

Article

Research on Thermal Overload Capability Enhancement and Selection Criterion of PMSMs with Phase-Change-Material-Based End-Winding Cooling

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Abstract

To address high end-winding temperature in permanent magnet synchronous motors under overload, this paper proposes a passive thermal management method using phase change material (PCM) in a capsule tightly contacting the windings. The PCM absorbs latent heat in its phase change range, buffering hotspots and retarding temperature rise. An electromagnetic–thermal-coupled model including loss distribution and PCM nonlinearity is built to analyze thermal characteristics under various overloads and PCMs. Results show that, at 2.0 times rated load, the time to reach insulation limit extends from 2500 s to 3500 s. The PCM benefit decreases with higher overload; an optimal phase change temperature exists, rising with overload. Direct placement improves the heat transfer path and suppresses transient hot-spot temperature, depending on selection. Experiments validate the model. This study provides a feasible cooling structure and theoretical basis for enhancing overload capability and thermal design of permanent magnet motors.

Keywords: permanent magnet synchronous motors; phase change material; overload capacity; electromagnetic thermal coupling analysis

1. Introduction

Permanent magnet synchronous motors (PMSMs) have been widely adopted in electric vehicles, aerospace, industrial robotics, and precision manufacturing, owing to their high power density, high efficiency, compact structure, and fast dynamic response [1–3]. In practical applications, motor systems frequently encounter short impact loads or fault cascades, which force motors to operate under overload conditions either intermittently or for extended periods. During overload operation, the winding current rises sharply, copper loss increases quadratically with current, and both rotor eddy current loss and permanent magnet loss increase. The generated heat accumulates rapidly within tens of seconds [4]. Because the internal heat dissipation paths are narrow and the thermal conductivity of air is low, heat cannot be removed in time, causing the temperatures of the end windings and permanent magnets to rise steeply. Excessively high temperature accelerates winding insulation aging and may lead to inter-turn short circuits, while also causing irreversible demagnetization of permanent magnets, severely threatening motor safety and reliability [5,6]. Therefore, effectively enhancing the short-term overload



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capability of a motor without significantly sacrificing its normal performance has become a research focus in motor thermal design.

To cope with the temperature during overload, researchers have conducted extensive work on motor design, material optimization, and external cooling. At the motor design level, some scholars have attempted to increase thermal capacity by enlarging the conductor cross-sectional area, adding cooling ribs, or adopting high-temperature-grade insulation materials [7,8]. However, these measures reduce the slot fill factor or increase volume and cost, and they offer only limited improvement for short duration high power overload. Among external cooling methods, relatively effective solutions include oil cooling, water jacket cooling, heat-pipe-assisted heat dissipation, and forced air cooling [9–11]. For instance, Chen et al. designed a novel cooling structure that extended the peak overload time [9]; Li et al. embedded heat pipes into the stator yoke and effectively reduced the winding hotspot temperature [10]. Nevertheless, these approaches suffer from two fundamental contradictions: On the one hand, whether oil pumps, water pumps, or fans are used, additional mechanical auxiliary devices and control systems are required, significantly increasing the system volume, weight, energy consumption, and potential failure points, making them difficult to apply in space-constrained and high reliability scenarios [11]. On the other hand, motors purpose-designed with large thermal capacity for short duration high overload tend to exhibit lower efficiency and reduced power density under rated conditions, leading to material waste and performance redundancy [12].

Phase change materials (PCMs) can absorb or release a large amount of latent heat within a constant or narrow temperature range, thus offering a potential solution to the above contradiction. The underlying principle is as follows: during motor overload, the PCM absorbs heat through a solid–liquid phase transition, suppressing the rapid temperature rise of the windings or housing; after the overload event, when the motor returns to normal load or shuts down, the PCM solidifies and regenerates via natural convection or low-power-assisted cooling [13]. Because PCM functions as passive heat storage rather than active heat removal, it requires no additional mechanical drive devices and operates only during overload, without affecting normal motor performance. In recent years, several researchers have explored the application of PCMs in motor thermal management. Lamarre et al. filled a paraffin-based PCM into the annular cavity of the motor housing, and experimental results showed that the time for the winding to reach the upper temperature limit was extended by 28% under a 2 times overload [14]. Wang et al. integrated PCM inside the end cap, effectively mitigating heat transfer from the rotor to the bearings [15]. In addition, studies have attempted to combine PCM with heat dissipating fins or metal foam to enhance thermal conduction [16]. Despite these advances, two notable gaps persist in the existing literature. First, the PCM is usually placed far from the highest temperature regions of the motor. The vast majority of studies place PCM in the housing or on the outer side of the stator yoke, whereas the highest temperature during motor overload typically occurs at the winding ends. Second, different overload factors cause changes in both heating power and thermal response time, which should impose different requirements on parameters such as the PCM phase change temperature. However, little is known about the inherent selection criterion between the overload factor and the optimal PCM phase change temperature.

To address these gaps, this paper proposes a closely contacting capsule-like PCM structure placed directly at the winding ends, with the aim of improving the motor overload capability. Different from previous studies where PCM is installed in the motor housing or end cover, the proposed capsule PCM is directly attached to the end winding, significantly shortening the heat transfer path from the hotspot to the thermal storage medium. Furthermore, this work establishes the selection criterion between overload level and PCM

phase transition temperature, providing a practical guideline for PCM selection in overload thermal design. It should be emphasized that the novelty of this work lies in the proposed cooling concept and the thermal selection mechanism rather than the numerical solution method itself. The paper is organized as follows: An electromagnetic–thermal-coupled model of the PMSM incorporating the capsule structure is established in Section 2. The improvement in overload capability achieved by the proposed structure is systematically analyzed in Section 3. The results are validated through experiments in Section 4.

2. Cooling Structure of End Winding Based on PCM and Thermal Analysis Model

2.1. Cooling Structure of End Winding Based on PCMs

During overload operation of a PMSM, the copper loss in the windings increases sharply, leading to rapid heat accumulation. The end winding is typically the hottest region within the motor, owing to its long heat dissipation path. Heat must first be conducted axially to the slot-embedded windings and then transferred through the stator core to the housing; this process is further impeded by the heat generated by the slot windings themselves, making effective heat removal difficult. The end winding adopts a cantilevered structure and relies primarily on thermal conduction and convective heat dissipation, with radiative heat dissipation contributing only a negligible fraction.

To overcome the shortcomings of conventional heat dissipation methods for end windings, this paper proposes a capsule PCM encapsulation structure for end-winding cooling. The structure is a hollow capsule consisting of a flexible wall, an internal chamber, and a filling port. It is made of silicone rubber that is electrically non-conductive, non-magnetic, and possesses good thermal conductivity. The capsules are installed at the front and rear ends of the motor. They closely fit against the outer surface of the end windings, the stator core end face, the inner wall of the motor housing, and the inner wall of the end cover. This arrangement fully utilizes the originally idle space around the end windings without altering the original motor structure or manufacturing process. As shown in Figure 1, the capsule PCM encapsulation structure is mounted at the end windings of the motor stator.

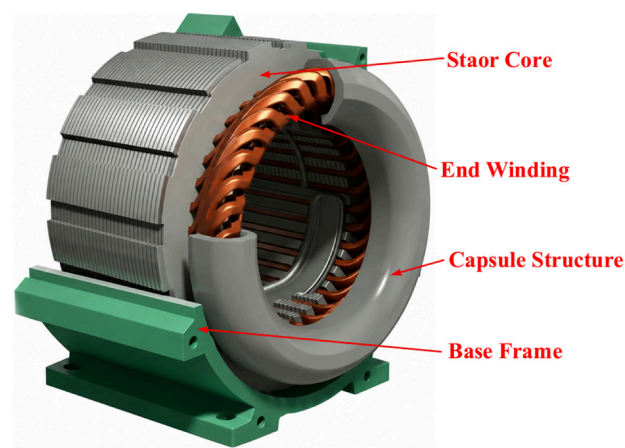


Figure 1. Package structure with saccular phase change material added at end winding.

