

ORIGINAL RESEARCH

Research on the speed-dependence of heat convection in high-speed EV motors and its application in the model-based rotor temperature monitoring technology

Tenghui Dong  | Taketsune Nakamura

Department of Electric Engineering, Kyoto University, Kyoto, Japan

Correspondence

Tenghui Dong, Department of Electric Engineering, Kyoto University, Kyoto, Japan.
Email: dong.tenghui.7v@kyoto-u.ac.jp

Funding information

JST A-STEP Program, Grant/Award Number: JPMJTR201A, Japan

Abstract

Using the embedded onboard digital thermal model is an economical and effective way to monitor the rotor temperatures of the electric vehicle (EV) propulsion Permanent Magnet Synchronous Motor (PMSM) in real-time. The onboard thermal model is generally in an analytical form with constant thermal resistances. However, in practical situations, the thermal convection intensities on the surfaces of the air gap and the end-cavity vary significantly with the rotational speed, producing a non-negligible influence on the estimation accuracy of the onboard thermal model. Aiming at eliminating this error and improving the accuracy, this paper explores the variation of the airflow's aerodynamics characteristics and the heat convection with the rotational speed through a syncretic study of theoretical, experimental, and numerical methods. It is found that the changing trend of the airflow presents a multi-stage characteristic in the speed range of 0–12,000 rpm. The speed-dependent convective thermal resistances are formulaically parameterised and then used to replace the related constant thermal resistances in the thermal model. The standard vehicle driving cycle test result shows that this optimisation brings a nearly 11% reduction of the overall estimation error.

KEYWORDS

computational fluid dynamics, electrical machines, finite element analysis, model-based rotor temperature monitoring

1 | INTRODUCTION

High-speed electric machines are receiving more and more attention in recent years as the electromechanical energy conversion unit in electric vehicles (EVs). Permanent Magnet Synchronous Motor (PMSM) is widely regarded as the most suitable motor type for EV propulsion among all motor types because of its high efficiency, high power density, and good speed regulation performance.

In future development, the EV PMSM is expected to have a higher power density. Increasing speed is one of the main ways to achieve it. However, numerous studies present that when the PMSM turns into the high-speed operation region, its energy dissipation rises rapidly and would result in excessive temperature rises, especially in the rotor area [1–3]. The residual magnetisation intensity of Permanent Magnets (PMs) in

the rotor is very sensitive to temperature variation. When the temperature exceeds the Curie point, the PM will lose its magnetism instantly [4, 5]. Therefore, the thermal problem is one of the main bottlenecks limiting the rotational speed.

Realising real-time monitoring of rotor temperature can significantly improve the thermal safety of the PMs. On the other hand, this technology also helpfully taps the potential output of the PMSM, attracting a lot of attention.

Nowadays, there are some available approaches for obtaining the temperature of the high-speed rotor, including the infrared thermometer sensor [6, 7], the wireless communication equipment (Bluetooth, WIFI, IR LED, or RFID) [6, 8, 9], the slip-rings on the shaft [10], flux observer [11–13], voltage signal injection, and so on.

In addition to these technologies, the onboard model-based estimation method is an economical option for the

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2022 The Authors. *IET Electric Power Applications* published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology.

EV industry. As illustrated in Figure 1, this method uses the embedded thermal model in the controller to realise real-time temperature monitoring [2, 14–16].

Compared to the techniques introduced above, this method has excellent stability, enough accuracy, zero electromagnetic interference, low energy cost, low repair cost, and most importantly, no hardware cost addition, which can fully meet the EV's requirements under mass production [17, 18]. As shown in Figure 1, in each calculation cycle, the onboard thermal model collects the operating information of the PMSM and then calculates the losses and temperatures of each component in the PMSM. Meanwhile, it receives feedback from the thermocouple mounted on the machine's static part (commonly on the end-winding) to eliminate transient error accumulation [14, 16]. Due to the calculation capacity limit of the motor controller, the onboard thermal model is generally in the analytical form [15]. Therefore, the model's accuracy has a decisive influence on the estimation accuracy.

However, the heat transfer in the PMSM includes not only conduction but also convection. In general, the thermal resistances of the heat conduction are approximately constant, but the intensities of the heat convections would change with the rotational speed [1, 18]. Especially for the rotor part, the vast majority of the heat exchanges through the air gap or the end-cavity (between the active region and endcap) with the outside environment, as illustrated in Figure 2. In other words, the main

thermal boundary conditions of the rotor are convections [7]. The study carried out to prove that the variation of heat convection is significant. Using the rough thermal model with the constant parameters may not meet the increasing accuracy requirement.

To eliminate these errors, this paper studies the variation of the airflow and the thermal convection intensities inside the high-speed PMSM. The results are transferred into a proper analytical form and used in the onboard digital thermal model to replace the constant parameters. It is worth mentioning that an innovative method of using the measurable windage losses to calibrate the roughness of the laminated surface of the air gap is adopted here to improve the accuracy of Computational Fluid Dynamics (CFD) simulations.

2 | INTRODUCTION OF MOTOR PROTOTYPE

The study is carried out on a typical PMSM for EV traction. Table 1 lists the basic configurations and geometric parameters of the machine. Figure 2 presents the inner structure of the PMSM and illustrates the main heat transfer paths.

3 | THERMAL MODEL OF THE PMSM

The thermal performance of the PMSM is modelled using the LPTN (Lumped Parameter Thermal Network) method [19–21], as shown in Figure 3. The machine is divided based on the heat transfer paths and the distribution of the heat sources. It should be noted that the model complexity is reduced properly to accommodate the spare computation capacity of the powertrain controller [15]. For a single LPTN unit (illustrated in Figure 4), the thermal capacities and the thermal resistances can be calculated using [14, 22–24].

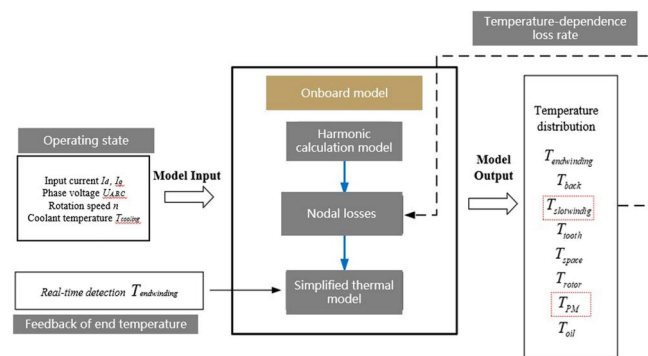


FIGURE 1 Model-based rotor temperature monitoring system

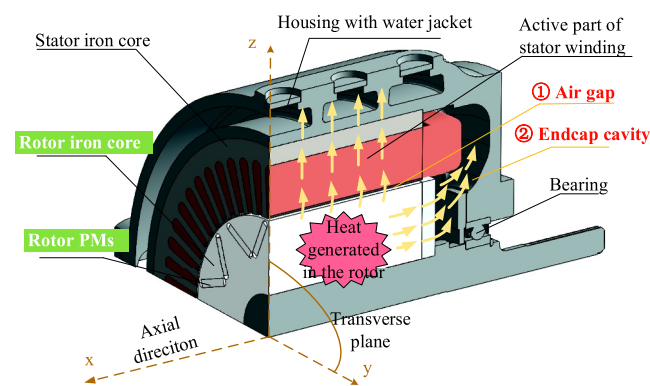


FIGURE 2 Heat dissipation path and thermal boundary conditions of the rotor

TABLE 1 Basic configurations and parameters of the PMSM

Continuous power/speed	21 kW/4000 rpm
Maximum power/speed	42 kW/12,000 rpm
Cooling method	Water jacket
Arrangement of PMs	Inserted V-type
Packing factor of the iron core	0.98
Length/diameter of active part	110 mm/200 mm
Rotor diameter	125 mm
Air gap	0.8 mm
Slot depth	28 mm
Overhang of end-winding	25 mm
Width of end-cavity	19–22 mm
Shaft diameter	43 mm

Abbreviations: PMSM, Permanent Magnet Synchronous Motor; PMs, Permanent Magnets.

