Research on heat dissipation and cooling optimization of a power converter in natural convection

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Abstract: A thermal model for the power converter in a switched reluctance motor drive under natural air cooling is presented. In this compact model, the modeling of the power device is simplified reasonably. Based on the computational fluid dynamics and finite element tools, the thermal and fluid characteristics of the power converter are obtained. The experiment platform is then established, which verifies the correctness of the simulation model. To increase the reliability of the power converter, the layouts of devices on the heat sink and the placement direction of the heat sink are optimized without changing the heat sink shape. Four cases of the device layout are designed and contrasted. Furthermore, the optimal layouts of the upper and lower rows of devices with different losses and different heat convection coefficients are derived by adopting a genetic algorithm. Three cases of the heat sink placement direction are designed and compared. Taking the maximum temperature rise and the temperature rise gradient as reliable indexes, the devices should be placed symmetrically on the heat sink if they have the same power losses. The heat sink should be placed horizontally with the fins opening up.

Key words: Thermal model, power converter, natural convection, cooling optimization, switched reluctance motor

1. Introduction

Switched reluctance motor drive systems have good application prospects [1–7], but the power converter as the central executive body has a large number of power electronic devices. These power devices have long working hours with high switching frequency, which results in a large quantity of heat. Thus, the power converter becomes one of the weakest part in the system [6,7]. Therefore, it is very important to study the heat dissipation of the power converter.

The cooling equipment is essential for a power converter. The most common cooling equipment is the heat sink, which is composed of a plate and many fins. The heat sink can be cooled by forced air or natural air. However, the natural air cooling system is more widely applied due to its low price, high reliability, simple equipment, easy maintenance, and so on when the heat flux is below approximately 0.7 W/cm².

Presently, there are some reports about studies of the heat dissipation of plate-fin heat sinks [8–11]. In [8], a practical thermal resistance model of a heat sink with rectangular fins was given. When the Reynolds number is from 500 to 5000, this model can predict the temperature and fluid properties well. It presents the optimal results of fin thickness, fin spacing, plate thickness, and plate length and width. In [9], the influence of fin shape on the heat sink cooling performance was presented and the thermal resistances of rectangular fins and nonrectangular fins were compared when the heat sinks are placed vertically under natural air cooling.
However, these studies were only aimed at the heat sink, while the power converter is a system with multiple heat sources and cooling equipment. Therefore, research should not only include the heat sink but also the power devices. Moreover, the previous studies of cooling optimization mainly focused on the heat sink shape [8–11], with little attention to other aspects.

In this study, a method for simplifying the modeling of power devices is proposed. Based on this, a thermal model for the power converter in switched reluctance motor drivers is built by a finite element tool. The power converter is assembled with a heat sink cooled by natural air. First, the temperature distribution of the power converter is obtained by using the natural convective heat transfer coefficient. Second, the fluid characteristics are derived by adding fluid calculation equations. By comparing with the experimental results, the correctness of the thermal model is proved. To optimize the cooling performance, 4 power converters with different device layouts and 3 different placements of the heat sink are designed. Furthermore, the optimal layouts of the upper and lower rows of the devices are studied by genetic algorithm. Finally, the experiments are carried out to verify the above calculation results.

2. Thermal models for power converter

2.1. System introduction

The power converter in this paper is used to drive a 500-W switched reluctance motor. The main circuit is a three-phase asymmetrical half-bridge circuit as shown in Figure 1. A power MOSFET (FAIRCHILD FQA160N08) and fast-recovery diode (IXYS DSEI 2x121) are used. Two power MOSFETs in parallel are adopted as a main switch unit, and there are 6 main switch units from VT1 to VT6. Thus, there are 12 power MOSFETs in the converter. The main circuit is fixed to a heat sink made of aluminum. The size of the heat sink is shown in Table 1.

![Figure 1. Main circuit topology of the power converter.](image)

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Height</th>
<th>Fin height</th>
<th>Fin width</th>
<th>Fin spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>132</td>
<td>20</td>
<td>15</td>
<td>2.6</td>
<td>5</td>
</tr>
</tbody>
</table>

2.2. Heat dissipation theory

To simplify the analysis, some assumptions are proposed as follows:

1) All materials are homogeneous and isotropic.
2) The thermal conductivities of materials are considered as constants, because the temperature rise is within 50 °C.

3) The thermal radiation is ignored because the convection heat transfer is much stronger than thermal radiation.

4) The air is regarded as an incompressible ideal gas, because the air flow speed is very small in natural air cooling conditions.

5) The ambient temperature is independent of time, and the initial temperatures of materials are equal to the ambient temperature.

