Research on High Efficiency Air Cooling Method of High Power Density Power Electronic Equipment

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Abstract. High power density is a trend of power electronic equipment development, but high power density will inevitably lead to high power consumption per unit volume. Due to the limitation of environmental conditions, some equipment can only use air cooling method, but the conventional way of air-cooled cooling is difficult to meet the requirements of reasonable temperature rise. Therefore, a new type of thermal resistance model is put forward, by using the good isothermal performance and high thermal conductivity of the heat pipe, the surface embedded composite heat dissipation substrate is made, which greatly reduces the diffusion thermal resistance, at the same time, and uses a new type of thermal conductivity material to reduce the contact thermal resistance. In order to improve the efficiency of thermal design, several mathematical inequalities are established, and the calculation of thermal resistance is transformed into a single objective optimization problem with multiple constraints. MATLAB is used to solve many discrete solutions, and then the finite element simulation software is used to further optimize. Finally, the temperature rise test of the prototype shows that the heat dissipation efficiency is increased by three times.

1. Introduction

With the development of power electronic equipment to high power, high efficiency, miniaturization and lightweight, in order to ensure safe and reliable work, we must pay attention to thermal design[1,2,3]. Some power electronic equipment can only use air-cooled cooling[4,5,6] mode due to the restriction of the application environment, high power density[7,8,9,10] will inevitably lead to high power consumption per unit volume, the conventional air-cooled cooling mode is difficult to meet the requirements, so this paper proposes an high efficiency air cooling method.

2. The topology of power electronic equipment

Power electronic transformation can be divided into four basic types, namely, AC/DC rectifier circuit, DC/AC converter circuit, DC/DC chopper circuit, AC/AC frequency conversion circuit. In the research of electric vehicle charging module, high-power DC charging point, LED driving power supply, DC / DC converter, photovoltaic grid connected converter, battery charging and discharging equipment and other power electronic equipment, an efficient air cooling method is summarized.

The components used in the four types of power electronic transformation are similar. The switch devices include Insulated-gate Bipolar Transistor(IGBT), Intelligent Power Module(IPM), diode, the loss of the switch device is very large; the working temperature of the magnetic components exceeds a
certain range will cause their own electromagnetic performance to change; the capacitance temperature exceeding the critical value will not only affect the performance of the capacitance itself, but also may cause the capacitor to burst or other dangerous situations. When the thermal design of the whole system, it is also necessary to consider the interaction influence between the various devices.

Figure 1. The three-phase PWM rectifier.

Figure 2. The phase-shifted full-bridge converter.

3. Thermal resistance model

Thermal resistance is not only a comprehensive parameter to show the ability to prevent heat transfer, but also a parameter to directly reflect the heat dissipation performance of the device. It is defined as the ratio of the temperature difference along the heat flow channel of the device to the heat consumption power on the channel, and the formula is as follows:

$$R = \frac{T_J - T_R}{P_H} = \frac{\Delta T}{P_H}$$

The thermal resistance model of the radiator is mainly composed of power device, silicon grease and aluminum heat sink, the copper substrate is the outer surface of the power device contacting with the radiator, which is a part of the power device. In order to analyze the heat dissipation, it is specially expressed separately. The total thermal resistance consists of junction-shell thermal resistance, conduction thermal resistance, contact thermal resistance and heat sink thermal resistance. The packaged semiconductor power device can be regarded as a series thermal resistance network composed of chip, solder, shell and other components, the junction shell thermal resistance of the device is the sum of the thermal resistance of each component in the heat conduction path.

The volume power density is defined as the thermal power per unit volume, the volume power density of IGBT used in this paper is calculated as follows:

$$\phi_v = \frac{\phi}{V} = \frac{691.7}{12.2 \times 6.2 \times 1.7} = 5.379 W / cm^3$$

The heat flux density is defined as the heat per unit cross-sectional area of the object in unit time, the heat flow density of the copper substrate at the bottom of IGBT is calculated as follows:

$$\phi_s = \frac{\phi}{S} = \frac{691.7}{12.2 \times 6.2} = 9.145 W / cm^2$$

The calculation results show that the volume power density and heat flux density are very large, and the traditional air-cooled radiator is difficult to solve the heat dissipation problem of high power density power electronic devices. Therefore, the author proposes a new type of thermal resistance model.
Figure 4. A new type of thermal resistance model.

