

Design and Thermal Analysis of a Heat Pipe for High-Temperature Stability in a Dy-Free Permanent Magnet Motor

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With the rapid growth of the electric vehicle (EV) market, the demand for high-efficiency and high-power motors has steadily increased. Consequently, the use of rare-earth materials such as neodymium (Nd) permanent magnets has also risen. However, the monopolistic supply chain and price volatility of rare-earth elements limit their wide adoption. In this study, we propose a motor structure that eliminates the use of dysprosium (Dy)—a rare-earth element critical for maintaining coercivity in high-temperature environments—to address concerns related to supply instability and cost escalation. While Dy plays a key role in preventing irreversible demagnetization by preserving magnet coercivity under elevated temperatures, this research demonstrates that stable performance can still be achieved at high temperatures without Dy by integrating a heat pipe into the motor design. The heat pipe effectively reduces the temperature of the permanent magnets; however, poor structural design may exacerbate eddy current losses, leading to further temperature increases. Hence, we conducted a thermal equivalent circuit analysis to verify that the heat pipe successfully controls magnet temperature rise and prevents irreversible demagnetization. The proposed structure is expected to reduce the consumption of rare-earth materials while enhancing both the efficiency and reliability of the motor.

Index Terms—Rare Earth, Demagnetization, Thermal Equivalent Circuit, Heat Pipe

I. INTRODUCTION

The global electric vehicle (EV) market is experiencing rapid growth, placing increasing demands on high-efficiency and high-power motor technologies. One of the most widely adopted motor types for EV propulsion relies on neodymium (Nd) magnets, particularly NdFeB (Neodymium Iron Boron), due to their high energy density and excellent magnetic properties. However, these magnets incorporate rare-earth metals, among which dysprosium (Dy) is crucial for enhancing coercivity, especially under elevated temperatures. The scarcity and price volatility of dysprosium raise significant concerns regarding supply stability and economic viability. Consequently, current research efforts focus on reducing or entirely eliminating dysprosium content in NdFeB magnets.

In high-temperature operating environments, the absence or reduction of dysprosium poses a serious challenge: maintaining sufficient coercivity to prevent irreversible demagnetization. As the temperature rises during motor operation, demagnetization can degrade performance and reliability. This underscores the importance of both selecting a magnet material with high coercivity and implementing effective thermal management strategies to mitigate excessive heat buildup.

In this study, we propose a motor structure that relies on NdFeB magnets without dysprosium while ensuring high-temperature stability through the integration of heat pipe technology. The heat pipe exploits the phase change of an internal fluid—evaporation and condensation—to efficiently transfer and dissipate heat. However, if the design is not optimized, eddy current losses can be amplified, leading to additional heating issues. Hence, we develop a thermal equivalent circuit model to examine the performance of the heat pipe under various conditions and apply this model to a motor design that can effectively control magnet temperature and prevent irreversible demagnetization.

II. HEAT PIPE APPLICATION

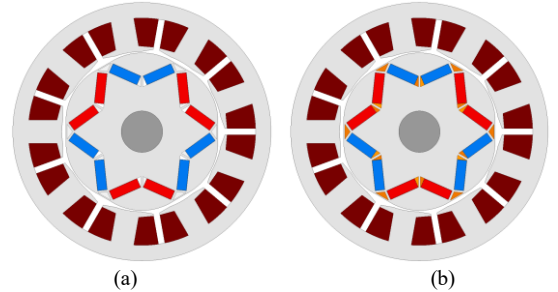


Fig. 1. (a) Conventional Model (b) Heat Pipe Inserted Model.

Figure 1(a) shows the conventional model, while Figure 1(b) shows the model with an applied heat pipe. In a V-type Interior Permanent Magnet Synchronous Motor (IPMSM), severe demagnetization was observed at the ends of the permanent magnets. This occurs because these regions are strongly affected by the stator's demagnetizing flux, making them more susceptible to demagnetization than other areas. Consequently, heat pipes were applied to the barrier regions with air structures located at these magnet ends. Furthermore, in the thin bridge sections where the permanent magnets bend, the flux can become saturated by the demagnetizing flux and flow into the permanent magnets, resulting in demagnetization. To address this issue, heat pipes were also installed in the barriers located at these bending sections.

