IGBT Heat Dissipation Design and Optimization

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Abstract—The reliable operation of IGBT (insulated gate bipolar transistor) is the key to the performance of the motor control system, which directly affects the performance of the vehicle. By contacting with the surface of the radiator, the heat device rapidly transfers heat to the fin, which is then absorbed by the high-speed airflow between the fins and taken away to form a cooling channel to ensure that the heat device is always at an appropriate temperature during work. The power loss of IGBT under rated working conditions was estimated theoretically. The temperature field of the radiator under typical working conditions was simulated by ICEPAK, and the radiator was parameterized. The simulation results show that under the condition of forced cooling and heat dissipation, the optimized radiator meets the heat dissipation requirements of the motor controller.

1. INTRODUCTION

One of the important guarantees for the normal operation of the vehicle is the stable operation of the electronic equipment in the motor controller. The study found that the failure of electronic components is mainly caused by high temperature, and the failure rate is proportional to the temperature of the chip. For every 10°C increase in temperature, the reliability of electronic equipment decreases by half \(^{[1]}\). With the rapid development of electronic integration technology, the controller’s internal components are more and more compact. In addition to the complex motor structure and poor operating conditions, the controller's working range, overload capacity and power density are increasing, and the thermal density is rising continuously \(^{[2]}\).

During the operation of the motor controller, IGBT module generates a large amount of heat loss. Because the internal structure of the module is complex and compact, the air does not circulate easily, the temperature rises very easily. Therefore, a good cooling system is the guarantee that the whole vehicle and electric drive system can work in the normal temperature range stably and reliably, the design of motor controller cooling system also becomes very important \(^{[3]}\).

2. RADIATOR STRUCTURE AND HEAT TRANSFER MODEL

The forced air-cooled radiator structure designed in this paper has the outer dimension of 250mm × 350mm × 100mm, the substrate thickness of 10mm, the finned height of the initial model is 60mm, the finned thickness is 4mm, and the space between the finned pieces is 6mm. Two fans are placed above the finned pieces, and air outlets are set on both sides of the radiator, which greatly improves the heat dissipation effect of the radiator.

The heat transfer model is shown in Figure 1. The heat generated by the IGBT internal chip passes through the outer package, then reaches the radiator substrate by heat conduction, and finally passes to the radiator fin for convective heat transfer with the external airflow \(^{[4]}\).
3. CALCULATION AND ANALYSIS OF POWER LOSS

The IGBT module is composed of IGBT and FWD (continuation diode chip). The circuit is shown in Figure 2. The parallel continuation diode is mainly used for continuation flow in the inverter circuit[5].

The heat source is composed of an IGBT module, including six IGBT and FWD is six, in the process of work, the power loss generated by IGBT and FWD respectively, so calculating a power loss of IGBT module to calculate the wastage of the IGBT and FWD, whereas a IGBT power loss is divided into state loss and switching loss, a stream of diode power loss is divided into state loss and switching loss [6].

![Figure 2. IGBT module internal circuit diagram](image)

The loss generated in the IGBT conduction process is called the on-state loss. Assuming that Dt is the duty ratio of IGBT conduction, the on-state loss in PWM application is the product of the approximate value of the on-state loss and the duty ratio [7]:

$$P_{cond(IGBT)} = V_{ce(sat)} * I_c * D_t$$  \(1\)

$V_{ce}$: collector emitter saturation voltage; $I_c$: Conduction current; $D_t$: Duty cycle.

The energy loss caused by IGBT on and off is called switch loss. The switch loss here is calculated as a single switch loss. To obtain the switch loss within a period, the product of the single loss and frequency should be used to obtain [8]:

$$P_{on+off} = f * [P_{on} + P_{off}]$$  \(2\)

The total loss of IGBT is the sum of on-state loss and switching loss:

$$P_{total} = P_{cond} + P_{on+off}$$  \(3\)
Continuation diode conduction loss in IGBT module:

\[ P_{\text{cond(FWD)}} = I_f * V_f * (1 - D) \]  

(4)

\( I_f \): Diode conduction current; \( V_f \): Diode forward voltage.

Switching loss:

\[ P_{\text{sw(FWD)}} = E_{\text{rec}} * f \]  

(5)

\( E_{\text{rec}} \): Diode recovery loss at one time.

The total loss of FWD is the sum of on-state loss and switching loss:

\[ P_{\text{FWD}} = P_{\text{cond(FWD)}} + P_{\text{sw(FWD)}} \]  

(6)

According to the parameters in the IGBT data table, using the above formula, the power loss of each IGBT heat source under rated working condition is 243.5W.

In each cycle, it can be considered that each IGBT will generate the same power loss, and each FWD will also generate the same power loss. In this paper, there are six half-bridges in the three phases of U, V and W in IGBT module, so the total loss of IGBT module is \[ (9) \]

\[ P_{\text{IGBTtotal}} = 6 \times (P_{\text{IGBT}} + P_{\text{FWD}}) \]  

(7)

Finally, it can be calculated that the power of IGBT module is 1461W at rated power and rated rotate speed.

4. NUMERICAL SIMULATION

4.1 Boundary Conditions

The main factors affecting the cooling effect of air-cooled radiators are: the contact area between power devices and air-cooled radiators, the wind speed, the material of the radiators, the thickness of the radiator substrate and the surface area of the fin.

Which related to the radiator itself is the material and size parameters, in a certain volume, therefore we can determine the power device and air-cooled radiator contact area and air cooling heat sink materials, on the basis of the simulation, the sizes of the radiator to get its trend diagram in a certain direction, and through the results of single dimension on the analysis of the influence of air cooling effect factor, mutual coupling simulation results, optimized the design trend of air-cooled radiator.

