Advanced rotor temperature estimation of permanent magnet synchronous machines for electric vehicles

Changhong Du¹, Zhiyuan Peng¹, Yong Ren², Anjian Zhou¹, Yongquan Ma¹, Jian Chen¹ and Tao Deng³

Abstract
The actual power capacity of permanent magnet synchronous machine for electric vehicles is usually limited by rotor temperature, and rotor overheating is one of the major reasons for permanent magnet synchronous machine failure. Therefore, an approach of rotor temperature estimation is proposed to improve motor peak power utilization and protect permanent magnet synchronous machine from serious demagnetization due to thermal damage. A real-time iterative algorithm is provided based on the equivalent thermal model for rotor temperature. First, the heat generating principle of each part as well as the power flow transferring of the motor system is analyzed. Second, rotor temperature model is built based on the conservation of energy loss from the stator and real-time superposition of temperature variation rate for the rotor. Finally, the motor performance test bench is built to validate the proposed algorithm and numerical models are also constructed to simplify estimation parameters for rotor temperature model. The algorithm accuracy is improved and verified by optimizing control parameters with given environment temperature and power load. The experimental result shows that the maximum error between actual test value and estimation value is within ± 10°C, and it meets the requirement of algorithm accuracy and also benefits on system performance and manufacture cost efficiently.

Keywords
Electric vehicle, convective heat transfer, motor, cooling, temperature control

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Introduction
Permanent magnet synchronous motor (PMSM) plays an important role in electric vehicle industry due to its advantages including high power density, high operation efficiency, as well as excellent start torque, and the present researches focus on how to improve motor thermal safety and excellent torque capability with smaller size. Copper, eddy-current, and hysteresis losses are responsible for an abundant temperature rise in magnets, and temperature is the core limiting factor for how long PMSM can continuously be loaded. The development of rotor temperature model (RTM) is not only a safety issue but also a performance issue. On one
hand, the magnet intrinsic coercivity is a function of temperature performance and its absolute value decreases with the increase in temperature. When the rotor temperature exceeds limiting value, irreversible demagnetization occurs in magnets.\(^1\)\(^2\)\(^3\) In general, PMSM design should ensure that no irreversible demagnetization occurs in expected operation condition. On the other hand, PMSM torque usage expectation is lower than its fact capability without high accurate rotor temperature estimation (RTE) to avoid its overheating and thermal damage.\(^4\)\(^5\)\(^6\) In addition, PMSM dimension can be avoided to cut down the cost of magnetic material usage if real-time RTE is available to assure continuous safe operation mode for motor. Usually, measuring the temperature of the rotor permanent magnet is very difficult by equipping sensors to rotate the body directly. Some common techniques include slip rings, infrared sensors, and wireless temperature device. Compared with direct measuring of temperature by embedding temperature measuring devices into motor integration, implementing real-time thermal model in motor controller is a cost-effective and rapid response protection method, but real-time RTE currently still faces some challenges on thermal model complexity, algorithm operation safety, as well as temperature estimation accuracy. According to this research, there are three main categories to estimate rotor temperature of the motor. The first method is the traditional experience formula which indirectly measures some parameters correlated with RTE to obtain the expected value of rotor temperature.\(^7\)\(^8\)\(^9\) The second method is the finite element analysis which builds thermal resistance between each unit and forms thermal network to verify estimation results by inputting compensation units into thermal network model.\(^10\)\(^11\)\(^12\) The final method is to measure counter electromotive force and calculate remaining field density used to look up the table with actual rotor temperature for PMSM.\(^13\)\(^14\)\(^15\) Based on previous arguments, there are still several disadvantage factors to estimate rotor temperature under actual operation state for PMSM. First, there is ignorance of rotor temperature variation after vehicle system powers off, especially in the condition of natural cooling, so there is no way to obtain the initial value of rotor temperature when vehicle system powers on again. Second, there is just consideration for the magnet temperature properties with the normal environment to bring the low level of robustness and estimation accuracy at the present, so it is necessary to optimize the algorithm by combining important factors such as environment temperature. Finally, it cannot be applied to unload the driving current during the actual motor operation when we adopt counter electromotive force to obtain the rotor temperature indirectly.

