Thermal modeling and measurement of a drive motor in a pure electric vehicle

Linpei Zhu *, Hu Chen, Fei Xiong, Xiong Liu and Ninghua Kong
GAC R&D Center, Guangzhou 511434, China

*Corresponding author e-mail: zhulinpei@gacrnd.com

Abstract. This research is concerned on the thermal modeling and measurement of an electric drive motor. The motor is a high-efficiency permanent magnet synchronous motor (PMSM) and is actively cooled by circulating coolant through a water jacket. A lumped-parameter thermal network (LPTN) based on the Amesim is established for thermal modeling, and the temperature histories of rotor and copper winding are obtained in a condition of 120kph@3% grade. Slip ring is employed to handle the problem of effectively testing the temperature of motor rotor. The LPTN thermal model is validated by comparing simulation results with the test ones. Based on this equivalent thermal model, temperature distribution along axial direction of the motor can be obtained. The proposed LPTN model is useful for motor design to avoid over heat and demagnetization.

1. Introduction
Drive motor, as the heart of electrical vehicle’s (EV) traction system, is usually working with a problem of overheat. This is because it is sometimes working in a condition with high power or torque density in addition to heat generation by friction with the air. On the other side, heat dissipation in the motor generally employs water jacket where coolant is actively circulated through. This heat dissipation strategy is effective for stator lamination and winding, but not good for rotor due to the poor heat conduction as a result of stator-rotor air gap. The heat accumulated in the motor can lead to overheat problem which can fail permanent magnet and insulating materials of the stator, thereby affecting the performance and life of the motor and even worse, the reliability of EVs.

To model thermal performance of the motor, Ilhan et al. [1] used a thermal equivalent circuit model to analyze for the steady-state and transient thermal behavior of permanent magnets, Galea et al. [2] applied a lumped-parameter thermal model along with the finite element analysis to investigate the temperature distribution of the winding, Alberti et al. [3] combined a thermal network, based upon an object-oriented programming model, and finite element analysis, to account for the impact on the material properties from temperature rise. In our previous research [4], the lumped-parameter thermal network approach is employed to analyze the temperature distribution of the drive motor; however, the temperature of the rotor has not been tested and validated. On the basis of that work, we conducted test to measure the temperature of the rotor and validated the accuracy of the LPTN model [5]; unfortunately, the temperature histories of the motor rotor and windings have not been obtained and compared with the tests.
This work establishes a LPTN model for thermal modeling of an EV’s motor rotor. The entire rotor model consists of 72 thermal nodes. The proposed LPTN model is used to obtain temperature-history results of rotor and winding in a condition of 120kph@3% grade when motor is with high rotating speed and low torque, and simulation results are compared with the test ones. Based on this LPTN model, the temperature distribution along axial direction of the motor is also obtained and discussed. The results obtained from this model shows that the temperature of the rotor is higher than the temperature of winding in the condition of 120kph@3% grade.

2. Model set-up and validation

2.1. Set-up of the model

The motor is cut along the central axis and a half motor is taken to set up the LPTN model with Amesim. The model consists of 72 thermal nodes where connection between nodes is based on thermal conduction and convection of actual structure. Motor rotor is consisted of 6 iron lamination stacks, and each lamination stack is regarded as to be composed of two layers along radial direction, an inner layer and an outer layer; therefore, there are a total of 12 thermal nodes in the rotor, 6 in the inner layer and 6 in the outer layer along axial direction. The selection of thermal nodes in the winding is carried out in a similar way. Thermal nodes in the rotor and winding as well as other component are shown in Fig. 1. The electromagnetic loss between rotor and winding as well as the stator-rotor air gap are dealt with in the same manner as in our work [5]. The material thermal properties are shown in Table 1.

![Figure 1. The LPTN model of the motor rotor.](image)

| Components               | ρ (kg/m³) | cp (J/kg-K) | k (W/m-K) |
|--------------------------|-----------|-------------|-----------|
| Lamination Stack (Stator and rotor) | 7650 | 450 | 22.2/22.2/3.2 |
| Magnet (PM)               | 7500 | 502 | 8.95 |
| Slot winding              | 7616 | 320 | 1.2/1.2/302 |
| End turn winding          | 7850 | 475 | 0.76/202/102 |
| Rotor Shaft               | 2660 | 880 | 46.6 |
| Housing                   | 2660 | 880 | 155 |

Table 1. Thermal material properties used in the modeling.
2.2. Simulation and tests

2.2.1. Introduction of the tests. To validate the accuracy of the proposed LPTN model, an experiment is conducted to obtain temperature history. Fig. 2 shows where RTD/thermocouples are placed. Specifically, RTD/thermocouples are attached on circular holes of laminations and the end of permanent magnet. Since the rotor is symmetrical in axial direction, only three lamination stacks close to slip ring are placed with RTD/thermocouples, two with each lamination.