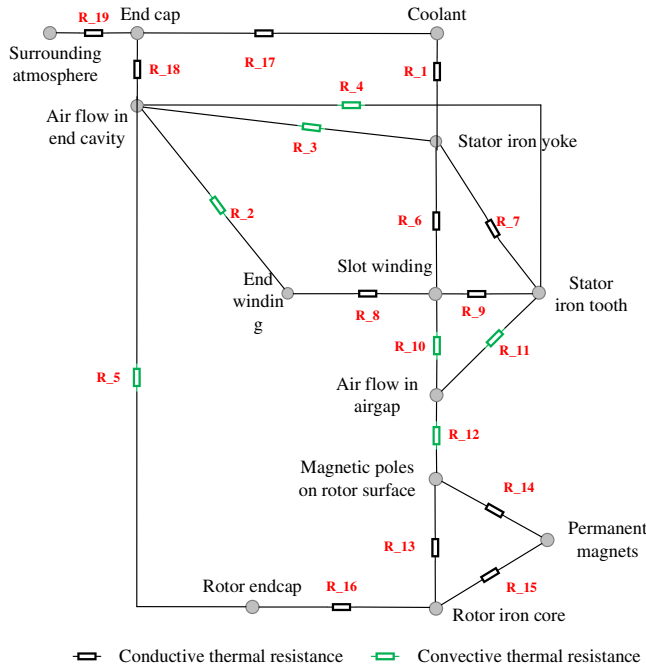


FIGURE 3 Simplified LPTN model of the PMSM. LPTN, Lumped Parameter Thermal Network; PMSM, Permanent Magnet Synchronous Motor

$$C = c_p \rho V, \quad (1)$$

$$R_{x1} = R_{x2} = \frac{l_x}{2k_x A_x}, \quad R_{x3} = -\frac{l_x}{6k_x A_x}, \quad (2)$$

$$\bar{T} = \frac{\iiint_V c_p \rho T dV}{\iiint_V c_p \rho dV}, \quad (3)$$

in which, $\bar{T}$ is the mean temperature of the component, T is the distribution function of temperature, k_x is the thermal conductivity in the x -direction, A_x is the conducting interface in the x -direction, l_x is the mean length in the x -direction, c_p is the specific heat capacity, ρ is the density, V is the total volume of this component.

4 | ROTATION-DEPENDENT CONVECTIVE THERMAL RESISTANCES

In the LPTN model, most of the thermal resistances are conductive, and not affected by the rotational speed. The values of conductive thermal resistances are first calculated by the analytical estimation method introduced above and then calibrated by thermal Finite Element analysis to compensate for the errors caused by irregular shapes. Considering that there is generally a contact thermal resistance between components, the thermal resistances are further adjusted in a small range using the genetic algorithm based on numerous experimental data.

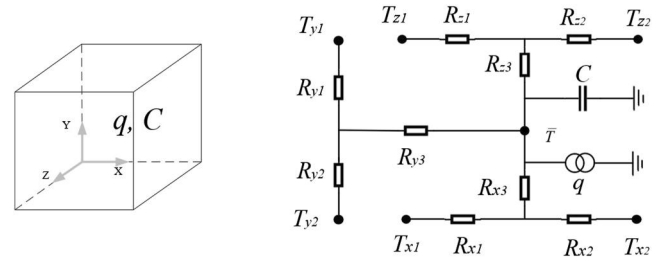


FIGURE 4 Illustration of the basic LPTN unit. LPTN, Lumped Parameter Thermal Network

The convective thermal resistances in the LPTN model change significantly with the airflow inside the machine. From the rotor's perspective, the heat mainly exchanges with its surrounding environment in two orthogonal directions by heat convection, as shown in Figure 5. This spatially separates the convective resistances into two independent groups.

In the radial direction, the rotor exchanges heat with the stator through the air gap, as shown in Figure 5a. The related convective thermal resistance is marked R_{10} , R_{11} , and R_{12} in the LPTN model. In the axial direction, the rotor exchanges heat with the other surfaces through the air in the end-cavity, as shown in Figure 5b. These convective thermal resistances are marked R_2 , R_3 , R_4 , and R_5 in the LPTN model.

The following content focuses on the rotational speed-dependence of these two groups of convective thermal resistances to improve the model estimation accuracy.

5 | THE CONVECTIVE THERMAL RESISTANCES OF AIR GAP

When the PMSM rotates at high-speed, the magnetic flux harmonics passing through the rotor will produce high eddy loss and hysteresis loss. Because of the skin effect, most of the loss concentrates on the rotor surface [7]. So, the rotor temperature is closely related to the convection in the air gap.

5.1 | Aerodynamic characteristics of airflow in the air gap

The airflow in the air gap is a typical coaxial-cylindrical rotating flow with a stationary outer cylinder, also known as Taylor-Couette flow. A non-dimensional parameter called Taylor number (T_a) is proposed in Ref. [25] and developed by the following studies [26, 27] to describe the relative effects of inertial forces and viscosity in the tangential flow

$$T_{am} = \frac{\Omega_i^2 r_g \delta^3}{\mu^2 F_g}, \quad (4)$$

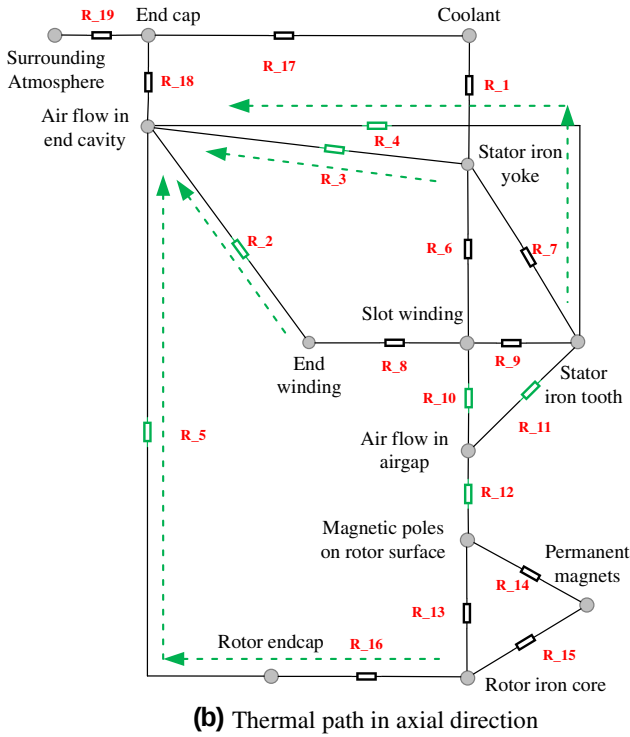
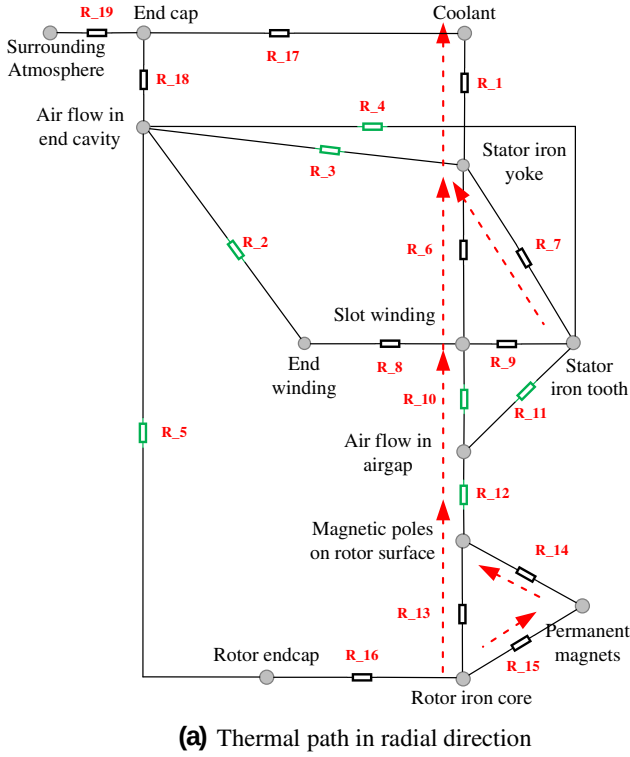