The encapsulation structure shown in Figure 1 has a capsule shape and is designed to support two operating modes. In one mode, a cooling medium can be introduced through the filling port to enable forced liquid cooling; in the other, the cavity is filled with the PCM and then sealed, allowing the latent heat of phase change to be harnessed for passive thermal management. This study adopts the latter approach. By encapsulating the PCM

within the capsule cavity, the heat dissipation path is improved, and a substantial amount of heat generated in the end windings can be absorbed during brief overload events, thereby effectively retarding the temperature rise.

2.2. Principle of Temperature Suppression by PCMs and Motor Analysis Model

A. Principle of Temperature Suppression by PCMs.

The PCMs are functional materials that undergo a phase transition between solid and liquid states within a specific temperature range. During this transition, a substantial amount of latent heat is absorbed or released, which endows the materials with efficient thermal energy storage and regulation capabilities. In the heat absorption stage, the material transforms from solid to liquid and absorbs latent heat, thereby buffering a large quantity of thermal energy under nearly isothermal conditions. Figure 2 presents the enthalpy change curve during the melting process of the PCM.

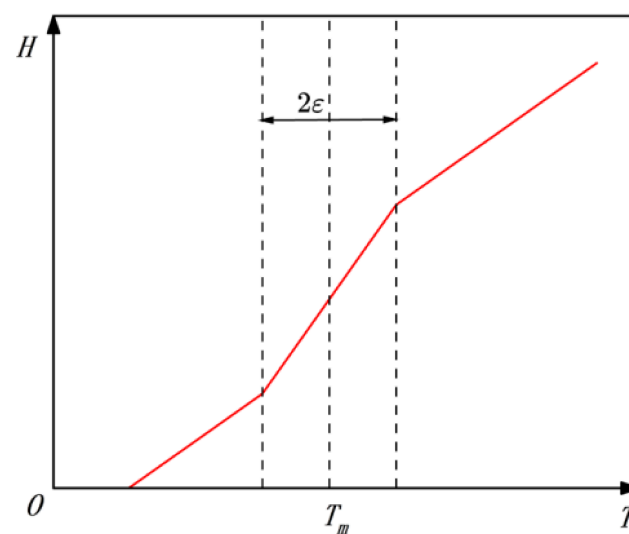


Figure 2. Enthalpy curve of PCM melting process.

In Figure 2, the horizontal coordinate T represents temperature, and the vertical coordinate H denotes the enthalpy of the material. T_m is the phase change temperature point, and 2ϵ is the width of the phase change temperature range. When the motor temperature rises into this phase change temperature range, the PCM undergoes a phase transition from solid to liquid and absorbs a large amount of latent heat, thereby suppressing the temperature rise rate in the regions in contact with it. As can be seen from the enthalpy change curve, the slope of the curve within the phase change temperature range is significantly greater than that in other temperature intervals, indicating that the amount of heat absorbed per unit temperature rise is much higher than that outside the phase change range.

The energy conservation equation for the working process of PCMs can be expressed using the enthalpy method [10]:

$$\rho \frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T) + Q \quad (1)$$

where ρ is the density, H is the total enthalpy, k is the thermal conductivity, T is the temperature, and Q is the internal heat source.

The relationship between the total enthalpy H and temperature T is given by [10]:

$$H = h_{ref} + \int_{T_{ref}}^T c_p dT + \beta L \quad (2)$$

where c_p is the specific heat capacity, L is the latent heat, and β is the liquid fraction. The liquid fraction β is calculated according to the following rule [11]:

$$\beta = \begin{cases} 0 & T < T_s \\ \frac{T-T_s}{T_l-T_s} & T_s \leq T \leq T_l \\ 1 & T > T_l \end{cases} \quad (3)$$

where T_s is the solidus temperature, and T_l is the liquidus temperature. Within the phase change interval, β varies linearly from 0 to 1, and the material is in a mixed state of solid and liquid.

Based on the foregoing principle, when the motor winding temperature rises into the phase change temperature range, the PCM absorbs latent heat to achieve isothermal or nearly isothermal energy storage, thereby effectively suppressing the temperature rise rate of the end windings and delaying the process of reaching thermal equilibrium.

B. Coupled electromagnetic and thermal model.

To analyze the temperature characteristics of PMSMs with a PCM structure at the winding ends under overload conditions, it is necessary to establish a coupled electromagnetic and thermal model. In this coupled model, the core task of the thermal analysis is to solve the temperature distribution inside the motor. The heat conduction in this motor obeys Fourier's law, and the transient heat conduction equation considering internal heat sources is given by [12]:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q_v \quad (4)$$

where ρ is the material density, c_p is the specific heat at constant pressure, T is the temperature, t is time, $\nabla \cdot (\lambda \nabla T)$ is the heat flow per unit volume, and q_v is the volumetric heat source density.

For the region of the capsule structure filled with PCMs, due to the presence of latent heat associated with the phase transition between solid and liquid states, the enthalpy method is required to describe its thermal process. The heat conduction equation for the PCM region is given by [11]:

$$\rho_{pcm} \frac{\partial H}{\partial t} = \nabla \cdot (\lambda_{pcm} \nabla T) \quad (5)$$

where H is the enthalpy of the phase change material, which includes both sensible heat and latent heat.

Substituting Equation (2) into Equation (5) and rearranging yields the governing equation expressed in terms of equivalent specific heat capacity [12]:

$$\rho_{pcm} c_{p,eff} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{eff} \nabla T) \quad (6)$$

where $c_{p,eff}$ is the equivalent specific heat capacity, which is much larger in the phase change interval than that outside it, thereby reflecting the suppression effect of latent heat absorption on temperature.

Regarding the boundary conditions, heat transfer among the internal components within the stator and rotor is dominated by heat conduction. Heat is dissipated from the housing surface through convective heat transfer, while the effect of radiative heat transfer is negligible and thus ignored.

C. Overload factor and its impact on heat sources.

The motor overload factor is defined as the ratio of the actual output torque to the rated torque.

$$k_{OL} = \frac{T_e}{T_{rated}} \quad (7)$$

For PMSMs adopting the $i_d = 0$ control strategy, the electromagnetic torque is proportional to the q axis current,

$$T_e = \frac{3}{2} p \psi_f i_q \quad (8)$$

where p is the number of pole pairs, ψ_f is the flux linkage of the permanent magnet, and i_q is the q axis current. In this case, the overload factor can be equivalently expressed as

$$k_{OL} = \frac{i_q}{i_{q,rated}} \quad (9)$$

It can be seen from Equation (9) that the overload factor is proportional to the current, while the copper loss is proportional to the square of the current. Therefore, during overload operation, the copper loss in the windings increases sharply, leading to a substantial rise in the winding temperature. The PCM thermal management structure at the winding ends proposed in this paper exploits the characteristic that the PCM absorbs a large amount of latent heat within the phase change temperature range, thereby providing thermal management for the end windings and extending the safe overload duration of the motor.

3. Simulation of Overload Capability Enhancement by PCM Structure at End Windings

3.1. Influence of PCM Structure on Motor Temperature

To verify the effectiveness of the proposed capsule PCM structure at the end windings in improving the overload capability of the motor, a 3 kW PMSM is taken as the research subject, which is cooled by its own fan. The PCM is RT-100, a paraffin PCM, with a phase change temperature of 100 °C. The main parameters of the motor are shown in Table 1.

Table 1. The parameters of the 3 kW PMSM.

