Thermal Measurement and Prediction of An Air-Cooled Induction Motor

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Abstract – Active cooling is typically required for continuously operated electric motors to prevent rotors and stators from overheating. Various motor cooling designs have been developed in the past to meet the needs and constraints for different motor applications. This paper presents thermal measurement and prediction of an induction motor which is an integral part of a large energy storage generator. The induction motor was designed to be cooled by unidirectional airflow ventilated across the air gap between the rotor and the stator.

Transient rotor and stator temperatures have been measured for the described induction motor in a 2.87-hr thermal test. The energy storage generator was held at a constant speed of 3,500 RPM during the test, and the heat generation included windage, bearing, and motor electrical losses. Transient 3-D motor rotor and stator thermal analyses were performed using thermal and airflow parameters obtained in the test. Comparisons between the predicted and measured temperatures indicate the 3-D motor thermal modeling can provide relatively accurate thermal predictions.

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I. INTRODUCTION

An induction motor has been designed to be an integral part of a large energy storage generator. Generator heat losses include windage, conductor, lamination, and bearing losses. The induction motor is designed to provide torque to overcome windage and bearing losses at the peak rotor speed without having acceleration load. As a transient load is applied, the generator is decelerated to a lower speed and more torque is required to be provided by the induction motor to accelerate the generator back to the peak speed before the next discharge.

A simple rotor/stator air-gap forced air cooling system has been designed to remove majority of the heat losses produced in the generator. The induction motor is identified as the most thermal demanding component in the generator due to its continuous electrical heat generation during the entire generator operation. This paper places emphasis on induction motor cooling test and associated 3-D transient motor rotor and stator thermal analyses. During the cooling test, the energy storage generator was held at a constant speed of 3,500 RPM for 2.66 hours. Active air coolant was pressurized and circulated by an external blower. The air impinged on the motor stator end turns and rotor end ring at the air inlet, ventilated through the rotor/stator air gap, and flew across the end turns and end ring at the other end of the motor. The exhausted motor cooling air merged with another fresh air stream and the combined airflow was then used for other generator component cooling before exiting the generator.

II. INDUCTION MOTOR DESIGN AND LOSSES

The rotor core is made of M-19 laminate. There are a total of 58 rectangular ETP copper bars in the rotor. Rotor end rings, made of ETP copper, are supported by alloy steel banding. The stator winding is made of rectangular copper conductors. In the stator conductor slots, there are conductor turn wrap, coil wrap, coil head wrap, slot mid stick, and slot liner. The stator is vacuum impregnated and the dimensional and assembly tolerances are filled with a potting resin. The overall stator copper conductor packing factor is approximately 65%.

A thermal test has been conducted to investigate the generator induction motor thermal behavior during a continuous high speed operation. The generator was brought to a speed of 3,500 RPM from rest in 769 s and was kept at this speed for 2.66 hours. The predicted induction motor component heat losses from an electromagnetic analysis at an elevated temperature are included in table 1.

Table 1. Predicted induction motor heat losses generated in motor thermal test

Time Period	Rotor bars & end rings (W)	Rotor lam. teeth (W)	Stator winding (W)	Stator lam. teeth and yoke (W)	Windage (W)	Total Loss (W)
0→769 s (average losses under acceleration load from rest to 3,500 rpm)	2,057 (bars:63%) (rings:37%)	2,809	7,319	5,348	1,483	19,016
769→10,337 s (no-load losses @ 3,500 rpm)	607 (bars:63%) (rings:37%)	3,885	4,216	9,760	4,745	23,213

III. AIRFLOW AND TEMPERATURE MEASUREMENTS

A high-pressure blower was used to provide pressurized air coolant for generator cooling. Airflow sensors were installed at immediate upstream of the blower and induction motor entrance to measure the airflow rates introduced into the entire generator and the induction motor. The measured air pressurization across the blower is approximately 2.345 psi. Air temperature rises caused by blower pressurization are largely dependent on the blower efficiencies. In general, 1-psi air pressurization increases air temperature by roughly 8.5°C (15.3°F). It is, therefore, anticipated that the 2.345-psi blower pressurization will increase the air temperature by 20°C (36°F). The measured air temperature rise across the blower during the 3,500-RPM thermal test is 21.7°C, which agrees well with the estimated value of 20°C. A measured induction motor airflow rate of 1,443 SCFM (Standard Cubic Feet per Minute) has been determined after temperature compensation necessitated by the blower pressurization and flow rate adjustment according to the blower performance curve provided by the blower manufacturer.

