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Partial Discharge Theory, Modeling and Applications To Electrical Machines

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Abstract: Partial discharge monitoring is an effective on-line predictive maintenance test for motors and generators, 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. 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. Then insulation modeling and partial discharge modeling in electrical machines will be introduced. At last traditional partial discharge test methods in electric machines will compare to new method of partial discharge monitoring and corrective actions will interpret.

Key Words: PD, Modeling, Online Detection, Electrical Machines

1 Introduction

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. Detailed motor failure analysis has been completed; resulting in the identification of approximately 30% of failure causes being related to electrical failures [1]. The IEEE publication, "IEEE P1434 - Guide to Measurement of Partial Discharges in Rotating Machinery" [2] 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. Then in third section partial discharge testing related to traditional testing methods will be introduced. After that corrective actions for MV motors is presented and in last section conclusions are said.

2 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 [3]. In an effort to promote a better understanding of partial discharge (PD), this paper attempts to provide simplified models and relates 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, and 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 Fig.1.

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 Fig.2.

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

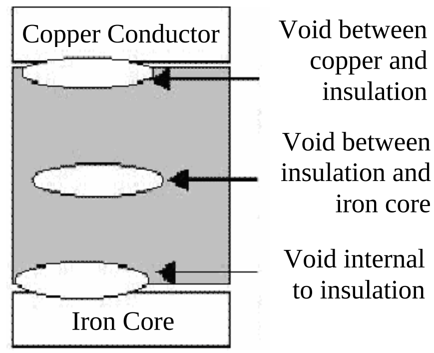


Fig.1 PD within Insulation System

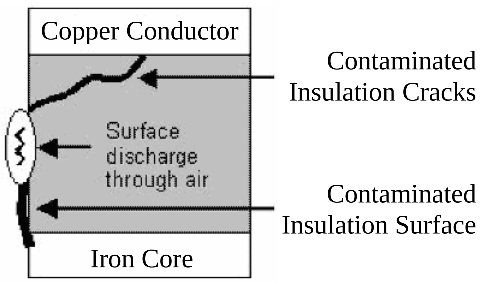


Fig.2 Surface Partial Discharge

2.1 Insulation System Model

A simplified model of an insulation system can be represented by a capacitance and resistance in parallel [4]. 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].
The above model is also used for attenuator circuits in electronics [6]. 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 that 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.

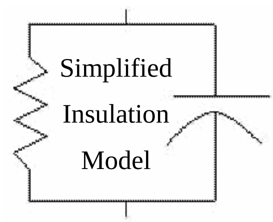


Fig.3 Simplified Insulation Model and Model for an Electronic Attenuator

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

2.2 Partial Discharge Void Model

Simplified models of the area of the void have been described as consisting of capacitors only. A review of the progressive failure mode of these voids indicates an additional resistive component in parallel with the capacitive component. Therefore the model of the partial discharge void is similar to that of the insulation medium itself.

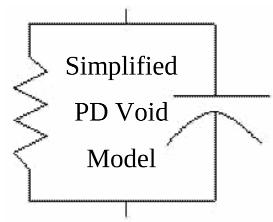


Fig.4 Simplified Partial Discharge Void Model

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 [4]: "Tracking damage has been traced entirely to the locally intense heat caused by leakage currents. These currents flow through 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. Fig.5 illustrates the failure mode of deteriorated insulation related to the intensity of partial discharge measurements.

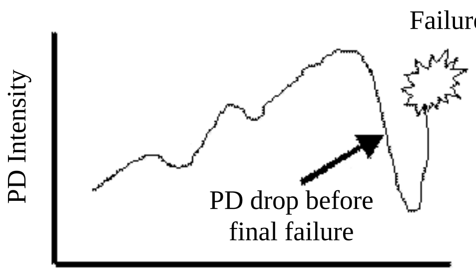


Fig.5 PD Versus Insulation Failure Mode

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.

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

Fig.6 is be used to provide an understanding of partial discharge activity.

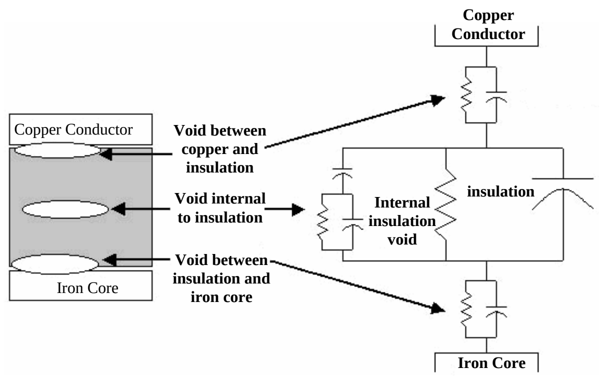


Fig.6 Insulation System Partial Discharge Model

3 Partial Discharge Testing Related To Traditional Testing Methods

Table 1 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, forth 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.