Item	Value	Item	Value
Rated voltage (V)	380	Stator outer diameter (mm)	155
Rated speed (r/min)	3000	Stator inner diameter (mm)	110
Air gap length (mm)	0.5	Number of stator slots	36
Insulation class	F	Permanent magnet grade	N35SH

For simulation, two cooling structures are configured for comparison. Structure 1 is the motor without a PCM structure, and Structure 2 is the motor with a capsule PCM structure installed at the winding ends and filled with RT-100. Since the available installation space around the end winding is fixed in practical motors, the PCM volume was kept constant. Optimization of PCM quantity will be considered in future work. The coupled electromagnetic and thermal calculation models of the motors with the two cooling structures are shown in Figure 3. In the actual prototype, phase change material (PCM) is encapsulated by a thin-walled flexible silicone rubber bag and tightly wrapped outside the end winding. However, in the finite element thermal model, the PCM capsule is simplified as a continuous solid area, while strictly maintaining the same total volume, equivalent thermal properties, and effective contact area as the prototype. The rationality of this equivalent strategy lies in that the wall thickness of silica gel is much smaller than the characteristic

size of the end winding, and PCM occupies almost the whole package volume, so the local deformation and fine geometric characteristics of the flexible shell have little influence on the macro heat transfer behavior. At the same time, this simplification can prevent having to deal with the moving grid problem of a solid–liquid interface, significantly improving calculation efficiency while not significantly sacrificing the accuracy of transient temperature prediction. On this basis, the interface between the end winding, the flexible cladding material, and PCM in the model is assumed to be perfect thermal contact, which is mainly due to the irregular geometry of the end winding and the local deformation of the flexible cladding, which makes it extremely difficult to accurately characterize the contact thermal conduction of the non-uniform interface, and the introduction of empirical parameters without a practical basis will increase the uncertainty of the model, so adopting the perfect contact assumption is a reasonable choice for both feasibility and reliability.

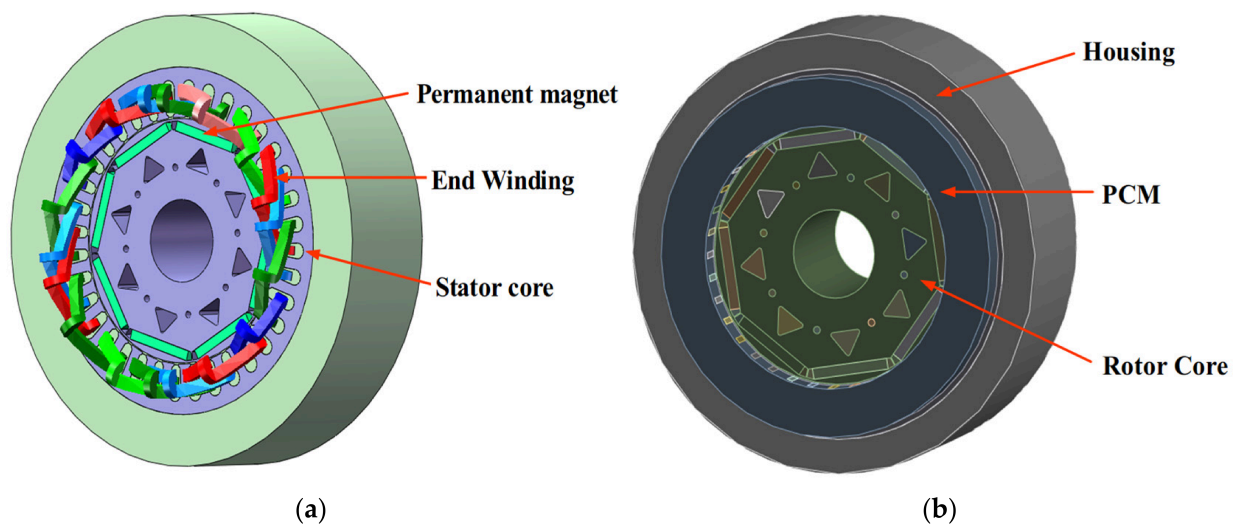


Figure 3. Electromagnetic–thermal coupling calculation model of 3 kW PMSM. (a) without PCM structure; (b) with PCM structure.

In addition, regarding material property setting, the model realizes the dynamic coupling between electromagnetic parameters and the temperature field. In addition to the dynamic renewal of copper resistivity with temperature, the remanence and coercivity of permanent magnets are also modified according to the current temperature.

In the setting of thermal boundary conditions, this paper fully considers the external convection, radiation, and heat transfer characteristics of the internal air gap of the motor. The ambient temperature is set to a constant value of 25 °C, consistent with the experiment. Aiming at the convection heat dissipation on the outer surface of the motor, since the prototype adopts a self-fan cooling structure, the convection heat transfer coefficient of the outer surface is set in different zones according to the surface position and airflow distribution: the equivalent convection heat transfer coefficient of the outer surface of the casing is set to 25 W/(m²·K); the equivalent convective heat transfer coefficient of the outer surface of the end cover is set to 15 W/(m²·K). In addition, the thermal radiation of the motor surface to the environment is also included in the calculation, and the surface emissivity is set to 0.85. Inside the motor, the heat transfer in the air gap between the stator and rotor is characterized by introducing equivalent thermal conductivity instead of complicated hydrodynamic calculation, so as to ensure the calculation accuracy and significantly improve the calculation efficiency of the transient thermal coupling simulation. An identical 2 times overload current excitation is applied to each, and the simulation is run for 9000 s, during which the end-winding temperature is recorded as a function of time.

In thermal analysis, the heat source loss consists of three parts: (1) the winding copper loss, which strictly considers the linear increase effect of copper resistivity with the increase of temperature and dynamically updates the resistance value and loss in the electromagnetic–thermal coupling iteration; (2) stator iron loss is calculated based on the Bertotti separation model, and the total iron loss is decomposed into hysteresis loss, classical eddy current loss, and abnormal loss to accurately reflect the loss distribution under alternating magnetic fields; (3) eddy current loss of permanent magnet, considering the actual conductivity of permanent magnet materials. Figure 4 presents the comparative temperature evolution curves of the end winding and permanent magnets under the two cooling configurations.

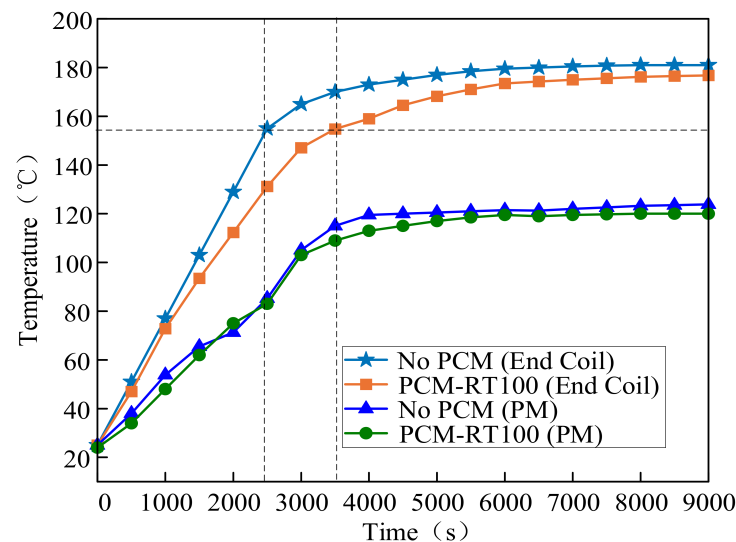


Figure 4. Comparison of the temperature of motor under overload with or without PCM.

