Lumped-Parameter Thermal Network Model and Experimental Research of Interior PMSM for Electric Vehicle

Qixu Chen, Zhongyue Zou, and Binggang Cao

Abstract—A 25kW interior permanent magnet synchronous machine (IPMSM) applied to the electric vehicle is introduced in the paper. A lumped-parameter thermal network model is presented for IPMSM temperature rise calculation. Furthermore, a 3D liquid-solid coupling model considering the assembly clearance is compared with the 2D lumped-parameter thermal network model. Finally, a dynamometer platform for temperature rise measurement is established to verify the above-mentioned methods. Testing result shows that the lumped-parameter thermal network have a high accuracy to predict each part temperature.

Index Terms—Interior permanent magnet synchronous machine, lumped-parameter thermal network, liquid-solid coupling, thermal resistance, thermal conductance.

I. INTRODUCTION

INTERIOR permanent magnet synchronous machine (IPMSM) is applied to the field of electric vehicle (EV) and hybrid electric vehicle (HEV) for its higher power density and torque density. The massive heat bring challenge for safe operation of PMSM. Therefore, accurate temperature rise calculation becoming increasingly more and more important.

There are three basic analysis methods: 1) lumped-parameter thermal model, 2) the finite element method (FEM) and 3) computed fluid dynamics (CFD). Mellor et al [2] studied an induction motor using the lumped parameter thermal model to calculate the average temperatures at different parts of the motor. A lumped-parameter thermal network model for radial flux PMSM [3–6] and axial flux PMSM [7–8] is used to calculate the average temperatures for different parts of PMSM. Fluid flowing characteristics including gap air and coolant are studied [9–10]. Coupled electromagnetic and thermal analysis of PMSM is carried out in the paper [11–14] and a testing platform was established by temperature sensor and infrared thermal imager.

FEM simulations can be accurate to compute temperature distributions of motor parts, but convection heat transfer coefficients generally use empirical formula, which lead to the uncertainty of results.

In this paper, an interior radial-flux PMSM is introduced in the paper. Forced liquid (50%water+50% glycol) cooling in shell jacket is adopted. A lumped-parameter thermal network models for thermal design and analysis of IPMSM is presented. This method that is divided into two stages combines both analytical method and CFD simulations. In the first stage, fluid can be modeled using CFD tools to compute the convective heat transfer coefficients between solid surface and fluid surface, which are necessary for FEM and lumped-parameter thermal network model. In the second stage, convection heat transfer coefficients obtained by CFD simulations can be used to amend the empirical formula. In this way, a simplified model considering the symmetry and period reduces the computation time obviously.

Finally, a temperature rise testing platform taking the rated load and overload into account is built to verify the above-mentioned lumped-parameter thermal network result and CFD simulation result. Furthermore, a measured efficiency map and phase current wave are obtained at operation region. The temperature measurements of PMSM are carried out using thermocouple PTC100 and an FLUKE infrared thermal camera device.

II. LUMPED-PARAMETER THERMAL NETWORK

A lumped-parameter thermal network model applied to IPMSM is presented in the paper. The main parameters of the IPMSM in the paper is listed in Table I. Its geometry model and equivalent heat source model are shown in Fig.1 and Fig.2 respectively. Each cylindrical component can be described by lumped-parameter thermal network composed of radial resistance, axial resistance and heat source. The definition of thermal resistances in lumped-parameter thermal network is related to thermal conductivity of material and its dimensional information. In the paper, the heat transfer mechanisms of IPMSM, which are generally classified as thermal conduction and thermal convection, are discussed in detail.
TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power $P$ [kW]</td>
<td>25</td>
</tr>
<tr>
<td>Rated speed $n$ [rpm]</td>
<td>3300</td>
</tr>
<tr>
<td>Stator inner diameter $D_i$ [mm]</td>
<td>148</td>
</tr>
<tr>
<td>Stator outer diameter $D_o$ [mm]</td>
<td>208</td>
</tr>
<tr>
<td>Stator iron length $L_{ef}$ [mm]</td>
<td>120</td>
</tr>
<tr>
<td>Number of stator parallel branches $a$</td>
<td>2</td>
</tr>
<tr>
<td>Number of turns per coil $N_s$</td>
<td>100</td>
</tr>
<tr>
<td>Length of air gap $\delta$ [mm]</td>
<td>1.5</td>
</tr>
<tr>
<td>Permanent magnet thickness $h_{pm}$ [mm]</td>
<td>7</td>
</tr>
<tr>
<td>Number of stator slots $Q$</td>
<td>36</td>
</tr>
<tr>
<td>Number of pole pairs $p$</td>
<td>3</td>
</tr>
<tr>
<td>Winding connection $Y$</td>
<td></td>
</tr>
<tr>
<td>Coolant inlet flow velocity $V$ [L/min]</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 1. IPMSM geometry model (half model).