For "Near-Failure" conditions, partial discharge arcing may have progressed to the point where permanent damage, or tracking, has occurred; therefore the level of partial discharges has decreased. This is also illustrated in Fig.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.

4 Data Interpretation And Corrective Actions Of MV Motors

Table 2 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 has progressed to the point where permanent carbonization, or tracking, has 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.

5 Conclusions

Partial discharge monitoring is an effective on-line predictive maintenance test for motors and generators, 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.

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. Partial discharge monitoring technology fully satisfies the cornerstone of a maintenance program designed to address the critical process support equipment.

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

References:

[1] G. Paoletti, A. Rose, "Improving Existing Motor Protection for Medium Voltage Motors," *IEEE Transactions on Industry Application*, May/June, 1989.

[2] IEEE standard 1434-2000, IEEE Trial Use Guide to the Measurement of PD in Rotating Machinary, , New-york, Aug. 16th 2000.

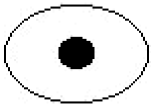
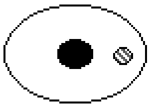
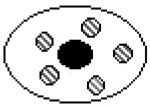
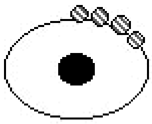
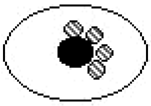
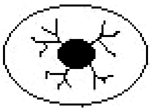
[3] R. Bartnikas, "Partial Discharges, Their Mechanism, Detection and Measurement", *IEEE Trans. On Dielectrics and Electrical Insulation*, Oct. 2002.

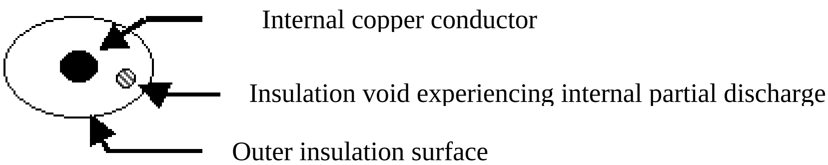
[4] D. Fink, H. W. Beaty, *Standard Handbook for Electrical Engineers*, Pages 4-117, 118, *McGraw-Hill Book Company*, 1987.

[5] Westinghouse Electrical Maintenance Hints, Pages 19-14 and 15, and Page 7-23, *Westinghouse Electric Corporation Printing Division*, Trafford, Pa, 1976.

[6] J. Millman, H. Taub, Pulse, Digital and Switching Waveforms, *McGraw-Hill Book Company*, 1965.

Table 1 – Partial Discharge Testing related to Traditional Testing Methods

Initial Model	Insulation Condition	Megger Test	Polarization Index Test	High-potential 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 discharge
	**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. Maybe required to limited test voltage.	High positive polarity discharges indicate probable surface tracking
	**Unacceptable** Major Repair or Rewind Requested	Low	Poor	Potential failure during testing	High negative polarity discharges indicate internal voids near the copper conductor.
	**Near-Failure condition** PD arcing has caused carbon tracking	Very low	Very low	High leakage current and probable failure during testing	Minimal partial discharge activity. Partial discharge arcing has progressed to the point where permanent damage (tracking) had occurred.



Insulation Model Description

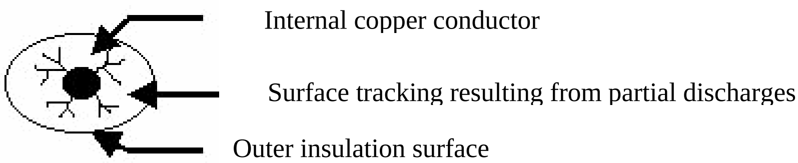


Table 2 – Motor Partial Discharge Data Interpretation & Corrective Actions

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	▪ Normal Partial Discharge ▪ Beginning of PD activity ▪ Insulation near failure	At first indication repeat on-line testing in 3 months If insulation is old and show signs of external wear, or any evidence of surface tracking, then scheduled outage for traditional insulation resistance testing.	If trending is level, extend on-line testing to 6 months, or as scheduled. If insulation is near failure, traditional testing should indicate low insulation resistance values.
Trending indicated increasing partial discharge activity	▪ Slot/Surface tracking PD ▪ Internal insulation voids ▪ Winding looseness if indicates by the "Load Variation Test" (Increase in positive polarity pulses with increased loading)	Repeat on-line testing in 1 to 3 months, depending on the severity of the increase. If the trend increase is substantial, schedule outage and test monthly until outage. Add permanent sensors if required to improve PD testing. During outage complete off-line/ Incremental testing and traditional resistance testing.	If positive polarity, schedule field or shop cleaning and reinsulating with end-turn bracing. If negative polarity, budget for major rewind and schedule outage. If winding loose-ness indicated, schedule for removal and shop rewedging.
Positive Polarity pulses prevalent	Voids in the slot between insulation and iron	Same as above	Schedule field or shop cleaning and reinsulating with end-turn bracing
Balance of Positive and Negative pulses	Voids internal to insulation system	Same as above	Budget for rewind and major outage