As can be seen from Figure 4, in the initial stage of overload, the temperatures under both cooling structures rise rapidly, but the temperature curve of the motor with the PCM structure remains slightly lower than that without the PCM structure throughout this period. This is because in the traditional natural cooling structure, the heat of the end winding is mainly transferred to the end cover by air, and its main heat transfer path contains a thick static air gap. The thermal conductivity of still air is extremely low, only $0.026 \text{ W/(m}\cdot\text{k)}$, which constitutes a great heat transfer resistance. In contrast, the tight-fitting bladder structure proposed in this paper eliminates the air gap and makes the main heat transfer path become a “winding surface-flexible bladder wall–PCM body”. The solid/liquid thermal conductivity of paraffin-based PCM used in this paper is about $0.20 \text{ W/(m}\cdot\text{k)}$ (natural convection enhancement is not considered), which is 7.7 times that of still air. This order of magnitude increase in the thermal conductivity of the medium in the heat transfer path quantitatively explains why the structure can significantly reduce the local heat transfer resistance from the end winding to the heat dissipation boundary. However, at this stage, the PCM primarily absorbs heat in the form of sensible heat, and the advantage of latent heat storage has not yet been brought into play. Consequently, the temperature difference between the two cooling structures is relatively limited.

As the temperature further increases and the end-winding temperature approaches the phase change temperature of RT-100, the temperature rise rate of the motor with the PCM structure slows down noticeably, while that of the motor without the PCM structure maintains a relatively high rate. This indicates that the PCM begins to undergo a phase transition from solid to liquid and suppresses the continuous increase in end-winding temperature by absorbing a large amount of latent heat, thereby effectively retarding the formation of hotspots. In contrast, the motor without the PCM structure lacks an additional

thermal storage buffering mechanism, allowing heat to accumulate continuously and leading to a rapid temperature rise.

As the overload time is prolonged, the PCM gradually completes the phase transition, and its latent heat absorption capacity tends to become saturated. As a result, the difference in temperature rise rates between the two cooling structures gradually diminishes, though the overall temperature of the motor with the PCM structure remains lower than that without the PCM structure. It is worth noting that the temperature of the permanent magnets is far lower than the winding temperature and does not reach the Curie temperature of the material. Meanwhile, because the capsule structure is arranged at the end windings, its effect on reducing the permanent magnet temperature is smaller than that on reducing the winding temperature.

Taking the maximum allowable operating temperature of Class F insulation, 155 °C, as the safety threshold, the winding temperature in the case without PCM reaches this limit at approximately 2500 s, whereas that with PCM is delayed to about 3500 s, representing an improvement of roughly 40%. The results demonstrate that the proposed PCM structure at the end windings can significantly enhance the short-term overload capability and thermal safety margin of the motor.

After thermal equilibrium is reached, a certain difference still exists in the final steady state temperatures of the two cooling structures, with the steady state temperature of the motor with PCM being lower than that without PCM. This suggests that the PCM not only absorbs a substantial amount of heat during the transient overload phase but also reduces the steady state temperature rise of the motor during long-term operation to some extent by improving the heat distribution and heat transfer conditions at the end windings. Therefore, the proposed PCM structure serves both transient thermal suppression and steady state temperature optimization and is of positive significance for enhancing the thermal reliability of high power density motors.

In addition, the temperature distribution maps of the motor windings at three instants, namely before, during, and after the phase change of the PCM, are also analyzed, as shown in Figure 5.

It should be noted that the contour plots in Figure 5 employ different temperature scales because they represent different stages of the transient thermal process. The purpose of these figures is to demonstrate the evolution of the temperature field and the migration of the hotspot during the PCM phase transition. Using a unified temperature scale would significantly reduce the visibility of the local temperature gradients in the early stages of the transient process and obscure the cooling mechanism discussed in this study. Therefore, independently optimized temperature scales are adopted to improve the clarity of the transient thermal evolution. It can be seen from Figure 5a that when the winding temperature has not yet reached the phase change temperature of the PCM, the end winding temperature is significantly higher than that of the windings in the slots. The main reason is that the windings embedded in the stator slots are in close contact with the iron core, and heat can be rapidly conducted to the housing through the silicon steel laminations, which have relatively good thermal conductivity, thus forming an effective heat dissipation path. In contrast, the end windings are located outside the iron core, and even though they are wrapped by the silicone rubber capsule structure filled with PCM inside, the PCM has not yet undergone phase change at this stage and absorbs heat only through sensible heat, resulting in limited overall heat absorption capacity. At the same time, the thermal conductivity of the silicone rubber material is relatively low, which increases the heat transfer path resistance of the end region to some extent. Consequently, heat tends to accumulate more readily at the ends, giving rise to the distribution characteristic that the end winding temperature is higher than that of the slot windings.

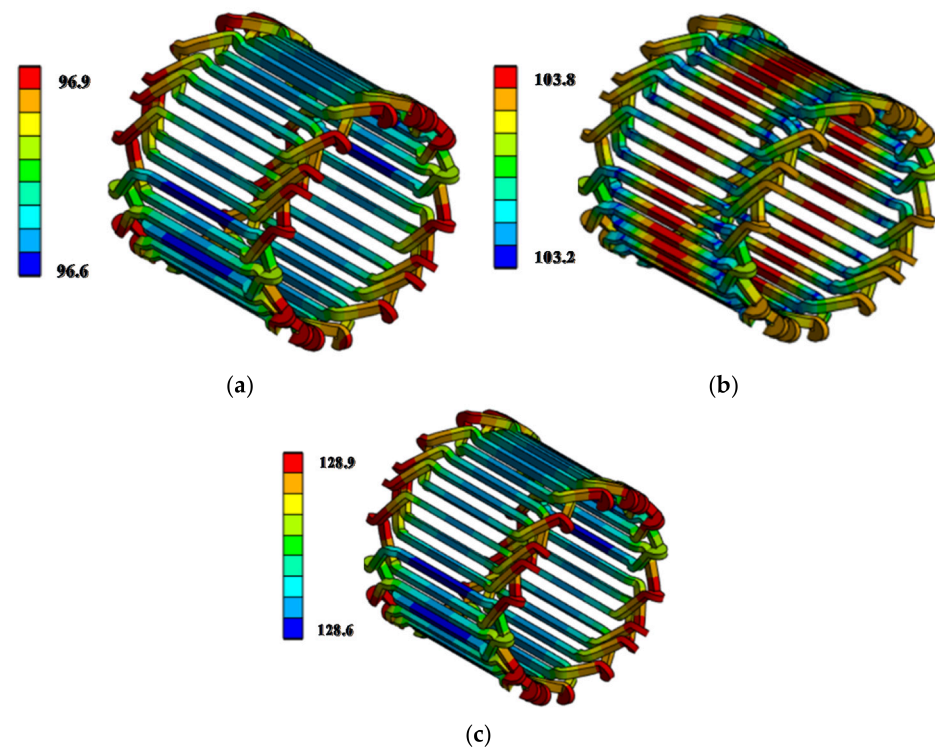


Figure 5. Temperature of winding before and after phase transition temperature of motor. (a) Before phase transition; (b) During phase change; (c) After the phase change. Note: Each temperature isoline is displayed with an individually optimized color scale to clearly illustrate the transient evolution of temperature field in different stages of PCM phase transition.

As the winding temperature further increases and enters the phase change temperature range of the PCM, as shown in Figure 5b, the PCM inside the capsule structure begins to undergo a phase transition from solid to liquid and absorbs a large amount of latent heat. Since the PCM is mainly distributed in the end winding region, its endothermic effect during phase change can significantly suppress the continued rapid rise of the end temperature. Meanwhile, the slot windings are still continuously heated by copper losses. Although the iron core can provide a certain amount of heat conduction and dissipation, after the temperature of the end windings is effectively restrained, the slot winding temperature gradually exceeds that of the end windings.

