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A Research on the EconoDUAL™ 3 Wave IGBT module for CAV main inverters

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Abstract

In recently years, new-energy vehicles have been developing rapidly. These, vehicles include passenger cars, buses, and trucks. The adoption of new-energy commercial vehicles can significantly reduce polluting emissions. This paper presents the results of research and tests conducted on the EconoDUAL™ 3 Wave IGBT module. The important characteristics of the EconoDUAL™ 3 Wave IGBT module are discussed, explaining the design points of the direct-cooling heatsink. Finally, this paper shows the advantages of the WAVE module through results of the DC voltage and AC voltage tests.

1 Introduction

Commercial, construction, and agricultural vehicles (CAVs) significantly contribute to fuel consumption and emissions of pollutants. The China Mobile Source Environmental Management Annual Report of 2023 estimates the national motor vehicle emissions to be 7.43 million tons for carbon monoxide (CO), 1.91 million tons for hydrocarbon (HC), 5.27 million tons for nitrogen oxides (NOx), and 53,000 tons for particulate matter (PM). Diesel engines are particularly impactful, with over 80% of NOx and PM emissions. Petrol engines, on the other hand, are responsible for more than 80% emission of CO and HC. Non-road mobile sources also emit substantial amounts of pollutants, with NOx emissions nearly matching those of motor vehicles [1][2]. The Energy Saving and New Energy Vehicle Development Report of 2021 highlighted that China's commercial vehicles, despite being only 20% of the fleet, consume 51% of the fuel and produce 56% of the CO2 emissions. Thus, adopting new-energy commercial vehicles is vital for China's goal of emissions. The CAV market demands powertrain inverters with high power density, superior performance, and cost effectiveness. The Wave IGBT module addresses these requirements by providing higher power density and lower system costs.

2 Current major powertrain inverter solutions about commercial vehicles

With the development of IGBTs in the early 1990s, using DC-AC-conversion to drive 3-phase machines using a DC-source became feasible. As permanent magnet synchronous machines (PMSM) achieve the highest torque density, they have become the dominant technology in commercial vehicles. Particularly, in applications where driving comfort, and smooth and low noise operation are important. Technically, the power conversion stage in such applications is very similar to the inverters that drive rotating machines in industrial applications.

For motor drive applications, the 2-level, 3-phase bridge is a very mature topology, due to its simple topology and high reliability. Infineon IGBTs that are most popular for these applications are the cost-efficient EconoDUAL™ 3 half-bridges IGBTs with ratings up to 900 A. Most electric buses and e-trucks are equipped with products from this family. They can cover 12~150 t e-truck main drive solutions with 450A, 600A and 900A products in single or parallel configurations. EconoDUAL™ 3 half-bridge IGBT modules can easily express the power rating through 2~3 PCs module in parallel [3]

3 Direct cooling

Currently, liquid cooling is the main cooling type in commercial vehicles. Most commercial vehicles use the

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standard solution with a closed liquid heatsink. Mounting an IGBT module with a closed heatsink requires thermal grease. The R_{th} of the thermal grease limits the IGBT's output current. Open heatsinks can help decrease the junction-to-liquid Rth because they don't require any thermal grease or heatsink base.

[4] and [5] have discussed the thermal distribution of the materials used in power modules, of which the thermal grease has a large share. So thermal grease is the key factor in reducing thermal resistance. In a convectional IGBT module, thermal grease is used for decreasing the contact thermal resistance between the copper baseplate and the heat sink. In direct cooling structures, the baseplate and the heat sink are integrated into one and the coolant directly contacts the baseplate. Thus, thermal grease and additional cooling heat sink are eliminated. As discussed in [6], the thermal resistance is reduced by about 30%.

Fig. 1. Standard solution using a closed liquid heat sink

Fig. 2. Direct cooling solution using an open liquid heat sink

4 Wave module's thermal test and results

To verify the performance of the Wave module, a thermal test was essential. The thermal test was conducted in two phases. The first phase involved conducting low-voltage, high current tests on individual modules under limited lab conditions. The second phase tested an inverter based on the Wave module with an AC load as the actual condition in the INVT EV department laboratory. Before the test, the gel from sample module was removed and a black coating was applied for the infrared IR thermal camera.

Fig. 3. No gel and black coating on the sample IGBT module

4.1 Low DC voltage and high DC current: Single module test

4.1.1 Test setup

- DC power supply: HIFB-3KA/12V
- Infrared camera: FLIR T620
- Test Points:
  - Center wire: SP1, SP2
  - Center chip: SP3, SP4
  - Corner wire: SP5
  - Corner chip: SP6

$$T_{vj-IGBT} = \frac{1}{3}(2 * T_{cemter} + T_{corner}) \quad (1)$$

Junction temperature of a chip is its average temperature. Two center points and one corner point were selected on the chip to calculate the T_{vj} of the IGBT. The chip included bonding wires. The thermal signals captured by the infrared thermal imager included both the chip and the bonding wires. As the temperature of the bonding wires can cause interference, it is necessary to distinguish between the temperature of chip and that of the bonding wires, and to mark the actual temperature of the chip. To achieve this, the infrared camera was adjusted so that the bonding wire could be identified. The temperatures at the center and the corners of the chip were than obtained. Using formula (1), the average temperature of the chip was determined.

