

Partial Discharge Theory and Applications to Electrical Systems

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Abstract - Partial discharge monitoring is an effective on-line predictive maintenance test for motors and generators at 4160 volt and above, as well as other electrical distribution equipment. The benefits of on-line testing allow for equipment analysis and diagnostics during normal production. Corrective actions can be planned and implemented, resulting in reduced unscheduled downtime. An understanding of the theory related to partial discharge, and the relationship to early detection of insulation deterioration is required to properly evaluate this predictive maintenance tool. This paper will present a theory to promote the understanding of partial discharge technology, as well as various implementation and measurement techniques that have evolved in the industry. Data interpretation and corrective actions will be reviewed, in conjunction with comprehensive predictive maintenance practices that employ partial discharge testing and analysis.

I. BACKGROUND

Reliable manufacturing operations will always be concerned with process production motors. Comprehensive programs to maintain electrical equipment for peak performance have been recommended and implemented at various plants [1]. Detailed motor failure analysis has been completed; resulting in the identification of approximately 30% of failure causes being related to electrical failures [2]. A summary of the IEEE transaction entitled: "Report of Large Motor Reliability Survey of Industrial and Commercial Installations, Part I [3] included both the results of an IEEE survey and an EPRI survey. The two sources of information proved extremely useful since the IEEE survey identified the "Failure Contributor", and the EPRI survey identified the "Percentage Failure by Component." The IEEE survey includes an objective opinion, whereas the EPRI survey includes actual failed components. The summary of the electrically related causes of the two studies is shown in Table 1, and will be referred to, when discussing root cause failures related to partial discharge test results.

Table 1 – Motor Electrical Failure Causes			
IEEE Study		EPRI Study	
Failure Contributor	%	Failed Component	%
Persistent Overloading	4.2	Stator Ground Insulation	23.0
Normal Deterioration	26.4	Turn Insulation	4.0
		Bracing	3.0
		Core	1.0
		Cage	5.0
Total	30.6	Total	36.0

The IEEE publication under development, "IEEE P1434 - Guide to Measurement of Partial Discharges in Rotating Machinery" [4] also identifies similar failure causes for motor insulation systems. These include thermal, electrical, environmental and mechanical stresses. These factors correlate to the two studies, since they result in the stator ground insulation and turn insulation failure (EPRI Study); as well as can be interpreted as normal deterioration (IEEE Study).

The next section provides a review of partial discharge theory. It is interesting to note that over 25 years ago, large motor manufacturers recognized the need for partial discharge testing in the slot area between the winding insulation and the iron [5]. The testing was called the "Slot Discharge Test" and involved applying a test voltage while observing the waveform on an oscilloscope. At that time only minimal partial discharge measurement technology was available, therefore limiting the wide spread use of such testing.

II. PARTIAL DISCHARGE THEORY

Partial discharge theory involves an analysis of materials, electric fields, arcing characteristics, pulse wave propagation and attenuation, sensor spatial sensitivity, frequency response and calibration, noise and data interpretation. It is obvious from the above that most plant engineers will not have the time, or available energy, to pursue such a course of study.

In an effort to promote a better understanding of partial discharge (PD), this paper attempts to provide simplified models and relate the characteristics of these models to the interpretation of PD test results.

First, we will present a few technical concepts relating to partial discharges. Partial Discharge can be described as an electrical pulse or discharge in a gas-filled void or on a dielectric surface of a solid or liquid insulation system. This pulse or discharge only partially bridges the gap between phase insulation to ground, or phase to phase insulation.

These discharges might occur in any void between the copper conductor and the grounded motor frame reference. The voids may be located between the copper conductor and insulation wall, or internal to the insulation itself, between the outer insulation wall and the grounded frame, or along the surface of the insulation. The pulses occur at high frequencies; therefore they attenuate quickly as they pass to ground. The discharges are effectively small arcs occurring within the insulation system, therefore deteriorating the insulation, and can result in eventual complete insulation failure.

The possible locations of voids within the insulation system are illustrated in Figure 1.

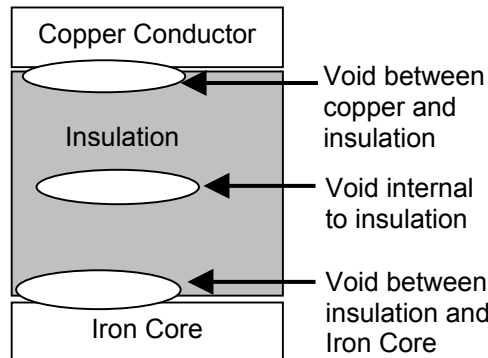


Figure 1 – PD within Insulation System

The other area of partial discharge, which can eventually result, is insulation tracking. This usually occurs on the insulation surface. These discharges can bridge the potential gradient between the applied voltage and ground by cracks or contaminated paths on the insulation surface. This is illustrated in Figure 2.

The above can be illustrated by development of a simplified model of the partial discharges occurring within the insulation system.

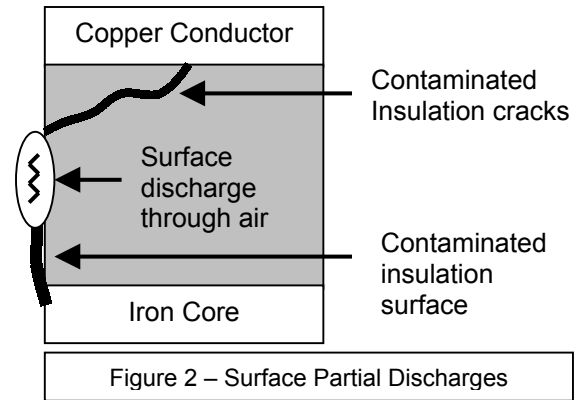


Figure 2 – Surface Partial Discharges

A. Insulation System Model

A simplified model of an insulation system can be represented by a capacitance and resistance in parallel [6]. This is the concept employed in the use of power factor testing of insulation systems. The leakage current is split between the resistive and capacitive paths. The power factor is the cosine of the phase angle between the total leakage current and the resistive component of leakage current [5].

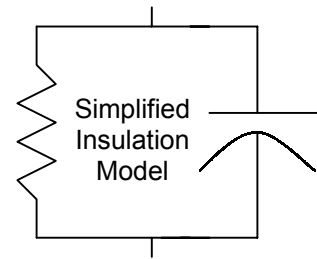


Figure 3 – Simplified Insulation Model and Model for an Electronic Attenuator

The above model is also used for attenuator circuits in electronics [7]. Signal attenuation results in reducing the amplitude of the electrical signal. This underlies the problem with partial discharge detection. The insulation medium, which is being exposed to the partial discharges, acts to attenuate the signal, therefore weakening this damaging signal which we are trying to identify at our sensor locations. In addition, the attenuated partial discharge signal can be masked by sources of electrical noise, which shall be reviewed later in this paper.