FIGURE 5 Two main heat exchange paths of rotor in the LPTN. LPTN, Lumped Parameter Thermal Network

in which, Ω_i is the mechanical angular velocity of the rotor, r_g is the mean annulus radius, δ is the thickness of the air gap, μ is the air viscosity coefficient, F_g is a geometric factor

$$F_g = \frac{\pi^2}{41.19\sqrt{S}} \left(1 - \frac{\delta}{2r_g}\right)^{-1}, \quad (5)$$

$$S = 0.0571 \left(1 - 0.652 \frac{2\delta}{2r_g - \delta}\right) + 0.00056 \left(1 - 0.652 \frac{2\delta}{2r_g - \delta}\right)^{-1} \quad (6)$$

Taylor-Couette flow exhibits different flowing patterns with the increasing speed [27, 28]:

- (1) When the inner wall's rotational speed is low, the air appears as a circumferentially symmetrical parallel laminar flow called a stable Couette flow. Inertial effects are negligible, and the velocity distribution is dominated by the viscous force
- (2) As the speed increases, the inertial force of the fluid increases. The radial pressure gradient and the viscous forces can no longer restore the centrifugal force's fluctuations caused by minor disturbances. Therefore, the fluid protrudes a secondary flow called Taylor vortices in the meridian plane [29]. The critical speed at which the laminar flow breaks down and the vortices form can be estimated by (7) corresponding to the Taylor number as $T_{am, critical} = 41.19$

$$\Omega_{i, critical} = 41.19 \mu \delta^{-1.5} r_g^{-0.5} \quad (7)$$

- (3) As the speed continues to increase, a relatively steady axisymmetric secondary flow with the regularly spaced vortices in the axial direction is formed. In this case, the adjacent vortices rotate in opposite directions [27].
- (4) As the speed continues to increase, the Taylor vortices flow will lose stability and present a new turbulent flow state with a high degree of disorder.

In conclusion, the airflow presents multi-stage characteristics with increasing speed. The number of stages that the PMSM may go through needs to be determined by doing enough case analysis in the speed range.

Besides, the air gap's surface in an actual motor is commonly far from the ideal case with smooth concentric circle walls. There are horn-shaped slots on its outer surface, as shown in Figure 6. The slotted surface increases the fluctuations of the airflow. Therefore, using theoretical estimation methods is hard to obtain an accurate result. The CFD method is suitable for the following analysis [30].

5.2 | Roughness calibration using windage loss data

The roughness of the convection surface has a non-negligible influence on the airflow state and the convection intensity.

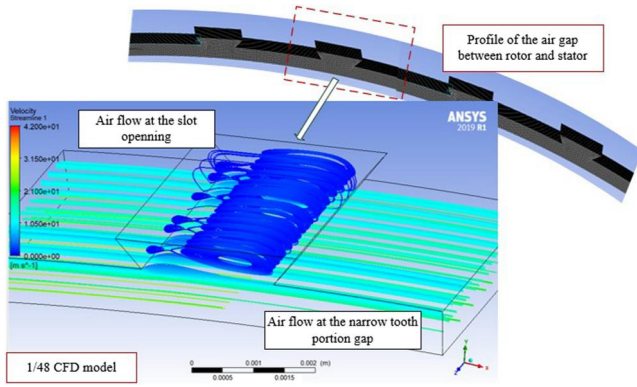


FIGURE 6 The 1/48 CFD model of the airflow in the air gap with horn-shaped slots on its outer surface. CFD, Computational Fluid Dynamics

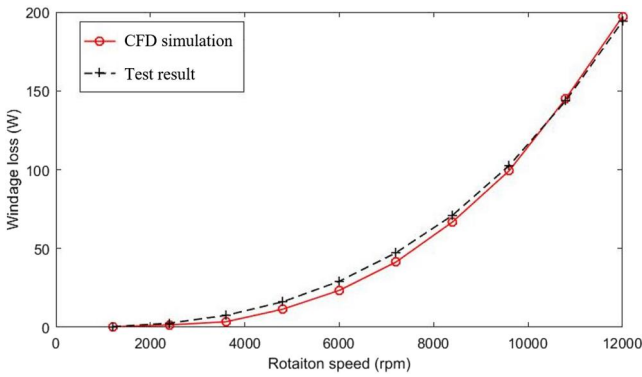


FIGURE 7 Windage losses obtained from the calibrated CFD simulation and the experimental test. CFD, Computational Fluid Dynamics

About 0.35 mm silicon steel sheets stack the iron cores of the stator and rotor. So, there are random bumps in the air gap's inner and outer surfaces, leading to significant uncertainties in simulation.

In this study, the surface roughness parameters used in the model are calibrated by the experimental test result of windage losses. First, a refined 1/48 CFD model of PMSM air gap is constructed using commercial software (ANSYS) to analyse the airflow's aerodynamics characteristics and windage losses, as shown in Figure 6. Meanwhile, the windage losses at different rotational speeds are measured on a test bench. They are then compared and used to calibrate the roughness parameters used in the CFD model, including the surface roughness and uneven surface thickness. As shown in Figure 7, the result of the calibrated CFD model offers a high consistency with the test results at different rotational speeds.

Table 2 lists the variables and settings used in the simulations. The maximum linear velocity of the airflow is below 0.3 Ma, so the density change of gas caused by high-speed compression is ignored. Figure 8 presents the velocity

TABLE 2 Variables and settings used in the CFD simulations

Air density (1 atm), ρ	129 kg/m ³
Air viscosity (80 °C), μ	1.95×10^{-5} Pa·s
Mechanical speed range, w_r	0–12,000 rpm
Surface roughness	0.500
Rough surface thickness	0.0454 mm
Thermal conductivity of air	0.0240 W/(m·K)
Boundary condition	Periodic condition

Abbreviation: CFD, computational fluid dynamics.

component in the axial direction at the different operating points. With the increase of the rotational speed, the airflow in the gap gradually develops into turbulent flow.

5.3 | Convective thermal resistance

For a rough estimation, the heat transfer coefficient of the rotor outer surface can be calculated by [31]

$$h_g = Nu \lambda_{air} / (2\delta), \quad (8)$$

in which, λ_{air} is the thermal conductivity of air, δ is the thickness of the air gap, Nu is the Nusselt number, whose value reflects the strength of convection

$$Nu = \begin{cases} 2\delta[r_{rotor} \ln(1 + \delta/r_{rotor})]^{-1} & T_a < 1700 \\ 0.128(T_a^2/F_g^2)^{0.367} & 1700 < T_a < 10^4 \\ 0.409(T_a^2/F_g^2)^{0.241} & 10^4 < T_a^2/F_g^2 < 10^7 \end{cases} \quad (9)$$

Then the convective thermal resistance can be deduced by

$$R_{Convection} = 1/(h_g A), \quad (10)$$

in which, A is the magnitude of the convection area.

