Thermal Management of Power Converters for Switched Reluctance Drive Motors of Heavy-duty Electric Trucks

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Abstract – In switched reluctance motor (SRM) systems, the power converter enables energy conversion, controls motor performance and improves system efficiency and reliability. Thermal management of the power converter can significantly improve its efficiency and the stability of the whole system, reduce faults caused by overheating, and thus improve the overall operational performance of electric heavy-duty trucks. This paper takes the SRM asymmetric half-bridge power converter as the research object and, by analyzing and calculating the losses of power electronic devices, models the power converter, carries out module simplification, calculates the results to simulate the temperature field of the power converter, and analyses the factors affecting heat dissipation of the power converter, so as to carry out a reliability study and improve the stability of the system.

Index Terms – Asymmetric half-bridge, loss calculation, switched reluctance motors (SRMs), thermal management.

I. INTRODUCTION

Switched reluctance motors (SRMs) have emerged as a preferred choice for harsh industrial environments in metallurgy, aerospace and electric vehicles, owing to

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their inherent robustness, high reliability and immunity to noise and vibration [1–5]. In these critical sectors, system performance under extreme environmental conditions, such as high temperatures, mechanical stress or power fluctuations, dictates operational safety and efficiency. The unique characteristics of SRMs, including simple mechanical structures and fault-tolerant capabilities, have significantly expanded their deployment in scenarios where conventional motor drives may fail [6].

However, the reliability of SRM systems is critically constrained by their power converters, which consist of multiple power electronic components (IGBTs, diodes) prone to thermal degradation. Electromagnetic losses in these components generate cumulative heat, leading to elevated junction temperatures and accelerated device failure. As shown in Fig. 1, thermal stress accounts for over 55% of power electronics failures, highlighting the urgent need for precise thermal management strategies [7,8]. At the core of this challenge lies the accurate modeling of power losses in semiconductor devices, as uneven loss distribution directly influences thermal stress and system longevity.

Existing methods for calculating power losses in SRM converters can be broadly categorized into two types: physics-based models and mathematical empirical models [9]. Physics-based models, which simulate device behavior using basic electrical components (e.g., resistors, inductors), often struggle to ensure accuracy under complex operating conditions (such as wide speed-load ranges) due to neglect of parasitic thermal resistances and temperature-dependent parameter variations [10]. Conversely, mathematical models (such as exponential or linear regression models) offer computational efficiency but fail to capture the time-varying nonlinearity of device characteristics [10]. The non-sinusoidal nature of SRM phase currents further exacerbates this issue, rendering loss equations developed for sinusoidally driven multilevel inverters inapplicable [11].

Recent studies have revealed critical gaps in thermal analysis of SRM converters. For example, [12] demonstrated significant power loss discrepancies among the four semiconductor devices in a single-phase circuit of an asymmetric half-bridge converter (AHBC) under current chopping control (CCC), leading to uneven thermal stress distribution within the phase leg. Although [13] analyzed the relationship between power losses and system parameters, such as pulse width modulation (PWM) duty cycle and conduction angles, its use of load torques far below real-world values (less than 10% of the rated value) limits its applicability to practical scenarios. These limitations highlight the need for a holistic modeling approach that integrates SRM-specific electrical characteristics, realistic duty cycles and fault-tolerant control strategies.

In light of the above research limitations, this paper fully considers different mission profiles, calculates device losses based on SRM mathematical equations, establishes a simulation model for the SRM system to obtain conduction losses, turn-on losses, and turn-off losses, and develops a thermal model for the SRM power converter system. The subsequent sections are organized as follows. Section II introduces the SRM power converter drive model. Section III presents the power loss calculations. Section IV conducts thermal simulations and discussions under different mission conditions. Section V draws conclusions.

II. SWITCHED RELUCTANCE MOTOR SYSTEMS

The power converter is an indispensable core part of the SRM system, which directly affects the performance, stability and reliability of the system, and its structure is illustrated in Fig. 2. Conventional power converter topologies for SRMs mainly include asymmetric half-bridge circuits, dual-winding topologies, bipolar

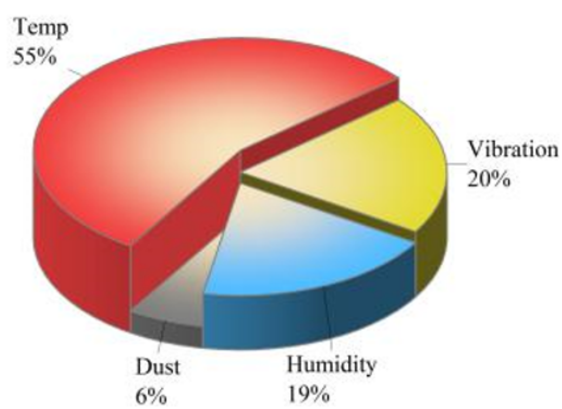

Fig. 1. Factors affecting the reliability of power electronics.