Using liquid metal product instead of silicon grease, the aluminum heat sink is divided into heat sink substrate and radiator fins parts, the heat sink thermal resistance is divided into conduction thermal resistance and convection thermal resistance parts, the concept of diffusion thermal resistance is introduced. When the heat is transferred from a smaller heat source to a larger radiator, the equivalent thermal resistance is larger than the calculated one, so an additional thermal resistance appears. This additional thermal resistance has a large resistance value in the heat transfer process of high power density power electronic devices, so necessary measures must be taken to minimize the diffusion thermal resistance.

The main function of heat sink substrate is to transfer heat to radiator fins, which mainly includes conduction resistance and diffusion resistance. The conductive thermal resistance is directly proportional to the thickness of the substrate and inversely proportional to the conductivity and contact surface area. The thickness of the substrate cannot be too thin, which affects the rigidity and thermal capacity of the radiator. The model of power device determines that the contact surface area cannot be increased, so only the conductivity can be increased to reduce the conductive thermal resistance.

The common materials of substrate are aluminum or copper, but when high power density devices heat dissipation, even copper substrate is difficult to meet the requirements, so heat pipe can be embedded in the surface of aluminum substrate to make a composite heat dissipation substrate of two materials, which can reduce not only the conduction heat resistance but also the diffusion heat resistance. The heat pipe technology makes full use of the principle of heat conduction and the fast heat transfer property of the cooling medium. It can transfer heat through the evaporation and condensation of the liquid in the totally closed vacuum pipe, which has high thermal conductivity and good isothermal property.

Figure 5. Diffusion thermal resistance leads to great temperature gradient.

The figure shows that the temperature gradient of the aluminum substrate is very large, after 7 heat pipes are embedded in the surface of the aluminum substrate, the temperature gradient of the aluminum substrate decreases significantly, which shows that the embedded heat pipe reduces the diffusion thermal resistance.

Unless both surfaces are completely smooth, or some form of adhesive is used to form a covalent bond between the two surfaces, there is an air gap in actual contact, which is the contact thermal
resistance. Surface roughness, extrusion pressure, thermal conductivity, flexible stiffness, thickness, the modulus of elasticity and insulation strength are closely related to contact thermal resistance.

There are four ways to reduce the contact thermal resistance: increasing the pressure between the contact surfaces; improving the machining accuracy between the two contact surfaces; selecting soft metal materials as far as possible to make the radiator and the device shell when the structural strength allows; filling the air gap between the heating device and the radiator with high thermal conductivity materials. However, each power device has a specified maximum screw tightening torque, so there is an upper limit to increase the pressure between the contact surfaces. Improving the processing accuracy is mainly to reduce the roughness and air gap between the contact surfaces, but the roughness is generally 0.8-1.6 affected by the processing cost. The device shell is generally copper substrate, and the radiator is generally aluminum, in fact, soft materials are rarely used.

### Table 1. The thermal conductivity of different contact materials.

| Thermal conductive material | Silicon grease | Silicon gasket | Liquid metal product | Graphite thermal pad |
|-----------------------------|----------------|----------------|---------------------|---------------------|
| Thermal conductivity (W/m.K) | 0.48-6.5       | 0.32-1.1       | 20-30               | 25-35               |

The conventional way to fill the air gap is to use thermal conductive silicone grease, new materials such as liquid metal product and graphite thermal pad can also be used now. The liquid metal product is a kind of metal sheet made of pure metal, it is used between the heating device and the radiator. By using its low melting point characteristics, it can melt through the device heat to ensure that the interface gap is fully filled to form a good thermal conduction channel. Graphite thermal pad has a unique grain orientation, which can conduct heat uniformly in two directions, and the lamellar structure can adapt to the surface well. The thermal conductivity of the two is close, but the price of the liquid metal product is lower, so which is chosen as the thermal conductivity material in this paper.

### Table 2. The thermal conductivity of different substrate materials.

| Substrate material | Aluminum | Copper | Heat pipe | Heat pipe + Aluminum |
|--------------------|----------|--------|-----------|----------------------|
| Thermal conductivity (W/m.K) | 204      | 330    | 2500-3500 | 450-1000            |

The heat pipe mainly plays the role of conduction, and the heat loss must depend on the radiator fins far away from the heat source. The convective thermal resistance is inversely proportional to the heat dissipation area and the convective heat transfer coefficient of the surface, the convective heat transfer coefficient of forced air cooling surface is closely related to the air volume of the fan. Blindly increasing the wind speed does not significantly increase the air volume, but will increase the noise, the air volume and air pressure curve of the fan determine the final working point of the fan.

