Evaluating Reliability of Insulation Systems for Electric Machines

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***Abstract*— In the design of electric machines for a variety of applications such as hybrid electric vehicles, severe and regular duty applications, it is important to determine the reliability of the machine. The insulation system, in particular, is subject to multi-factor stresses including electrical, thermal and mechanical that impact the reliability of the machine. In this paper we will present a model for the analysis of multi-factor aging an insulation system developed to estimate the reliability of machine insulation systems in the design phase.**

Keywords—insulation system; electric machine life; multi-factor aging; hybrid vehicle

I. INTRODUCTION

The concept of insulation life prediction is the Holy Grail of electric motor design and reliability analysis of machines. The variety of stresses that are seen by the electric machine over its life, including transients and minor, but acceptable, defects in materials create a significant level of complexity. However, both the potential life expectancy and the estimated life in application for a population of machines can be evaluated with an accuracy that depends on the design data provided. The question should not be related to the length of time the insulation system will survive, but, instead, related to what percentage of machines with the insulation system will survive to a specific point in time.

Once a target time and survival rate is determined, then materials selection, testing and investigation can be accomplished much more effectively. As part of the survival rate, the investigator must define the operating environment from power supply to potential contamination and maintenance expectations to operating profile. The operating context should be related to the extreme operating conditions for the machine and for defining the laboratory and field testing used to confirm the reliability of the materials.

For this paper we will define an experimental machine operating in a mobile environment powered by an inverter and cooling oil injected directly onto the windings. The vehicle is expected to exceed 100,000 km at an average speed of 60 km, or a potential of 1,665 hours, and 10 years at an L10 life expectancy. The operating context includes PWM inverter supply, direct oil-cooling on the windings, acids and contaminants present in aging oil, surges in operation, varying speed, high vibration, and thermal shock.

The capability of the machine insulation system operating reliably over these considerations include: understanding the potential thermal age; combined thermal/electrical stresses; impact on life due to thermal shock; impact of vibration; and, impact of maintenance frequency related to oil changes. The primary fluid used in mobile equipment motor applications is transmission fluid.

II. ENDURANCE

The first consideration is the insulation system's ability to endure thermal and electrical stresses. A review of Brancato [1] identifies that thermal and hot spot temperatures can be evaluated and extrapolated from experimental evidence. The life of an insulation system at elevated temperatures would be related as in (1) with L as life in units of time, β an experimental constant, φ is the activation energy in eV, T is the absolute temperature in Kelvin, and k is the Boltzmann Constant (0.8617×10^{-4} eV/K).

$$L = \beta \exp\left[\frac{\varphi}{kT}\right] \qquad (1)$$

This approach assumes that the primary cause of insulation end-of-life would be thermal in nature. However, in operating electric machines electrical stresses must also be applied. As endurance decreases with applied thermal and electrical stresses, they must be combined in such a way that an electro-thermo model is developed. This is followed by the application of mechanical conditions, resulting in an electro-thermo-mechanical model, such as that derived by Nelson, Azizi-Ghannad, and Li.[2]

Prior to the mid-1970s, insulation systems were relatively simple and a combination of Brancato's work and mathematical modeling methods proposed by Whitman and Doigan [3] in 1954, Whitman and Whitman [4] in 1959, and Manning [5] in 1960, were plausible. With the advent of modern insulation systems, both present and proposed, the question becomes more complex even before the consideration of modern controls and inverters, in addition to the applications.

The question of endurance in modern insulation systems and applications is considered one of multifactor stress [6] and analysis. Attempts at developing a singular model to evaluate data of combined systems, including similar materials between manufacturers, have been ineffective, to date. It instead relies upon the proper design of experiment to evaluate the system and to determine the potential endurance of the system in the environment it is being developed for. This approach allows us to rely upon past works and to apply models such as those developed by Simoni.[7]

$$cT = \frac{1}{K_R} - \frac{1}{K_E} \qquad (2)$$

The conventional thermal stress, cT, is related to the absolute temperature being evaluated in Kelvin (K_E) and absolute room temperature in Kelvin (K_R), usually expressed as 298 K.