Although RTE has been studied, there are still other problems such as large parameter dependence, complicated measuring, and computation. In order to solve these problems, an iterative algorithm is provided based on the equivalent thermal model to estimate real-time rotor temperature and it is necessary to equate and simplify thermal model with fewer control parameters and computation. Hence, an applicable and advanced RTM is proposed to predict the real-time thermal performance of PMSM. First, the power loss of each part is analyzed and the power flow transferring of PMSM is described. At the same time, RTMs with fewer control parameters are constructed precisely based on conservation of energy loss from the stator. Second, the control strategy is introduced based on different operation states and numerical models which are provided to support RTM algorithm. Finally, the performance test bench for PMSM is built and a series of experiments are carried out on the hardware and software of PMSM controller to verify whether the RTM estimation accuracy meets the requirement with different environment temperature and variation power load.

### Thermal analysis based on PMSM power loss

In order to attain actual rotor temperature precisely, the essential reason for heat generation should be deeply explored and the principle of energy flow transfer among motor thermal nodes is described in Figure 1. Based on motor operation state, important factors of thermal effect are analyzed and power loss models of thermal nodes are built. There are four parts of power loss such as copper power loss, iron power loss, mechanical loss, and heating power of the stator for PMSM. The energy flow transferring diagram is shown in Figure 1.

![Figure 1: Energy flow analysis for main parts.](image)
loss, mechanical power loss, and cooling power loss, respectively.16–18

Copper loss analysis

Copper loss power \( P_{Cu} \) contributes the most percentage of power loss during motor operation state due to the heat generated by internal resistance when three-phase current goes through the stator. Here, it is assumed that phase current distributes on the section of the stator winding equably and the winding copper loss can be calculated as 6,19

\[
P_{Cu} = 3I_{Phase}^2R_{Phase}
\]

where \( I_{Phase} \) is the phase current of the motor and \( R_{Phase} \) is the resistance of each phase at temperature \( T \) which can be obtained as

\[
R_{phase} = \frac{R_{20}(235 + T)}{(235 + 20)}
\]

where \( R_{20} \) is the resistance of the stator winding at 20°C.

Iron loss analysis

Iron loss power \( P_{iron} \) consists of hysteresis loss power and eddy loss power. Hysteresis loss power is caused by alternating magnetic field generated from alternating current, while eddy loss is caused by induced current which generated by variational magnetic field. Therefore, iron loss power can be expressed with the following empirical equation 20,21

\[
P_{iron} = k_0fB_m^2 + k_fB_m^2 + k_{ex}f^{1.5}B_m^{1.5}
\]

where \( B_m \) is the maximum magnetic flux density for PMSM, \( f \) is the alternating frequency for armature magnetic field, \( k_0 \) is the hysteresis loss coefficient, \( k_f \) is the eddy loss coefficient, and \( k_{ex} \) is the extra loss coefficient.

Mechanical loss analysis

Mechanical loss \( P_{mech} \) consists of friction loss caused by bearing turning and damping loss caused by the air flow. Therefore, the equation of mechanical loss is expressed as 22,23

\[
P_{mech} = k_cC_f\rho_\text{air}\omega_m^3r^4l
\]

where \( k_c \) is the coarseness coefficient, \( C_f \) is the friction coefficient, \( \rho_\text{air} \) is the air density, \( \omega_m \) is the angle speed of motor, \( r \) is the radius of rotor, and \( l \) is the length of rotor.

Cooling loss analysis

Cooling loss consists of two parts: one is absorbed by cooling water in the cooling circuit and the other is consumed by the stator and the rotor to the atmosphere. Therefore, cooling loss for water can be concluded by the following empirical equation 24,25

\[
P_w = \rho_wC_wA_w\nu(T_{in} - T_{out})
\]

where \( \rho_w \) is the water density; \( C_w \) is the specific heat of water; \( A_w \) is the section area of the cooling circuit; \( \nu \) is the flow speed of cooling water; \( T_{in} \) and \( T_{out} \) are the water temperature of inlet and outlet, respectively; and \( t_1 \) and \( t_2 \) are the interval time points of sample periods.

In addition, cooling power which comes from the stator and the rotor to the atmosphere can be expressed by the following empirical equations 26,27

\[
P_{s-air} = \frac{8A_s(T_s - T_{eir})}{(t_2 - t_1)}
\]

\[
P_{r-air} = \frac{8A_r(T_r - T_{eir})}{(t_2 - t_1)}
\]

where \( A_s \) and \( A_r \) are the section areas of the stator and the rotor, respectively; \( T_s \) and \( T_r \) are the current temperature of the stator and the rotor, respectively; \( T_{eir} \) is the environment temperature; and \( \delta \) is the coefficient of heat transfer which can be expressed as

\[
\delta = 9.73 + 14V^{0.62}
\]

where \( V \) is the speed of air flow on heat exchange surface.