The induction motor rotor temperature measuring sensors are very small resistance temperature detectors (RTD) which are attached to the rotor end plate peripheries located at cooling air exit end and are in direct contact with the rotor copper conductor bars. Therefore, the measured rotor copper bar temperature can be considered to be a fairly accurate indication of the local maximum rotor conductor temperature. However, the stator temperatures measured by the RTDs embedded in the stator mid stick are not local maximum temperatures. As shown in figure 1, each of the stator RTDs has a sensing element width of 2.25 in. The entire induction motor stator core length is 11.25 in. Instead of local maximum temperatures, the measured stator mid-stick temperatures are actually averaged temperatures at the RTD sensing element locations. The rotor and stator temperatures were measured every one second during the motor thermal test.

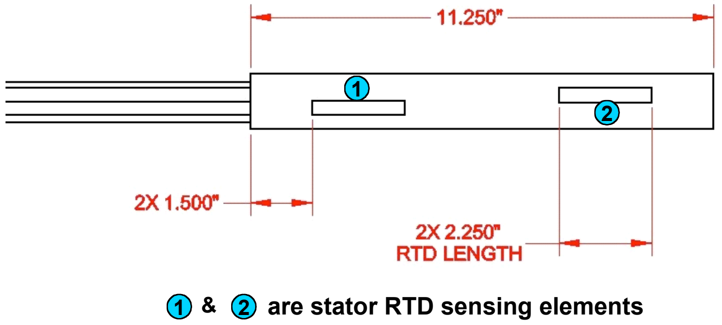

Figure 1. Induction motor stator mid stick and embedded RTDs

IV. TRANSIENT 3-D THERMAL MODELING

The rotor components are relatively simple and have been modeled individually in the rotor thermal analysis. A 0.0025-in thick air layer was assigned in between the rotor bars and rotor lamination, and was also allocated in between the rotor bars and steel bandings. It is not practical to consider the stator slot conductor and insulation details in a transient 3-D stator thermal model; instead, the slot conductors and various insulations were smeared and equivalent thermal properties were used to reduce modeling and computational effort. Due to geometrical symmetries, only sectors of the rotor and stator were actually modeled. The transient thermal modeling has been performed under the following conditions:

- Consider time-dependent heat losses shown in table 1
- Consider time-dependent and position-dependent air cooling boundary conditions on a time-averaged basis by assuming 75% of total motor loss removed in 769-s motoring period and 100% of total motor loss removed in 2.66-hr idling period
- Ambient temperature = 6.7^{o}C (44^{o}F)
- Initial induction motor rotor temperature = 47.5^{o}C
- Initial induction motor stator temperature = 44^{o}C

Several checkup tests were performed prior to the actual induction motor thermal test; therefore, the listed motor initial temperatures are higher than the ambient temperature.

V. PREDICTED AND MEASURED INDUCTION MOTOR TEMPERATURES

The predicted rotor and rotor copper conductor temperature distributions at time of 10,337 s (2.87 hr), which is the end of the motor thermal test, are shown in figure 2. The predicted stator and stator mid-stick temperature distributions at time of 10,337 s (2.87 hr) are shown in figure 3. The predicted transient maximum rotor copper conductor temperatures and measured transient rotor copper temperatures at air exit are plotted and compared in figure 4. The predicted transient maximum stator winding mid-stick temperatures and measured transient stator winding mid-stick temperatures near air exit are plotted and compared in figure 5.