However, due to the irregularity of the surface profile and the non-uniform distribution of the velocity, expressing the heat exchange by a definite convection parameter is not an accurate way in practical usage. Therefore, in the CFD simulation, the thermal convection module and the first kind of boundary conditions with fixed temperatures adopt to calculate the convective thermal resistance according to

$$R_{Convection} = \Delta T_{boundary} / q, \quad (11)$$

in which, $\Delta T_{boundary}$ is the temperature difference between the air and the objects, q is the heat flow rate across the boundary.

As a result, the LPTN thermal model can directly use the derived convective thermal resistances. Figure 9 shows the calculated result of the equivalent thermal resistance between

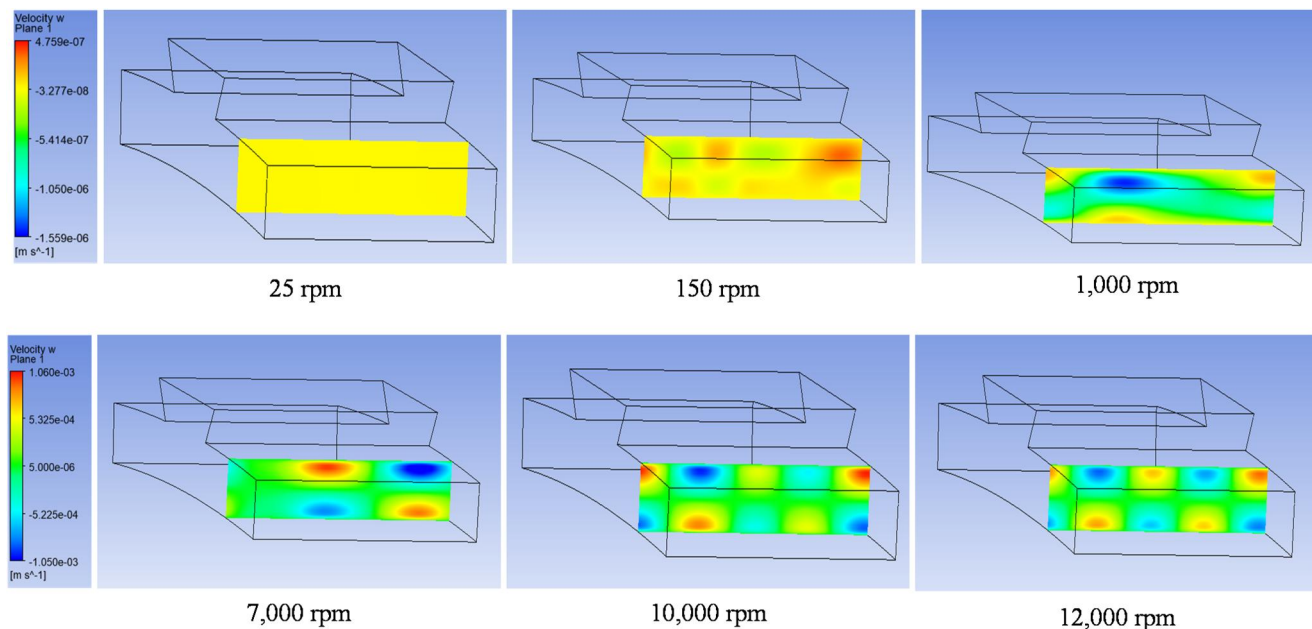


FIGURE 8 The velocity component of the airflow in the axial direction at different rotational speeds (0–12,000 rpm)

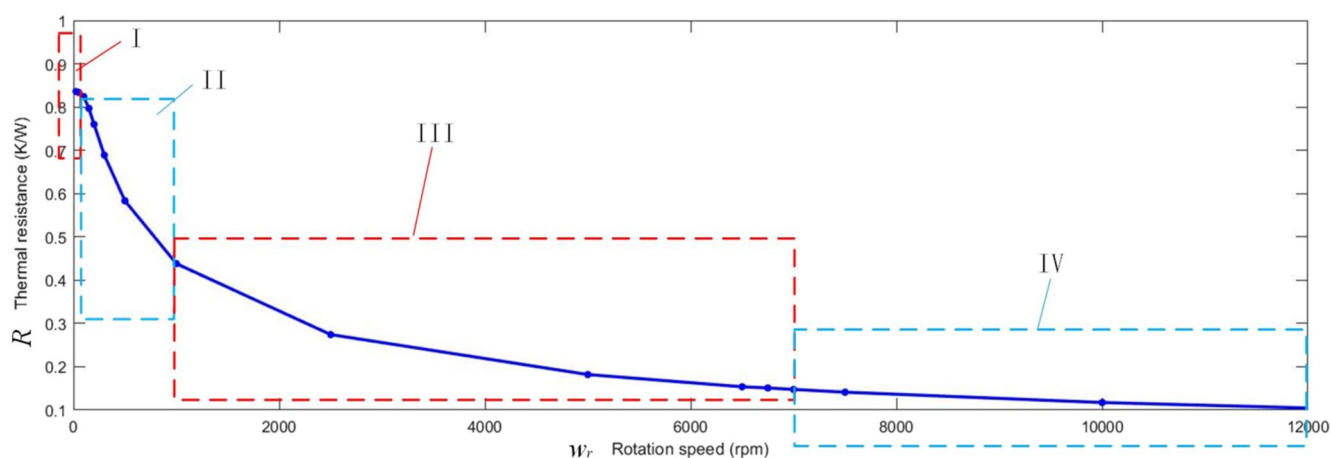


FIGURE 9 The change of convective thermal resistance R_{12} with the rotational speed (0–12,000 rpm)

the rotor and air gap flow in the radial direction (R_{12}) within the speed range of 0–12,000 rpm.

It shows that the laminar flow only appears in a very narrow velocity zone: 0 ~ about 100 rpm (*zone I*). The heat transfer mainly depends on the air's radial heat conduction. And the heat exchange efficiency is low.

When the speed increases to above 100 rpm, slight irregular disturbances appear, and the thermal resistance decreases rapidly in the speed range of 100–1,000 rpm (*zone II*).

As the speed increases to around 1,000 rpm (*zone III*), the decrease of thermal resistance with speed becomes much slower. There is a small step change around 7,000 rpm, at which stable regular Taylor vortices are formed.

When the motor speed exceeds 7,000 rpm (*zone IV*), the curve is almost linear with a shallow gradient.

In general, the CFD calculation results and theoretical analysis form a reasonable mutual verification. For the convenience of application in the onboard thermal model, the calculated thermal resistance data is converted into an analytical form, as shown in the piecewise polynomial fitting result Equation (12). The theoretical study of the aerodynamic characteristics in Equation (4)–(10) reflects a fundamental region division and analytical solution structure for the CFD result. Therefore, the speed-dependence of the radial thermal resistance R_{12} is formulated in four sections:

$$R_{12} = \begin{cases} -1.413 \times 10^{-7} w_r^2 + 1.814 \times 10^{-5} w_r + 0.8285 & 0 \leq w_r \leq 100 \\ 3.583 \times 10^{-7} w_r^2 - 8.284 \times 10^{-4} w_r + 0.9082 & 100 < w_r \leq 1000 \\ 9.947 \times 10^{-9} w_r^2 - 1.253 \times 10^{-4} w_r + 0.5535 & 1000 < w_r \leq 7000 \\ -7.229 \times 10^{-6} w_r + 0.2144 & 7000 < w_r \leq 12000, \end{cases} \quad (12)$$

in which, w_r is the mechanical rotation velocity (rpm).