The above concept of the insulation system being an effective attenuator circuit gives rise to critical detection issues, such as:

- Sensor locations and sensitivity
- Measurement system response to attenuated signals
- Noise detection and elimination

B. Partial Discharge Void Model

Simplified models of the area of the void have been described as consisting of capacitors only [8]. A review of the progressive failure mode of these voids indicates an additional resistive component in parallel with the capacitive component. An electrical equipment design handbook [9] states: “Discharges once started usually increase in magnitude with stressed time, but discharges can become short circuited by semiconducting films inside the void and discharging is terminated.” The referenced semiconducting films can also consist of carbonization of the organic insulation material within the void due to the arcing damage. Therefore the model of the partial discharge void is similar to that of the insulation medium itself.

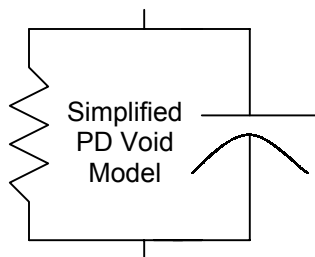


Figure 4 – Simplified Partial Discharge Void Model with Internal Resistive Leg

Actual failure modes have indicated a drop in partial discharge intensity shortly prior to complete failure. This would occur when the internal arcing had carbonized to the point where the resistive component of the model was low enough to prevent a build-up of voltage across the void. This new low resistive component would also allow higher current flows, and additional heating and resultant insulation damage. The above model, including the resistive component correlates to the actual failure mode of a partial discharge void, with the resistive component passing more leakage current as the partial discharges increase with time. One form of this resistive component is visible tracking on the surface of insulation. An explanation of tracking, and how surface partial discharges are related to the development of tracking follow [5]: “Tracking damage has been traced entirely to the locally intense heat caused by leakage currents. These currents flow thru any contaminated moisture film on the bridging insulating surface. As long as this film is fairly broad and continuous, the heat associated with the leakage current is spread over a wide area and is dissipated. However, heating promotes film evaporation. This causes the film to break up into small pools or islands. Each break in the film tends to interrupt a segment of the leakage current, causing a tiny

arc. Even though the arc is small, severe local heating results. The intense heat of the leakage current arc is sufficient to cause a molecular and chemical breakdown of the underlying insulation. On organic materials, a frequent by-product of arcing is carbon.” The above “tiny arc” along the insulation surface can be represented by partial discharge activity. Figure 5 illustrates the failure mode of deteriorated insulation related to the intensity of partial discharge measurements.

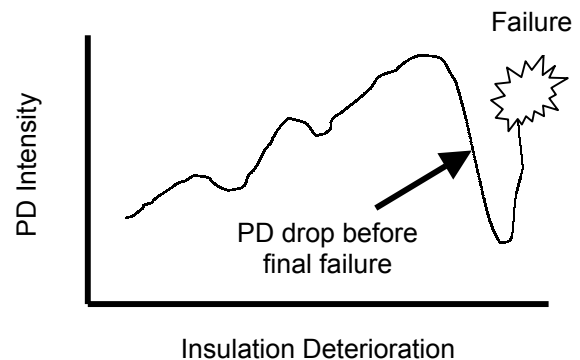


Figure 5 – PD versus Insulation Failure Mode

Figure 6 illustrates a circuit breaker bushing which as progressive tracking highlighted for presentation purposes. At the point near eventual failure, the tracking and resistive component of the insulation have increased to the point where partial discharges have been reduced, since the “tiny arcs” have caused the carbonization and tracking, therefore providing a direct path for current flow. At this point, evidence of insulation deterioration is usually detected by traditional methods of insulation resistance, or megger testing. For the above reason, partial discharge on-line testing and traditional insulation resistance testing are complimentary. On-line partial discharge testing can detect insulation in the progressive phases of deterioration, with trending identifying problems long before eventual failure. Traditional insulation resistance testing provides a “current-state” of the insulation system.

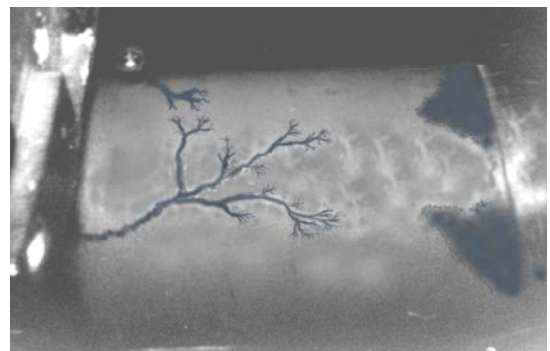


Figure 6 – Bushing with progressive tracking

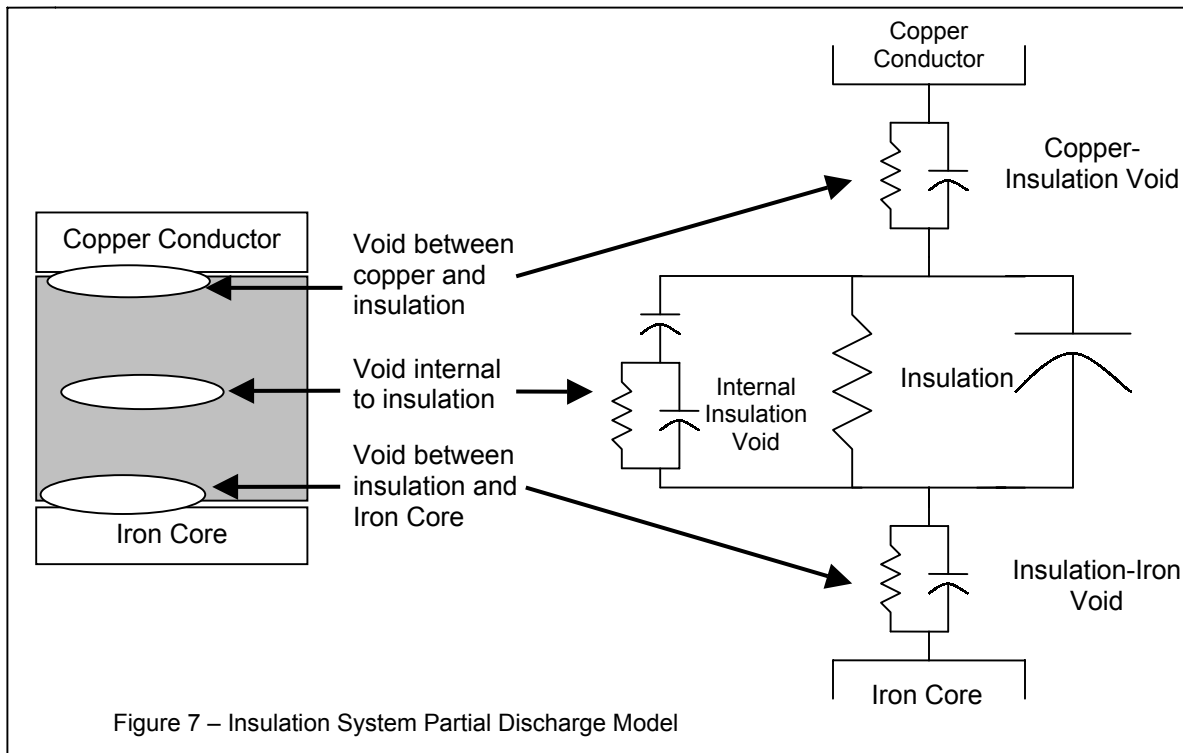


Figure 7 – Insulation System Partial Discharge Model

With the development of the above models, we can illustrate a complete model of the various insulation system discharges represented in Figure 1.