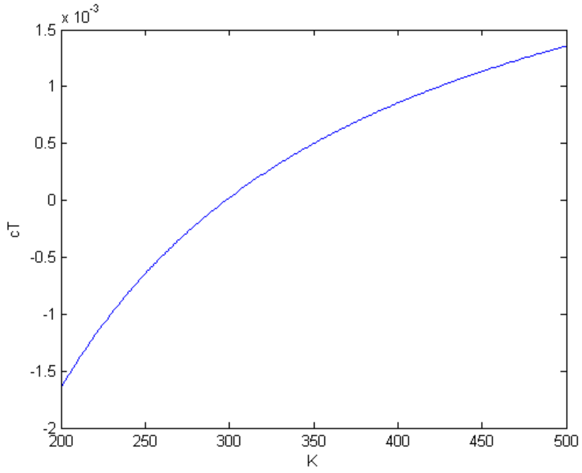

Figure 1: cT vs K

$$L = T_{log} * 0.5^{\frac{T_1 - T}{B}} \qquad (3)$$

The base thermal life of the insulation system (L) at temperature (3) is based upon the log average life from thermal endurance testing in hours (T_{log}), the temperature of interest (T_1), the temperature of the thermal life study (T), and the slope of the corresponding Arrhenius curve (B) resulting from the study.

$$L_0 = T_{log} * 0.5^{\frac{25-T}{B}} \qquad (4)$$

The base thermal life at room temperature (L_0), which should approach infinite (4) and (3) are applied in the voltage stress formula in order to look at thermo-electro stresses, as defined by Simoni.

$$L_{S0} = L_0 * \exp(-B * cT) * \left(\frac{E_0}{E_I}\right)^{-\left(\frac{\log(E_I)}{\log(E_2)} - 1 * cT\right)} \qquad (5)$$

L_{S0} is the adjusted base life, in hours, of the insulation system with electrical stress at room temperature. It incorporates the additional stress based upon the initial electrical endurance of the winding insulation system (E_2), the voltage applied during the study (E_I), and the voltage applied to the winding (E_0).

$$L_{TE} = L * \exp(-B * cT) * \left(\frac{E_0}{E_I}\right)^{-\left(\frac{\log(E_I)}{\log(E_2)} - 1 * cT\right)} \qquad (6)$$

L_{TE} is the thermo-electro stress life at temperature. In the case of hybrid vehicle application, the temperature will vary during operation and must be taken in context.

III. IMPACT OF THERMAL SHOCK

With the application under review including significant exposure to thermal variations, depending on the local climate and vehicular storage, dramatic changes in temperature can occur. Rothe and Hameyer [8] identify the dynamic temperature and driving cycle issues for traction vehicles and the potential for error. It becomes very important to identify the most severe application that should be considered with the understanding that some applications will exceed this value. Due to the type of application, the nominal value should not be used. The 'thermal shock' value for the insulation system must also be defined. Thermal shock is defined as the low temperature at which a rapid increase towards operating temperature will cause a degradation in the insulation system.

$$L_{TS} = \frac{T_{TI} - T_{SH}}{T_{TI}} * L_{TE} \qquad (7)$$

The L_{TS} is the expected life of the system based upon the amount of time in the range of the thermal shock value (T_{SH}), usually within 10°C, and T_{TI} is the log average life from severe thermal shock testing.

Thermal shock starts are expected to have a significant impact on overall insulation life, should the vehicle expect to operate in an environment where this can be an issue. It must also be understood that vehicle applications are not the limit, and that thermal shock applications exist elsewhere including such applications as wind energy.

IV. IMPACT OF VIBRATION

This testing is performed in a similar manner to thermal shock testing. Severe vibration is determined as the maximum shock, instant or continuous, that the system should see during operation. The level and type of vibration required must be determined based upon the type of application seen by the vehicle. This impact is of similar value in a variety of other applications.

$$L_{TV} = \frac{T_{VI} - T_{VS}}{T_{VI}} * L_{TS} \qquad (8)$$

The L_{TV} is the expected life of the system based upon the amount of time in the range of the severe vibration value (T_{VS}) and T_{VI} is the log average life from severe vibration testing.