Similarly, the convective thermal resistances between the air gap flow and stator (R_{10} , R_{11}) can be calculated using the method introduced above.

6 | CONVECTIVE THERMAL RESISTANCES IN END-CAVITY

When the PMSM is rotating, the air in the end-cavity will be driven by the viscous force, forming a strong convective heat transfer with the envelope surfaces. Therefore, the convection on these surfaces is an important heat dissipation path, especially at high-speed operation [32, 33]. Reference [27] provides a detailed theoretical analysis of the free-disk flow. However, it is still challenging to obtain the convections on the complex end-cavity profile, as shown in Figure 10a. A CFD model is constructed in this study to analyse the aerodynamics characteristics and the convection, as shown in Figure 10b.

The airflow in the end-cavity is driven by the rotating end surface of the rotor and, at the same time, constrained by the static inner contour surfaces, as illustrated in Figure 10. Eventually, a spiral airflow with an enormous velocity gradient is formed. The staggered streamlines show that the airflow has

developed a good mix in the end-cavity. Besides, the vortices are randomly generated in the irregular streamlines, and there is no stable state point like the Taylor-Couette flow.

In the end-cavity, convection mainly occurs in these four faces (marked in Figure 11): the outer surface of the rotor endcap (rotating), the outer surface of the end-winding, the inner surface of the endcap, and the inner surface of the housing.

Based on the CFD simulation results at different rotational speeds, the convective thermal resistances on the above surfaces are deduced and shown in Figure 12.

In general, the changes of the convective thermal resistances with the speed w_r can be divided into two sections in the speed range of 0–12,000 rpm. At the low-speed section (0–3000 rpm), the convective thermal resistances decrease drastically with rotational speed. When the rotational speed exceeds 3000 rpm, the decrease slows down and gradually develops into a linear trend. Take the convective thermal resistance between the outer surface of the end-winding and the air as an example:

$$R_{2} = \begin{cases} 5.182 \times 10^{-8} w_r^2 - 8.44 \times 10^{-4} w_r + 2.991 & 0 \leq w_r \leq 3000 \\ -4.605 \times 10^{-5} w_r + 1.0635 & 3000 \leq w_r \leq 12000 \end{cases} \quad (13)$$

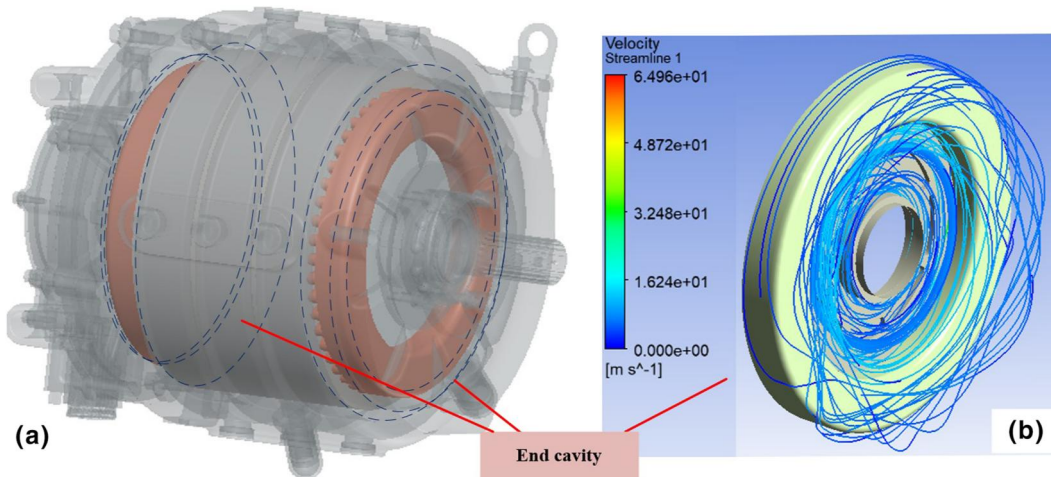


FIGURE 10 CFD simulation result of airflow in the end-cavity dragged by the rotor (speed $w_r = 8000$ rpm). CFD, Computational Fluid Dynamics

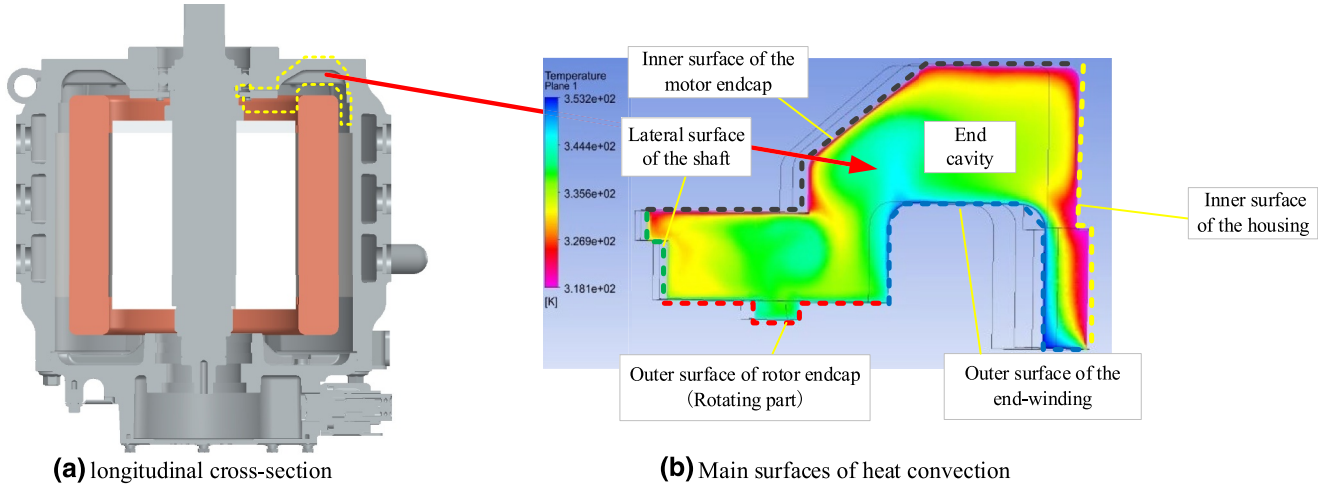
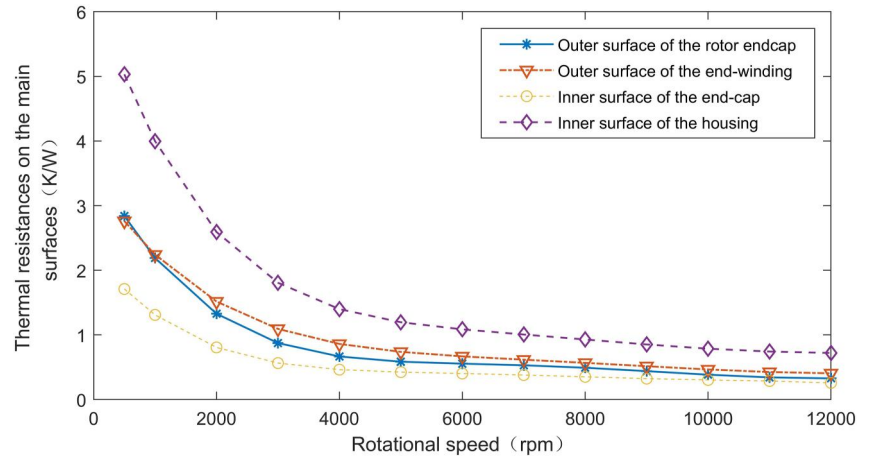