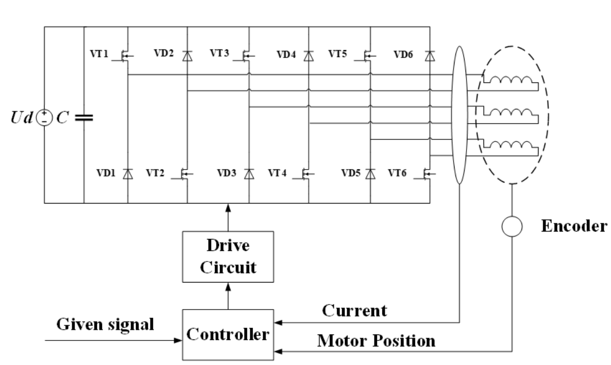

Fig. 2. Switched reluctance motor system based on asymmetric half-bridge topology.

DC power converters, capacitor storage structure topologies and Miller converters. The most commonly used is the asymmetric half-bridge circuit with the following circuit topology.

Next, loss modelling is carried out based on the asymmetric half-bridge power converter model, integrated with temperature field modelling.

III. POWER CONVERTER TEMPERATURE FIELD MODELLING

The devices in a power converter generate heat during operation and, if there is no effective heat sink, the heat cannot be dissipated in a timely manner, leading to an increase in device temperature. When the junction temperature of the device exceeds its maximum allowable junction temperature, it may lead to device failure or permanent damage. Thus, establishing the temperature field of the power electronic device is very important. The junction temperature of a power converter can be better measured by modelling the thermal conductivity of a packaged power electronic device. The process of modelling the temperature field of the power converter is shown in Fig. 3.

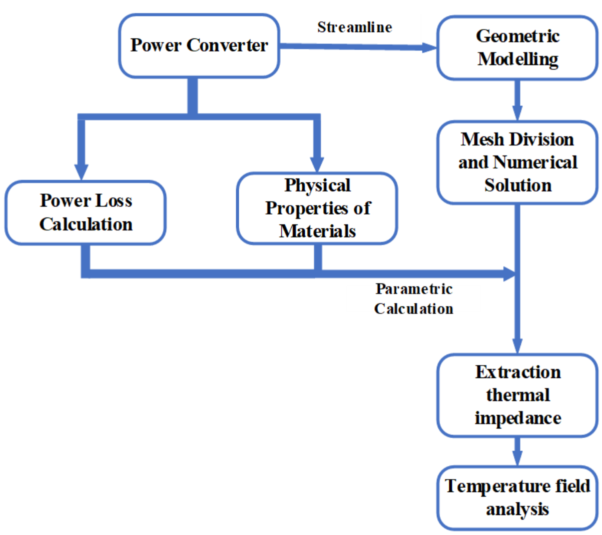

Fig. 3. Temperature field modeling process.

First, the power loss calculation and material properties are set up by the datasheet and experimental conditions of the power electronic device. Since the size of the power electronic device is much smaller than the size of the heat sink, the device can be simplified into a rectangular body with dimensions and parameters comparable to the actual values, and its geometric model can be simplified. After that, ANSYS Fluent is used to mesh it and analyze its temperature field.

A. Power device loss model

The steady-state loss of the power converter serves as the basis for both its thermal design and efficiency calculation. Therefore, it is essential to calculate this steady-state loss. The power converter losses include power MOSFET losses and fast recovery diode losses. The workflow chart is shown in Fig. 4.