When the winding temperature continues to rise beyond the phase change temperature range of the PCM, as shown in Figure 5c, the PCM in the capsule structure has been almost completely melted, and its latent heat absorption capacity approaches saturation, so it can no longer effectively absorb heat. At this point, heat accumulation at the end windings resumes, and their temperature once again becomes higher than that of the slot windings. The slot region, on the other hand, can still maintain relatively good heat conduction and dissipation conditions through the iron core. As a result, the overall temperature distribution reverts to the pattern of higher temperatures at the ends and lower temperatures in the slots. These results indicate that the PCM alters the transient temperature distribution of the motor windings during the phase change process, achieving a shift of the hotspot region from the ends to the slots.

3.2. Improvement in Thermal Endurance of End Windings Under Different Overload Factors

To investigate the influence of a fixed PCM type on the effective overload duration of the motor under different overload factors, the coupled electromagnetic and thermal model is used to calculate the time required for the motor without PCM and the motor

with RT-100 to rise from the initial temperature to the upper limit temperature permitted by the insulation, within the overload range from 2.0 to 2.5 per unit. The results are shown in Figure 6.

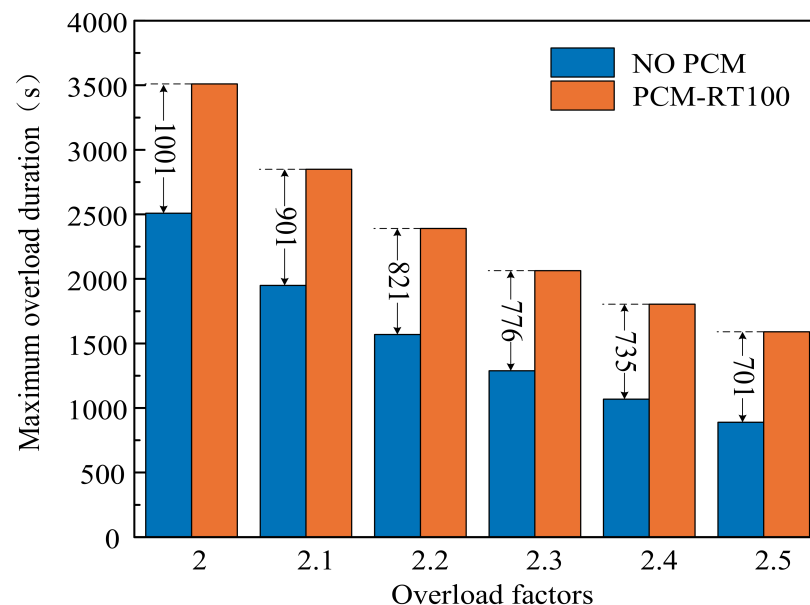


Figure 6. Comparison of maximum running time of PCM under different overload conditions.

Figure 6 shows that, as the overload factor increases, the maximum overload duration under both cooling structures exhibits a declining trend. The effective overload time of the motor without PCM decreases from about 2500 s at 2.0 times the rated load to about 900 s at 2.5 times, while that of the motor with RT-100 decreases from about 3500 s to about 1500 s. Under each overload factor, the effective overload time of the motor with a PCM is significantly longer than that of the motor without the PCM, though the difference between the two gradually narrows as the overload factor increases. At 2.0 times, the extension is approximately 1000 s, while at 2.5 times, it is about 700 s. This indicates that the enhancing effect of the PCM on overload capability is more pronounced under lower overload factors. As the overload intensifies, the heat storage capacity of the PCM is depleted more rapidly, and the time gain exhibits a decreasing trend. This result is consistent with the theoretical analysis in the preceding section, namely that the higher the overload factor, the more the loss power grows exponentially, and the finite latent heat of the PCM is quickly consumed, leading to a rapid reduction in the effective overload duration.

3.3. Selection of PCM Phase Change Temperature Under Different Overload Factors

To investigate the effect of the PCM with different phase change temperatures on the effective overload duration of the motor under the same overload factor, a series of PCMs with five phase change temperatures, namely RT-70, RT-100, RT-120, RT-130, and RT-140, were selected. The basis for selecting five PCMs in the RT series is as follows: When the phase transition temperature changes, the physical parameters such as density, thermal conductivity, and latent heat of this series of materials change little, which can approximately ensure the consistency of other thermophysical properties except the phase transition temperature, thus satisfying the principle of single variable. The selected temperature point of 70 °C to 140 °C covers the complete working temperature range from the rated operation of the motor to the upper insulation limit, and the step interval is moderate. It should be noted that the purpose of this study is to reveal the overall design trend of the optimal phase transition temperature migrating to the high temperature side with the

increase of overload multiple, rather than determining the accurate optimal value at a certain overload multiple with high precision. Under the current discrete sampling points, the migration direction from 100 °C (2.0 times overload) to 120 °C (2.5 times overload) is clearly visible, which is enough to support the basic judgment of engineering selection. However, the accurate performance curves between adjacent discrete points (such as 110 °C and 115 °C) have not been directly simulated, and the exact optimal position under various overload multiples still needs to be further refined, but this does not affect the core conclusion of this paper on the migration direction. In order to ensure the integrity and reproducibility of the research, Table 2 lists in detail the key thermophysical properties of five paraffin-based phase change materials selected in this paper.

Table 2. The detailed thermophysical properties of selected PCMs.

Item	Phase Transition Temperature Range (°C)	Latent Heat (kJ/kg)	Solid Thermal Conductivity (W/(m·k))	Liquid Thermal Conductivity (W/(m·k))	Density (kg/m ³)	Specific Heat Capacity (kJ/(kg·K))
RT-70	68–72	230	0.20	0.15	880	2.1
RT-100	98–102	225	0.20	0.15	910	2.1
RT-120	118–122	210	0.20	0.15	920	2.1
RT-130	128–132	195	0.20	0.15	930	2.1
RT-140	138–142	180	0.20	0.15	940	2.1

Simulations were conducted under overload conditions of 2.0, 2.3, and 2.5 times the rated torque, and the time required for the winding temperature to rise to the upper limit permitted by the insulation was recorded for each case. The results are shown in Figure 7.

It can be observed from Figure 7a that under 2 times overload operation, RT-100 yields the longest maximum allowable operating time, reaching 3500 s, followed by RT-120 at 3455 s and RT-130 at 3435 s. The effective overload times for RT-70 and RT-140 are 3380 s and 3381 s, respectively, which are relatively close to each other. This indicates that under the 2.0 times overload condition, the PCM with a phase change temperature of 100 °C provides the best cooling performance. A PCM with too low a phase change temperature completes its phase transition prematurely, and thereafter, its relatively low thermal conductivity in the liquid state impairs heat dissipation. On the other hand, a PCM with too high a phase change temperature cannot be fully triggered by the winding temperature rise, so the latent heat is not effectively utilized.

Figure 7b presents the effective overload times of the motor corresponding to different PCM types under 2.3 times overload. Compared with the 2.0 times condition, the effective overload times of all PCM cases decrease significantly, but RT-100 still maintains the best performance, reaching 2022 s. The times for RT-70 and RT-120 drop to 1733 s and 1782 s, respectively, while those for RT-130 and RT-140 are 1756 s and 1729 s, respectively. It is worth noting that the gap between RT-120 and RT-70 narrows, and RT-130 performs slightly better than RT-70. This suggests that as the overload factor increases, the optimal phase change temperature tends to shift toward a higher value.

Figure 7c shows the effective overload times of the motor corresponding to different PCM types under 2.5 times overload. At this point, RT-120 becomes the optimal choice, with an effective overload time of 1887 s, while RT-100 drops to 1601 s. The times for RT-70, RT-130, and RT-140 are 1552 s, 1500 s, and 1480 s, respectively. Compared with the 2.0 and 2.3 times conditions, the optimal phase change temperature shifts from 100 °C to 120 °C. This is because under high overload, the winding temperature rises extremely fast. A PCM with a low phase change temperature completes its phase transition within a very short

time and can no longer provide thermal buffering afterward. A PCM with an excessively high phase change temperature, however, cannot reach its phase change range within a short time, so the latent heat cannot be fully released. Only a PCM with a moderate phase change temperature can match the rapid temperature rise curve under high overload and continuously absorb heat within the critical temperature interval.

