Thermal Evaluation of High Voltage Hermetic Motors Experiencing Recurrent Insulation Failures

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Abstract

A high voltage hermetic compressor motor design developed for chiller applications has shown recurrent insulation failures in certain stator end-turn regions. Initial investigations found discoloration of failed coil insulation and suggested that the stator coils over heated during operation at rated load. Thermal modeling was conducted to develop an understanding of the causes of the unacceptably high motor failure rate so that corrective actions could be taken for future motor designs.

This paper presents thermal modeling efforts for predicting steady-state temperature distributions within the stator coil in the end-turn region under full-load electrical heating and a refrigerant cooling environment. Insulation thermal conductivity and coil surface convection heat transfer coefficient were identified as two critical heat transfer parameters which dictate the effectiveness of coil heat dissipation. Thermal analysis results have been correlated with measured temperature dependent insulation thermal conductivities and stator coil surface temperatures measured in motor cooling tests. The results of thermal evaluation indicate that the premature motor failures are likely caused by excessive conductor heating due to high operating current density in a non-uniform coolant distribution.

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I. INTRODUCTION

An abnormal number of insulation failures have been experienced on a high voltage hermetic motor design developed for chiller applications. Evidence of coil overheating had been found on both lead end and non-lead end coils based on discoloration of the coil insulation. The motor insulation was rated as a Class F insulation, which has a maximum temperature limitation of 155^{o}C. If the motor stator winding was exposed to temperatures higher than the insulation temperature limit over a period of time, insulation degradation would cause motor failures.

Thermal modeling and analysis were performed to predict the stator coil temperatures of the high voltage motor operating under its rated load condition. To support the thermal modeling effort, a series of data collection activities relative to the motor failures have been initiated. These activities include review of motor failures and application history, review of existing motor test data, inspection of failed motors for failure characterization, evaluation of insulation quality and geometry, and measurement of insulation material properties. For those motor failures attributed to insulation thermal breakdown, it was found that the run hours at failure ranged from 100 hours to 3000 hours.

As a response to the premature motor stator insulation failures, a new motor design was implemented which featured larger stator laminations, increased stator winding cross sectional area, and reduced current resulting in a 36% reduction in the stator winding current density at rated load. Considering differences in conductor volume and assuming equivalent conductor temperatures, the decreased current density results in a 41% reduction in the ohmic losses in the new motor stator winding. In addition to the electrical design changes, the cooling system was also improved by providing more uniform coolant distribution to the stator coil head regions, particularly to the region where most of the insulation failures occurred.

II. FAILED COIL INSPECTION

A thermally failed motor was examined by dissecting the stator coil end turn sections. The coil end turn was sectioned into multiple specimens and polished for visual inspection. Figure 1 shows the coil dissection map. Figure 2 displays the sectioned coil specimens. Discoloration of insulation is evident in figure 2, in which both the outside and inside coil sections show a dark ring adjacent to the conductors. Coil specimen one is nearest to the stator iron core and specimen eight is closest to the coil knuckle. As shown in figure 2, the insulation discoloration progresses through the full thickness of the ground wall insulation from specimen one to specimen eight. This appears to indicate that the coil temperatures increase as the coil extends away from the stator core.