FIGURE 11 The four main convection surfaces in the end-cavities of the PMSM. PMSM, Permanent Magnet Synchronous Motor

FIGURE 12 The convective thermal resistances on the four main envelope surfaces of the end-cavity with the increasing speed



The LPTN thermal model of the PMSM is transformed into ime-discrete differential equations below for the convenience of real-time calculation in the motor control system [34]

$$[T]_{(i+1)} = \Delta\tau [C]^{-1} [A]_{(i)} + I [T]_{(i)} + \Delta\tau [C]^{-1} [Q]_{(i)}, \quad (14)$$

$$\begin{aligned} [C] &= \begin{bmatrix} C_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & C_n \end{bmatrix} \quad [T] = \begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} \\ [A] &= \begin{bmatrix} A_{11}(w_r) & \cdots & A_{1n}(w_r) \\ \vdots & \ddots & \vdots \\ A_{n1}(w_r) & \cdots & A_{nn}(w_r) \end{bmatrix} \\ [Q] &= \begin{bmatrix} Q_1 \\ \vdots \\ Q_n \end{bmatrix} = \begin{bmatrix} K_1(T_1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & K_n(T_n) \end{bmatrix} \begin{bmatrix} Q_1^{ref} \\ \vdots \\ Q_n^{ref} \end{bmatrix} \end{aligned} \quad (15)$$

in which, T_k is the temperature increment above the reference temperature T_{ref} at the k th node, C_k is the thermal capacity of

the k th node, and Q_k is the loss rate in it. i represents the time node, and $\Delta\tau$ is the size of the time step, Q_n^{ref} is the loss rate at the reference temperature. Table 3 lists the analytical equations of the loss components used in the thermal model. Table 4 explains the variables used in the equations. $K_k(T_k)$ is the temperature coefficient of nodal loss determined by the material.

In the thermal model described in Equation (14), the matrix $[A]$ is the lumped parameters derived from the thermal resistances, including the constant conductive and the rotation-dependent convective thermal resistances.

It is worth mentioning that the constant conductive thermal resistances and the heat capacity parameters in the final form of the optimised thermal model have been trained and calibrated with plenty of experimental data to improve the transient accuracy under changing operating conditions.

7 | EXPERIMENTAL VALIDATION

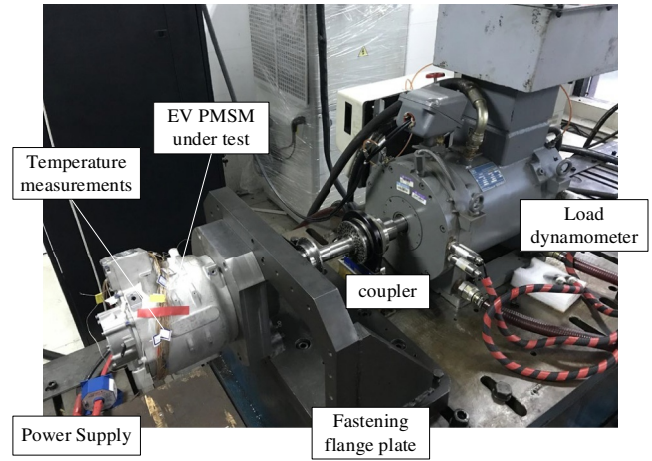
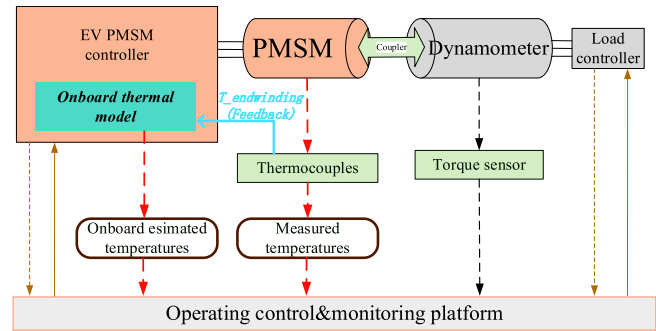
To validate the improvement after using the rotation-dependent convective thermal resistances in the onboard thermal model, the experimental bench test is carried out on

TABLE 3 Analytical expressions of the loss components used in the thermal model

Parts	Analytical expressions of the loss components
Slot winding	$P_{ac,act} = P_{dc,act} \sum_n K_{ac,slot}$, in which, $P_{dc,act} = \frac{2N_f^2 l_A \rho_0}{\pi d^2}$
End-winding	$P_{ac,end} = P_{dc,end} n K_{ac,end}$, in which, $P_{dc,end} = \frac{2N_f^2 l_E \rho_0}{\pi d^2}$
Stator iron yoke and iron tooth	Hysteresis loss $p_b = V \cdot \sum_{n=1}^{n_{loop}} K_b f_1 B_m$ Eddy current loss $p_e = V \cdot \sum_{k=1}^{N_f} K_e f_k^2 B_m^2$
Rotor iron core	$p_{rc} = [a, b] \cdot [f_1^2, f_1]^T$
Permanent magnets	$p_{PM} = [p, q] \cdot [f_1^2, f_1]^T$
Air flows in the air gap and the end-cavity	$P_{airgap} = k_s C_f \pi \rho_a \omega_r^3 d_{rotor}^4 L$, $P_{airgap} = [x, y, z] \cdot [\omega_r^3, \omega_r^2, \omega_r]^T$
Bearing	$P_{Bearing} = 0.5 \omega_r k_{fr} F d$

TABLE 4 Variables used in the loss estimation equations

l_A	Average length of the winding part in the slot
l_E	Average length of the end-winding part out of the slot
n	Number of wires in one slot
d	Diameter of the copper wire
I_s	Amplitude of the input current
ρ_0	Electrical resistivity of copper at reference temperature
N	Slot number
$K_{ac,act}$	Ac loss factor of the active winding part in the slot
$K_{ac,end}$	Ac loss factor of the end-winding
K_b, K_e	Hysteresis loss coefficient; eddy current loss coefficient
f_1, f_k	Fundamental and harmonic frequencies of power supply
B_m	Amplitude of the flux density
V	Volume of the nodal area
a, b, p, q, u, v, w	Polynomial coefficients obtained by curve fitting
k_s	Surface roughness factor of air gap surfaces
ρ_a	Air density
ω_r	Rotational angular velocity
L	Axial length of the rotor active part
d_{rotor}	Rotor outer diameter
C_f	Surface friction coefficient, determined by Re number
k_{fr}	Bearing friction coefficient
F	Dynamic load

**FIGURE 13** Experimental bench test on the electric pulsion system**FIGURE 14** Illustration of the experimental tests system

the electric pulsion system shown in Figure 13. The framework of the test system is illustrated in Figure 14.

The PMSM is controlled by an EV motor controller and connected with a load dynamometer. During the operation, the onboard thermal model collects the operation information of the PMSM to estimate the nodal temperatures of the PMSM. Meanwhile, the temperature of the end-winding is feedback to

the onboard thermal model to eliminate the accumulation of the transient error. The temperature distribution in the static part of the PMSM is measured by thermocouples embedded in the motor. The rotor is a nearly solid metal cylinder, so its temperature is assumed to be uniformly distributed [35]. The rotor temperature is collected by an infrared detector, and a small hole was made in the endcap to transmit the signal.