Figure 7 is be used to provide an understanding of partial discharge activity.

C. Partial Discharge Concepts

The first concept to review is the characteristic trait that partial discharges occur only during the first and third quarter of each cycle. This is the initial rising positive signal, and the initial rising negative signal. Effectively, during the initial rising positive signal, all of the capacitive components are being charged until the partial discharge inception voltage is reached across each specific void, and partial discharges commence. When the positive wave cycle begins to decrease the positive voltage across each void is reduced, since some capacitive charge remains. Some level of charge must exist since the voltage across a capacitor can not be changed instantaneously. During the first quarter cycle we are creating a positive charge and the resultant partial discharges. During the third quarter cycle, this positive charge is effectively reversed, resulting in a positive charge in the reverse direction, and the resultant partial discharges.

The second concept to review is that partial discharges are measured as voltage pulses; therefore, during the

positive waveform cycle, a discharge, or a partial short-circuit, results in a negative, downward oriented pulse.

This is referred to as a partial discharge with a negative polarity, and occurs during the first quarter-cycle of increasing positive voltage applied to the void. During the third quarter-cycle, a partial short-circuit results in a positive, upward oriented pulse. This is referred to as a partial discharge with a positive polarity and occurs during the third quarter-cycle of the increasing negative voltage applied. These partial discharges, which are measured as a high frequency change in the power signal in millivolts to a few volts, can not be observed with a standard scope; therefore they are exaggerated in Figure 8 for illustration purposes.

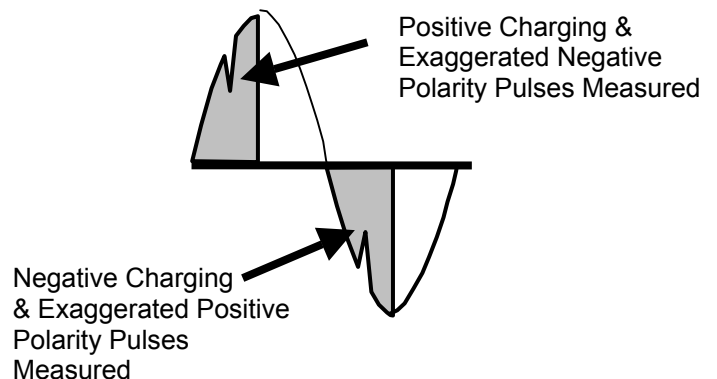


Figure 8 – Exaggerated Positive & Negative Polarity Pulses for Illustration Purposes

As stated, since the pulse of voltage change is being measured, the negative polarity pulses occur during the first quarter cycle, or during the rising positive cycle of the wave; and conversely, the positive polarity pulses occur during the third quarter cycle, or during the rising negative cycle of the wave.

When viewing the results of partial discharge signals, the above will be illustrated, on a three dimensional graph, with two critical measurements plotted in relation to the 360 degrees of a typical cycle. The 360 degrees is usually split into four segments, therefore the level of partial discharge in the first quarter cycle, or negative polarity discharges, can be compared to the third quarter cycle, or positive polarity partial discharges. The differentiation of positive versus negative polarity partial discharge pulses will be related to a probable root cause and corrective actions. The two measurements illustrated on the two dimensional graph are partial discharge Maximum Magnitude, usually represented in millivolts, and Pulse Repetition Rate, represented by the number of partial discharge pulses during one cycle of an AC waveform. This is discussed further in Figure 12.

The partial discharge magnitude is related to the extent of damaging discharges occurring, therefore related to the amount of damage being inflicted into the insulation. The pulse repetition rate indicates the quantity of discharges occurring, at the various maximum magnitude levels. Both play a role in determining the condition of the insulation under test. Whereas seldom possible with on-line motors, the maximum magnitude level should be calibrated to reflect the actual charge, measured in pico-coulombs. The benefits of such calibration are offset by the relative comparison of similar motors, and more importantly by trending of the partial discharge activity over time. On-line partial discharge testing allows for such trending and analysis of the electrical equipment. The illustration of the partial discharge activity relative to the 360 degrees of an AC cycle allows for identifying the prominent root cause of partial discharges, therefore appropriate corrective actions can be implemented.

The third concept to review is the effect of high negative polarity pulses, occurring during the first quarter cycle of the positively rising wave, in relation to the high positive polarity pulses, occurring during the third quarter cycle; and vice versa. It has been found that if the positive polarity discharges exceed the negative polarity discharges then the probable root causes are either voids between the insulation and iron core (slot discharges), or at the winding end-turns, or surface partial discharges. It has also been found that if the negative polarity discharges exceed the positive polarity charges then the probable root cause is voids in between the copper conductor and insulation.