Equivalent estimation for RTM

The effect of RTE is greatly influenced by factors of operation states and environment temperature. Therefore, actual RTM which is embedded into PMSM controller should be simplified to the equivalent estimation model based on theory and experiment method.

RTM for motor operation state

According to the power flow analysis of main thermal nodes from Figure 1, it is concluded that heating power of the stator \( P_s \) mainly consists of three parts including copper loss power \( P_{Cu} \), iron loss power \( P_{iron} \), as well as mechanical loss \( P_{mech} \) based on conservation of energy as

\[
P_s = P_{Cu} + P_{iron} + P_{mech}
\]
principle according to following classical equations respectively\textsuperscript{28,29}

\[ P_s = \frac{C_s M_s (T_{s2} - T_{s1})}{(t_2 - t_1)} \quad (10) \]

\[ P_r = \frac{C_r M_r (T_{r2} - T_{r1})}{(t_2 - t_1)} \quad (11) \]

where \( C_s \) and \( C_r \) are the specific heat of the stator and the rotor, respectively; \( M_s \) and \( M_r \) are the mass of the stator and the rotor, respectively; \( T_{s1} \) and \( T_{s2} \) are the stator temperatures at interval time-points of sample period; and \( T_{r1} \) and \( T_{r2} \) are the rotor temperatures at interval time-points of sample period.

Meanwhile, the stator will liberate heat energy to the atmosphere using cooling water and the rotor acts as a heating energy resource. Therefore, the absorbing heat of the rotor can be concluded based on the conservation of energy as

\[ P_r = P_s - P_w - P_{s-air} - P_{r-air} \quad (12) \]

Combining equations (5)–(12), real-time rotor temperature \( T_{r\text{-real}} \) of PMSM operation state can be obtained by iterative algorithm as

\[ T_{r\text{-real}} = T_{r2} = T_{r1} + \Delta T_r \quad (13) \]

\[ \Delta T_r = \frac{C_s M_s (T_{s2} - T_{s1}) - (P_w + P_{s-air} + P_{r-air})(t_2 - t_1)}{C_r M_r} \quad (14) \]

here, the value of \( T_{r1} \) is replaced by that of \( T_{r2} \) continuously to attain real-time estimation results \( T_{r\text{-real}} \) during motor operation state.

**RTM for motor stationary state**

When motor comes to the stationary state, the rotor, acting as a heating energy resource, liberates heat energy to the atmosphere and its temperature goes down to the environment temperature with stationary time. Therefore, temperature variation regulation of the natural cooling state should be explored. When vehicle is on, rotor initial temperature is attained by adopting the previous rotor temperature \( T_{r\text{-pre}} \), stationary time \( t_{stop} \), and environment temperature \( T_{evir} \) as follows:

1. Read values of \( T_{r\text{-pre}} \) and \( t_{stop} \) are stored in electrically erasable programmable read-only memory (EEPROM) of motor controller last time.
2. Receive value of environment temperature \( T_{evir} \) from air-condition controller, and initialization time-point \( t_0 \) can be captured by looking up the experimental result table of rotor temperature variation with stationary time under the 10°C interval between operation environment temperatures \( T_1 \) and \( T_2 \) from Figure 2.
3. According to stationary time \( t_{stop} \), current rotor initial temperature (such as \( T_{r\text{-init}(T1)} \)) can be obtained at time point \( (t_0 + t_{stop}) \) by looking up the table of rotor temperature variation under different environment temperatures from Figure 2.
4. Finally, rotor initial temperature \( T_{r\text{-init}(T)} \) at different environment temperatures \( T_{evir} \) can be matched as follows

\[ T_{r\text{-init}(T)} = \xi T_{r\text{-init}(T1)} + (1 - \xi) T_{r\text{-init}(T2)} \quad (15) \]

where \( T_{r\text{-init}(T1)} \) and \( T_{r\text{-init}(T2)} \) are the rotor initial temperatures at environment temperatures \( T_1 \) and \( T_2 \), respectively, and \( \xi \) is the fitted coefficient depending on actual environment temperature zone between \( T_1 \) and \( T_2 \). When vehicle is power-on initially, the value of \( T_{r1} \) in equation (13) is equal to that of \( T_{r\text{-init}} \) in equation (15).