6) The power losses of devices are constant, and actually they are the average power losses.

7) The compact modeling of devices is established.

The internal structure of devices is complex, and it is difficult to obtain the internal dimensions and material parameters. Therefore, the device modeling needs to be simplified. The power electronic devices can be regarded as cuboids with single material. The compact model for the power converter is shown in Figure 2. The thermal conductivity $\lambda$ of the material can be calculated by the formula below:

$$\lambda = l/(A \times R_{thCE}),$$

(1)

where $R_{thCE}$ is the thermal resistance from the device bottom to the device top, $l$ is the device thickness, and $A$ is the device bottom area.

Figure 2. 3D compact simulation model.

Thus, the thermal conductivities of the power MOSFET and the diode are 52 W/(m K) and 42 W/(m K), respectively.

The temperature rise $\theta$ is defined as $\theta = T - T_a$. Therefore, the transient temperature rise of the power converter can be expressed as follows:

$$\nabla^2 \theta - \frac{1}{\lambda/\rho c} \frac{\partial \theta}{\partial t} = 0,$$

(2)

where $t$ is the time, $\rho$ is the density, and $c$ is the specific heat.
The boundary condition between the fluid and solid is:

\[-\lambda \nabla \theta = h \theta,\]

(3)

where \( h \) is the convective heat transfer coefficient, the unit of which is \( \text{W/(m}^2 \text{K}) \).

When the heat sink is cooled by natural air, the buoyancy lift is the main force that drives the air motion. The air flow takes the high temperature away from the heat sink, which transfers the heat from the device to the ambient.

There are two coupling conditions between the device and the heat sink. One is temperature continuation:

\[\theta_d = \theta,\]

(4)

where \( \theta_d \) is the temperature rise on the device bottom.

The other is heat flux continuation:

\[-\lambda \frac{\partial \theta}{\partial z} \bigg|_{z=d} = p_1,\]

(5)

where \( p_1 \) is the power loss that is loaded on the device bottom.

Therefore, the junction temperature of the device can be calculated as follows:

\[T_j = \theta_{up} + p_1 R_{CE} + T_a,\]

(6)

where \( \theta_{up} \) is the surface temperature rise on the device top.

3. Experiments

3.1. Experimental platform

The experimental platform is built, and it is used to measure the temperature rise of the power converter from the motor starting up to the temperature rise becoming stable. The ambient temperature is 15 °C, and the motor speed is 646 rpm. The motor is a 12/8 switched reluctance motor, and the supply voltage of the power converter is 24 V. Twelve thermistors are adhered to the top surface of the power MOSFETs to measure the device temperature. The measurement time interval is 1 s, and the accuracy is 1 °C.

The control strategy is alternated voltage PWM, chopping the upper transistor in one cycle and then chopping the lower transistor in the next cycle. Thus, the average power losses of the upper and lower transistors are equal. The device power losses are shown in Table 2.

<table>
<thead>
<tr>
<th>Components</th>
<th>VT1</th>
<th>VT2</th>
<th>VD1</th>
<th>VD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power losses (W)</td>
<td>1.745</td>
<td>1.745</td>
<td>0.105</td>
<td>0.105</td>
</tr>
</tbody>
</table>

3.2. Comparison of simulation and experiment

In the case of not studying the fluid characteristics, the natural convection heat transfer coefficient is always applied to simplify the heat dissipation model. This coefficient is about 5–10 W/(m K). Due to the fins opening down, 5 W/(m K) is chosen in the simulation.
Figure 3 shows the experimental temperature rise curves of 12 measurement points, the distribution of which is illustrated in Figure 4. It can be seen that all the temperature rise curves become stable from 5000 s. This is because the rise time is dependent on the system thermal time, which is a product of the thermal resistance and the thermal capacity. It is independent of the device location and the power loss. The curves display nearly linear rises at the beginning. This is because the startup winding current is so huge that the chopping transistors produce a large number of power losses in a short time, especially the turn-off losses.

![Figure 3. Experimental temperature rise curves of the measuring points.](image1)

Figure 4. Measuring points distribution on the power converter.

Figure 5 illustrates the steady-state temperature rise distribution of the power converter. The comparisons of the simulated steady-state temperature rises and experimental ones of 12 points are shown in Figure 6. It can be seen that the calculated results are very close to the measured values with acceptable errors within 1 °C or less. The main reason for this mistake is the uneven current distribution that results in uneven distributed power losses between the two parallel transistors, but this is ignored in the simulation. Secondly, there is an error of 1 °C in the measuring instrument. The temperature rise derived from the simulation is mainly used for design, and a certain margin must be considered in the design process. Therefore, the absolute error that is less than 1 °C, is very small and meets the application demand. In summary, the simulation results match well with the experimental ones, which verifies the correctness of the heat dissipation model.