Fig. 2. Equivalent model of heat source (half model).

A. Thermal Resistance Definition

A general cylindrical component and its lumped-parameter thermal network that is derived from the solution of the heat conduction equations are shown in Fig.3. The corresponding thermal resistance definition is given in Table II [5-7], where $k_r$ and $k_a$ are the thermal conductivities in the radial and axial directions respectively; $l$ is the axial length and $r_2$ and $r_1$ are the outer and inner radius of the cylindrical component; $T_3$ and $T_4$ are the unknown temperatures on the inner and outer surfaces, and $T_1$ and $T_2$ are the unknown temperatures at two end face; $T_m$ represents the average temperature of the component; $P$ and $C$ represent the corresponding internal loss and thermal capacitance. Thermal capacitance in steady state analysis is here under no consideration.

Heat conduction and thermal convection including liquid coolant and air are considered in the calculation of the IPMSM temperature rise.

B. Heat Conduction Calculation

General formula of heat conduction is shown as

$$G_{mat} = \frac{\lambda \cdot A_{mat}}{L_{mat}}$$  \hspace{1cm} (1)

The equivalent thermal conductance with or without assembly clearance is considered as follows.

$$G_{mat1,2} = \frac{1}{1/G_{mat} + 1/G_{air} + 1/G_{mat2}}$$  \hspace{1cm} (2)

C. Heat Convection Calculation

Most of heat generated by IPMSM could be taken away by circulating liquid coolant in shell jacket. Shell jacket includes S-type channel filled with liquid coolant, and its pressure loss is shown in Fig.4.

Table III gives some typical values for the thermal conductivities of solid materials applied to IPMSM [6].

TABLE II

<table>
<thead>
<tr>
<th>Thermal Resistance Definition Of Cylindrical Component</th>
</tr>
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<tbody>
<tr>
<td>$R$</td>
</tr>
<tr>
<td>$R_1$</td>
</tr>
<tr>
<td>$R_2$</td>
</tr>
<tr>
<td>$R_3$</td>
</tr>
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</table>

| TABLE III

<table>
<thead>
<tr>
<th>PMSM THERMAL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>Silicon steel sheet $\lambda_{si}$ <a href="x,y,z">W/(K.m)</a></td>
</tr>
<tr>
<td>Copper $\lambda_{cu}$ [W/(K.m)]</td>
</tr>
<tr>
<td>Aluminum alloy $\lambda_{al}$ [W/(K.m)]</td>
</tr>
<tr>
<td>Winding insulation $\lambda_{ins}$ [W/(K.m)]</td>
</tr>
<tr>
<td>PM $\lambda_{pm}$ [W/(K.m)]</td>
</tr>
<tr>
<td>Steel 42CrMo $\lambda_{st}$ [W/(K.m)]</td>
</tr>
</tbody>
</table>

Fig. 3. (a) Cylindrical component (b) Radial and axial thermal network.

Fig. 4. Pressure loss along the path.
The classical Bertotti loss separation model [15] is used to calculate core loss, which breaks the total core loss into static hysteresis loss, classical eddy current loss and extra loss. Core loss \( P_v \) is obtained by a group of flux density loss BP curve at different sinusoidal work frequency 100Hz, 200Hz, 400Hz, 1000Hz.

\[
P_v = P_h + P_c + P_e
\]

(3)

where \( P_h \)—iron core loss; \( P_c \)—hysteresis loss; \( P_e \)—eddy current losses; \( B_m \)—AC component magnitude of flux density; \( f \)—frequency; \( K_h \)—coefficient of hysteresis losses (\( \alpha = 2 \)); \( K_e \)—coefficient of the eddy current losses; \( K_c \)—coefficient of the extra eddy current loss.