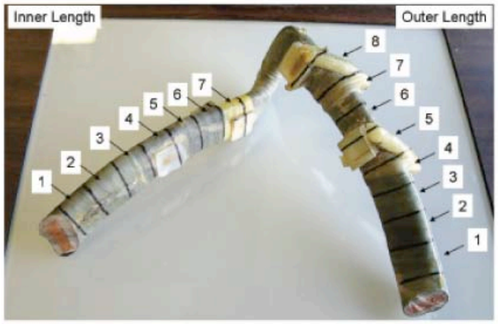


Figure 1. Stator coil dissection map

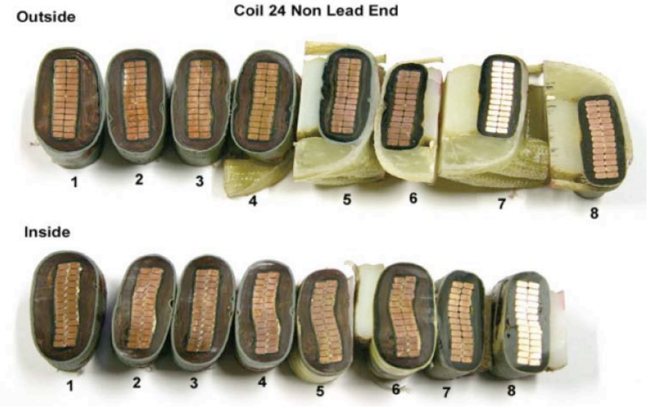


Figure 2. Insulation discoloration in specimens

III. FINITE ELEMENT THERMAL MODELING

For the coils outside the stator core, the non-uniform potting resin penetration causes the total coil insulation thickness to vary around the coil periphery and along the end turn length. In order to perform finite element thermal analysis on the failed motor stator end turns, it is necessary to develop a representative coil cross section that reflects the variation in ground wall insulation thickness around the perimeter of the coil and along the length of the coil arm. Coil samples from a failed motor coil heads were sectioned at eight different axial locations and the ground wall insulation thicknesses were measured at eight peripheral locations around each coil sample. The XY coordinates of the eight points along the coil perimeter were calculated on an averaging basis. A spline curve was then defined to pass through each of the eight profile points to generate a two-dimensional (2-D) coil profile that closely matched the shape of the coil cross sections. There are a total of 26 copper conductors (26 turns) in each coil cross section. Each conductor is surrounded by a layer of turn insulation which has a uniform thickness of 0.005 in. The heat input used in the thermal model is the ohmic loss generated in the copper conductors at a full-load current. Thermal modeling was based on a two-phase refrigerant spray providing a convective cooling environment with a uniform ambient temperature of 18.3°C (65°F) at an elevated coolant pressure.

For forced convection cooling on a stator coil in the end-turn region having a fixed coolant temperature, the steady-state coil conductor temperatures are determined by the thermal resistances between the heat source (copper conductors) and the heat sink (refrigerant coolant). These thermal resistances can be categorized as coil internal and external thermal resistances. For a given motor design with fixed coil dimensions, the coil's internal and external thermal resistances are dictated by the component thermal conductivities and convection heat transfer coefficients, respectively.

The high voltage hermetic motor cooling mechanism is considered to be forced convective boiling heat transfer. Without knowing the flow distribution in such a complex spray cooling environment, it is very difficult to analytically predict or experimentally measure the overall convection heat transfer coefficients, which are essentially coil position dependent. To determine appropriate convection coefficients for the thermal modeling, thermal analysis results based on a range of estimated convection heat transfer coefficients have been correlated with measured stator coil surface temperatures obtained from motor refrigerant cooling tests with multiple thermocouples attached to the coil surfaces in the coil head region during steady-state operation at various current levels. Accurate measurement of coil surface temperatures proved challenging and some discrepancies were identified in the temperature data.

For the failed motor design under a full-load operation, the measured maximum coil surface temperature rise, which was defined as the temperature difference between the measured maximum coil surface temperature and the refrigerant coolant temperature, was 15^{o}C. However, for the new motor design with reduced ohmic losses as described earlier, the measured maximum coil surface temperature rise was 21^{o}C. Considering the differences of ohmic losses and coil surface cooling areas between the failed and the new motor designs, it was estimated that the maximum coil surface temperature rise of the failed stators should be on the order of 42^{o}C. Factoring in a consideration of the non-uniform cooling system, the maximum coil surface temperature rise of the failed motor stators was estimated to be as high as 50^{o}C at 100% rated load condition. From these comparisons, it appears that the maximum coil surface temperature of the failed motor design may not have been detected by the limited thermocouples during the cooling test. To evaluate worst-case conditions, thermal analyses were performed based on a 50^{o}C surface temperature rise.

Stator coil insulation samples were prepared and sent to a thermal property measurement laboratory to measure temperature dependent insulation thermal properties. A summary of the 2-D finite element thermal modeling efforts is described as follows:

- Determine thermal model coil geometries by dissecting coil at multiple locations and generate coil profile with averaged coil dimensions
- Examine coil void sizes and distributions in dissected coil samples to form a basis for investigation of thermal impact of the voids on maximum coil temperature
- Determine copper conductor current densities at various current loads
- Calculate temperature-dependent copper losses based on temperature-dependent electrical resistivities of copper
- Conductor and insulation modeling details
    - conductors and insulations
    - void-free or void-included model
    - input temperature-dependent thermal properties
    - assign non-uniform volumetric copper losses, calculated using individual conductor temperatures, in non-uniform copper loss model
    - assign refrigerant coolant temperature and estimated convection heat transfer coefficient as cooling boundary condition
    - perform double iterations on convection heat transfer coefficient and copper losses until the predicted average coil surface temperature is equal to the measured maximum coil surface temperature and predicted copper temperatures are equal to the temperatures used for copper loss calculations

To evaluate void content in the stator coils, photographs of 44 different coil cross sections have been examined. For those cross sections with voids, an average of approximately two discrete voids was observed, with the majority of the voids found in the ground wall insulation., Voids adjacent to copper conductors were found in nine cross sections. A generic 2-D void free thermal model is shown in figure 3.

To qualitatively evaluate the effect of operating temperatures at the 155ºC temperature rating, a small coil sample was heated to 155ºC and a visual inspection was conducted. It was found that the sample showed signs of significant resin flow and a marked reduction in mechanical properties at this temperature. The reduced mechanical properties will make the coil more susceptible to insulation damage from relative motion, either from electromagnetic forces or mechanical vibrations. Figure 4 is a picture of this coil sample just after removal from the 155ºC oven.