**Rotor temperature control strategy**

According to the previous RTM, a comprehensive control strategy is built to estimate the real-time rotor temperature which is fit for different environment temperatures and motor operation states. There are two main parts to be described in detail.

**Control algorithm procedure**

Algorithm process is developed based on previous RTM in Figure 3. First, power supply state and actual operation state of electric vehicle should be determined.
by signals of vehicle speed and gear position to meet requirement of real-time estimation on rotor temperature. Second, RTM is used to predict rotor temperature according to motor actual state. And then, rotor temperature should be modified in appropriate condition due to accumulation error generated by iterative algorithm. Finally, rotor temperature should be stored in EEPROM of motor controller when vehicle comes to power down. 

$$\begin{align*}
  n_{cal-1} &\leq |n_{mot}| \leq n_{cal-2} \\
  |T_{mot-trq}| &\leq T_{cal} \\
  \Delta \psi_{mot} &\leq \Delta \psi_{cal}
\end{align*}$$

where $n_{mot}$ is the actual motor speed; $n_{cal-1}$ and $n_{cal-2}$ are the low- and high-level limitations of motor speed for calibration, respectively; $T_{mot-trq}$ is the actual motor torque; $T_{cal}$ is the motor torque limitation for calibration; $\Delta \psi_{mot}$ is the motor actual flux linkage changing rate; and $\Delta \psi_{cal}$ is the motor flux linkage variation rate for calibration.

**Software framework description**

According to previous RTM and algorithm process of RTE, algorithm framework can be built to develop software details. There are five main parts from Figure 4 to describe their functionalities, respectively, as follows:

1. Stator loss power model is responsible for calculation of the stator loss power based on the stator temperature;
2. Cooling loss power model is responsible for calculation and calibration of cooling loss power based on the stator temperature changing rate from the stator loss power model;
3. Rotor temperature look-up table with enable model is responsible for judging whether to enable look-up table or not based on motor speed and motor torque;
4. Rotor temperature modification model is responsible for obtaining rotor temperature modification value based on three-phase vector volts, motor speed, as well as look-up table enabled flag;
5. RTE model is responsible for estimating and modifying rotor temperature based on support of previous four models.

**Numerical models for RTM estimation**

To improve the actual application of RTM, correlative numerical models are built by experiment and embedded into algorithm framework of software. In addition, RTM should also be simplified to applicable and effective algorithm model for hardware support of motor controller.

**Flux linkage model**

Usually, there is accumulation error for RTE by iterative algorithm. Therefore, flux linkage model related with rotor temperature should be obtained to modify the estimation error of rotor temperature when it meets the requirement of modification condition from equations (16)–(18).

The numeric model of flux linkage can be built by actual experimental results in Figure 5. Furthermore, actual flux linkage can be calculated based on given motor speed, counter electromotive force, as well as pole pairs in equation (19)

$$\psi_{mot} = \frac{E_{\phi}}{\omega_{mot}} = \frac{7.8E_{mot}}{n_{mot}p_{mot}}$$

where $E_{\phi}$ is the maximum phase electric potential of motor, $\omega_{mot}$ is electric angular frequency of motor, $E_{mot}$ is the effective line electric potential of motor, and $p_{mot}$ is the pole number of motor.
Cooling numerical model for motor operation state

There are three main parts of cooling loss power including cooling water loss power $P_{w}$, stator loss power $P_{s-air}$, as well as rotor loss power $P_{r-air}$ based on previous analysis. Here, three parts of cooling loss power are combined together and equated to total cooling power $P_{cool}$ as equation (20) and the numerical model of total cooling power related with the stator temperature variation rate is built in Figure 6. In addition, the numerical model from Figure 6 can be obtained by optimization and calibration based on the error between estimation value and actual test value in Figures 12 and 13.

$$P_{cool}(\Delta T_s/\Delta t) = P_{w} + P_{s-air} + P_{r-air} \quad (20)$$

where $\Delta T_s/\Delta t$ is the stator temperature variation rate.