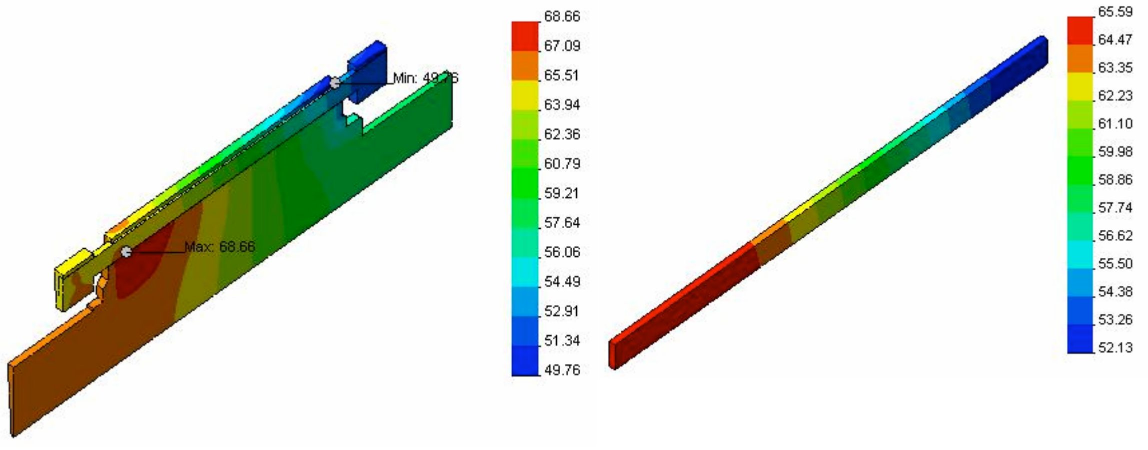

Figure 2. Predicted rotor and rotor conductor temperature distributions (^oC, time=10,337 s)

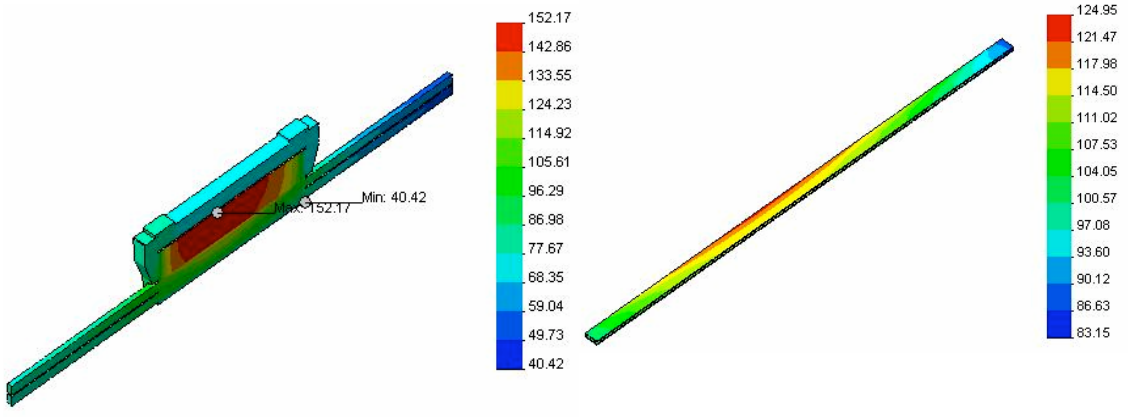

Figure 3. Predicted stator and stator mid-stick temperature distributions (^oC, time=10,337 s)