TABLE I
SPECIFICATIONS OF MODEL

Parameter	Value	Unit
Poles / Slots / Phases	6 / 9 / 3	-
Maximum Speed	12,000	RPM
Air gap	0.5	mm
Stack length	40	mm
Stator outer diameter	50	mm
Rotor outer diameter	30.5	mm
Magnet Material	Dy-free Nd	-

III. THERMAL EQUIVALENT CIRCUIT

A. Thermal Equivalent Circuit

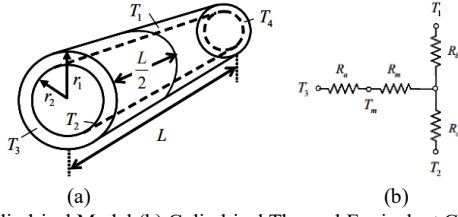


Fig. 2. (a) Cylindrical Model (b) Cylindrical Thermal Equivalent Circuit

$$R_a = \frac{L}{6\pi k_a (r_1^2 - r_2^2)} \quad (1)$$

$$R_b = \frac{1}{2\pi k_r L} \left[1 - \frac{2r_2^2 \ln(\frac{r_1}{r_2})}{(r_1^2 - r_2^2)} \right] \quad (2)$$

$$R_c = \frac{1}{2\pi k_r L} \left[\frac{2r_2^2 \ln(\frac{r_1}{r_2})}{(r_1^2 - r_2^2)} - 1 \right] \quad (3)$$

$$R_m = \frac{-1}{4\pi(r_1^2 - r_2^2)k_r L} \left[r_1^2 + r_2^2 - \frac{4r_1^2 r_2^2 \ln(\frac{r_1}{r_2})}{(r_1^2 - r_2^2)} \right] \quad (4)$$

Equations (1), (2), (3), and (4) represent the axial conduction thermal resistance, the radial conduction thermal resistance up to r_1 , the radial conduction thermal resistance up to r_2 , and the radial temperature-correction thermal resistance for calculating the average temperature, respectively. Here, k_a and k_r denote the thermal conductivities in the axial and radial directions, respectively. In the case of a motor, the thermal conductivities in these directions differ due to lamination and electrical steel coating processes during manufacturing, necessitating the use of separate values for each direction.

B. Thermal Equivalent Simplified Model

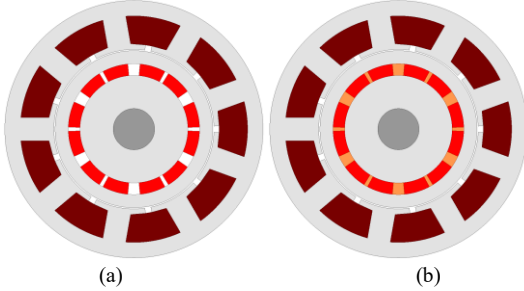


Fig. 3. Thermal Equivalent (a) Conventional (b) Heat Pipe Applied Model.

Figures 3 illustrate simplified models derived from the cylindrical model in Figure 2, used to construct the thermal equivalent circuit. The geometry and arrangement of the original permanent magnets, barriers, and heat pipes—including their angles, positions, and areas—were taken into account to develop an equivalent yet simplified representation.

C. Temperature Calculation

$$\begin{bmatrix} \lambda(1,1) & \cdots & -\lambda(1,i) & \cdots & \lambda(1,n) \\ \vdots & & \vdots & & \vdots \\ -\lambda(i,1) & \cdots & \lambda(i,i) & \cdots & -\lambda(i,n) \\ \vdots & & \vdots & & \vdots \\ -\lambda(n,1) & \cdots & -\lambda(n,i) & \cdots & \lambda(n,n) \end{bmatrix} \begin{bmatrix} T(1) \\ \vdots \\ T(i) \\ \vdots \\ T(n) \end{bmatrix} = \begin{bmatrix} P(1) \\ \vdots \\ P(i) \\ \vdots \\ P(n) \end{bmatrix} \quad (5)$$

In Equation (5), λ represents the thermal conductivity matrix, T represents the temperature rise matrix, and P represents the loss matrix. The thermal conductivity and loss values can be represented based on the calculations at each node, and the inverse matrix relationship $T = \lambda^{-1}P$ allows the temperature values to be determined.

IV. COMPARISON OF TEMPERATURE AND DEMAGNETIZATION

TABLE II
COMPARISON OF KEY AREA TEMPERATURES

Parameter	Conventional Model	Heat Pipe Applied Model
Coil	129.9°C	128.9°C
Rotor	123.7°C	104.9°C
Stator	127.9°C	127.6°C
Permanent Magnet	123.9°C	105.7°C

As shown in Table 2, the application of the heat pipe resulted in minimal temperature reduction in the stator core and winding areas located in the stator. However, a significant temperature reduction was observed in the permanent magnet and rotor areas. For the permanent magnet, it is critical to ensure that the temperature does not exceed a certain threshold.

TABLE III
COMPARISON OF DEMAGNETIZATION

Parameter	Conventional Model	Heat Pipe Applied Model
Demagnetization	1.53%	0.08%

Initially, the back electromotive force (EMF) was measured under zero current conditions, and then the demagnetization current was applied. Subsequently, the reduction rate of the back EMF was expressed as the demagnetization rate.[3] The differences in demagnetization rates are shown in Table 3.

V. CONCLUSION

Thermal analysis time was reduced using a thermal equivalent circuit, enabling the evaluation of temperature reduction when applying a heat pipe. The results showed that the temperature of the permanent magnet decreased by approximately 18°C with the application of the heat pipe. This reduction in temperature prevented the motor from operating below the knee point, leading to a decrease in the demagnetization rate.

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