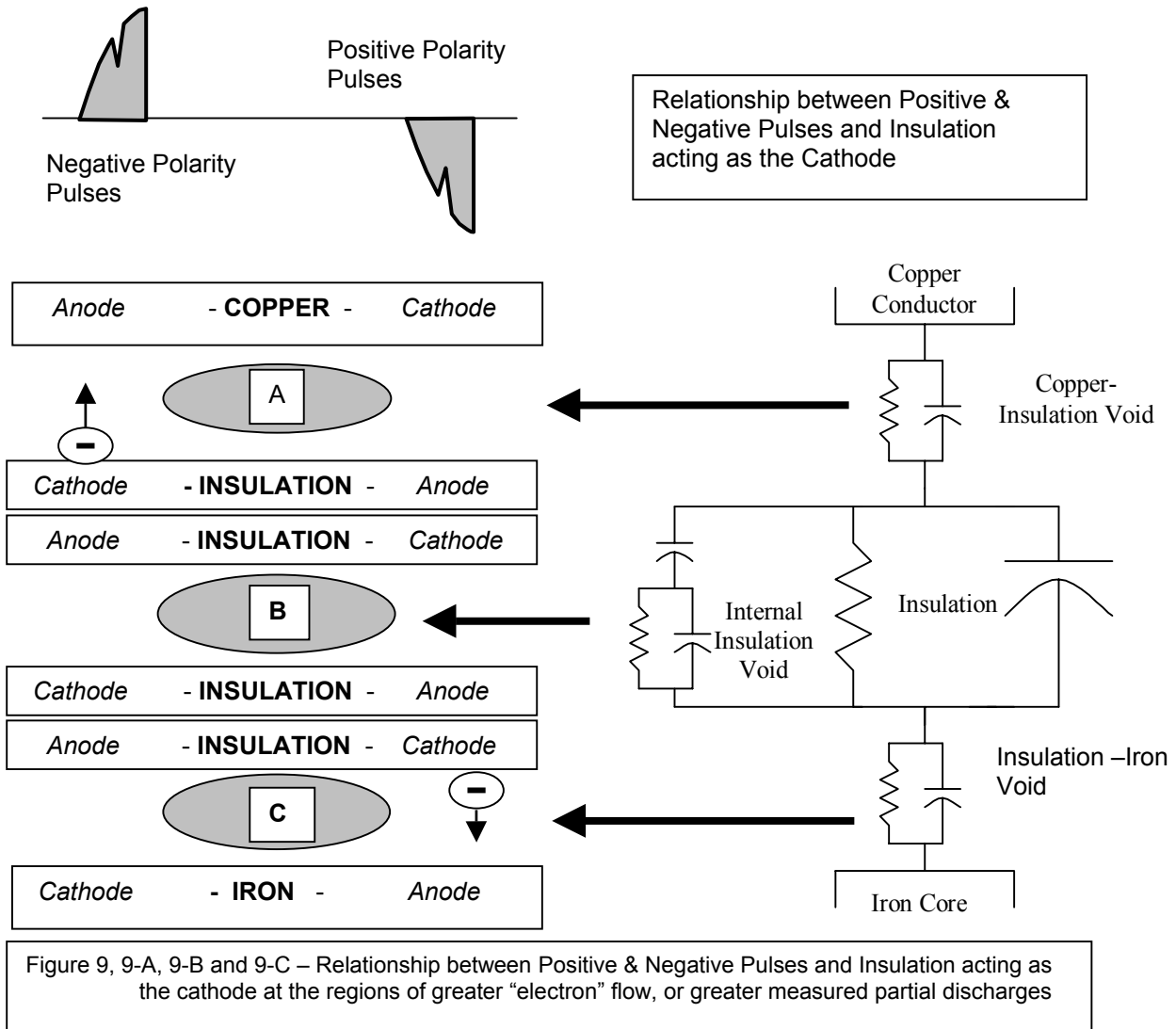
This interesting phenomenon is related to the applied voltage level to the void, the void's geometric shape and the specific materials that are acting as the anode and cathode. The critical material is the cathode, since the cathode supplies free electrons to allow the partial discharges to continue. As illustrated in Figure 9 the various anodes and cathode materials are shown for the rising positive and negative parts of the AC cycle, which is the two areas where discharges are measured.

Depending on the part of the power cycle, the material representing the cathode differs. The cathode material is most important since the cathode will supply the electrons to support partial discharge activity. The characteristics of copper and iron are defined in their role of a cathode, related to their conducting characteristics. When the insulation becomes the cathode, and a partial discharge occurs at the surface of the insulation, the characteristics of the insulation create a plasma. A plasma is a very good source of free electrons to promote partial discharge, and in addition, the discharge area is extended by the nature of the plasma area. The result is that a greater tendency of partial discharges will occur when the insulation is in the cathode role.

For the negative polarity pulses, occurring in the first quarter cycle, the insulation acts as a cathode across voids in the copper conductor-to-insulation space (*Fig. 9 – A*). During these negative polarity pulses, a greater tendency of discharges will occur in this area near the copper conductor. Therefore if negative polarity pulses greatly exceed the positive polarity pulses, then the root cause is considered to be voids in the copper conductor-to-insulation area.

For the positive polarity pulses, occurring during the third quarter cycle, the insulation acts as a cathode across voids in the insulation-to-iron space (*Fig. 9 – C*). During these positive polarity pulses, a greater tendency of discharges will occur in this area near the iron. Therefore if positive polarity pulses greatly exceed the negative polarity pulses, then the root cause is considered to be voids in the insulation-to-iron area, or in the area of surface tracking since this also bridges the outer insulation wall to the iron.

Also note that when the voids are prevalent internal to the insulation material itself (*Fig. 9 – B*), then for both the positive polarity and negative polarity pulses, the cathode remains the insulation itself. In this regard, when positive and negative polarity pulses are equally prevalent, then the root cause is considered voids within the insulation material itself, and not between the insulation and either the copper conductor, or the iron.



The above-simplified modeling attempts to provide an understanding of the measurement results of partial discharges, and their interpretation related to corrective actions. The following section shows the relationship to traditional testing methods and details the results, and associated corrective actions.

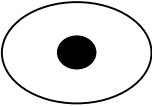

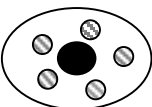

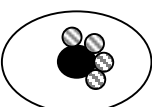
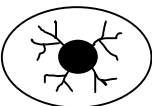
III. PARTIAL DISCHARGE TESTING RELATED TO TRADITIONAL TESTING METHODS

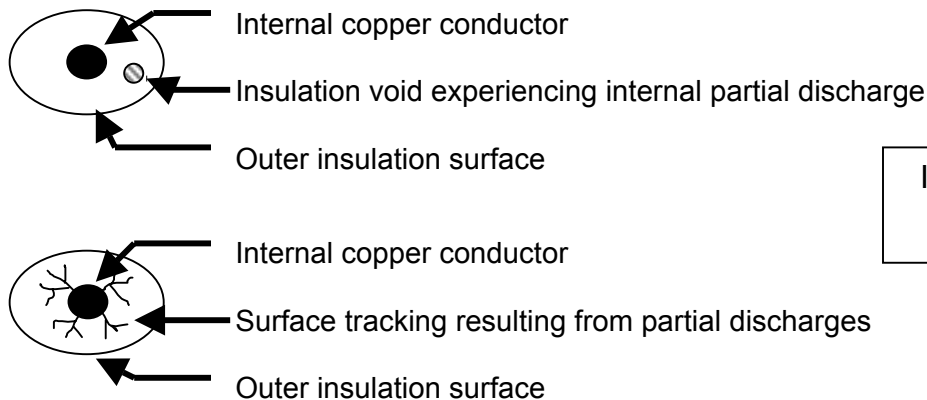
Table 2 illustrates the relative relationships between the results of partial discharge testing and traditional testing methods. The insulation model, contained in the first column, illustrates the internal copper conductors, the outer insulation surface and various formations of voids within the insulation. The second column states the insulation condition. The third, fourth and fifth columns indicated the expected results from the following

traditional testing methods: Insulation Resistance Testing or “Megger Test” which is at a reduced DC voltage, Polarization Index Test (1 and 10 minute readings of the insulation resistance test to equalize the effects of humidity and temperature) and High-Potential Testing (higher DC voltage test with leakage current monitored). The fifth column includes the expected results from Partial Discharge Testing.