Three iron loss coefficients \( K_h, K_c, K_e \) is obtained by

\[
P_e = K_1 B_m^2 + K_2 B_m^{1.5}
\]

(4)

where \( K_1 = K_h f + K_c f^2; K_2 = K_e f^{1.5} \)

Coefficient of the classical eddy current losses \( K_c \) is calculated by

\[
K_c = \pi^2 \cdot \sigma \cdot d^2 / 6
\]

(5)

where \( \sigma \)—electrical conductivity; \( d \)—thickness of a slice of silicon sheet.

In order to satisfy the minimum of the quadratic form, the parameter \( K_1 \), \( K_2 \) can be computed by

\[
f(K_1, K_2) = \sum_i \left[ P_{vi} - (K_1 B_{mi}^2 + K_2 B_{mi}^{1.5}) \right] ^2 = \text{min}
\]

(6)

where \( P_{vi}, B_{mi} \)—the \( i \)th data point \((P_{vi}, B_{mi})\) measured on the iron core loss curve

Loss coefficient \( K_h, K_c, K_e \) can be described as

\[
K_h = (K_1 - K_c f_i^2) / f_0; K_c = K_2 / f_0^{1.5}
\]

(7)

where \( f_0 \)—measured frequency of loss curve

Due to the stator slot opening and harmonic current, rotor iron core and PM are exposed to high-order time harmonic of current and armature magnetic-motive-force (MMF) space harmonic in the air-gap field, which rotate at different speed relative to the rotor speed. The induced eddy current loss [16], [17] in PM and rotor iron core is calculated by

\[
P_{\text{edd,PM}} = \int \frac{1}{T} \int \sigma E^2 dV dt = \int \frac{1}{T} \int \frac{J_z^2}{\sigma} dV dt
\]

(8)

where \( P_e \)—total rotor loss; \( \sigma \)—electrical conductivity; \( E \)—electric field intensity; \( J_z \)—eddy current density; \( V \)—space integration volume of loss.

The induced eddy current density \( J_z \) can be represent by

\[
J_z = -\sigma \frac{\partial A_z}{\partial t}
\]

(9)

The eddy current losses \( P_{\text{edd,PM}} \) can be determined directly from the magnetic vector potential as

\[
P_{\text{edd,PM}} = \frac{1}{T} \frac{1}{V} \int \sigma \left( \frac{\partial A_z}{\partial t} \right)^2 dV dt
\]

(10)

The above equation (10) in discrete form is

\[
P_{\text{edd,PM}} = p \cdot \sigma \cdot f^2 \cdot N_{\text{step}} \cdot V \cdot \sum_{k=1}^{N_{\text{step}}} (A_{z,k} - A_{z,k-1})^2
\]

(11)

The total loss is the sum of the losses of all parts as shown in

\[
P_{\text{losses}} = P_{Cu} + P_{Fe} + P_{\text{edd,PM}} + P_{ro} + P_{alr} + P_{he} + P_{es}
\]

(12)

\[
Q \cdot C \cdot \Delta T
\]

(13)

where \( P_{\text{losses}} \) is total loss of PMSM, \( P_{Cu} \) is copper loss, \( P_{Fe} \) is stator iron loss, \( P_{pm} \) is eddy current loss of PM, \( P_{ro} \) is eddy current loss of rotor, \( P_{alr} \) is friction loss of air, \( P_{he} \) is bearing loss, \( P_{ex} \) is extra loss, \( V_2 \) is the velocity of the liquid coolant, \( A_2 \) is the cross-sectional area of water channel.

Thermal conductance between inner wall of shell jacket and liquid coolant is shown by

\[
Nu_{wa} = \begin{cases}
1.86 Re_{wa}^{0.13} Pr^{0.13} \left( \frac{d_e}{L} \right)^{0.24} & \text{for } Re_{wa} < 2200 \\
0.023 Re_{wa}^{0.8} Pr^{0.4} & \text{for } Re_{wa} > 2200
\end{cases}
\]

(14)

\[
Re_{wa} = \frac{v_2}{\nu_{wa}} = \frac{2ab}{\nu_{wa}(a+b)}
\]

(15)

\[
h_{wa} = Nu_{wa} \frac{\lambda_{wa}}{D_e}
\]