![Figure 5. Temperature rise contours of the power converter.](image2)
4. Cooling optimization

The junction temperature of the power device is a vital index for the device’s thermal reliability. However, the differences of the junction temperatures among the devices need to be investigated, because the device has different electrical characteristics at different junction temperatures. A large difference will make the electrical characteristics deviate from the design target seriously. To make the devices have similar electrical performances, the junction temperature differences among the devices should be reduced to be as small as possible. Therefore, the temperature rise gradient of the power converter is defined as another index for the reliability. The formula for the temperature rise gradient $G_\theta$ is expressed as follows:

$$G_\theta = \frac{\theta_{\text{max}} - \theta_{\text{min}}}{100\%},$$

where $\theta_{\text{max}}$ is the maximum and $\theta_{\text{min}}$ is the minimum temperature rise of the device.

4.1. Influence of device layout

To investigate the influence of the device arrangement on the heat dissipation performance, 4 power converters with different device layouts on the heat sink are designed, including the original one named as Layout 1. Figure 7 illustrates Layout 2 and Layout 3, and Layout 4 is shown in Figure 8. The thermal models for Layout 2 and Layout 3 are similar to Layout 1, and the temperature distributions for Layout 2 and Layout 3 are shown in Figure 9. Correlative temperature rise experiments are also carried out. The comparisons of the experiment and simulation are shown in Figure 10, which proves the correctness of the simulation.

In Layout 1, the highest temperature rise is at point 9, located in the middle of the power converter. The highest temperature rise is about 22 °C. The temperature rise gradient is approximately 0.5%. Figure 9 illustrates that in Layout 2, the highest temperature rise is also about 22 °C, but it appears at Point 1 and Point 12, which are located on the border of the heat sink. The temperature rise gradient is about 0.8%, and it is bigger than in Layout 1. In Layout 3, the maximum temperature rise, about 21.7 °C, appears at Point 12. It is on the right edge of the upper row of devices. The temperature rise gradient is approximately 1.2%, so the temperature difference in Layout 3 is obviously much larger than that in Layout 1 and Layout 2. By comparing
Layout 1, Layout 2, and Layout 3, it is seen that Layout 1 has the highest thermal reliability. Therefore, when the devices have the same power losses, the symmetrical layout excels the asymmetrical one.

4.2. Optimal layout of upper and lower rows of devices

Because the device locations on the heat sink affect the temperature rise of the power converter, the optimal device layout should be investigated [12,13]. To analyze it simply, the upper and lower rows of devices are considered as two devices, which have the same shape and same material. Thus, the original 3D model can be simplified to a 2D model as shown in Figure 11. The length of the device is 20 mm. The left device is named as Device 1 with power loss $P_1$, and the right device is named as Device 2 with power loss $P_2$. The optimization mathematical model can be expressed as follows:

$$\begin{align*}
\min f &= T(L_1, L_2) \\
\text{st. } 1 &\leq L_1 \leq 56, 1 \leq L_2 \leq 111, |L_1 + L_2 - 132| \geq 21
\end{align*}$$

The genetic algorithm, imitating genetic heredity and evolution, is a self-adaptation optimization method. It uses a parallel search to seek the optimal individuals, where it is not easy to fall into local optimization. It has the advantage of briefness, efficiency, and robustness, especially for solving nonlinear or multitarget issues. Therefore, the genetic algorithm is applied to solve the device layout problem with the genetic algorithm program in MATLAB. The flow chart is shown in Figure 12. The population chromosomes are the device locations that are limited to integers for simplified calculation.
Figure 9. Simulated temperature rise contours of 2 power converters.

Figure 10. Comparisons of experimental results and simulated ones.

Figure 11. Simplified 2D model for the power converter.
When the two devices have the same power loss, the optimal positions varying with the power loss under different convective heat transfer coefficients are presented in Figure 13a. When the two devices have different power losses, the optimal positions with variation in power loss ratio under the convective heat transfer coefficients are shown in Figure 13b. The corresponding diagram of the optimal device layout on the heat sink is presented in Figure 14.

![Figure 12. Flow chart of the optimization algorithm.](image)

![Figure 13. Optimal locations of two devices.](image)
Figure 14. Schematic of optimal device distributions with different power loss ratios.