For insulation considered “Good” or “Marginal” the results are similar for all test methods. For insulation which is “Dry but insulation delaminated”, traditional test methods will provide a false sense of a “Fair” condition; whereas partial discharge testing indicates the presence of internal insulation voids. “Poor” or “Unacceptable” insulation conditions can not be differentiated with traditional testing methods; whereas partial discharge testing identifies the regions of insulation voids, and the appropriate corrective actions.

Table 2 – Partial Discharge Testing related to Traditional Testing Methods

Insulation Model	Insulation Condition	Megger Test	Polarization Index Test	High-Pot Test	Partial Discharge Testing
	Good	High	Good	Linear leakage current vs. voltage is minimal	Unmeasurable partial discharge activity
	Marginal	Fair	Fair	Linear leakage current vs. voltage is stable	Minimal discharge activity, balanced both positive and negative discharges
	Dry but insulation delaminated	False Fair Result	False Fair value	False linear leakage current vs. voltage	Partial discharges observed, therefore accurately showing insulation problems which are missed by traditional tests
	Poor - Cleaning or Overhaul Required	Low	Poor	High leakage current. May be required to limited test voltage.	High positive polarity discharges indicate probable surface tracking
	Unacceptable - Major Repair or Rewind Required			Potential failure during testing	High negative polarity discharges indicates internal voids near the copper conductor.
	Near-Failure condition - PD arcing as caused carbon tracking	Very low	Very low	High leakage current and probable failure during testing	Minimal partial discharge activity. Partial discharge arcing as progressed to the point where permanent damage (tracking) as occurred.



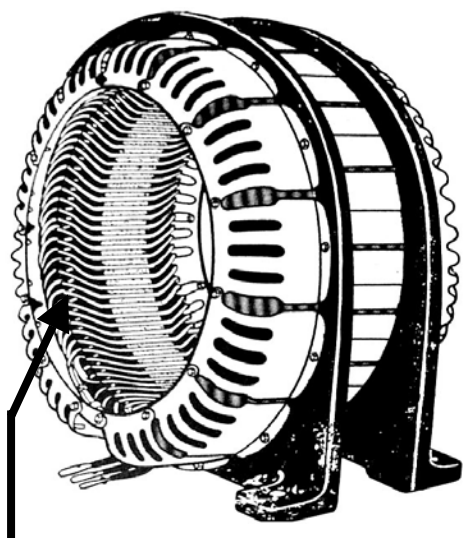
Insulation Model Descriptions

For “Near-Failure” conditions, partial discharge arcing may have progressed to the point where permanent damage, or tracking, as occurred, therefore the level of partial discharges as decreased. This is also illustrated in Figure 5. During this condition, traditional test methods more accurately reflect the insulation condition, whereas a High-Potential traditional test may cause insulation failure during the test period. For this reason, trending is recommended for the first year of partial discharge testing.

IV. DATA INTREPRETATION AND CORRECTIVE ACTIONS OF MV MOTORS

Table 3 is used to summarize data interpretation and corrective actions, but first a discussion is presented concerning viable corrective actions.

Based on the partial discharge characteristics and various root cause analysis, we can begin to identify deficient areas of an on-line motor. The presence of relatively high positive polarity partial discharges indicates potential problems at end-turns, surface discharges or tracking due to contamination, or voids between the outer insulation wall and the iron core. The end-turn potential problems and surface discharges can be effectively addressed, thereby mitigating any additional insulation deterioration, and possibly providing extended equipment life.



End turn stress where the winding extends from the iron core.

Figure 10 – Motor Stator End Turns

The author, having over ten years of association with motor repair shops, was witness to many medium voltage

motor failure modes. One specific weakness that was identified in medium voltage motors was the end-turn insulation, specifically at the junction where the motor winding extended from the iron core. This region is shown in Figure 10. After several motors had failed, it was decided to review and ensure that the originally installed differential motor protection was operating properly. It was found on several 13.8KV motors, equipped with operable differential motor protection, that this specific end-turn area, exactly at the point where the winding extended from the iron core, was the root cause of repeated failures. These motors were operating in a wind-tunnel application, therefore were subjected to repeated starts, stops, and thermal loading swings. It was determined that the cycling was causing excessive stress on the end-turn windings, therefore causing small cracks and voids to the insulation at this point where the winding extends from the iron core.

This damage went unnoticed by traditional testing methods, therefore resulted in the ultimate failure of large and costly machines. Only due to the presence of the differential protection relaying, was the root cause identified, since the motor had been de-energized immediately after the initial fault. Detailed inspections, and attempts at patch-repairs to this junction of the winding and core-iron proved unsuccessful, resulting in complete rewinds of the entire motors. Following the costly rewind of three units, it was determined to remove the remaining nine units and complete a cleaning of the winding, baking, dipping with new varnish and a final bake cycle. In addition, the end-turn support rings were reinforced, therefore minimizing the mechanical stress on the insulation at this junction, due to the cyclic operations. The remaining nine motors operated satisfactory for the next eight years, until the wind tunnel was decommissioned. If on-line partial discharge technology was utilized at that time, we would have expected to see an increasing trend of the positive polarity discharge pattern, which would have identified the weakened end-turns, and resulted in a considerable savings in repair costs, as well as operating up-time. This facility had the personnel and funding to complete such on-line testing, but partial discharge technology was not yet widespread.

Referring back to Table 1, which summarized the results of an IEEE and EPRI study: Stator Ground Insulation accounted for 23% of the failures, while Bracing accounted for an additional 3%. This total of 26%, may be related to end-turn damage to some extent.

In contrast, if on-line testing indicated a negative polarity partial discharge pulse rate to be more prevalent, this would indicate voids between the copper conductor and the insulation, which could be evidence of possibly poor

impregnation during construction, or a recent rewind. Partial discharge testing after the rewinding of medium voltage motors is highly recommended to provide baseline data, and possibly uncover potential quality problems involving the rewound motor. Partial discharges between the copper conductor and insulation result in limited low-cost corrective actions, since access to the problem areas is not possible, even if the motor is removed from service. In these cases, repeated monitoring should be maintained, and the unfortunate budgeting for a major future repair and the associated downtime. One operating advantage is the possibility of completing the necessary major repairs, during other major plant improvements. It would be most embarrassing to allow a large potential cost item to go unapprised, and then to possibly fail after a plant as been restarted following other major improvements.