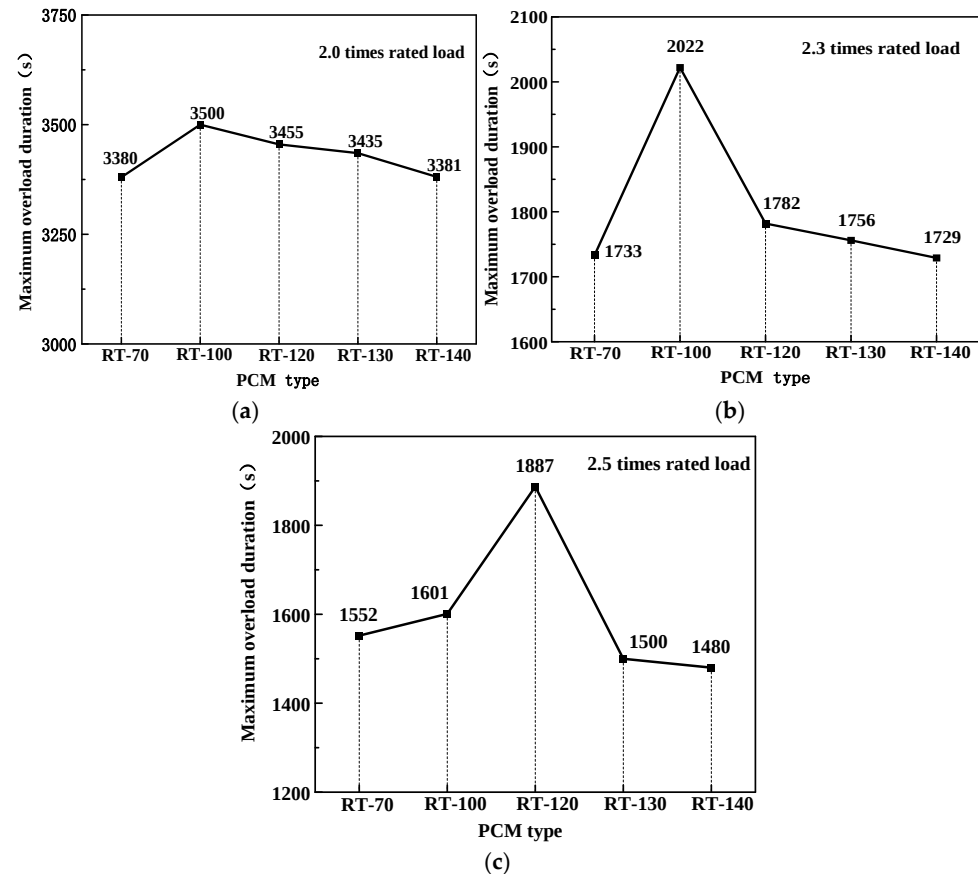


Figure 7. Influence of phase change materials on overload operation time. (a) 2.0 times overload; (b) 2.3 times overload; (c) 2.5 times overload.

A comprehensive comparison of Figure 7 reveals that under the same overload factor, the effect of PCMs with different phase change temperatures on the effective overload time exhibits a unimodal distribution, with an optimal phase change temperature point. Deviation from this point leads to a decline in performance, and the optimal point increases with the overload factor. At 2.0 times overload, the optimum is 100 °C. At 2.3 times, it remains close to 100 °C, but the performance gap with 120 °C narrows. At 2.5 times, the optimum rises to 120 °C. The underlying reason for this trend is that the overload factor determines the temperature rise rate of the windings. Under low overload, the temperature rises slowly, so a PCM with a relatively low phase change temperature can be activated in time and continue to absorb heat for a longer period. Under high overload, the temperature rises rapidly, requiring a PCM with a higher phase change temperature to delay the onset of phase transition, thereby avoiding premature depletion of the heat storage capacity and exerting a buffering effect within a higher temperature range.

Although the observation that the higher the overload factor, the higher the required optimal phase-transition temperature is intuitive from a macroscopic view, its internal physical mechanism involves complex, nonlinear dynamic competition between the heat generation rate and phase-transition heat absorption rate. Under the condition of high overload, the heating power of winding increases sharply; if a PCM with a low phase

transition temperature is selected, the material will melt quickly and completely at the initial stage of overload, which will lead to the loss of thermal buffering ability in the middle and late stages of overload, causing serious thermal penetration effect, which will make the winding temperature rise uncontrollably and soar in the later stage. On the other hand, if the phase transition temperature is too high, the PCM cannot be fully melted during the overload period, resulting in a low utilization rate of latent heat. Therefore, high overload requires higher phase transition temperature to delay the melting process, the essence of which is to achieve accurate time synchronization between complete melting time of the PCM and overload duration, so as to maintain the optimal thermal buffering effect in the whole overload period.

This discovery provides an important new engineering insight for the thermal management of motors: it breaks the misunderstanding of blindly pursuing the selection of materials with low phase-transition temperature or high latent heat in traditional design. In practical engineering applications, the thermal design of PCM should be oriented from material to working condition. Designers should not evaluate PCM materials in isolation from operating conditions but must customize the phase transition temperature of PCM according to the expected typical impact load characteristics of the motor (that is, specific overload multiple and target duration) to maximize the thermal buffering efficiency and material utilization rate of the system.

4. Experimental Verification

To verify the feasibility of the proposed cooling structure with the PCM, as well as the validity and accuracy of the analytical calculations, an experimental platform for temperature testing of the PMSM is constructed, as shown in Figure 8.

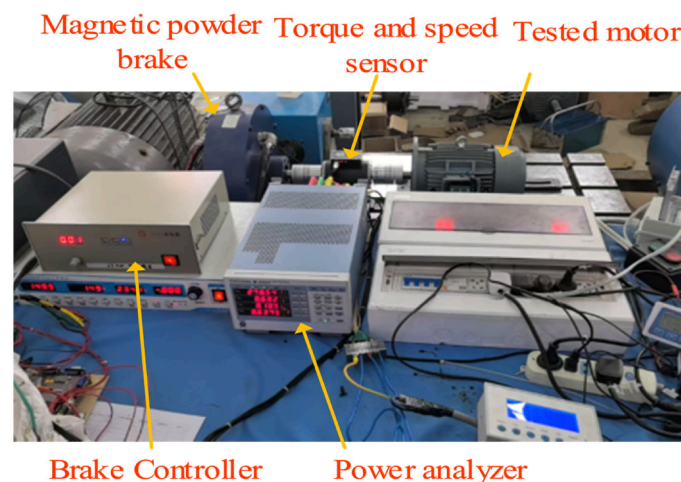


Figure 8. Test platform for temperature of the PMSM.

The platform mainly consists of the tested motor, a drive inverter, a magnetic powder brake, a digital power analyzer, a torque and speed sensor, an electronic thermometer, a voltmeter, and an ammeter. To comprehensively monitor the temperature variations of the key components of the motor, temperature-measuring devices were designed for both the stator end windings and the rotor permanent magnets. A temperature measurement device was embedded in the stator end windings, as shown in Figure 9. In this arrangement, the temperature sensor is inserted into the interior of the winding ends and connected to an external display through leads, allowing real-time reading of the end temperature.