(16)

\[
G_{wa} = h_{wa} \cdot A_{wa}
\]

(17)

where \( \lambda_{wa} \) is the thermal conductivity of liquid coolant, \( Nu_{wa} \) is the Nusselt number of liquid coolant, \( Re_{wa} \) is the Rayleigh number of liquid coolant, \( Pr \) is the Prandtl number, \( D_e \) is the equivalent diameter, \( a \) is the width of water channel, \( b \) is height of water channel, \( \nu_{wa} \) is kinematic viscosity coefficient of liquid coolant, \( h_{wa} \) is convective heat transfer coefficient of liquid coolant, \( L \) is the path length of water channel.

Thermal conductance between inner wall of shell jacket and gap air is shown by (18)–(21). Where the heat transfer coefficient \( h_{air} \) of air can be obtained by classical Nusselt number.

\[
h_{air} = \frac{Nu_{air} \cdot \lambda_{air}}{D_e}
\]

(18)

\[
Nu_{air} = \begin{cases}
2 & \text{for } Ta < 1700 \\
0.128 Ta^{0.367} & \text{for } 1700 < Ta < 1e^4 \\
0.409 Ta^{0.241} & \text{for } 1e^4 < Ta < 1e^7
\end{cases}
\]

(19)

\[
Ta = \frac{\rho \cdot \delta}{\nu}
\]

(20)

\[
Re = \frac{v \cdot \delta}{\nu}
\]

(21)
where $v$ is kinematic viscosity of the air (m$^2$/s) and $v$ is linear speed of the rotor (m/s); Thermal conductance at air gap is obtained by

$$G_{air} = h_{air} A_{air} = h_{air} \pi D_o L$$  \hspace{1cm} (22)$$

Heat transfer coefficient $h_{air2}$ and thermal conductance $G_{air2}$ between the rotating shaft and internal air can be written as

$$G_{air} = h_{air} A_{air} = h_{air} \pi D_o L$$  \hspace{1cm} (23)$$

$G_{air2} = h_{air2} \cdot A_{air2}$  \hspace{1cm} (24)$$

Heat transfer coefficient $h_{air3}$ and thermal conductance $G_{air3}$ at the location of end winding surface can be written as illustrated by

$$h_{air3} = 14.2 \cdot (1 + k \sqrt{v})$$  \hspace{1cm} (25)$$

$$G_{air3} = h_{air3} \cdot A_{air3}$$  \hspace{1cm} (26)$$

where $k$ is the coefficient of the air blowing rate.

The thermal conductance $G_{air4}$ and external surface heat transfer coefficient $h_{air4}$ between frame and ambient air can be evaluated as

$$h_{air4} = 14 \cdot (1 + 0.5 \sqrt{v}) \left( \frac{T_{shell}}{2.5} \right)^{1/3}$$  \hspace{1cm} (27)$$

$$G_{air4} = h_{air4} \cdot A_{air4}$$  \hspace{1cm} (28)$$

where $v$ is wind speed (that is linear speed of shell surface. unit: m/s); $T_{shell}$ is external surface temperature of shell (unit: K). $A_{air3}$ is surface area of shell (unit: m$^2$)

D. Thermal Conductance and Lumped Parameter Thermal Network

For steady-state thermal analysis, the temperature rise $T$ of each node of lumped-parameter thermal network is calculated as shown in equation (29)–(31), where the dimension of thermal conductance matrix $G_{nxn}$ is $n = 34$.

$$G \cdot T = W$$  \hspace{1cm} (30)$$

$$G(i,i) = \sum_{j=1}^{n} G(i,j) = G(i,1) + G(i,2) + \cdots$$  \hspace{1cm} (31)$$

Gauss elimination method, Gauss-seidel iterative method, Jacobi-cholesky elimination method, or Conjugate gradient method can be adopted to solve thermal conductance matrix $G$.