![Figure 2. Schematic of the RTD/thermocouple placed in the rotor.](image1)

To effectively test the rotor temperature is known as a challenging task as rotor is operating with high speed. Here the rotor shaft is modified and small holes are drilled along radial directions as shown in Fig. 3, through which RTD wires can be directed to the central line of rotor shaft as shown in Fig. 2. To resolve the issue that RTD wires tangling and broken as a result of high rotating speed, a slip ring is used to serve as the media to transmit temperature signal. The slip-ring shaft should be aligned with the rotor shaft. In addition, the slip-ring rotor connects to the RTD wires on the one side, the slip-ring stator connects to the data acquisition system on the other side. Fig. 4 shows the actual rotor temperature measurement set-up.

![Figure 3. Wires into the rotor shaft.](image2)  ![Figure 4. Rotor temperature measurement set-up.](image3)

2.2.2. Simulation and comparison with the tests. The LPTN model is employed to run in the condition of 120kph@3% grade for a period of 4500 seconds, and the results from a number of test points are obtained. As seen from Fig. 2, those test points include #1, which locates in the outer layer of the rotor lamination, #4, which locates in the inner layer of the rotor lamination, and a test point located in the winding close to the end cap resolver side. The initial condition for test and simulation are the same and shown in Table 2. As can be seen from the table, the final temperature results at steady state obtained from both the simulation and tests agree well with each other and the error between them is less than 3%.
Table 2. Summary of numerical and test results in 120kph@3% grade condition.

| Initial condition | Final temp (℃) |
|-------------------|----------------|
|                   |                |
| Coolant inlet temp (℃) | Ambient temp (℃) | Rotating speed (RPM) | Torque (N-m) | Rotor 1# | Rotor 4# | Winding |
| Simulation        | 60             | 65              | 8600             | 49          | 132     | 131     | 117     |
| Test              | 131            | 130             | 115              |

The temperature histories for these three test points are shown in Fig. 5, where it is clear that the temperature of the winding reaches to the steady state much faster than the results from the other two test points as a result of a smaller specific heat capacity. It also can be seen from this figure that the numerical results match the test results in the entire period, and the max error in the entire period is less than 5%. It should be mentioned that, in this operating condition, the rotor temperature is much higher than the winding temperature. This is because, from the view of heat generation, the iron loss of the rotor and the magnetic loss of the permanent magnets are large due to the high rotating speed of 8600 rpm, and winding loss is relatively small due to the small torque of 49 Nm. In addition, from the view of heat exchange, the thermal path of the winding is mainly from itself to the iron stack lamination and to the water jacket, whereas the thermal path of the rotor needs to go through the stator-rotor air gap and then to the iron lamination and further to the water jacket. Due to the large thermal resistance of the stator-rotor air gap, the heat exchange by the latter path is much lower.

Figure 5. Comparison between numerical and test results for the entire period.

3. Application of the model
The validated LPTN model can be applied to predict the temperature distribution along rotor axial direction, and the test to do so is hard to set up measurement facilities and costly. Numerical results from a total number of 8 observing points, from the end cap resolver side to each of 6 laminations and to end cap spline side, are obtained by the proposed model and shown in Fig. 6. From the figure, it can be seen that the temperature of the laminations is higher than the both end sides as the end sides can effectively exchange heat from the outside. Moreover, the third and fourth laminations are with a litter higher temperature (less than 5 ℃) than the remaining four because of their middle-placed location which leads to hard heat exchange with the outside.
4. Conclusion
In this work, a LPTN model for modeling thermal behavior of motor is established. The effectiveness of the model is validated by comparing numerical results with the test ones. The steady state temperature of rotor and winding from both simulation and test are within error of 3%, and the temperature histories from both the rotor and winding matches each other and the max error is less than 5%. The agreement between the simulation and test results confirmed the accuracy of the proposed LPTN model.

The numerical and test results show that rotor temperature is higher than the winding temperature, and this raise an issue that the rotor temperature needs to be measured for safety design of the motor. For this measurement, a slip-ring technique is employed to effectively acquire rotor temperature data.

The proposed LPTN model and the test approach can be applied to the design process of the motor to avoid overheat and demagnetization of permanent magnets. Furthermore, the temperature history can be obtained by the proposed model and this temperature behavior can be used to provide an accurate control logic for the motor, which is important to the safety and reliability of the motor.

References
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