Evaluation of Capacitance in Motor Circuit Analysis Findings

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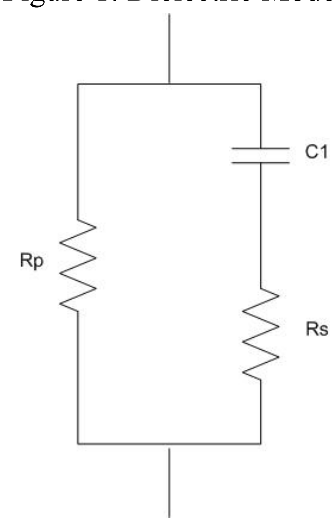
Introduction

The question related to the ability of low voltage testing to detect winding contamination, insulation degradation and winding faults relies upon the changes to the insulation system. These changes directly result in modifications to the dielectric in terms of capacitance and conductivity. The description for the changes, based upon certain conditions, will be explained in this paper.

Insulation System Model

The standard insulation system model for electrical insulation can be found in Figure 1. This describes the dielectric capacitance in series and parallel with conductivity.

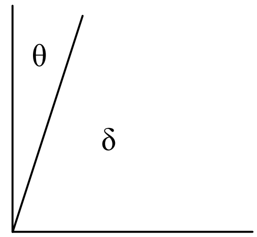
Figure 1: Dielectric Model



The Capacitance of a dielectric material is $C = \varepsilon' \varepsilon_0 A/t$ where ε' is the relative permeability of the material, ε_0 is the dielectric constant equal to 8.84 x 10^{-12} farads per meter, A is the area in square meters and t is the thickness of the dielectric in meters. A perfect dielectric capacitor has a current that leads voltage by 90^o.

However, as noted in Figure 1, there is some level of conductance, and resulting current flow through the dielectric resulting in a variance from 90^o with a loss angle of θ such that the loss angle would be 90^o- θ = δ and the dissipation factor would be Tan δ. The AC power loss directly in the dielectric (heat) is $V^2 2\pi fC\mathrm{Tan}\delta$ watts (Where V = the applied voltage-potential across the dielectric).

Figure 2: Dissipation Factor (Fi)



As Rp in Figure 1 approaches infinity, then Tan $\delta = 2\pi fCRs$, as Rs approaches 0, then Tan $\delta = (2\pi fCRp)^{-1}$.

There is also a force of attraction of dielectrics within an electric field such that $\frac{1}{2}\varepsilon'\varepsilon_0 E^2 x10^2 N/cm^2$ where E is the electric field in voltage per cm. Dielectric material has a tendency to move to a location with a high electric field. If two or more dielectrics are present, the one with the higher permittivity will displace the one with lower permittivity. For instance, air bubbles in a liquid are repelled from high field regions. [Note: A material's Dielectric Constant is equal to its Dielectric Permittivity.]

Elongated dielectric bodies (molecules) are rotated into the direction of the electric field and all materials will have a tendency to 'expand' in electric field and magnetic fields, such as moisture.

The resistance of the dielectric is rated as $R = pt/A$ Ohms where t = the thickness in cm, A is the area in cm^2 and p is the dielectric resistivity in ohm-cm. Dielectric materials in parallel must be considered as parallel resistors and the resistance is both time and frequency dependant.

Electric Motor Insulation Considerations

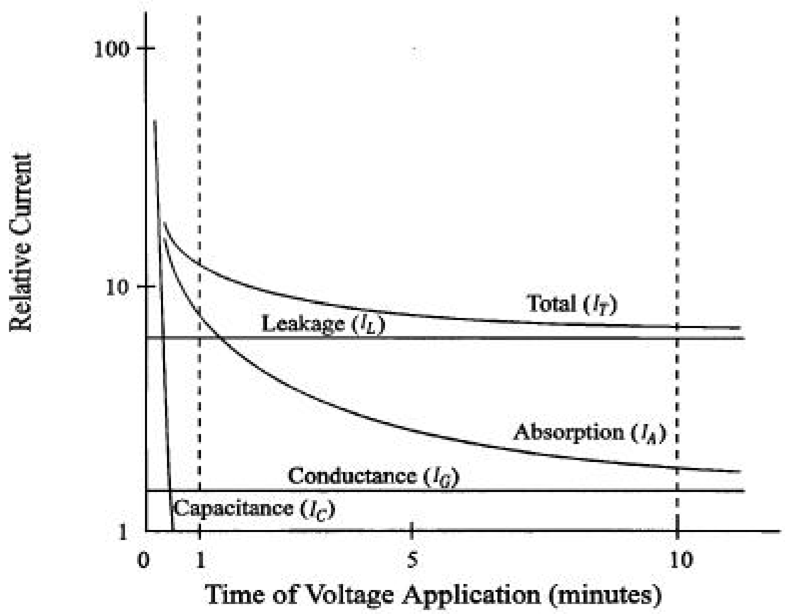
IEEE Standard 43-2000 (R2006) defines a number of currents that exist within the dielectric insulation system as follow[1]:

- **Absorption (Polarization) Current (I_A):** A current resulting from molecular polarizing and electron drift, which decays with time of voltage application at a decreasing rate from a comparatively high initial value to nearly zero, and depends on the type and condition of the bonding material used in the insulation system;

[1] IEEE Standard 43-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, IEEE, New York, 2006

- **Conduction Current (I_G):** A current that is constant in time, that passes through the bulk insulation from the ground surface to the high-voltage conductor, and that depends on the type of bonding material used in the insulation system;
- **Insulation Resistance (IR_t):** The capability of the electrical insulation of a winding to resist direct current. The quotient of applied direct voltage of negative polarity divided by current across machine insulation, corrected to 40^oC, and taken at a specific time (t) from start of voltage application. The voltage application time is usually 1 minute or 10 minutes, however, other values can be used.
- **Geometric Capacitive Current (I_C):** A reversible current of comparatively high magnitude and short duration, which decays exponentially with time of voltage application, and which depends on the internal resistance of the measuring instrument and the geometric capacitance of the windings.
- **Surface Leakage Current (I_L):** A current that is constant with time, and which usually exists over the surface of the end-turns of the stator winding or between exposed conductors and the rotor body in insulated rotor windings. The magnitude of the surface leakage current is dependent upon temperature and the amount of conductive material, ie, moisture or contamination on the surface of the insulation.

Figure 3: Dielectric Currents Over Time (Applied DC)



If the windings are contaminated or wet, the I_T will be constant over time since I_L and I_G will be much larger than I_A. If the windings are clean and dry, the I_T will normally decrease with time since the I_T is dominated by the I_A.

In Annex B of the IEEE Std 43, the discussion of DC versus AC voltage for testing the condition of the insulation system is presented such that R = pL/A (where R is resistance, p is the resistivity of the material, L is length of the path and A is the cross-sectional area). Because the resistivity values of the dirt, oil, and water that often contaminate the insulation system are quite low, DC testing of a contaminated winding normally results in a high surface leakage making it effective for contamination detection.

When a high AC voltage is connected between the terminals, the capacitance of the insulation system dominates the current. This capacitance is determined as C = εA/d where C is the capacitance, ε is the dielectric permittivity of the material, A is the cross section and d is the thickness of the material. Since the permittivity of the insulation system is greatly affected by the presence of voids and/or water, an AC voltage test is more sensitive than DC.

Finally, in applied AC, $i_t = C\frac{dv(t)}{dt}$, where i_t is the current response, $\frac{dv(t)}{dt}$ is variation in voltage and C is the capacitance of the dielectric material.

The level of conduction current is an indication of the ionic concentration and 'mobility' of the dielectric. The mobility, expressed in cm/sec-volt/cm is very low for hard resins but increases with the temperature and softness of materials. The conductivity of ions is $\sigma = \mu e c \Omega^{-1}\mathrm{cm}^{-1}$ where μ is the ion mobility, e is the ionic charge in coulombs, c is the ionic concentration per cm^2. The ionic conductivity increases with the applied temperature exponentially such that $\sigma = \sigma_0 e^{-B/T}$ where σ_0 and B are constants and T is the Kelvin temperature.

Variations with Temperature and Frequency

The permittivity tends to decrease with increasing frequency. This is due to the inability of polarizing charges to move with sufficient speed to follow an increasing rate of alterations in the electric field. This can result in a sharp decline in permittivity known as the dispersion region in a dielectric.

A maximum at a frequency corresponding to the dispersion region is associated with a molecular dipolar rotation and occurs when the rotational mobility is such that the molecular rotation can just keep up with the frequency of the applied field. By and large, both soft and hard polymers that make up modern electrical insulation systems tend to occur at lower frequencies (within the range of modern Motor Circuit Analysis –MCA- instruments).

With dielectric polymers the dissipation factor is likely to occur, at power frequencies, at a temperature close to the softening point, or internal second-order transition point, temperature. Reactive conditions at the point of failure in a dielectric insulation system due to dielectric heating will contribute to localized conditions. Regardless of size of the region, it will affect the entire dielectric and the resulting Tan δ.

Effects Of Insulation Systems at Low Voltages and High Frequencies

The use of a combination of lower alternating voltages applied at higher frequencies provides an excellent balance to detect Capacitive and Permittivity issues by ensuring that those values are more significant in the insulation system. By maintaining the applied AC voltage at values under 10Vac such considerations as the AC power loss and the dielectric force of attraction are negligible with a low enough electric field such that Capacitance dominates over Current.

By using the higher applied frequencies, coupled with the low voltage, AC power loss remains negligible, the i_t remains low, allowing for the detection of permittivity issues and, the frequency is balanced such that mobile dielectrics (insulation systems) react more than contaminants. With the dispersion rate of electrical insulation, as well as the mobility changes, falling outside the range of low voltage, higher frequency instrumentation, the dielectric constant remains steady with good polymers. However, contaminants, including moisture, have a different mobility and the dispersion rate is well within the test range as water and water vapor have dramatically different dielectric constants across a relatively short temperature and frequency range.