Table IV gives loss values for the heat generation applied to IPMSM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator tooth losses $P_{st}$ [W]</td>
<td>110</td>
</tr>
<tr>
<td>Slot winding copper losses $P_{cu}$ [W]</td>
<td>276</td>
</tr>
<tr>
<td>End winding copper losses $P_{cu}$ [W]</td>
<td>141</td>
</tr>
<tr>
<td>Stator yoke losses $P_{sy}$ [W]</td>
<td>205</td>
</tr>
<tr>
<td>PM eddy losses $P_{ed}$ [W]</td>
<td>28</td>
</tr>
<tr>
<td>Rotor iron losses $P_{ri}$ [W]</td>
<td>41</td>
</tr>
<tr>
<td>Air friction losses $P_{fr}$ [W]</td>
<td>10</td>
</tr>
<tr>
<td>Bearing losses $P_{be}$ [W]</td>
<td>4</td>
</tr>
<tr>
<td>Extra losses $P_{ex}$ [W]</td>
<td>13</td>
</tr>
</tbody>
</table>

Losses values at 25kW power and speed of 3300rpm

Nodal temperature rise data at rated case are obtained in table V, which follow the flow chart of nodal temperature rise calculation using lumped-parameter thermal network model is shown in Fig. 5.

It is very important to figure out the heat generation, heat conductance, heat convection, and heat dissipation. Therefore, the temperature node distribution and the equivalent lumped-parameter thermal network model in Fig. 6 and Fig. 7 are established in the thermal analysis.

The power losses defined in Table IV are injected into the specified thermal nodes of the parts. In the thermal model, the geometry of the IPMSM is divided into the following parts:

1), 2) internal air, 3), 4) shell, 6) stator yoke, 8), 12) end-winding, 10) slotting winding, 14) stator teeth, 16) gap air, 18) rotor shoe, 21) magnet, 24) rotor yoke, 27), 31) bearing, 29) shaft, 33), 34) end cap.

Fig. 6. Temperature node distribution of IPMSM.

Fig. 7. Lumped-parameter thermal network model.
coupling model is built, which considers assembly clearance, equivalent insulation, gap air and internal air in Fig.8. According to heat source and heat dissipation, the parts temperature distribution at rated load is reasonable as shown in Fig.9.

<table>
<thead>
<tr>
<th>Part</th>
<th>Node</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator winding</td>
<td>8</td>
<td>52.5</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>50.7</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>50.2</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>52.3</td>
</tr>
<tr>
<td>Stator yoke</td>
<td>5</td>
<td>36.1</td>
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<tr>
<td></td>
<td>6</td>
<td>36.5</td>
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<td>7</td>
<td>36.2</td>
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<tr>
<td>Stator tooth</td>
<td>13</td>
<td>41.2</td>
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<tr>
<td></td>
<td>14</td>
<td>42.5</td>
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<td></td>
<td>15</td>
<td>41.4</td>
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<tr>
<td>Rotor shoe</td>
<td>17</td>
<td>44.2</td>
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<td></td>
<td>18</td>
<td>46.6</td>
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<tr>
<td></td>
<td>19</td>
<td>44.7</td>
</tr>
</tbody>
</table>

ΔT (Unit: K)

III. PROTOTYPE TESTING

In order to verify the lumped-parameter thermal network model and liquid-solid coupling model of IPMSM, a load testing platform is established. Rotor and stator of IPMSM are shown in Fig.10.

Dynamometer system platform mainly include DC power supply, load motor controller, load motor, electric parameter sensor box, power analyzer, AC current clamp, oscilloscope, upper computer console, IPMSM, controller, constant temperature cooling tank and cooling-water machine as shown in Fig.11-Fig.12.

Measured phase current wave at rated load case is obtained by three current clamps in Fig.13.

Fig. 8. Liquid-solid coupling model.

Fig. 9. Temperature distribution of PMSM.

Fig. 10. Rotor and stator of PMSM.

Fig. 11. Dynamometer platform.

Fig. 12. Power supply and upper computer console.

Hall current sensors and voltage sample probe are mounted on the bus bar. Three voltage probes are used to gather the phase voltage. In addition, another two voltage probes are used to gather the bus voltage. Two hall current sensor are located on the 3 phase AC bus bar in order to gather the phase current data. At the same time, a hall current sensor located on the DC bus bar is used for obtaining the DC bus current in Fig.14 (L). For the aspect of output power, a torque-speed data acquisition analyzer gathers data of torque and speed, which transmit data to the power analyzer in Fig.14 (R). Finally, IPMSM efficiency...
map in both the constant torque and the constant power 
operating regions is measured as shown in Fig.17. 
\[
P_{in} = \sqrt{3}\cdot I_{rms}\cdot U_{rms}\cdot \cos\phi 
\]
\[
P_{out} = \frac{T\cdot n}{9549}; \eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}
\]
where \(P_{in}, P_{out}\) are the input power and output power of IPMSM respectively; \(U_{line\_rms}\) is the root-mean-square value of line voltage; \(I_{pha\_rms}\) is the root-mean-square value of phase current; \(\cos\phi\) is the power factor; \(T\) is torque; \(n\) is speed (rpm); \(\eta\) is the 
efficiency; \(P_{loss}\) is the sum of all the losses. 