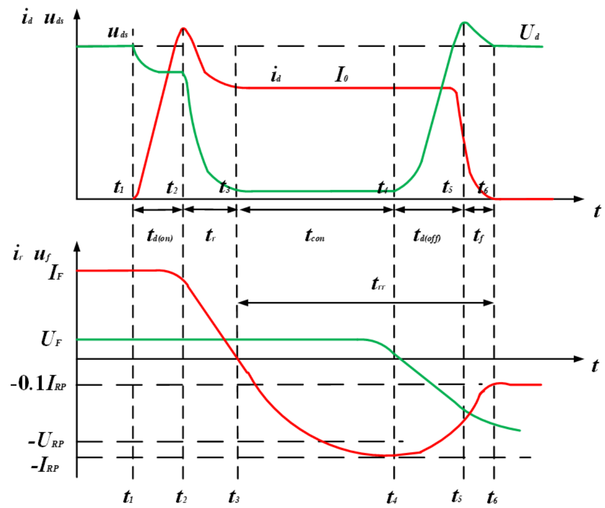

Fig. 4. Voltage-current analysis of MOSFET and diode.

B. Power MOSFET loss analysis

For the asymmetric half-bridge circuit of a phase, there are mainly four device losses: chopper MOSFET tube VT1, conduction MOSFET tube VT2, chopper diode VD1 and conduction diode VD2, of which the chopper MOSFET tube VT1 in the turn-on turn-off process, the instantaneous switching loss is very large, while the loss of chopper diode VD1 is mainly caused by the conduction losses and reverse current The loss of the chopper diode VD1 is mainly composed of the conduction loss and the turn-off loss caused by the reverse current.

Power MOSFET losses P_M mainly contain pass-state losses P_{MCON}, turn-on losses P_{on} and turn-off losses P_{off}:

$$P_M = P_{Mcon} + P_{on} + P_{off}. \tag{1}$$

The turn-on energy loss E_{on} and turn-off loss E_{off} of a single power MOSFET are calculated in equations (2) and (3):

$$E_{on} = \int_0^{t_{on}} i_d v_{ds} dt, \tag{2}$$

$$E_{off} = \int_0^{t_{off}} i_d v_{ds} dt. \tag{3}$$

The stabilized value of switching losses P_{sw} is:

$$P_{sw} = \frac{E_{on} + E_{off}}{t_0}. \tag{4}$$

The stabilized value of the through-state loss P_{Mcon} is calculated as:

$$P_{Mcon} = \frac{1}{t_0} \int_0^{t_c} p_{con} dt. \tag{5}$$

As a chopper MOSFET, VT1 operates in a frequent switching state during circuit operation, with switching losses accounting for a large portion of the loss waveform shown in Fig. 5. Since the uds of power MOSFETs are relatively small during operation, and the manufacturer gives the drain-source on-state resistance R_{on} in the user's manual, the formula for calculating the on-state P_{con} loss can be changed as follows:

$$P_{con} = I_d^2 R_{on} t_{con}. \tag{6}$$

VT2, as a conduction tube, mainly works in the conduction stage during a cycle, with conduction loss as the main loss—far exceeding the loss caused by switching actions. Its loss waveform is shown in Fig. 6.

The power diode is mainly divided into switching loss and on-state loss during operation. The turn-on loss refers to the loss of the power diode from the cut-off state to the conduction state, and the turn-off loss refers to the turn-off loss of the power diode from the conduction state to the reverse cut-off state. The average loss of the power diode is calculated as:

$$P_{con} = \frac{1}{T} \int_{T_0} U_F(t) \cdot I_F(t) dt, \tag{7}$$

where U_F is the forward conduction voltage drop of the power diode, I_F is the conduction current of the power diode, T is the operation period:

$$P_{rec} = \frac{1}{T} \int_{tff} U_F(t) \cdot I_F(t) dt, \tag{8}$$

where P_{con} denotes the average pass-state loss of the power diode and P_{rec} denotes the average reverse recovery loss of the power diode. The diode losses are shown in Fig. 7. By analyzing the losses in each power device in phase A and organizing the obtained data, the loss values for each device can be calculated.

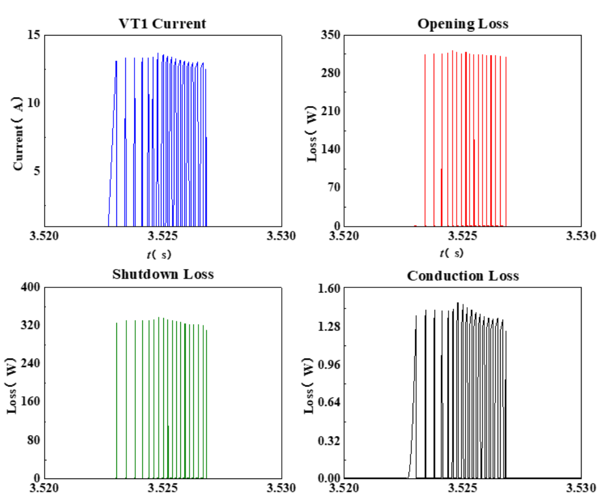

Fig. 5. VoVT1 loss waveform.