The last alternative, is an equal balance between positive and negative pulses. Based on the theoretical discussions presented, a balance would indicate either an equal intensity of voids at the inner copper conductor-insulation interface versus the outer insulation wall and iron (slot discharge) or surface tracking related voids; or most likely, that the majority of pulses are emulating from voids internal to the insulation, as illustrated in Figure 7 and 9-B. In either case, repeated on-line trending would be recommended to identify a difference in polarities. If no difference is evident, then the conclusion can be made that the voids are within the internal insulation. Corrective actions are similar to negative polarity pulses, since the internal voids can not effectively be repaired without a complete motor tear down and rewinding

Other viable solutions now include effective field cleaning of large machines involving either corncob materials, CO₂ or traditional hand cleaning. In all such cases, the following testing protocol is recommended:

1. Review of on-line PD measurements for the last six months.
2. Off-line PD testing, with additional sensors installed where possible.
3. Pre-cleaning off-line insulation resistance testing and polarization index determination. Power factor testing is another tests that can be completed, if available.
4. Since the unit is out-of-service, it is also recommended to complete a three-phase surge test to determine if any turn-to-turn problems may exists at this time. During this off-line test a periodic high frequency signal is injected to all three phases

simultaneously, and the resultant waveforms are compared. If turn-to-turn problems are clearly identified, this may limit the effect of the cleaning process since internal turn-to-turn faults can not be accessed by external cleaning.

5. Retest of the following after initial cleaning:
 - a) Partial Discharge
 - b) Insulation Resistance and optional power factor testing
 - c) Polarization Index
 - d) Three-phase surge test if available and required based on initial test results.
6. Repeat Item #5 as cleaning progresses.
7. Retest as in Item #5 before unit reinsulation.
8. Retest as in Item #5 after unit reinsulation.
9. Final pre-energization tests as in Item #5, after complete baking of new insulation applied.

NOTE: Temperature and humidity should also be recorded each time Item #5 testing is repeated. During on-line testing, loading levels should also be recorded.

Results have shown that some insulation systems can be improved by cleaning and reinsulating, but it depends on the extent of existing insulation damage. This effort is usually much less costly than a complete rewind, therefore is worth considering, even though positive results can not be guaranteed.

The previous theory, and data interpretation can be applied to the following two illustrations of actual measured partial discharge activity.

First, Figure 11 illustrates the two critical parameters, partial discharge Maximum Magnitude and Pulse Repetition Rate plotted separately for the first half of the sine wave, 0 to 180 degrees, and also shown for the second half of the sine wave, 180 to 360 degrees. Keep in mind, as illustrated by Figure 7, that the negative polarity pulses will be represented in the first half of the sine wave (0 to 180 degrees); while the positive polarity pulses will be represented in the second half of the sine wave (180 to 360 degrees).

The 'y' axis indicates Pulse Repetition Rate, shown in pulses per cycle and the 'x' axis indicates the Maximum Magnitude, shown in volts. By plotting this relationship as two separate curves, for each polarity, we can begin to determine the possible root cause for the partial discharge activity.

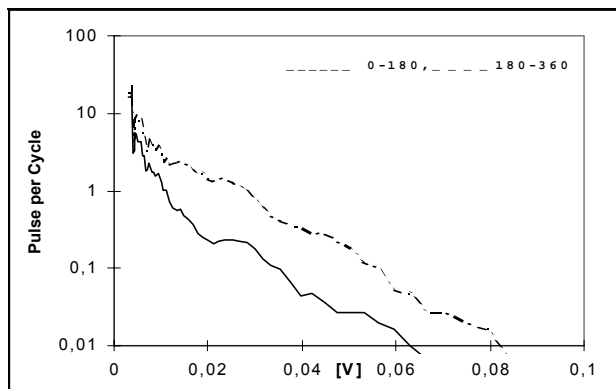


Figure 11 – Positive & Negative Polarity Partial Discharges

The example illustrated in Figure 11 shows the positive polarity pulses exceeding the negative polarity pulses. After further on-line monitoring and trending the root cause may be considered the interface between the insulation and iron, or surface tracking contributing to surface partial discharges. In this case, repeated observations and trending are required, and external cleaning and reinsulating should be considered if the partial discharge trend increases.

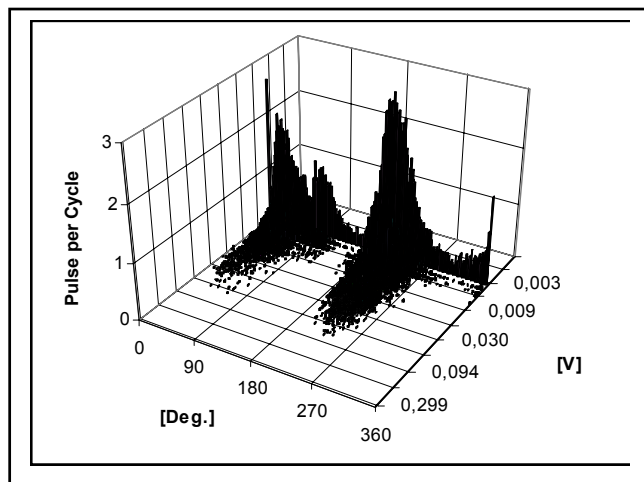


Figure 12 – Partial Discharge – 3D View

Figure 12 illustrates the above two critical parameters, with the full power cycle degrees (0 to 360) as the third axis; thereby providing a two dimensional presentation of the partial discharge activity. This figure also illustrates the higher level of partial discharges during the rising negative half of the power cycle (180 to 270 degrees), or as previously discussed the higher level of positive polarity discharges.

Table 3 summarizes the data interpretation and recommended corrective actions. The first column includes the partial discharge results. This is followed by the possible root-cause, based on the partial discharge levels and the regions of associated insulation voids. The next two columns include the short-term and long-term recommendations. The root causes vary from normal partial discharges to significant regions of voids within the insulation system. Concerning recommendations, trending is recommended within a 3 to 6 month period at the first indication of substantial partial discharges. In most cases the root cause and partial discharge activity is comparative except for the situation when the insulation is old and shows signs of external wear, or if there is evidence of surface tracking. These situations may indicate insulation at a “near-failure” state where the partial discharge arcing as progressed to the point where permanent carbonization, or tracking, as occurred to the insulation system. In this case it is recommended to schedule an outage for traditional insulation resistance testing, and possible installation of permanent partial discharge sensors for improved on-line measurements.

Incremental Testing can help further identify, or clarify possible root causes. The first Incremental Test is the “Temperature Variation Test”. In this test, you start the motor at as close to full load as possible, thereby maintaining the load as constant as possible, during the test. The voltage should also be constant for this test. Record partial discharges as the temperature increases. If the positive polarities increase, then the problem maybe related to slot discharges or end-turn tracking. If the negative polarities increase, then the root cause maybe related to the copper conductor-to-insulation area. The second Incremental Test is the “Load Variation Test”. In this test, you attempt to start lightly loaded and record partial discharges as the load is increased. The voltage and temperature should remain constant, since the increase in load should be completed in a relatively short time period. If the positive polarities increase, then the root cause is most likely loose windings, or end-turn tracking. This is another area where a cost-effective repair is possible, by having the motor removed and re-wedged, or other winding tightening techniques applied. This approach is still much less costly than a complete rewind. Off-line partial discharge testing would involve applying a voltage to the motor and recording partial discharge activity. This testing may not be possible without a variable voltage supply. Lastly, during repeated on-line monthly testing, for cases under investigation, the humidity and temperature should be recorded. If the partial discharge activity substantially varies with humidity, then the cause may be surface tracking.