Cooling numerical model for motor stationary state

It is necessary to attain rotor initial temperature $T_{r-init(T)}$ when system comes to power-on. Rotor temperature variation related with stationary time is recorded to build the numerical model of natural cooling state according to actual test results from different environment temperatures in Figure 7. When the environment temperature comes below $10^\circ C$, initial rotor temperature can be attained by adopting equation (21) because rotor temperature decreases under lower temperature condition

$$\begin{cases} T_{r-init(T)} = 0.75T_{r-init(10^\circ C)} + 0.25T_{envir} & T_{envir} \geq 10^\circ C \\ T_{r-init(T)} = T_{envir} & T_{envir} < 10^\circ C \text{ and } t_{stop} \geq t_0 \end{cases} \quad (21)$$

where $\epsilon$ is the matching coefficient, $T_{r-init(10^\circ C)}$ is the rotor initial temperature at $10^\circ C$ after stationary time $t_{stop}$, and $t_0$ is the calibration parameter of time.

Experimental test for RTM algorithm

The performance test bench for PMSM is built to verify the estimation accuracy of RTM algorithm in Figure 8.
For this test bench, it consists of electric dynamometer, battery simulator, adjustable low volts power, electric parameter tester, personal computer, CAN sample device, water cooling system, environment chamber, PMSM sample, as well as motor controller.

**Temperature sensors layout**

Based on RTM algorithm proposed in this article, it is necessary to monitor the stator real-time temperature and calculate the stator temperature variation rate. Here, temperature sensors are attached to the surface of the stator winding with insulated and heat-resistant glue (from Figure 9). In addition, temperature sensor is attached to the surface of the rotor alnico with insulated and heat-resistant glue (from Figure 10) to verify rotor estimation accuracy compared with RTM algorithm.

**RTM algorithm accuracy verification**

To verify RTM algorithm accuracy at different operation states, the proposed algorithm in this article is embedded into motor controller and a series of experiment schemes are worked out as below.

**Result analysis for test 1.** When it comes from operation state to stationary state, PMSM is in the state of natural cooling. According to the test results from Figure 11, RTE value decreases with stationary time because there is no operation power from PMSM and no heat radicalization from the rotor to the environment. The maximum error between the estimated value and the actual test value is within $\pm 4^\circ \text{C}$ during stationary condition.  

![Figure 7. Rotor temperature variation with stationary time.](image)

![Figure 8. PMSM performance test bench.](image)

![Figure 9. Stator temperature sensor layout.](image)
When it comes into constant load power with the same environment temperature, PMSM is in the constant operation state. According to test results from Figures 12 and 13, RTE value increases.

**Figure 10.** Rotor temperature sensor layout.

**Figure 11.** Test results with environment temperature 30°C during stationary state: (a) estimated results compared with measured results during stationary time and (b) the error between the estimated and the measured results during stationary time.

**Figure 12.** Test results with environment temperature 30°C during constant operation state (100 Nm with 3000 r/min): (a) estimated results compared with measured results and (b) the error between the estimated and the measured results.

**Figure 13.** Test results with environment temperature 30°C during constant operation state (130 Nm with 3000 r/min): (a) estimated results compared with measured results and (b) the error between the estimated and the measured results.

**Result analysis for test 2.** When it comes into constant load power with the same environment temperature, PMSM is in the constant operation state. According to test results from Figures 12 and 13, RTE value increases.
with operation time because heating radialization power from the stator is greater than rotor dissipation power from cooling water and environment. The maximum error between the estimated value and the actual test value is within $\frac{6}{10}$ during constant operation condition. In addition, estimation errors can be considered as feedback that is used to optimize total cooling power $P_{\text{cool}}$ related with temperature variation rate of the stator from Figure 6.

**Conclusion**

1. To protect PMSM from overheating, breakdown, and improve continuous behavior of motor torque, an applicable real-time algorithm of RTE is proposed in this article. Each part of heat generation and power flow transferring of PMSM is analyzed;
2. RTM is constructed based on real-time iterative algorithm of the equivalent thermal model and conservation of the stator energy loss under PMSM’s actual operation state. The proposed algorithm is embedded into motor controller by obtaining experiment datum to build correlative numerical models and simplify RTM;

3. The test bench of motor performance is built, and a series of experiment schemes are worked out to optimize and verify the real-time accuracy of the proposed algorithm in this article. Test results show that the estimated accuracy is within ±5°C and ±10°C during constant operation and variational operation conditions, respectively. Computation effectiveness of real-time rotor temperature algorithm can meet the requirement of high-accuracy estimation to improve continuous utilization of motor torque, power intensity, and cut down manufacturing cost with smart PMSM size in the next step.

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ORCID iD
Tao Deng https://orcid.org/0000-0001-6881-9854

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