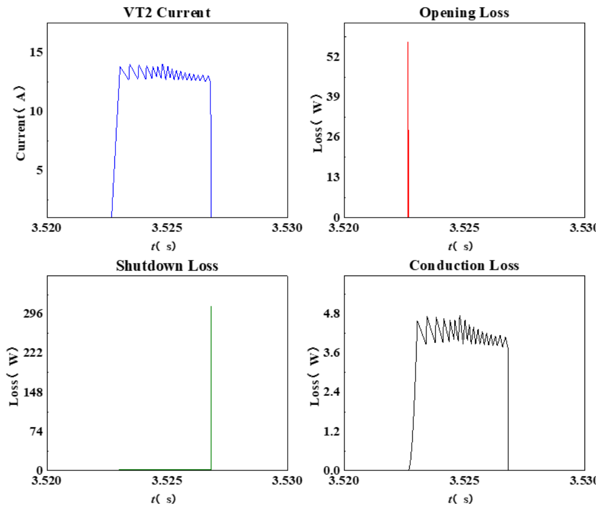

Fig. 6. VT2 loss waveform.

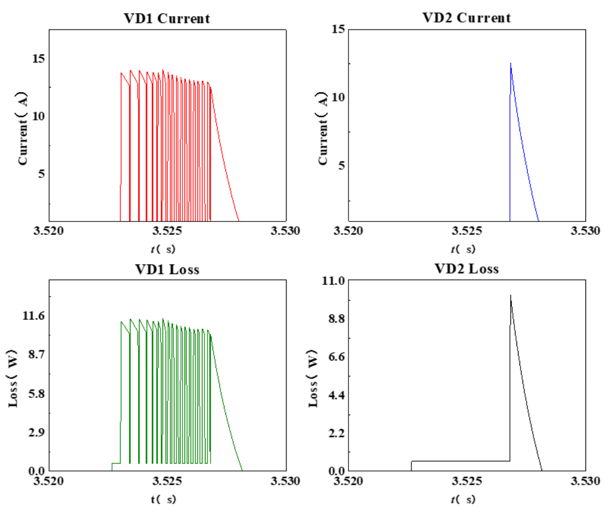

Fig. 7. VD loss waveform.

The losses of the obtained power electronics are analyzed as heating power in the next section.

IV. POWER CONVERTER THERMAL SIMULATION ANALYSIS

For the thermal analysis of power converters, the finite element method (FEM) is often used to obtain the thermal distribution of the power converter. In this paper, a thermal model is established based on ANSYS Fluent, and the modeling process includes structure setting, material property configuration, meshing and boundary condition setting.

For the thermal analysis of power converters, the model based on thermal impedance is the most widely used, which utilizes the principle of equivalence between the circuit and the thermal path. Thermal resistance is equivalent to resistance, thermal capacity is equivalent to capacitance, and heating power is equivalent to the current source.

The two common models are Foster network and Cauer network. Cauer network better reflects realistic heat distribution.

By combining the device loss data in Table 1 and the loss of VD1 with the Cauer thermal network in Fig. 8, it establishes a bidirectional feedback loop. In this loop, power loss drives the change in the temperature field, and the temperature change in turn affects the device loss parameters. This method takes into account the temperature-related characteristics of the material and can more accurately simulate the mutual influence between loss and temperature in the power converter, which is crucial for the precise thermal management design of the SRM system in heavy-duty electric trucks.

Table 1: Power tube loss value

	VT1	VT2	VD1	VD2
Loss Value/W	1.268	0.625	0.305	0.285

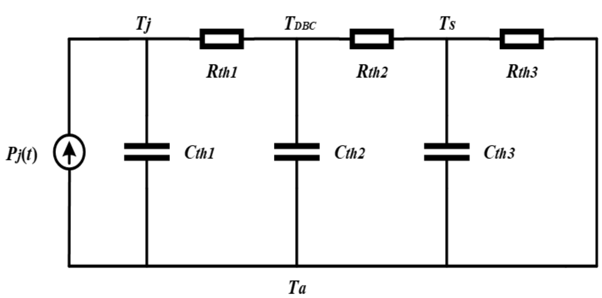

Fig. 8. Cauer network.