The area of heat dissipation is related to the height, thickness, length and shape of fins. Multiple mathematical inequalities can be established, and the calculation of heat resistance can be transformed into a single objective optimization problem with multiple constraints. Multiple discrete solutions can be calculated with the help of MATLAB software, and then the effect of heat dissipation can be verified by finite element simulation software to avoid blind design. It can save time and improve the efficiency of thermal design, and it can not rely on experience design, avoid randomness and make the work of the thermal design more logical.

Fin effect is defined as the ratio of heat flow on the surface with fins to that on the surface without fins, the calculation formula is as follows:

\[ \eta = \frac{h_{f}}{h_{a}} = \frac{\sinh h_{a} + \frac{h}{a} \cosh h_{a}}{\cosh h_{a} + \frac{h}{a} \sinh h_{a}}. \]  

(4)

Fin efficiency is defined as the ratio of the actual heat transfer to the maximum heat transfer of the fin, the calculation formula is as follows:

\[ \eta = \frac{h_{f}}{h_{a}} = \frac{\sinh h_{a} + \frac{h}{a} \cosh h_{a}}{\cosh h_{a} + \frac{h}{a} \sinh h_{a}}. \]  

(5)

The efficiency of fins is directly proportional to the thermal conductivity of fins, the high efficiency geometry of fins is that the ratio of perimeter to cross-sectional area is large. The allowable height
The width ratio of fins is as high as 60, and the thickness of fins can be 0.7mm. After optimizing the radiator of the same volume, the heat dissipation area increases by 4.58 times, and the mass decreases by 3.4kg.

4. Thermal simulation and experiment

The temperature rise of IGBT and diode is within 30 ℃, which shows that the design of air cooling radiator is reasonable. The temperature rise of high-frequency transformer and output inductor is about 50 ℃, but the temperature limit of magnetic components is high, which is also a reasonable range. The temperature distribution of radiator is gradually reduced along with height.

Air volume is the product of fan ventilation area and plane velocity in this area, air pressure indicates the ability to overcome the resistance within the ventilation stroke, the air flow will encounter the obstruction of cooling fins in its flow path, which will restrict the free flow of air. It is necessary to fully consider the fan performance curve and system resistance curve, and select an optimal fan working point.

The velocity distribution and velocity flow state reflect the flow path and the velocity of the air inside the module, that is, the distribution of the air duct. The velocity distribution in the above figure is reasonable, and the design of air duct is also reasonable.

The actual test shows that the distribution of velocity and the temperature rise of radiator are basically consistent with the simulation data. Considering the accuracy of simulation model and the accuracy of loss estimation of components, it can be considered that the simulation data can effectively reflect the real thermal temperature field.

Finally, a new type of radiator is designed, which is composed of liquid metal product, surface embedded heat pipe composite aluminum substrate and high density radiator fins. It makes full use of the high conductivity of liquid metal, good isothermal property of heat pipe, high convective heat transfer capacity of high width ratio radiator fins and the design skill of air duct. These four kinds of technologies are integrated into the design of a radiator, and the module power level is successfully changed from 10kW increase to 30kW to meet the initial design requirements and final engineering application objectives.
5. Parallel or series connection high power electronic equipment

Multiple power modules are connected in parallel or in series to form a higher power equipment, the most important thing in the cabinet design is the air duct structure design. There are three air duct structures: the upper-lower air duct structures, the lower air blowing and the upper side use centrifugal fans to extract air; the left-right air duct structures, one side axial fan blowing and the other side axial fan exhausting; and the third is the combination of upper-lower air duct and left-right air duct.

![Figure 11. Three air duct structures.](image)

6. Conclusions

The author found some rules in the study of the structural design of air duct:

A. The partition can be used to form an independent air duct, reduce the branch of the air duct and avoid the short circuit of the air duct, so as to make the air flow according to the specified path, and at the same time reduce the wind resistance as much as possible;

B. The split structure is used to avoid the influence of the heat generated by the power module on the power supply unit and the control unit;

C. When the air duct has a long distance, the wind resistance is stronger, the air flow path should be as short as possible due to large loss of pressure and poor heat dissipation effect;

D. Ensure the consistency of air flow and the ventilation volume of each power module to avoid too high temperature of one module;

E. The air inlet is too low from the ground, catkins and dust are more likely to block the filter screen, so the choice of location needs to be considered comprehensively;

F. For outdoor cabinets, the influence of solar radiation is very great, and black and dark cabinets should be avoided as far as possible, while sensitive electronic devices are not should be attached to the metal shell.

![Figure 12. The physical structure of left-right air duct](image)

![Figure 13. The physical structure of upper-lower air duct](image)
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