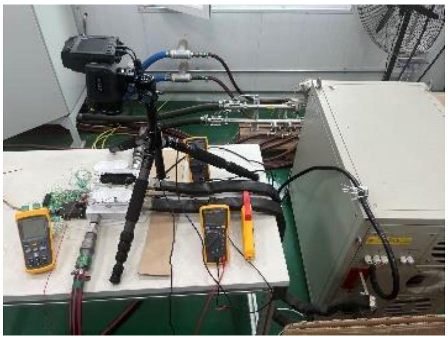

Fig. 4. Low voltage and high current test setup

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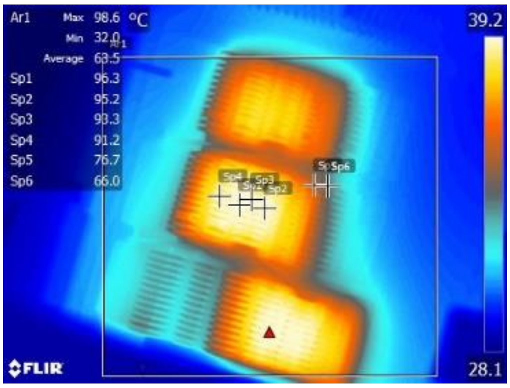

Fig. 5. Infrared test image

4.1.2 Test result

The initial current was set to 100A. It was, gradually increased and the test data from the IR camera was recorded.

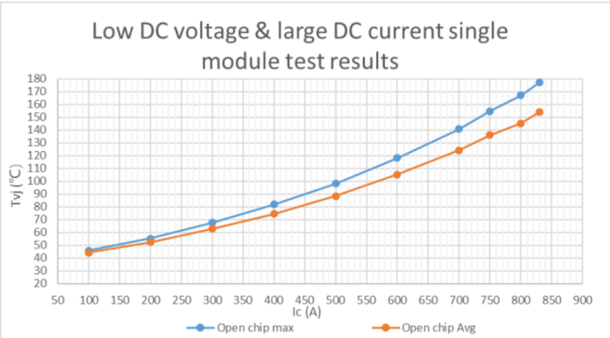

Fig. 6. Results of the low-voltage and high current test

4.2 AC load test

The target application of the Wave module is the main inverter. An AC load test was conducted to further verify the performance of the module.

4.2.1 Test setup

Typically, the driver board is positioned above the module. However, in this position, the driver board can block the infrared thermal imager's line of sight, making it impossible to measure the temperature of the chip accurately. A test platform was established using the gel-less and blackened module shown in Fig.3.

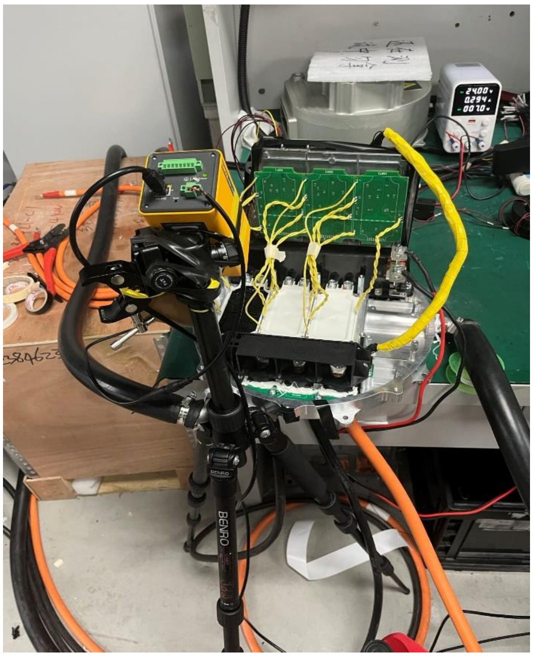

Fig. 7. AC load test setup

The test conditions were:

- DC voltage = 574V
- Switching frequency = 4 kHz
- AC output
- 65℃ water cooling
- Water cooling: 25L/min
- Inductance load
- Stable operation for at least 60 seconds

4.2.2 Test result

The goal of this test goal was to determine the chip's junction temperature at a current of 700A. The test was started an initial current setting of 140A. The current was then progressively increased in increments of 70A to reach 700A.