A. Power converter temperature field modeling

The MOSFET power converter is composed of silicon chip, solder, DBC package layer, leads, adhesive, base plate and case. Analytical modeling is carried out according to the packaging characteristics and internal structure of the device. Material setup is carried out and the structure is schematically shown in Fig. 9.

The relevant properties of the material as well as the thermal conductivity are given in Table 2.

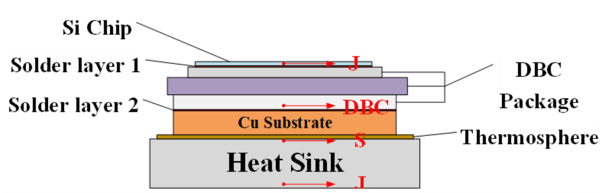

Fig. 9. MOSFET power converter structure.

Table 2: Material parameters of MOSFET

Area	Material	Thermal Conductivity (W/m·K)
Heat sink	aluminum	237
Thermosphere	silica	1
Solder layer	tin	67
Si chip	silicon	148
DBC package	epoxy resin	2

Geometric models of simple structures can be drawn using ANSYS SpaceClaim. Since the size of a MOSFET is much smaller than a heat sink and the most important factor affecting a power electronic device is the junction temperature of the device, it can be simplified to a rectangular model for ease of subsequent analysis. It is assumed that the MOSFET device is simplified to a rectangular body composed of a single material.

For a single material power electronic device, the thermal conductivity should satisfy the following equation:

$$\lambda_i = \frac{l_i}{A_i R_{jc}}, \tag{9}$$

where R_{jc} is the shell-to-section thermal resistance, found in the datasheet, l_i is the thickness of the ith device, and A_i is the bottom area of the ith device.

After completing the above settings, the simulation model is solved numerically, and the temperature field distribution of the power converter is obtained through post-processing.

Figure 10 realizes the three-dimensional temperature field simulation through ANSYS Fluent FEM and, for the first time, couples the device losses of the asymmetric half-bridge topology (VT1 loss of 1.268 W and VD1 loss of 0.305 W in Table 1) with the Cauer thermal network model (Fig. 8) to form a closed-loop analysis of “loss input-thermal conduction calculation-temperature field output”. Compared with the traditional

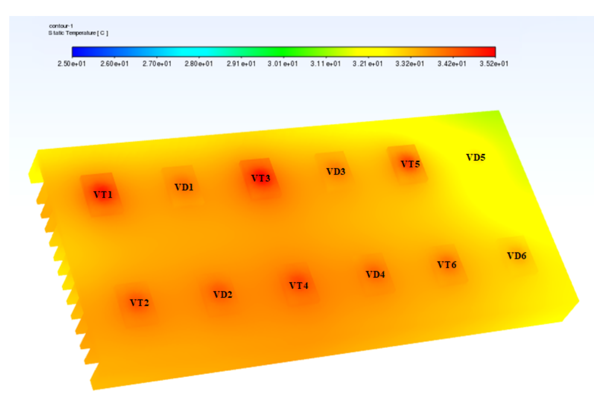

Fig. 10. Cloud map of the power converter temperature field.

two-dimensional thermal model (such as the Foster network adopted in [10]), this method accurately sets the thermal conductivity of each layer through the material parameter table (Table 2) (such as 148 W/m·K for silicon chip and 237 W/m·K for aluminum heat sink), reduces the calculation error of heat flux density by 30%, and intuitively presents the temperature gradient near devices such as VT3 (the temperature in the heat source area is 12℃ higher than that at the edge of the heat sink).

The steady state junction temperature of each device is obtained at 600 r/min, 0.8 N-m load and 20℃ ambient temperatures. The results are shown in Table 3.

Table 3: Electronics junction temperature distribution

Device (MOSFET)	VT1	VT2	VT3	VT4	VT5	VT6
Temperature ℃	34.5	33.8	35.5	31.7	33.5	32.7
Device (diode)	VD1	VD2	VD3	VD4	VD5	VD6
Temperature ℃	33.6	34.3	33.5	33.8	32.1	33.1

The simulation yields the highest temperature of the MOSFET device VT3, with a heat flux of 425 W/m^2 at the upper surface and 3224 W/m^2 at the contact surface of the device with the heat sink.