Severe vibration incidents are expected to have a significant impact on overall insulation life, should the vehicle expect to operate in an environment where this can be an issue. It must also be understood that vehicle applications are not the limit, and that severe vibration applications exist elsewhere.

V. IMPACT OF CONTAMINATION

Depending on the application, this can have a significant impact, as well. For application-specific machines, it is simpler to identify the potential contaminants. When this is not possible, saline spray may be used to identify a severe contaminant. In the case of this paper, however, we need to consider the cooling medium which is a transmission fluid.

A common error in setting up oil-cooled, or special media-cooled, machines is the use of new oils through the testing process. During testing the coils are immersed in the fluid under specified conditions. Clean oils may have the effect of improving insulation life, such as with the elimination of partial discharge with inverters or effectiveness as a cooling medium. However, during the life of a machine in application oils will break down for any number of reasons, including age, regardless of the type of mineral or synthetic oil. Significant products from the aging of oil include a series of acids and settled materials, including metals from the application. Testing should be done with both clean and aged oils with the aged oils coming from similar applications.

$$L_{CO} = \frac{T_{CI} - T_{CS}}{T_{CI}} * L_{TV} \qquad (9)$$

The final life calculation for the scope of this paper results in the L_{CO}, or life impact from contamination. The contamination life in hours from experiment (T_{CI}) is based upon the immersion time in aged oil, known contaminant or saline. The time exposed (T_{CS}) is determined based upon the contaminant threshold from experiment.

VI. APPLICATION OF MODEL

Upon first glance there appears to be a few things left out, such as a model based upon the application of the inverter and other conditions. These conditions were included. However, they need to be considered in the design of experiment.

When designing the laboratory tests, several things must be considered:

1. The type of control and output must be utilized in all energized testing of the machine. This means that if a specific controller will be used, then it must be used in the laboratory testing;
2. All laboratory testing must be performed as close to real conditions as possible for each condition being examined;
3. When unusual conditions are found, they must be investigated;
4. Pre-laboratory work must be performed to determine and define the conditions to be met based upon the application; and,
5. In the case of a model such as a hybrid vehicle machine, operating temperature rise will vary as will other conditions and must be considered in the final model. The use of modeling software that can handle significant amount of data is usually required.

An area that required a fair amount of investigative work was related to unusual failure patterns. For instance, if the motorette or statorettes fail prematurely, the cause must be investigated. In the case of one study utilizing this model, it was discovered that different manufacturers do not use the same binders or fillers in their insulating materials. Ground wall insulation material was rate at a specific temperature, yet components of that insulation material were rated well under the thermal rating of the material.

This issue also brought up another condition that had to be considered. With the manufacture of some materials accelerated thermal and other testing may result in a very rapid failure which would not equate to the operating conditions of the machine. At the same time, such conditions are an indicator of limitations of the material that must be considered as part of the material selection.

Another benefit to the exercise of applying the model and laboratory experiments has been the ability to identify production and process issues before mass production. For instance, problems with materials, vendors, production equipment, training of personnel, and other issues.

To date, this model has been used to determine the L20 life of the insulation system, or the point where 20% of the insulation systems have failed within a specified period of time.

VII. CONCLUSION

When reviewing the insulation endurance of a machine in order to estimate the potential life, it is important to define limitations, application and experiments up front. This includes defining the expected machine survival level for a specific period of time and conditions. If the model then provides a point longer than the expectations, then it is successful. If it falls below that time, then the materials or application must be investigated.

Models become less complex when conditions approaching practical application are utilized. When designing the experiments it is vital that near practical conditions are selected and that each type of component failure is broken out into separate studies. This allows both the ability to determine the application suitability of the selected materials, but also to allow investigators to pinpoint potential defects or application issues prior to manufacturing a final product.

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