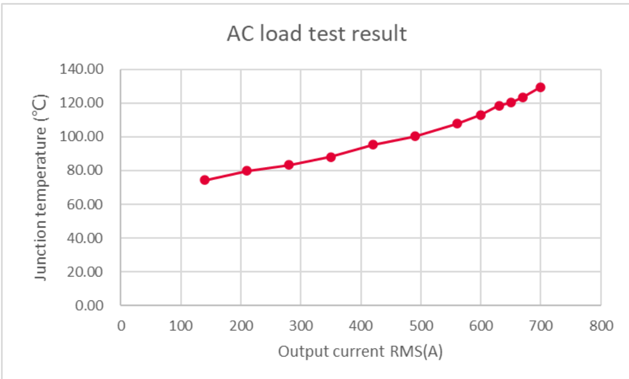

Fig. 8. AC load test result

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As previously discussed, the temperature at both the central point as well as the corners of the chip was measured. Using equation(1), the chip's average junction temperature was calculated. In this case, the calculated average junction temperature of the chip was directly documented. Based on Fig.8, when the output RMS current was 700A, the junction temperature of the chip was 129.5°C. Under normal circumstances, user inverters require two 600A modules in parallel to achieve an output capability of 700A RMS. Now they can use one 900A wave module to replace two 600A modules in parallel.

4.3 Data analysis based on test results and thermal simulation

4.3.1 Simulation with same chip loss to get output current

The two tests discussed in the previous sections were conducted using low voltage with high DC current and high voltage with AC load, respectively. To verify the accuracy of their results, thermal simulation was used to convert the low-voltage DC test results into the AC test results. The thermal performance characteristics were assumed to be identical. In the simulation, the output current was adjusted to correlate the DC test with the AC test based on the same chip losses.

Conditions for the thermal simulation were:

- DC link voltage = 574V
- Output frequency = 100Hz
- Switching frequency = 4kHz
- Modulation index = 1

Through the simulation software PLECS, the following results were obtained:

DC test data		AC simulation data	
Ic (A)	chip loss(W)	I_out (A)	chip loss(W)
100	89.72	138	89.5
200	202.00	276	201.2
300	331.49	405	332.6
400	479.80	525	479.1
500	655.95	612	651.1
600	847.03	720	844.3
700	1057.00	817	1057.1
750	1197.93	905	1199.8
800	1315.04	950	1310
830	1387.43		

Table 1. AC load test result

4.3.2 Data analysis

a. For the ambient temperature $T_a = 65℃$, select the test data for 600A and 630A from Fig 8.

b. Get the linear mean value. At 615A output current, the junction temperature was 115.7℃ for $T_a = 65℃$.

c. The corresponding AC output current would be 612A. The DC test data 500A is listed in Table 1.

d. $T_a = 32℃$, $I_c = 500A$, the chip average $T_{vj} = 82.4℃$.

e. Considering different ambient temperature, at the same level for comparison, the value transferred from the DC test data based on simulation was 116.4℃, and as per the actual AC load test results, $T_{vj} = 115.7℃$ when the output current was 615A RMS.

As the difference is low, this test data can be considered reliable.

5 WAVE module mounting instruction and guidelines for the open heatsink design

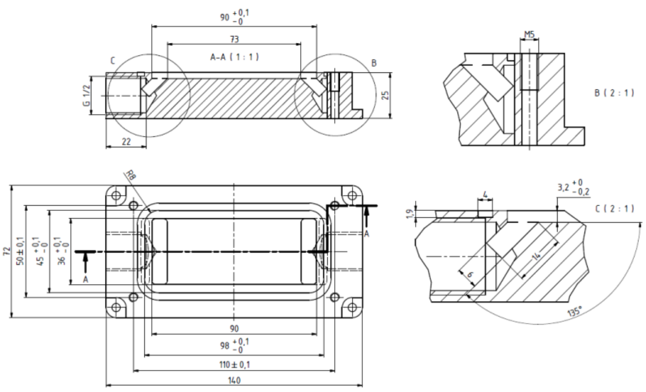

Fig. 9. Drawing of a reference heat sink

The depth of the heatsink tank significantly impacts thermal performance. The recommended depth is 3.2 millimeters (mm).

Infineon recommends using a sealing ring to ensure a proper connection between the module and the heat sink. General recommendations for specific sealing rings cannot be provided because the power module is only one part in the entire cooling system. The designer of the application (cooling system) is responsible for selecting the appropriate sealing ring.[7]

Changing the depth from 5mm to 3mm helped in improving the Wave module's performance. Reducing the depth forces the cooling liquid to flow over the aluminum strip, enhancing heat dissipation. To conduct the comparative experiment, a 2mm thick transparent plastic spacer was placed in the water tank, to reduce its depth from 5mm to 3mm. It was clearly observed that when the depth of the water tank was 3mm, the temperature of the chip was significantly lowered.

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This experiment demonstrated the impact of the cooling liquid's depth on the efficiency of heat dissipation. A higher flow rate enhances the convective heat transfer. This leads to more effective cooling and a reduce chip's temperature. This reduction in the chip's temperature duo to the water tank's lower depth confirms the hypothesis that cooling efficiency can be improved by manipulating the depth of the cooling liquid. It is a valuable insight for optimizing thermal management designs.

6 Conclusion

This paper showed that the EconoDUAL™ 3 Wave IGBT module, with its innovative direct-cooling design, can significantly enhance the thermal efficiency and reliability of powertrain inverters for CAVs. The findings from rigorous thermal testing and simulation confirm its potential to improve the performance and sustainability of commercial vehicles. This research underscores the pivotal role of advanced power electronics in achieving environmental sustainability goals within the transportation industry.

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