Table 3 - Motor Partial Discharge Data Interpretation & Corrective Actions

Partial Discharge Results	Possible Root-Cause – PD Site	Short Term Corrective Actions	Long Term Corrective Actions
Moderate to low partial discharge Magnitude and Repetition Rate	<ul style="list-style-type: none"> • Normal Partial Discharge • Beginning of PD activity • Insulation near failure 	<p>At first indication, repeat on-line testing in 3 months.</p> <p>If insulation is old and shows signs of external wear, or any evidence of surface tracking, then schedule outage for traditional insulation resistance testing.</p>	<p>If trending is level, extend on-line testing to 6 months, or as scheduled.</p> <p>If insulation is near failure, traditional testing should indicate low insulation resistance values.</p>
Trending indicates increasing partial discharge activity	<ul style="list-style-type: none"> • Slot / surface tracking PD • Internal insulation voids • Winding loose-ness if indicated by the “Load Variation Test” (Increase in positive polarity pulses with increased loading). 	<p>Repeat on-line testing in 1 to 3 months, depending on the severity of the increase.</p> <p>If the trend increase is substantial, schedule outage and test monthly until outage.</p> <p>Add permanent sensors if required to improve PD testing. During outage, complete Off-line / Incremental Testing and traditional insulation resistance testing.</p>	<p>-If positive polarity, schedule field or shop cleaning and reinsulating with end-turn bracing.</p> <p>-If negative polarity, budget for major rewind and schedule outage.</p> <p>-If winding loose-ness indicated, schedule for removal and shop rewedging.</p>
Positive Polarity pulses prevalent	<ul style="list-style-type: none"> • Voids in the slot between insulation and iron, • Surface tracking at end-turns 	Same as above	Schedule field or shop cleaning and reinsulating with end-turn bracing
Negative Polarity pulses prevalent	<ul style="list-style-type: none"> • Voids at inner copper / insulation interface. 	Same as above	Budget for rewind, and schedule off-line test, in hope of minor problems.
Balance of Positive and Negative Pulses	<ul style="list-style-type: none"> • Voids internal to insulation system 	Same as above	Budget for rewind and major outage.

V. PULSE MEASUREMENT ISSUES

As discussed in the theoretical review, partial discharges are high frequency pulses originating at various sections within an insulation system. These pulses generate a voltage and current signal into the insulation, returning through a ground path. There are three partial discharge measurement methods actively being applied in the field today.

The first involves sensing the pulse voltage signal of the partial discharges. This pulse voltage signal does attenuate rapidly as it is transmitted away from the discharge site. One method is to apply coupling capacitors at the motor terminals directly [10]. Since these sensing units are at the motor terminals, they may not identify partial discharges within the winding depth, which have attenuated to the level of background noise. They would identify discharges at the terminal connections and at the end of the winding where the higher voltage stress is present. These sensors do require an outage for installation; therefore no partial discharge testing can be implemented until the sensors are installed.

Using these types of sensors allows for elimination of noise, and partial discharges external to the motor based on the rise-time of the signal. The assumption is that noise external to the motor will have a slower rise-time, therefore can be eliminated without further consideration; and that motor internal discharges will consist of high frequency, high rise-time signals. One problem with this approach is that brush excitation, or brush sparking can produce high frequency, high rise-time noise inside of the machines, therefore resulting in a false indication of partial discharges. These false indications of internal discharges can be eliminated if properly detected, identified and eliminated from the signal under analysis. Terminal mounted coupling capacitors also may miss the internal discharges that have a slower rise-time due to attenuation within the insulation, since the low rise-time noise elimination technology which accompanies the coupling capacitor approach will eliminate this signal. As with all discharge measurements, trending results with coupling capacitors will identify deteriorating conditions.

Another method of obtaining a level of the partial discharge pulse voltages is to attach special sensors to existing RTD's external wiring connections. The RTD wiring within the motor is exposed to the partial discharge pulse traveling through the insulation. In addition, motor manufactures apply RTD's at locations of greatest thermal stress in the winding. The result is the identification of discharges that are closer to the root cause. Field data has been compiled [8] which

illustrates discharges identified by RTD's sensors, which were not detected by RFCT's (radio frequency current transformers) on the ground circuit of a surge capacitor. In addition to identifying discharges further within a winding, the other major advantage is obtaining discharge data from RTD's can be completed on-line, without an outage as shown in Figure 13. By this method, motors equipped with RTD's can be analyzed now, and a preliminary evaluation completed.



Figure 13 – RTD's Connections for Partial Discharge Detection – On Line

One recommendation may be to install permanent sensors on critical motors, which have evidence of high partial discharges. Any type of permanent sensor will require an outage for installation, but will allow for more accurate on-line partial discharge measurements. As with all partial discharge readings, trending is critical and the use of RTD's also allows for ease of data collection, and minimum investment to start a partial discharge predictive monitoring program.

One issue of obtaining discharge measurements from RTD's is that noise must be properly identified and eliminated. Advanced noise and discharge monitoring techniques, using eight channel data collection units, have resulted in adequate elimination of noise, and have improved detection of partial discharges. This is not possible using traditional coupling capacitors connected at motor terminals.

The other method of measurement is applying RFCT's on the ground circuit of motor surge capacitors, or on the cable shielding grounding conductor. These are generally more sensitive than coupling capacitors, since the capacitors attempt to measure the attenuated voltage

of the discharge signal; whereas the radio-frequency current transformers (RFCT's) have a greater zone of sensitivity to discharges further into the winding depth. Referring back to partial discharges being high-frequency signals necessitates the need for RFCT's, that are designed to have a high-frequency response band. Installation does require both an outage, and if not already installed, the addition of an insulated surge capacitor unit. On motors with an existing surge capacitor unit, a difficulty may arise since the frame of the units may be grounded. The RFCT must be installed on the ground connection between the insulated surge capacitors ground and the earth ground; or as an alternate on the supply cable shielding ground connection. Insulation of an existing surge capacitor base may be necessary; therefore an inspection is required for each motor to determine the best sensor application. The addition of surge capacitor units on large critical motors has much merit in itself, since all plant switching surges, or disturbances shall be shunted via the surge capacitor, and not induced into the motor winding.



Figure 14 –Low Level PD Identification & Noise Detection & Elimination

With available measurements of lower frequency partial discharges, originating closer to the root cause, via RTD's and via RFCT's, the issue of noise and partial discharge identification will be reviewed. With the use of eight channel recorders and advanced software and analysis techniques [11], data processing consists of the following areas.

- 1) Background noise detection. With the additional channels, noise originating from specific sources such as brush sparking can be targeted and eliminated from the signal analysis.
- 2) Elimination of synchronous noise, or noise occurring in a cyclical pattern, every cycle. Examples of sources are thyristor-firing circuits.