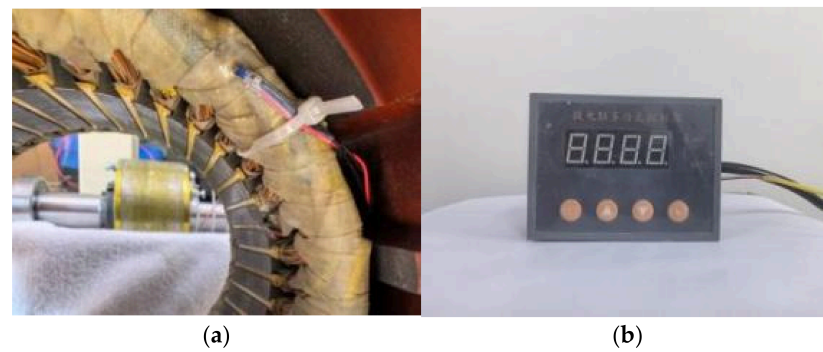


Figure 9. End-winding-temperature-measuring device. (a) temperature sensor; (b) Temperature display.

Since the rotor is in a rotating state, a wireless temperature measurement scheme is adopted. A temperature sensor is installed in the permanent magnet slot of the rotor core and, together with a rotary transmitter for temperature signals, a receiving antenna, and a display, it constitutes the rotating temperature measurement device for the rotor permanent magnets, as shown in Figure 10. Specifically, Figure 10a shows the temperature sensor mounted on the permanent magnet; Figure 10b shows the wireless temperature sensor, transmitter, receiving antenna, and display; and Figure 10c shows the rotor assembly after installation of the rotating temperature sensor.

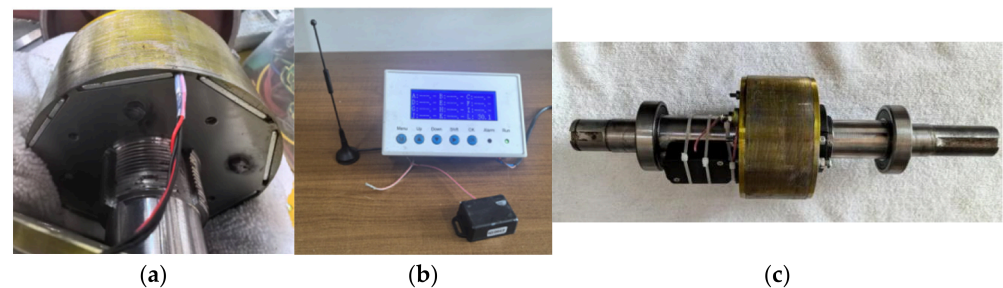


Figure 10. Rotor permanent magnet temperature-measuring device. (a) Permanent magnet temperature sensor; (b) Wireless temperature sensor, transmitter, receiving antenna, and display; (c) Rear rotor assembly with rotating temperature sensor installed.

In order to ensure the reliability and preciseness of the experimental data, this paper analyzes the uncertainty and repeatability of the measurement system. In the aspect of temperature measurement, a PT100 platinum-resistance temperature sensor is used in the experiment, and its calibration accuracy is $0.2\text{ }^{\circ}\text{C}$, which is matched with a high-precision multi-channel data acquisition system (resolution is $0.01\text{ }^{\circ}\text{C}$). Considering the lead resistance, contact non-uniform gap, and electromagnetic interference when the motor is running, the uncertainty of the integrated system of temperature measurement is controlled within $0.5\text{ }^{\circ}\text{C}$. Moreover, in order to evaluate the repeatability of the experiment, three independent repeated experiments were carried out under 2.0 times overload condition. The results show that the maximum repeatability deviation of the temperature of each key measuring point is less than $1.2\text{ }^{\circ}\text{C}$, which proves that the experimental measurement system has good stability and data repeatability and eliminates the influence of accidental errors on the core conclusions.

The temperature variations of the end windings and permanent magnets over time, as measured on this experimental platform, are shown in Figure 11.

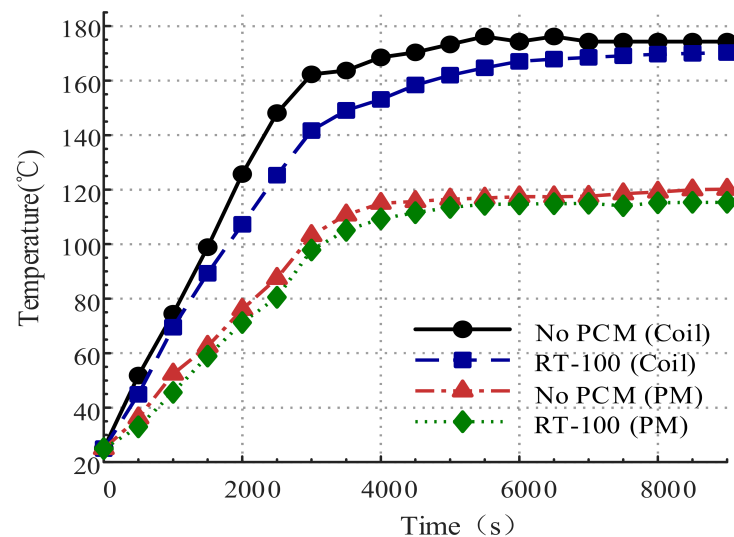


Figure 11. Temperature curve of end winding and permanent magnet.

In order to quantitatively evaluate the prediction accuracy of the simulation model, normalized root mean square error (*NRMSE*) is introduced as an evaluation index. The calculation formula of *NRMSE* is,

$$NRMSE = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (T_{sim,i} - T_{exp,i})^2}}{\frac{1}{N} \sum_{i=1}^N T_{exp,i}} \quad (10)$$

where $T_{sim,i}$ and $T_{exp,i}$ are the simulated and experimental temperature values of the first sampling point, respectively, and N is the total number of sampling points.

By comparing Figure 11 with Figure 4, it can be seen that the simulation results are consistent with the experimental temperature trends. Among them, the *NRMSE* of the simulation and experiment of end-winding temperature is 4.6%; for the permanent magnet temperature, the *NRMSE* of the wireless temperature-measuring module is 5.8% due to the slight signal transmission delay in the rotating state and the fact that the actual installation position of the sensor is difficult to absolutely coincide with the observation node in the simulation model. On the whole, the errors of both are controlled within a reasonable engineering allowable range, which provides confidence in the accuracy of the electromagnetic–thermal coupling model.

It should be noted that due to the procurement cycle of PCM materials with different phase transition temperatures, the engineering difficulty of multiple disassemblies, the cleaning of the prototype, and the time cost of long-period thermal testing, only the most representative RT-100 is selected for experimental verification. However, the core purpose of this experiment is to verify the accuracy of the established electromagnetic–thermal coupling model and PCM phase change model. The high agreement between the RT-100 experiment and the simulation provides a reasonable basis for the reliability of the numerical model in capturing the transient temperature rise and the latent heat absorption process of phase change. Because the key thermal properties of the selected RT series PCMs are similar, simulation results for other operating conditions obtained using the validated model with only phase transition temperature adjusted are deemed reliable within the scope of this study.

5. Engineering Feasibility and Implementation Analysis

In order to comprehensively evaluate the practical engineering feasibility of the proposed sealed PCM cooling structure, this paper makes an in-depth discussion from four dimensions: manufacturing, packaging, weight and cost: (1) manufacturing complexity: thermal conductive silica gel casting or a high-temperature-resistant polyimide (PI) film hot-pressing process can be used for capsule packaging, highly mature areas in the field of existing motor encapsulation and electronic packaging. The structure does not need complicated mechanical processing of the stator and rotor punching sheet and the casing of the motor, and the manufacturing complexity is low. (2) Packaging limitation and reliability: In view of the problems of leakage prevention after PCM liquefaction and reliability in motor vibration environment, a double-layer capsule wall design or high-strength edge hot-pressing sealing technology can be adopted in engineering. Moreover, adding a porous metal skeleton or expanded graphite into PCM can not only improve thermal conductivity but can also effectively restrain the flow and leakage of liquid PCM by capillary force, thus ensuring the reliability of long-term operation. (3) Extra weight: Taking the prototype of this paper as an example, 150 g of PCM and flexible packaging materials only account for about 1.5–2.0% of the total weight of the motor. This slight weight increase has little influence on the overall power density, moment of inertia, and rotor dynamic characteristics of the motor. (4) Implementation cost: The cost of paraffin-based PCM raw materials is low, and the main cost increase comes from customized packaging and assembly man-hours. However, for the application scenarios such as electric vehicle drive motors and aerospace actuators, which require extremely high short-term peak overload capacity and have high added value, the comprehensive benefits brought by this structure in improving overload performance and simplifying the system (eliminating active cooling components) far outweigh its increased implementation cost. Generally speaking, the structure has high feasibility of engineering landing.