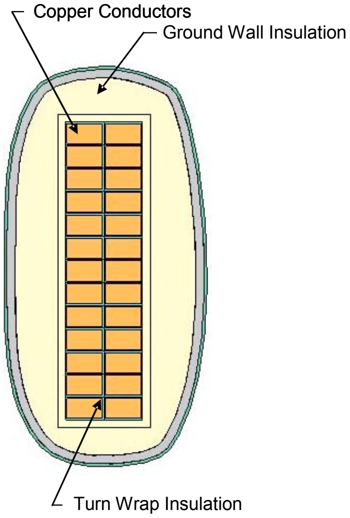
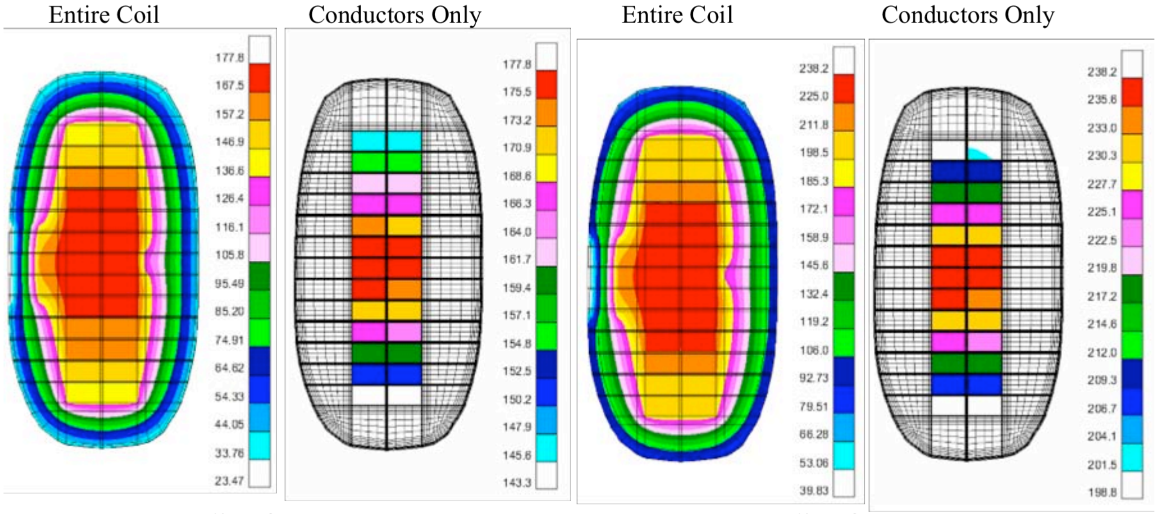


Figure 3. Stator coil thermal model

Figure 4. Coil removed from 155°C oven

IV. THERMAL ANALYSIS RESULTS OF FAILED MOTORS

Two thermal analyses have been performed with a range of estimated convection heat transfer coefficients to match the predicted average coil surface temperature rises of 15°C and the presumed maximum coil surface temperature rise of 50°C. For the thermal model with two voids included (one void in the ground wall insulation and the other void adjacent to the conductors) and non-uniform conductor loss distribution considered, the predicted stator coil and copper conductor steady state temperature distributions at the full-load current are shown in figure 5. A convection heat transfer coefficient of 300 $W/m^2/K$ was used in the thermal analysis to make the predicted average coil surface temperature approximately 15°C higher than the coolant temperature, and the predicted maximum copper conductor and maximum turn insulation temperatures are 177.8°C. A convection heat transfer coefficient of 100 $W/m^2/K$ was used to make the predicted average coil surface temperature approximately 50°C higher than the coolant temperature, and the predicted maximum copper conductor and maximum turn insulation temperatures are 238.2°C. Both of these predicted maximum insulation temperatures exceed the insulation temperature rating of 155°C.



Entire Coil

Conductors Only

Entire Coil

Conductors Only

average coil surface temperature
= coolant temperature + 15^{o}C

average coil surface temperature
= coolant temperature + 50^{o}C

Figure 5. Predicted steady-state coil temperature distribution (^{o}C) in stator end turn coils at full-load current

V. CONCLUSIONS

Research was conducted to develop a fundamental understanding of the causes of recurrent insulation failures experienced on hermetic motors installed in chiller applications. Finite element thermal models were used to predict steady-state temperature distribution within a stator coil in the end-turn region under a full-load electrical heating and forced refrigerant cooling at an elevated pressure. Insulation thermal conductivity and the convection heat transfer coefficient determine the effectiveness of the coil heat dissipation. A range of convection heat transfer coefficients were used to confine the thermal analysis. Thermal analysis results based on measured insulation thermal conductivities were correlated with measured stator coil surface temperatures. The results of this thermal evaluation indicate that the premature motor failures are likely caused by excessive conductor heating due to high operating current density in a non-uniform coolant distribution.