- 3) PD identification through attenuation analysis. Since PD sensors detect pulses originating close to it as well as pulses coming from different locations, this attenuation can be observed, thereby rejecting cross-coupled pulses, and recording only signals originating from a particular sensor. This further eliminates false PD activity measurement, and allows for improved identification of PD activity.
- 4) Pulses width validation. Pulses with a width considered to be noise, and not high frequency partial discharges, can be quickly identified and eliminated.
- 5) Experience and the effective use of eight channels of input data, as shown in Figure 14, allow for comparisons to external signals to further improve the PD data collection process.

VI. APPLICATIONS TO OTHER ELECTRICAL SYSTEMS

Partial discharge testing as been used primarily for predictive maintenance of medium voltage motors. Obtaining measurements on other electrical systems such as switchgear units as identified severely deteriorated insulation, approaching eventual failure. A post-failure root cause analysis of a failed transformer bushing showed evidence of partial discharges occurring internal to the bushing porcelain. If partial discharges were monitored these could have been found, and corrective actions may have prevented a complete bushing failure. The following Figure 15 illustrates insulation deterioration found, resulting from on-line measurements of partial discharge activity within energized 15KV switchgear cubicles. An outage was scheduled and an internal inspection performed. Severe insulation deterioration was found at the junction between the two cubicles which had high partial discharge activity.

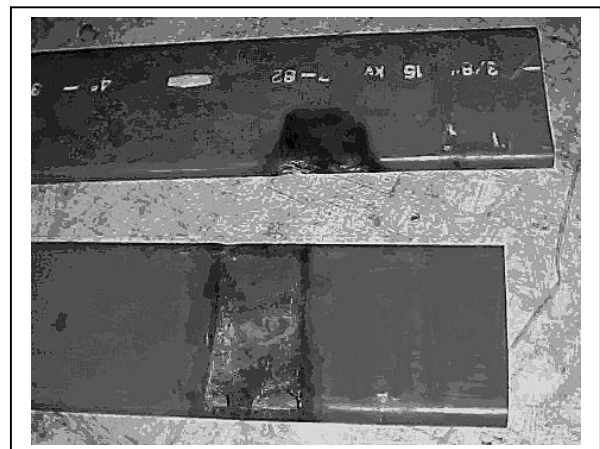


Figure 15 - Bus Insulation Deterioration found by partial discharge measurements

Figure 16 indicates a side view of a failed transformer bushing, which resulted in substantial equipment and environmental damage, with considerable downtime.

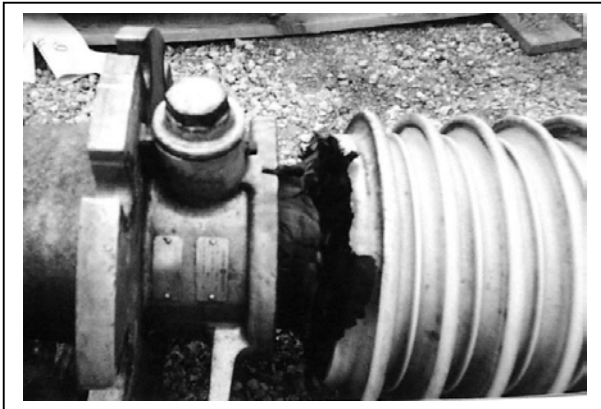


Figure 16 – Failed porcelain bushing, with sections removed for evaluation

Figure 17 illustrates the internal examination of the above failed transformer bushing porcelain. Evidence exists of carbonization and partial discharge activity, which if identified could have prevented a complete bushing failure.



Figure 17 – Evidence of internal partial discharges occurring within the failed transformer porcelain bushing

VII. RELIABILITY CENTERED MAINTENANCE AND PARTIAL DISCHARGE PREDICTIVE DIAGNOSTICS

Most manufacturing plants are being forced to operate at greater efficiencies at lower costs [12] and [1]. A new process called “Reliability Centered Maintenance” involves the review of plant processes and supporting

power distribution equipment. A RCM study can be completed for the electrical distribution system within a plant, thereby providing the following benefits:

- 1) Identification of critical electrical equipment and recommended predictive and preventive maintenance on each device. A RCM study will identify which equipment warrants the installation of on-line sensors and other technologically advanced predictive maintenance tools. A cornerstone of RCM is on-line predictive measurements.

The partial discharge discussion concerning motors, within this paper, ideally satisfies these requirements. In addition, continuous predictive maintenance methods of measuring the change in transformer bushing capacitance and power factor on-line are also available, with periodic partial discharge testing being completed without an outage. In addition to motor and generator insulation systems, switchgear, circuit breakers, bus duct, medium voltage cable systems and instrument transformers can be adapted for on-line partial discharge measurements. A recent partial discharge test of switchgear shown in Figure 15 identified high levels between two specific cubicle. A scheduled outage and internal switchgear inspection identified badly deteriorated bus insulation at the interface to the bus supports between cubicles. The small air-gap between the bus insulation and these through-cubicle bus supports creates an effective void for partial discharges to develop.

- 2) Identification of specific preventive maintenance functions to be completed on a periodic basis, and more specifically during unplanned outages. This allows for effective maintenance, on critical equipment, to be completed rather than randomly selecting equipment to be maintained. During an unplanned outage, the RCM study would direct which equipment should be serviced and a specific workscope. Part of the implementation of the RCM study would be on-site training of plant personnel to ensure they can properly complete all maintenance tasks in a safe and effective manner.
- 3) Identification of auxiliary spare equipment such as feeder, or main circuit breakers, which should be on-hand, related to the critical nature of the equipment, rather than past practices of purchasing only less costly spares.
- 4) Identification of equipment which would be maintained at a minimum level, thereby redirecting these maintenance dollars to more critical equipment.

VIII. SUMMARY

Partial discharge monitoring is an effective on-line predictive maintenance test for motors and generators at 4160 volt and above, as well as other electrical distribution equipment. Partial discharges in 2300 volt equipment can also be observed depending on the equipment design, level of partial discharge activity and sensor placement. The benefits of on-line testing allow for equipment analysis and diagnostics during normal production. Corrective actions can be planned and implemented, resulting in reduced unscheduled downtime.

Understanding of partial discharge theory allows for improved interpretation of results, and the benefits of such measurements. Data interpretation and corrective actions can be clearly identified with cost effective field corrections implemented, prior to further equipment deterioration. Advanced noise analysis techniques and new diagnostic measurement methods using existing RTD's rather than permanently installed sensors, allow for the implementation of a partial discharge predictive maintenance program with a small initial investment. Partial discharge monitoring technology fully satisfies the cornerstone of a maintenance program designed to address the critical process support equipment, which can be identified by a Reliability Centered Maintenance study.

The technology as advanced, with improvements resulting in a minimal initial investment, thereby allowing for partial discharge testing to become a part of everyday predictive maintenance.

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