6. Conclusions

This paper addresses the issue of excessive temperature in the end windings of the PMSM under overload operation by proposing a close-contact capsule cooling structure. In this design, a PCM is encapsulated in a capsule structure that is tightly attached to the end windings, thereby constructing a passive thermal management scheme based on the PCM. The major contribution of this work is not merely proposing a new PCM arrangement but revealing the coupling relationship between overload factor and PCM phase transition temperature. The main conclusions are as follows:

(1) Placing the PCM directly at the winding ends can improve heat transfer and absorb excess heat, which is beneficial for improving the cooling effect of the end windings. Under 2.0 times overload, the safe overload time of the motor with RT-100 PCM is extended from 2500 s (without PCM) to 3500 s, representing an improvement of about 40%. During the phase change process, the winding temperature distribution temporarily shifts from a pattern of higher temperatures at the ends and lower in the middle to the opposite pattern, i.e., higher in the middle and lower at the ends, which verifies the targeted suppression effect of PCM on the end winding temperature.

(2) There exists an optimal selection criterion between the phase change temperature of the PCM and the overload factor. At 2.0 times overload, the optimal phase change temperature is 100 °C; at 2.5 times overload, the optimal value rises to 120 °C. Deviation from the optimal phase change temperature leads to a notable decrease in the effective overload time in all cases, indicating that the selection of PCM should be determined according to the target overload condition.

Although this paper confirms the advantages of the close-fitting PCM bladder structure in improving the single overload capacity of permanent magnet synchronous motors, several limitations remain. First, experimental verification has only been conducted with RT-100 PCM due to prototype and schedule constraints; while the validated numerical model provides a credible basis for predicting other PCM candidates, further experimental validation with additional materials is needed. Second, this study only considers single constant-rate overload conditions, whereas real-world applications often involve frequent start-stop or cyclic impact loads; future work should investigate the melting–solidification hysteresis and heat accumulation effects under cyclic thermal loads. Third, passive PCM cooling alone cannot meet the steady-state dissipation requirements for prolonged high-load operation; future research will explore hybrid systems combining PCM with heat pipes, microchannel liquid cooling, or phase change thermal diodes. In parallel, the thermal conductivity bottleneck of pure paraffin will be addressed through optimized PCM geometries or composite structures incorporating porous metal skeletons, expanded graphite, or internal fins.

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References

1. Luo, Z.; Guo, Y.; Huang, Y.; Guo, L.; Zhang, W.; Peng, Y. Research on sensorless control of a permanent magnet synchronous motor based on an improved sliding mode controller with improved phase-locked loop. *Electronics* **2025**, *14*, 3822. [\[CrossRef\]](#)
2. Xue, H.; Zhang, Z.; Lin, Q.; Liu, Y.; Gao, H.; Yao, Y.; Hua, Y. Torque density improvement of different flat PMSM topologies using a hybrid optimization method considering end effects and shape ratio influence. *IEEE Trans. Ind. Electron.* **2025**, *73*, 1804–1815.
3. Wang, Y.; Li, C.; Fu, Z. NCS-BWO algorithm for permanent magnet synchronous motor parameter identification. *Electronics* **2025**, *14*, 4631. [\[CrossRef\]](#)
4. Hoang, D.T.; Nguyen, M.D.; Kim, S.M.; Bang, T.K.; Kim, Y.J.; Shin, K.H.; Choi, J.Y. Irreversible demagnetization prediction due to overload and high-temperature conditions in PMSM based on nonlinear analytical model. *IEEE Trans. Energy Convers.* **2024**, *40*, 2256–2267.
5. Wang, S.; Chen, J.; Yang, J.; Zhang, C.; Qiu, S.; Liu, K.; Lyu, B. Analysis of temperature rise in short-term high overload torque motor with LPTN considering demagnetization and saturation. *IEEE Trans. Energy Convers.* **2025**, *40*, 2268–2279. [\[CrossRef\]](#)
6. Hu, J.; Lv, K.; Huang, W.; Lin, H.; Wang, D. Temperature measurement of PMSM rotor based on wound-rotor resolver reuse technique. *IEEE Trans. Transp. Electrification* **2024**, *11*, 2415–2424.
7. Liu, Y.; Huang, X.; Li, J. Direct cooling of arc permanent magnet synchronous motor based on additive-manufacturing winding. *IEEE Trans. Ind. Appl.* **2025**, *61*, 9086–9094. [\[CrossRef\]](#)
8. An, H.; Pei, R.; Deng, W.; Li, M.; Hou, Q.; An, Y. Research on the thermal protection capability of nano-thermal insulation materials for permanent magnet motors in high-temperature vacuum environments. *Electr. Eng.* **2025**, *107*, 12403–12422. [\[CrossRef\]](#)
9. Chen, H.; Xiao, J.; Huang, Y.; He, P.; Zhang, J. Cooling enhancement of axial flux permanent magnet motors by corrugated spiral channels with nanofluid. *J. Electr. Eng. Technol.* **2025**, *20*, 1523–1540. [\[CrossRef\]](#)
10. Li, J.; Duan, W.; Chen, Y.; Chen, H.; Song, M.; Liao, S.; Shi, E.; Sun, X. Thermal performance of pin fin heat sinks with phase change material for electronic devices thermal management. *Appl. Therm. Eng.* **2024**, *250*, 123456. [\[CrossRef\]](#)
11. Gundabattini, E.; Mystkowski, A.; Raja Singh, R.; Darius Gnanaraj, S. Water cooling, PSG, PCM, cryogenic cooling strategies and thermal analysis (experimental and analytical) of a permanent magnet synchronous motor: A review. *Sādhanā* **2021**, *46*, 124. [\[CrossRef\]](#)

12. Wróbel, R. Thermal management of electrical machines for propulsion-challenges and future trends. *Arch. Electr. Eng.* **2022**, *71*, 175–181. [[CrossRef](#)]
13. Yousefi, E.; Nejad, A.A. Waste heat management in electric motors using thermoelectric generator integrated with phase change material and metal foam-embedded heat sink. *Energy Rep.* **2024**, *11*, 6199–6207. [[CrossRef](#)]
14. Lamarre, J.M.; Ibrahim, M.; Pelletier, R.; Vatandoost, H.; Bernier, F. Permanent magnets with embedded phase changing material for electric motor thermal management. *J. Appl. Phys.* **2024**, *136*, 174901. [[CrossRef](#)]
15. Wang, S.; Li, Y.; Li, Y.Z.; Wang, J.; Xiao, X.; Guo, W. Transient cooling effect analyses for a permanent-magnet synchronous motor with phase-change-material packaging. *Appl. Therm. Eng.* **2016**, *109*, 251–260. [[CrossRef](#)]
16. Wang, S.; Li, Y.; Li, Y.Z.; Wang, J.; Xiao, X.; Guo, W. Conception and experimental investigation of a hybrid temperature control method using phase change material for permanent magnet synchronous motors. *Exp. Therm. Fluid Sci.* **2017**, *81*, 9–20. [[CrossRef](#)]

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