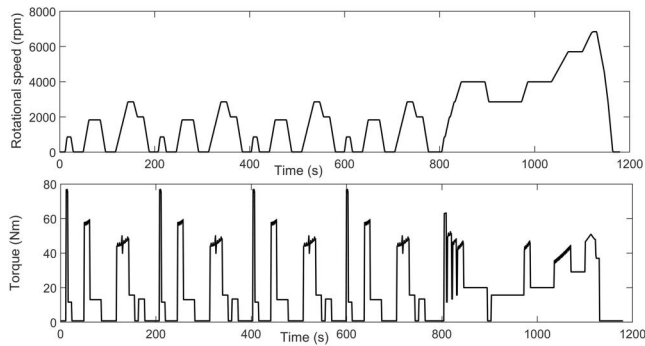


FIGURE 15 The standard driving cycle used in the test

FIGURE 16 The comparison of the rotor temperatures estimated by the original and the optimised onboard thermal models with the measurement result

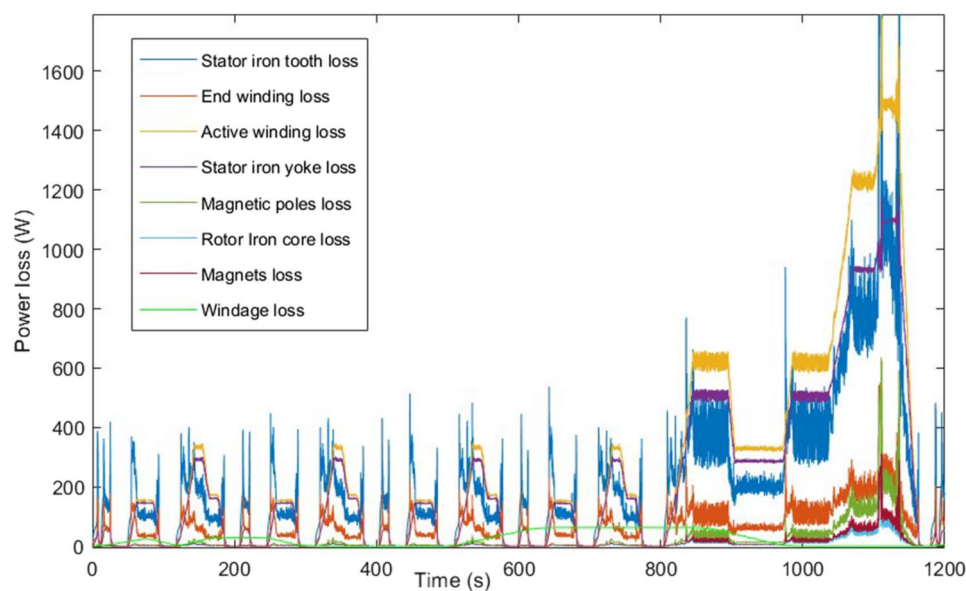
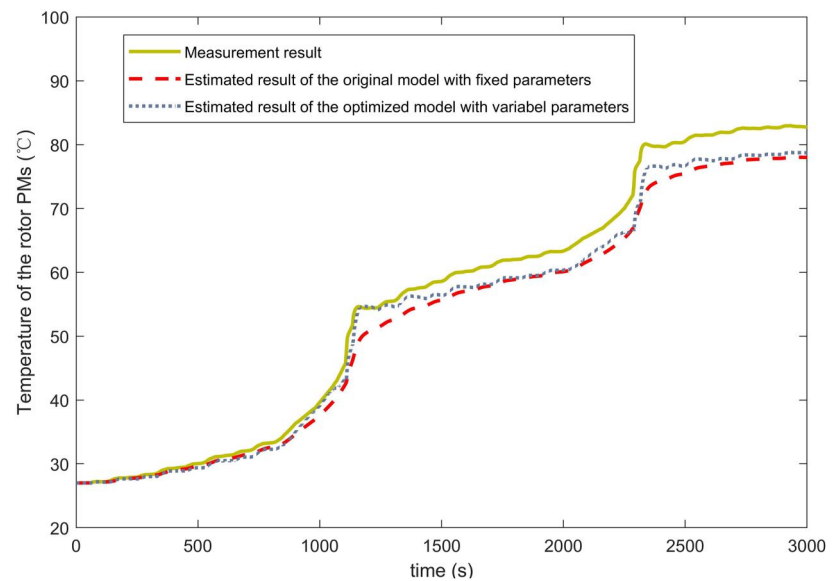


FIGURE 17 The nodal losses estimated by the optimised model

The temperature of the rotor is estimated by the traditional and the optimised onboard thermal models to validate the promotion after using the rotation-dependent convective thermal resistances. Figure 15 shows the standard EV driving cycle used in the test. The motor starts running from a known temperature along with the thermal model. The onboard model estimated results are compared with the measurement results in Figure 16. In addition, the nodal losses estimated by the optimised onboard thermal model are presented in Figure 17.

For a better illustration, Figure 18 shows the temperature estimation error of these two onboard thermal models. It shows that the estimation error gradually increases over time

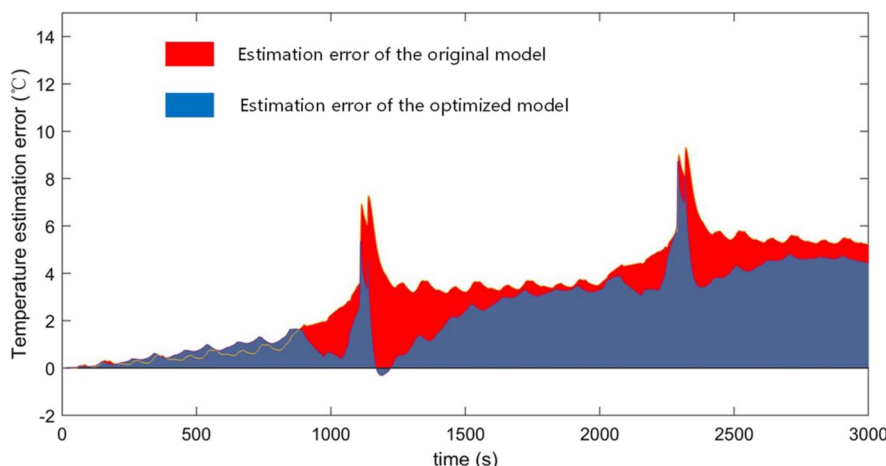


FIGURE 18 The temperature estimation error of the original and the optimised onboard thermal model

and approaches flattening. It is clear that the estimation accuracy is improved by using the rotation-dependent convective thermal resistances, especially at the moments where the speed changes drastically. In other words, the new model became more sensitive to the actual operation state of the EV motor.

According to the statistics of the rotor temperature data in Figure 17, the average error has been reduced by about 11%. In addition, the increment of calculation amount after using the variable parameters is evaluated and proven to be negligibly small for the EV motor controller.

8 | CONCLUSION

The onboard model-based estimation method is an economical option to improve the thermal safety of the high-speed PMSM. In this paper, several essential parameters in the thermal model have been improved, and a significant increase in estimation accuracy has been achieved.

However, the onboard thermal model still needs to be improved in many aspects. For example, the thermal conductivities and the electromagnetic parameters of the materials will change with the usage time. Also, the residual magnetism of the PMs may decrease even without apparent damage. These issues require the onboard thermal model to be more flexible on the time scale.

Besides, the study concluded that the thermal boundary conditions have a substantial effect on the temperature rise of the rotor. The slots on the inner wall of the stator enhance the disturbance of the airflow in the air gap, which then impacts the heat exchange and the temperature rise of the rotor. The vortices in the air gap form a stronger radial flow component, which strengthens the heat transfer of the rotor. Thus, considering the compromise between windage loss and heat transfer, there may be an optimal solution for the stator inner profile for the high-speed thermal issue.

Besides, in recent years, a more efficient internal oil cooling method has been widely used in automotive motors. Establishing a precise relationship between the convective thermal

resistance and the intensity of the oil spray force at different rotational speeds is very important to the thermal management of the motors. It should be noted that the temperature has a significant effect on fluid viscosity.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

CONFLICT OF INTEREST STATEMENT

All the authors have no conflict of interest to disclose.