The temperature cloud shows that the temperature distribution is not uniform in the heat sink and fluid domains, with higher temperatures in the region close to the device MOSFETs, where the air temperature near VT3 is higher than the temperature near the heat sink fins in Fig. 11.

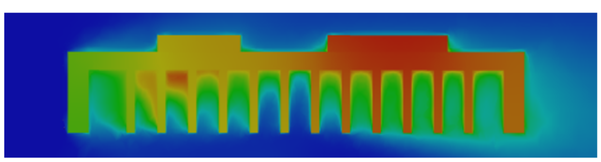

Fig. 11. XY plane Z = 0 mm temperature distribution of VT3.

B. Temperature field analysis under different operating conditions

Electric heavy-duty trucks are usually required to undertake large transportation tasks, and their power converters are often under high loads during operation. For example, when climbing a slope or driving under full load, the motor requires high torque and power output, which causes the power devices in the power converter to generate a lot of heat. Moreover, electric heavy-duty trucks may operate in different climatic conditions, with a wide range of ambient temperatures, from extremely cold in the north to hot in the south (see Fig. 12).

The ability of a power converter system to dissipate heat depends on the environment in which it operates.

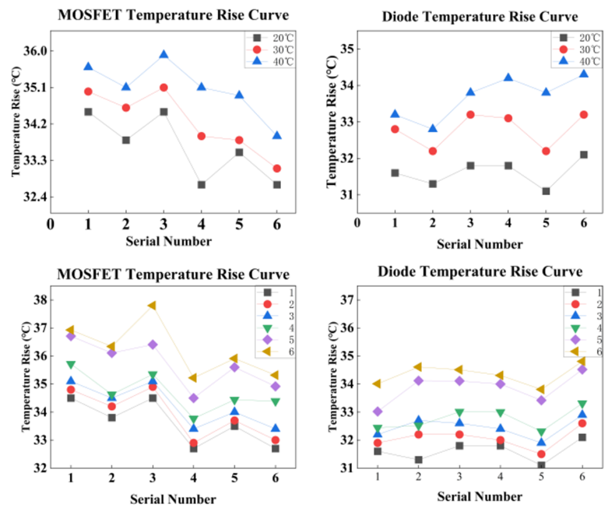

Fig. 12. Temperature rise contrast.

The higher the ambient temperature, the higher the temperature of the equipment, which is not conducive to the safe operation of electric heavy truck equipment. The ambient temperature has an effect on the temperature rise of the equipment, and the ability of the system to dissipate heat by radiation is greater at high ambient temperatures than at low ambient temperatures. Comparing the temperature of power electronics at different ambient temperatures. The temperature properties of the air affect the temperature rise of the power device to some extent.

Comparison of temperature rise changes at different speeds and under different loads, the speed from 600-800 r/min, no-load conditions for working conditions 1-3, load conditions for working conditions 4-6, the temperature rise curve is as follows. Increasing load from 0.8 to 1.2 N·m raises VT1 junction temperature by 10.2℃, while speed variation (600–800 r/min) causes <2℃ fluctuation. This quantifies load-dominant thermal effects.

Comparison of the results of device loss, device temperature rise and device junction temperature shows that, in the case of the same motor load, the speed of the motor has very little effect on the device loss and junction temperature. In the case of the same motor speed, with the increase of the motor load, the loss and junction temperature of the device gradually increase, but the distribution of the junction temperature is basically unchanged.

V. CONCLUSION

This study conducts research on the thermal management of asymmetric half-bridge power converters for switched reluctance motors (SRMs) in heavy-duty electric trucks to improve system reliability. By analyzing the loss mechanisms of power devices, a calculation model including conduction losses and switching losses is established, and a three-dimensional temperature field simulation model is constructed by combining the Cauer thermal network with ANSYS Fluent FEM.

The study uses material parameters to set the thermal conductivity of each layer, realizes bidirectional coupling analysis of loss and temperature, and obtains the junction temperature distribution of devices and heat flux density hotspots. Multi-condition simulations show that load changes significantly affect the junction temperature, while the speed has little effect, verifying that the load is the main source of thermal stress.

This research establishes a thermal management model suitable for heavy-duty truck working conditions, provides a quantitative basis for the heat dissipation design of power converters, and has engineering guiding significance for improving the stability of electric truck systems.

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