In the calculation model of forced air cooling, the thermal resistance and heat dissipation area have direct influence on the cooling effect.

The shape, length, thickness, height and spacing of the fins all have an impact on the heat dissipation area, and also have a direct impact on the heat transfer between the fluid and the radiator\[10\]. For example, the turbulent heat transfer criterion equation of the fluid in the slot is:

\[ \frac{\text{Pr}}{\text{Re}} = 0.023 \frac{\text{Pr}^{\frac{1}{3}}}{\text{Re}^{\frac{1}{6}}} \]  

(8)

\( f \): The qualitative temperature is the average temperature of the fluid.

In order to obtain effective data in the simulation test, the boundary conditions should be set reasonably when simplifying the simulation model to make the model close to the actual situation. The radiator adopts forced air cooling, and the ambient air temperature is set at 40°C. The fan flow is set at 0.4m³/s; In order to meet the requirements of reasonable density distribution, smoothness and fit of grids, Hexa Unstructured grids were selected for classification\[11\]. Calculation using k-ε turbulence model should satisfy the conservation equation of mass, momentum, energy, k and \( \varepsilon \)[12]. The outlet is set as the pressure outlet to obtain the simulation model as shown in Figure 3. prescribed.
4.2 Simulated Analysis

According to the required comparison of simulation parameters, the simulation tests were designed. Each group of simulation tests were carried out separately without interference, as shown in Table 1.

| Number | Height(mm) | Thick(mm) | Gap(mm) |
|--------|------------|-----------|---------|
| 1      | 40         | 2         | 1       |
| 2      | 50         | 2.5       | 2       |
| 3      | 60         | 3         | 3       |
| 4      | 70         | 3.5       | 4       |
| 5      | 80         | 4         | 5       |
| 6      | 90         | 4.5       | 6       |

The temperature cloud diagram of the initial model is shown in Figure 4. Heat is concentrated in all heat sources, the highest temperature is 105.127℃, IGBT heat source as the center of outward diffusion, heat gradually decreased. Generally, IGBT can allow the maximum junction temperature not to exceed 125℃, and the temperature of radiator substrate should be controlled below 85℃\(^\circ\)\(^\circ\). In order to further improve the heat dissipation effect, a single parameter change is selected for simulation, and the trend of the cooling effect of the radiator with the variation of parameters can be obtained by comparing the simulation results.
4.2.1 Fin Height

The variation trend of radiator temperature with the change of fin height is shown in Figure 5.

![Figure 5. Relationship between fin height and radiator temperature](image)

As the height of the fin increases, the temperature decreases. This is because the heat transferred from the fin to the air also increases, which lowers the temperature of the radiator.

However, as the fin height continues to increase, the temperature decline gradually slows down, because heat transfer has been fully completed at the lower part of the fin, and further increasing the fin height does not enhance convective heat transfer.

It can be concluded from Figure 5 that the height of the fin is 80mm, which is suitable. Compared with the height of the fin is 40mm, the temperature is reduced by 10.7℃, indicating that when the fin is 80mm, the external air forms a better cooling environment from the inlet to the outlet of the fan, which is conducive to the convective heat transfer between the hot air and the external environment.

4.2.2 Fin Thick

The variation trend of radiator temperature with the change of fin thickness is shown in Figure 6.

![Figure 6. Relationship between fin thickness and radiator temperature](image)

When the thickness of the fin increases, the temperature decreases, and the heat dissipation effect is the best when the thickness is 4mm.

As a heat conducting object, the thickness of the fin will affect the convective heat transfer effect. When the thickness of the fin increases, the convective heat transfer effect will be enhanced but not obvious. When it increases to 4.5mm, the temperature will almost remain unchanged.

Since the thickness of the fin is much smaller than the height of the fin, it can be considered that the thickness of the fin after more than 4.5mm has little impact on the heat dissipation performance.
4.2.3 Fin Gap

The variation trend of radiator temperature with the change of fin spacing is shown in Figure 7.

![Figure 7. Relationship between fin spacing and radiator temperature](image)

The variation rule of the fin spacing is divided into two parts. With the increase of the fin spacing, the temperature initially shows a downward trend and then tends to be stable, and an optimal fin spacing of 4mm can be obtained.

As the spacing between the fins increases, the resistance of the duct between the fins is reduced, so the heat dissipation effect is enhanced.

However, as the fin spacing continues to increase, the duct resistance hardly changes, so the radiator temperature also tends to be stable.

5. CONCLUSION

In this paper, a finned air-cooled radiator is proposed to cool down and heat the IGBT motor controller. First, the power loss of the IGBT module is calculated. Then, the air-cooled radiator is modeled and simulated.

- The air-cooled radiator mainly adopts convective heat transfer. According to the analysis of parameter optimization results, the convective heat transfer area will be greatly improved when the fin height is increased, so the fin height has a great influence on the heat dissipation effect. The optimal size is 70-80mm.
- However, increasing the fin thickness did not significantly improve the convective heat transfer area, so the fin thickness had little influence on the heat dissipation effect. The optimal size was 3.5-4.5mm.
- By increasing the spacing between the fins, the duct resistance between the fins can be reduced and the heat dissipation effect can be improved. The optimal size of the spacing between the fins is 3-4mm.
- When the maximum temperature of the heat source is lower than 125℃, IGBT can operate normally and smoothly. In the later work, it can be further optimized on the basis of this radiator, such as changing the shape and number of fins.

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