ORCID

Tenghui Dong  <https://orcid.org/0000-0003-1823-0595>

REFERENCES

1. Cai, X., et al.: Thermal modeling of flux-switching permanent-magnet machines considering anisotropic conductivity and thermal contact resistance. *IEEE Trans. Ind. Electron.* 63(6), 3355–3365 (2016)
2. Sun, T., et al.: Active motor rotor temperature management based on one-node thermal network model predictive control. *IEEE Trans. Power Electron.* 35(10), 11213–11221 (2020)
3. Mo, L., et al.: Temperature rise calculation of a flux-switching permanent-magnet double-rotor machine using electromagnetic-thermal coupling analysis. *IEEE Trans. Magn.* 54(3), 1–4 (2018)
4. Calin, M., Helerea, E.: Temperature influence on magnetic characteristics of NdFeB permanent magnets. In: *International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, pp. 1–6. (2011)
5. Ruoho, S., et al.: Interdependence of demagnetization, loading, and temperature rise in a permanent-magnet synchronous motor. *IEEE Trans. Magn.* 46(3), 949–953 (2010)
6. Du-Bar, C., et al.: Design of an online temperature monitoring system for an experimental IPMSM. In: *XXII International Conference on Electrical Machines*, pp. 1533–1538 (2016)
7. Huang, Z., et al.: Loss calculation and thermal analysis of rotors supported by active magnetic bearings for high-speed permanent-magnet electrical machines. *IEEE Trans. Ind. Electron.* 63(4), 2027–2035 (2016)
8. Solar, H., et al.: A robust, -40° to $+150^{\circ}\text{C}$ wireless rotor temperature monitoring system based on a fully passive UHF RFID sensor tag. In: *Microwave Symposium* (2014)
9. Brahim, S.B., et al.: A wireless on-line temperature monitoring system for rotating electrical machine. *Wireless Pers. Commun.*, 1–21 (2016)

10. Nategh, S., et al.: Thermal analysis of a PMSRM using partial FEA and lumped parameter modeling. *IEEE Trans. Energy Convers.* 27(2), 477–488 (2012)
11. Ganchev, M., Kral, C., Wolbank, T.: Hardware and software implementation of sensorless rotor temperature estimation technique for permanent magnet synchronous motor. In: *Electrical Systems for Aircraft*, pp. 1–6. Railway and Ship Propulsion (2012)
12. Ganchev, M., et al.: Sensorless rotor temperature estimation of permanent magnet synchronous motor. In: *37th Annual Conference of the IECON 2011*, pp. 2018–2023. IEEE Industrial Electronics Society (2011)
13. Reigosa, D.D., et al.: Magnet temperature estimation in surface PM machines using high-frequency signal injection. *IEEE Trans. Ind. Appl.* 46(4), 1468–1475 (2010)
14. Hey, J., et al.: Online monitoring of electromagnetic losses in an electric motor indirectly through temperature measurement. *IEEE Trans. Energy Convers.* 31(4), 1347–1355 (2016)
15. Sciascera, C., et al.: Analytical thermal model for fast stator winding temperature prediction. *IEEE Trans. Ind. Electron.* 64(8), 6116–6126 (2017)
16. Kral, C., Haumer, A., Sang, B.L.: A practical thermal model for the estimation of permanent magnet and stator winding temperatures. *IEEE Trans. Power Electron.* 29(1), 455–464 (2013)
17. Kubaisi, R., Gauterin, F., Giessler, M.: A method to analyze driver influence on the energy consumption and power needs of electric vehicles. In: *IEEE International Electric Vehicle Conference (IEVC)*, pp. 1–4 (2014)
18. Wallscheid, O., et al.: A critical review of techniques to determine the magnet temperature of permanent magnet synchronous motors under real-time conditions. *EPE J.* 26(1), 1–10 (2016)
19. Wrobel, R., et al.: Power Loss Analysis in Thermal Design of Permanent Magnet Machines—A Review, pp. 1. *IEEE Transactions on Industry Applications* (2016)
20. Wrobel, R., et al.: Impact of Slot Shape on Loss and Thermal Behaviour of Open-Slot Modular Stator Windings. *Energy Conversion Congress and Exposition* (2015)
21. Mellor, P.H., Roberts, D., Turner, D.R.: Lumped parameter thermal model for electrical machines of TEFC design. *Electric Power Appl. IEE Proc. B [see also IEE Proc. Electric Power Appl.]* 138(5), 205–218 (1991)
22. Boglietti, A., et al.: Stator-winding thermal models for short-time thermal transients: Definition and validation. *IEEE Trans. Ind. Electron.* 63(5), 2713–2721 (2016)
23. Holtmann, C., Rinderknecht, F., Friedrich, H.E.: Thermal model of electric machines with correction of critical parameters. In: *IEEE International Electric Machines and Drives Conference*, pp. 1–8 (2017)
24. Wang, W., Yuan, X.: Lumped-parameter-based thermal analysis for virtual prototyping of power electronics systems. In: *IET International Conference on Power Electronics* (2016)
25. Geoffrey, T.: Distribution of velocity and temperature between concentric rotating cylinders. *Proc. R. Soc. Lon. A, Math. Phys. Sci.* 151(874), 494–512 (1935)
26. Becker, K.M., Kaye, J.: Measurements of diabatic flow in an annulus with an inner rotating cylinder. *J. Heat Transfer* 84(2), 97–104 (1962)
27. Howey, D.A., Childs, P.R.N., Holmes, A.S.: Air-gap convection in rotating electrical machines. *IEEE Trans. Ind. Electron.* 59(3), 1367–1375 (2012)
28. Kim, K., Lee, B., Hong, J.: Improvement of thermal equivalent circuit network and prediction on heat characteristic of motor by calculation of convection heat transfer coefficient. In: *Sixth International Conference on Electromagnetic Field Problems and Applications*, pp. 1–4 (2012)
29. Faist, H., Eckhardt, B.: Transition from the Couette-Taylor system to the plane Couette system. *Phys. Rev. E* 61(6 Pt B), 7227–7230 (2000)
30. Staton, D., Boglietti, A., Cavagnino, A.: Solving the more difficult aspects of electric motor thermal analysis in small and medium size industrial induction motors. *IEEE Trans. Energy Conv. Manage.* 20(3), 620–628 (2005)
31. Churchill, S.W.: Correlations for laminar forced convection in flow over an isothermal flat plate and in developing and fully developed flow in an isothermal tube. *J. Heat Transfer* 95(3), 416–419 (1973)
32. Liang, D., et al.: Influence of critical parameters in lumped-parameter thermal models for electrical machines. In: *22nd International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1–6 (2019)
33. Li, M., An, Y., Zhang, Z.: Improving thermal analysis accuracy of LPTN for vehicle claw-pole alternator by calibrating forced convection coefficients based on experimental results. *IEEE Access.* 7, 129327–129334 (2019)
34. Mellor, P., Wrobel, R., Simpson, N.: AC losses in high frequency electrical machine windings formed from large section conductors. In: *Energy Conversion Congress and Exposition (ECCE)* (2014)
35. Phuc, P.N., et al.: Rotor temperature virtual sensing for induction machines using a lumped-parameter thermal Network and dual Kalman filtering. *IEEE Trans. Energy Convers.* 36(3), 1688–1699 (2021)

How to cite this article: Dong, T., Nakamura, T.: Research on the speed-dependence of heat convection in high-speed EV motors and its application in the model-based rotor temperature monitoring technology. *IET Electr. Power Appl.* 16(12), 1452–1463 (2022). <https://doi.org/10.1049/elp2.12197>