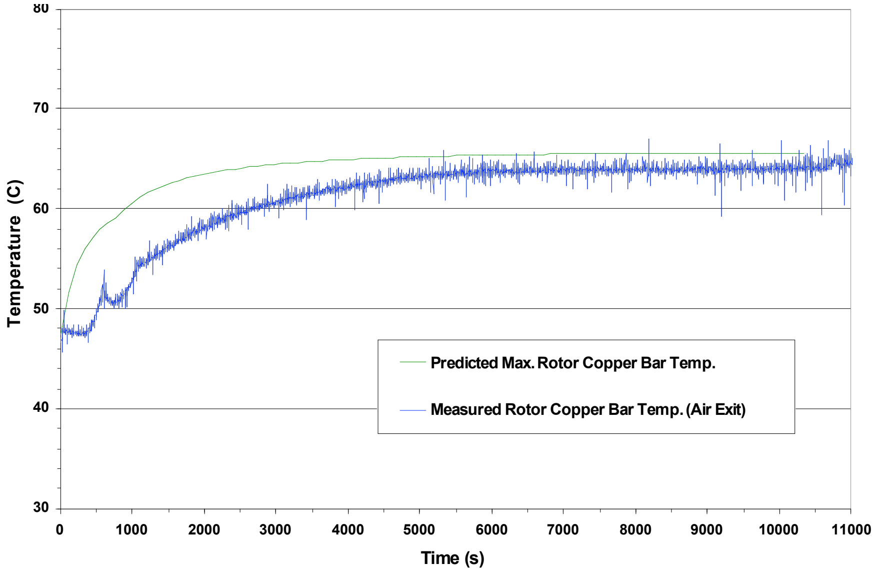

Figure 4. Comparison between predicted and measured maximum rotor conductor temperatures

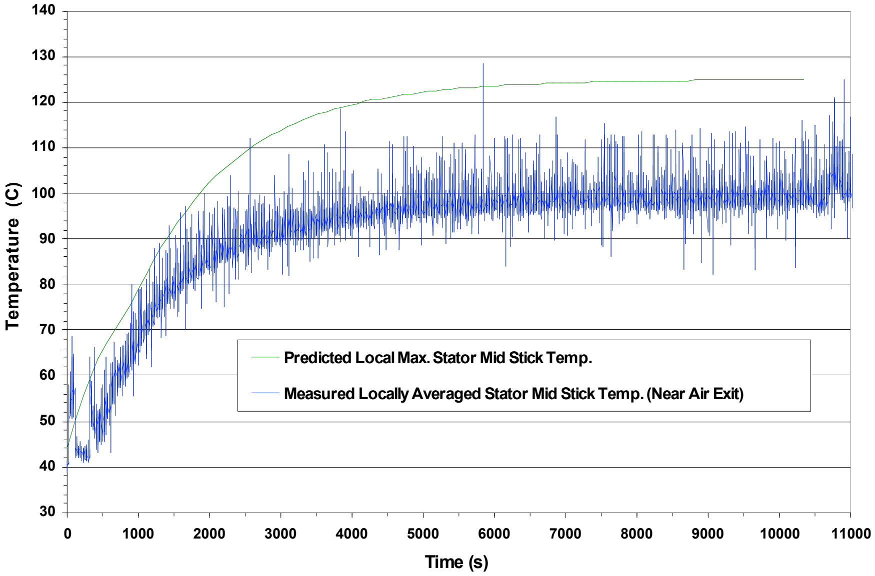

Figure 5. Comparison between predicted local maximum and measured locally averaged stator mid-stick temperatures

The measured maximum rotor conductor temperature and locally averaged stator mid-stick temperature at end of the test are 64°C and 104°C, respectively. The predicted maximum rotor conductor and stator mid-stick temperatures at end of the test are 65.5°C and 125°C, respectively. The predicted and measured maximum rotor conductor steady-state temperatures agree very well. The transient rotor temperature discrepancies between prediction and measurement during early stage of the test (shown in figure 4) are primarily due to a conservative assumption of 75% loss removal in the 769-s motoring period and 100% loss removal in the 2.66-hr idling period. This assumption makes the motor air temperatures higher than they actually were during the early stage of the test.

The thermal analysis results indicate the stator mid-stick temperature distributions are quite non-uniform. The predicted absolute local maximum mid-stick temperature is 125°C and the predicted locally averaged mid-stick temperature at the RTD near the air exit is approximately 115°C (shown in figure 3). The difference between the predicted temperature of 115°C and measured temperature of 104°C at the stator mid-stick RTD near the air exit can be attributed to possible overestimation of stator lamination losses.

VI. CONCLUSIONS

Induction motor thermal test was conducted for test duration of approximately 3 hours, in which the generator speed was held at 3,500 RPM for 2.66 hours. Motor rotor conductor and stator mid-stick temperatures have been monitored during the entire test duration. Transient 3-D motor thermal analyses were performed using thermal and airflow parameters obtained in the test. Both position and time dependent thermal loads and air cooling boundary conditions were considered in the thermal modeling. Comparisons between the induction motor thermal analysis and test results indicate that the 3-D motor thermal modeling can provide relatively accurate thermal predictions.