utilized.

Trending diagnostic test data such as power factor, dissipation factor and PDIV/PDEV during scheduled outages will give further details on the degradation and quality of the insulating systems' in critical assets. Implementing an offline and online testing program is the foundation of true predictive based asset management, providing the information needed to develop data records of assets, including:

- Current condition and 'health' for each asset,
- Timeline predictions of likely failure, and
- The ability to prioritize and schedule maintenance and replacement

Busted - Stationary

5.2 Rotating Equipment

A condition-based maintenance program is a step-by-step analysis designed to diagnose a machine for performance deterioration or any upcoming faults. As the machine condition is studied continuously by electronic monitoring, costs associated with maintenance activities are low. At each step along the way the potential problems for the machine are identified, and subsequent tests and actions are planned because of the potential problems identified. In other words, perform costly tests and maintenance on the generators that need it when they need it and not be surprised in the interim.

Though nothing will ever replace a thorough visual inspection for discovering problems at an early stage, there are better ways to establish a maintenance program - a method that is intended to reduce outages, minimize costs related to unnecessary tests or repairs, and eliminate unexpected failures. Though no method is completely fool proof, this approach is intended to give you the most information in an economical way. As shown below in Table 2, start with the potential problem then go to the suitable on-line monitoring system for trends obtained at various operating and ambient conditions. If the On-line monitoring indicates a problem, then follow-up with the appropriate Off-line test is required. The goals are to pre-plan maintenance and testing to reduce outage time and costs, discover potential problems before unforeseen failures, and repair problems if possible.

5.2.1 Condition-Based Maintenance Program

Table 2 Condition-Based Maintenance Program

Potential Problem	On-Line Monitoring		Off-Line Testing	
	Technique	**Advantages and Disadvantages**	**Tests**	**Advantages and Disadvantages**
Stator Winding Turn-to-Turn Damage – Manu/ Thermal ***(high risk of shorted turns in stator winding)***	PD Monitor *(IEEE 1434)* (IEC 60034-27-2) *(Negative PD predominant)*	*Advantages:* • Trend data at variable conditions • In-service voltage distribution in windings • Determines the effects of temperature on voids in winding • Increase in number and size of voids can be determined by trending *Disadvantages:* • Does not indicate how general the problem is	Off-line PD *(IEEE 1434)* (IEC 60034-27) Dissipation Factor Power Factor (IEEE 286)	*Advantages:* • Results of PD, Dissipation Factor and Power Factor can be trended to determine if the groundwall de-lamination is becoming more severe *Disadvantages:* • Whole winding is raised to the same voltage so voltage distribution is different from that in service. Thus for PD test on- and off-line values cannot be directly compared.
Coil Movement ***(high risk of damage to groundwall insulation)***	PD Monitor *(IEEE 1434)* (IEC 60034-27-2) *(PD increases with load)*	*Advantages:* • Trend data at variable conditions • Effects of load variations on PD levels can be determined • Condition can be trended to determine if it is getting worse *Disadvantages:* • Requires installed sensors and signal processing	Visual Inspection *(No Off-line electrical test is adequate)*	*Advantages:* • Determines the exact location of the winding looseness *Disadvantages:* • Requires machine shutdown, opening up and perhaps a rotor pull • Ineffective for global VPI windings • Difficult to determine what is really loose • Cannot test at different loads
Voltage Grading Coating Deterioration ***(moderate risk – but may lead to coil movement)***	PD Monitor *(IEEE 1434)* (IEC 60034-27-2) *(PD influenced by humidity, but NOT load)*	*Advantages:* • Trend data at variable conditions • Effects of temperature and humidity on semicon and grading materials performance can be determined • Condition can be trended to determine if it is getting worse *Disadvantages:* • Requires installed sensors and signal processing	Dissipation Factor Power Factor (IEEE 286) *Off-line PD (IEEE 1434)* (IEC 60034-27)	*Advantages:* • Exact location of the problem can be determined *Disadvantages:* • Requires machine shutdown, opening up and perhaps a rotor pull • Difficult to evaluate the impact of humidity on PD patterns
Contamination ***(low risk for failure but can accelerate aging)***	PD Monitor *(IEEE 1434)* (IEC 60034-27-2) *(PD influenced by humidity and erratic patterns)*	*Advantages:* • Trend data at variable conditions • Effects of temperature and humidity can be determined • Condition can be trended to determine if it is getting worse *Disadvantages:* • Requires installed sensors and signal processing	IR/PI/PDT Dissipation Factor Power Factor (IEEE 286) *Off-line PD (IEEE 1434)* (IEC 60034-27)	*Advantages:* • Can determine conductivity of contaminant *Disadvantages:* • Requires machine shutdown, opening up and perhaps a rotor pull • Cannot evaluate the impact of ambient conditions on results
Inadequate spacing	PD Monitor *(IEEE 1434)*	*Advantages:*	Visual Inspection	*Advantages:*

(rare occurrence with low risk of failure unless severely contaminated)	(IEC 60034-27-2) *(PD based on phase-to-phase voltage)*	• Measure at phase-to-phase voltage stress • Condition can be trended to determine if it is getting worse *Disadvantages:* • Requires installed sensors and signal processing	*(No Off-line electrical test is adequate)*	• Determines the exact location of the inadequate spacing *Disadvantages:* • Requires machine shutdown, opening up and perhaps a rotor pull • Difficult to locate due to accessibility