As such, the use of very low AC voltage coupled with higher than power frequencies, the ability to detect problems within insulation systems is limited to the insulation system capacitance and permittivity.

Additional Discussion on Aging and Effects in Dielectrics

“The trend of increasing insulation resistance with time ... It is believed that this trend is the result of the continuous polymerization of the epoxy in the insulation system during aging. This phenomena has been observed by other workers and treated by Olyphant in a detailed discussion.

“In brief, the DC conductivity in the polymer insulation is a function of the number and mobility of ionic species (as opposed to electrons which are the predominant contribution to the electric current in metals). Before aging has occurred these charge carriers are relatively small and can therefore travel easily through the material.

“As aging occurs in the epoxy insulation, polymerization of the charge carriers occurs which increases their size. Crosslinking between the polymer chains proceeds which further restricts the movement of the charge carriers. Both of these phenomena contribute to the reduction in the flow of charge carriers in the DC current throughout the material."[2]

"When cracks do appear in the slot insulation, discharges to ground will occur more easily and the intense localized heat generated by the discharges will eventually carbonize the epoxy and form a conductive path to ground."[3]

"The dissipation factor… shows a decreasing trend with reversals which is consistent with the increasing trend in DC resistance discussed above. The dissipation factor (Tan δ) can be expressed as the ratio of the energy dissipated to the energy stored…

"As the epoxy in the slot wedge ages, the same charged species that are responsible for the DC current can also contribute to the flow of AC current. Similarly, the AC current will decrease as polymerization and crosslinking progress. This will cause Tan δ to decrease as observed in the figure. The decrease in Tan δ is a potential method for monitoring the aging occurring in the insulation depending on the materials used in the motor.

"The decrease in capacitance is relatively small but consistent with the trends in the DC resistance and dissipation factor."[4]

Modeling the Capacitance for Different Faults

For the purposes of the model, it was determined that the motor and conditions considered were as shown in Attachment 1. In considering the model, it was determined that the Capacitance would be calculated for different conditions and that there would be a number of assumptions for demonstration purposes only:

- No permittivity in Dielectric Model
- Capacitance to ground not included
- Capacitance and Capacitive Coupling not included
- Inductance would be calculated for each coil assuming an silicone steel core

Equation 1: Parallel Capacitors

$$C = \varepsilon_0 \left(\frac{\varepsilon_1' A_1}{t_1} + \frac{\varepsilon_2' A_2}{t_2} \right)$$

[2] Sugarman and Sheets, "The Accelerated Aging of a Small Electric Motor," 1987 International Coil Winding Association, Inc. and IEEE Electrical Insulation Conference, EIC/EMCWA, 1987

[3] Sugarman and Sheets

[4] Sugarman and Sheets

The Capacitive Formula utilized through the model can be found as Equation 1. The assumption is that the turns would be evaluated as individual turn-pairs and then brought together in parallel. The following conditions were evaluated:

1. In a good winding, the parallel dielectric constants were for the enamel and resin. The turn-pairs were evaluated and modeled, then each coil, then group and then phase. The result was a series phase-to-phase circuit capacitance of 2.13×10^{-11} Farads or 2.13 pico-Farads.
2. A shorted winding with a fault area of 1mm between two turns mid-way in a single coil was evaluated. The good, bad, good, bad, good portions of the coil were evaluated as a series capacitance. As determined in the reference materials for this study, the lowest capacitive component in the system will affect the entire dielectric circuit and the value would be significantly lower than the good winding. In the model, it was determined that the carbonization value (tracking) dielectric would be similar to that used for carbon black. However, as the model leaves out conductance and resistivity, the end impedance (based only on capacitance) showed a very high value as determined by Sugarman and Sheets. The phase-to-phase result was 4.57×10^{-14} Farads or 0.00457 pico-Farads.
3. One group of three coil-ends was determined to be saturated with water at 25^{o}C. The result was a total phase-to-phase Capacitance of 1.95×10^{-11} Farads or 1.95 pico-Farads. The results were what was expected for pure water. With a dielectric constant of 1.0059, the value changed to 1.13 pico-Farads. With the change in conductivity with temperature and additional contaminants, the dielectric value used to calculate the actual circuit impedance would decrease, as opposed to increase in the Capacitance model used.

Because of the complexity of the model, and the availability of data for some of the materials considered, the conductivity was not included. Therefore, for number 2, while the capacitance increased, which would increase the AC power loss at the fault point significantly (reactive loss), the conductivity would be very low and would approach zero as the temperature of the fault increased. This would generate a shorted condition and a change in the Tan δ as the fault started and progressed.

Conclusion

The effect of low voltage and higher frequencies on the evaluation of electric motor dielectric insulation systems can be demonstrated and explained mathematically. For the purposes of this paper, an Excel® workbook was used to model the change to the capacitance of a circuit as it failed. These failures included a small winding short, of which changes to ten times and one-tenth the value of the size of the fault had only a very small impact on the results, and water contamination of the end turns of one group of coils. The model results demonstrated that the low voltage and higher frequencies do have an ability to detect specific conditions.

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About the Author

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