When the devices have the same power loss, the device optimal position is constant and independent of the power loss and the convective heat transfer coefficient. When the device power loss is different, the optimal position is independent of the power losses and their difference, but dependent on the power loss ratio. When the power loss ratio is equal to 1, the optimal layout on the heat sink is a symmetrical distribution.

When the ratio changes from 1.1 to 1.8, the optimal location of Device 1 is moving to the edge of the heat sink, while the optimal location of Device 2 is moving to the middle. When the ratio is between 1.9 and 20, the optimal location of Device 1 is on the very edge of the heat sink, and the optimal location of Device 2 is moving slowly to the right middle. When the ratio is bigger than 20, the optimal location of the Device 2 is in the right middle of the heat sink.

4.3. Influence of heat sink placement

In the case of natural convection, the common placement direction of the heat sink is fins opening down, fins opening up, and fins opening vertically, as shown in Figure 15. In the above studies and experiments, the fins are opening down. Since the convective heat transfer coefficient is different in these three cases, the fluid characteristics need to be solved. Therefore, fluid calculation equations are added to obtain the fluid and temperature distribution. These equations include the mass conservation equation, momentum conservation equations, and the energy equation.

The simulation results are presented in Figure 15. The device layout and the measuring point distributions are illustrated in Figure 8. Two transistors located on two sides of one diode are connected in parallel, such as 1 and 2. Figure 16 shows the comparisons of the steady-state simulated temperature rises and the experimental ones in three cases.

The simulated results are close to the experimental results, which validates the correctness of the simulation model.

When the fins open down, the maximum surface temperature rises of the power converter are at Point 3 and Point 10. Thus, the power converter has a higher temperature rise in the middle. The maximum temperature rise is about 24 °C, and the temperature rise gradient is about 2%. The fluid speed around the fins is nearly 0.01 m/s, and it is large at the heat sink border, but small in the middle.

When the fins open vertically, the maximum surface temperature rises of the power converter are present at Point 6 and Point 12, which are located on the heat sink’s top. It is about 22 °C. The fluid flows from the bottom, through the fins and the devices, then to the top. The fluid velocity in the top is higher than that
in the bottom. The maximum speed is approximately 0.16 m/s. Although the heat dissipation performance is stronger in the top, the large amount of heat generated from the bottom flows through the top and heats the top. Therefore, the rise in temperature at the top is relatively high, and the temperature rise gradient is found to be so high that it is practically 4%.

![Diagram](image1.png)

(a) Fins opening up

![Diagram](image2.png)

(b) Fins opening vertically

**Figure 15.** Contours of temperature rise and fluid velocity in 3 power converters.
Figure 15. Continued.

Figure 16. Comparisons of simulation results and experimental ones in 3 cases.
When the fins open up, the highest surface temperature rises on the power converter lie at Point 3 and Point 10 with the maximum value of 22 °C. Thus, the temperature rise is higher in the middle in this case. The speed of the fluid surrounding the fins is about 0.05 m/s, which is faster than in the phase when the fins open downwards. The fluid velocity around the fins is stronger than that observed on the surface of the device itself. The temperature rise gradient is about 1%, which is smaller than in the stage during which the fins open vertically.

In the case of fins opening down, Layout 4 can be compared with other device layouts. The devices in Layout 4 are all placed in the middle of the heat sink, which is similar to Layout 1. However, the maximum temperature rise is 24 °C and the temperature gradient is 2% higher than those in Layout 1 at 22 °C and 0.5%, respectively. Thus, Layout 1 is the best choice among the 4 device layouts. Moreover, Layout 4 indicates that the locations of two parallel transistors can be separated, and it has little influence on the electrical performance but much impact on the heat dissipation property.

In summary, although the fluid velocity is bigger when the fins open vertically, the maximum temperature rise and the temperature gradient are smaller when the fins open up, and especially the temperature gradient is much lower. Therefore, the case of fins opening up provides the highest thermal reliability among these 3 cases.

5. Conclusion
In this paper, a reasonable compact thermal model for the power converter in switched reluctance motor drives is proposed and implemented in the case of a heat sink cooled by natural air. With this model, the fluid and thermal properties of the power converter can be calculated. The experiment platform is then established, which validates the correctness of the simulation model. Four power converters with different device arrangements are designed and analyzed, and Layout 1 has the highest thermal reliability among the 4 cases. Furthermore, the upper and lower rows of devices are simplified as two devices, and then the optimal positions of the two devices are obtained as shown in Figure 13. Three different placement directions of the heat sink are designed and investigated. When the fins open up, the power converter has the highest thermal reliability among the 3 cases. Future work will be dedicated to further optimization of the whole system and give the optimal rules for different heat sink sizes.

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References