The efficiency of IPMSM in the region of low speed and high 
torque is relatively low. Because the motor armature current is 
large, and the in-duced voltage is obviously lower than stator 
voltage, which leads to the small DC bus voltage utilization 
ratio and the low power factor. The output power of the motor 
compared with the rated operation condition is still relatively 
low. However, winding copper loss is larger with re-spect to the 
rated operation condition in the proportion of the input power. 
Therefore, effi-ciency is still low. 

The efficiency is relatively low in the constant power region, 
especially at high speed and low torque. On the one hand, 
high-frequency skin effect in armature winding leads to 
increase of the phase winding resistance, which consequently 
result in increase of the high frequency copper loss. At the same 
time, a large percentage of stator current is used to produce 
negative d-axis demagnetization current, copper loss also 
increases significantly in the weak magnetic area. On the other 
hand, the hysteresis loss, eddy cur-rent loss in the stator core 
and eddy current loss in the rotor core and PM are proportional 
to the square of the frequency. In addition, extra loss is 
proportional to the 1.5th power frequency as described in 
equation (3) and (11), which result in loss of stator core and 
rotor losses increase obviously in the proportion of total input 
power. Therefore, efficiency in the region of the constant power 
relative to rated condition fallen remarkably.

The temperature measurements of IPMSM are carried out 
using thermocouple PTC100 and an FLUKE infrared thermal 
camera imager. Thermocouple temperature sensors PTC100 
are located into each phase slot windings for measuring 
winding temperature and iron core temperature. The 
temperature measurement of outer surface including PMSM 
and its controller is measured by using a FLUKE infrared 
thermal camera imager in Fig.18-Fig.19.
The results of the lumped-parameter thermal network method, fluid-solid coupling CFD method and experimental validation method are listed in Table V. Due to using many empirical formulas in computing the coefficient of heat conductance, heat convection and heat source. The methods of the lumped-parameter thermal network and the fluid-solid coupling CFD need to amend by experiment validation. By comparing results among three methods in Table VI, the methods of the lumped-parameter thermal network and the fluid-solid coupling CFD can better predict the parts temperature of the IPMSM.

### Table VI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method A</th>
<th>Method B</th>
<th>Method C</th>
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<tbody>
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<tr>
<td>Stator iron</td>
<td>60</td>
<td>62</td>
<td>64</td>
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<td>Rotor iron</td>
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<td>Shaft extension</td>
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### IV. CONCLUSION

In this paper, convective heat transfer coefficients of fluid can be accurately computed using CFD simulation, which can be used to amend the empirical formula. Therefore, a simplified model considering the symmetry and period is built to reduce the computation time obviously. Assembly clearance between shell and stator iron core is taken into account. By comparing lumped-parameter thermal network model with 3-D liquid-solid coupling FEA model, lumped-parameter thermal network method is more effective and accurate than traditional thermal network. Meanwhile, temperature rise testing platform including prototype manufacture is built to validate the above two methods using FLUKE infrared thermal imager and thermocouple PTC100. Efficiency map, no-load EMF, line voltage and phase current wave are tested on dynamometer. The agreement between simulation and experimental results shows that proposed lumped-parameter thermal network model is quite convincible. The method will be important for practical engineering application.

### REFERENCES


Qixu Chen was born in Shandong, China in 1982. He received bachelor’s degree in mechatronic engineering from North University of China, Taiyuan, China, in 2007, and master’s degree in mechatronic engineering from Xidian University, Xi’an, China, in 2010. He is currently working toward a doctor’s degree in electric engineering from Xi’an Jiaotong University, Xi’an, Shaanxi, China. His research interests include AFPMSM design and drive of the electric vehicle.

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