THE TRANSIENT TEMPERATURE FIELD SIMULATION OF THE MICRO-GRID INVERTER

by

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For the power electronics devices with the insulated gate bipolar transistors, the thermal management is very important and necessary for the devices reliability. In this paper, power losses of the inverter were evaluated based on its electro-thermal model and control logic. Accordingly, its thermal management system using forced air cooling is designed and simulated. The transient temperature filed simulation results showed that the thermal management system is feasible and can guarantee the working temperature of the inverter. Experimental results were also obtained to verify the simulation results in this paper.

Key words: *transient temperature, micro-grid inverter, simulation, electro-thermal model, control logic*

Introduction

Renewable energy, distributed generation and micro-grid technology have been widely concerned for a long time. In order to improve the power supply based on power electronic inverter interface to maintain the stability of the power system, grid-connected inverters controlled by virtual synchronous generator technology have more and more widely applications in the distributed power generation system and micro-grid. However, inverters are one of the key components, which include multi-insulated-gate bipolar transistor modules.

It is well known that power semiconductor devices are now going through a rapid evolution and the insulated-gate bipolar transistor (IGBT) modules are getting more accepted and increasingly used in the power electrical devices as high power and high voltage switching components, such as pulse-width-modulated (PWM) inverters, voltage-sourced converter based flexible AC transmission systems devices, and so on.

With the development of widely applying requirement, IGBT modules are developed towards the high power density, high on-off switch frequency and small volume. All these characteristics made its power losses increases, and heat dissipation area decreases. Accordingly, its

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thermal problem is becoming more and more serious. This will lead to high junction temperatures, and affect its transfer performance and output characteristic. In addition, the thermal problem also restricts the miniaturation of the IGBT, and reduces its application field. So, its thermal management system is very important for the power electronics devices to ensure its reliability and stability.

To develop the thermal management of the IGBT modules, their power losses need to be evaluated at first. The IGBT modules are switching power electronics, and they are turned on or off by logic control circuitry during the device switching cycle. Thereby, their power losses relate with the control rules, and the electrical model related with control rule needs to be known. The earliest IGBT modules model is Hefner and Diebolt [1] IGBT electrical model, which comprehensively takes into account IGBT various operating characteristics to ensure the model accuracy. Most IGBT modules operating characteristics, such as static characteristics, dynamic characteristics and so on can be evaluated based on the electrical model. Till now, many IGBT models are still built based on the Hefner's electrical model in [2-4].

Li *et al*. [5] calculated the IGBT modules power loss with the help of the circuit simulation software, but it requires the accurate IGBT electrical model, and it also needs to use the programs to achieve the power loss. Zhang *et al*. [6] optimized the IGBT modules electrical model by united the existing ideal switch model with a non-linear resistor by the MATLAB software. Lu [7] proposed a simple IGBT modules electrical model according to the external characteristics parameters in the PROTEL.

When the IGBT modules are used in different devices, their logic control rules are different so that their thermal models are different. Their thermal model can be established by relaxation method and direction method [8, 9]. The relaxation method couples the electrical circuit simulations (operating by SPICE and SABER softwares) with finite element method (FEM) together to deduce the thermal resistance and junction temperature, and the direct method calculates their thermal information in a coupled manner along with the electrical models. Hao *et al*. [8] established an electro-thermal model of 200 W boost converter using IGBT modules by the relaxation method, and designed a natural convection cooling aluminum heat sink. Ahmed and Putrus [9] used the direct method to predict junction temperature under transient conditions.

Hefner [10] built a compound IGBT modules electro-thermal model by combining physical structures with the heating effect of Henfner's electrical model, then the IGBT modules loss and junction temperatures were simulated with the computer aided circuit analysis software. To build the model, the IGBT modules structural parameters, which are difficult to obtain by experiments, need to be known. On the other side, IGBT modules switching transient process is nanosecond, the simulations of IGBT are time-consuming, especially for a multi-chip IGBT module.

A 3-D structure model of the IGBT modules is established in the FEM software to derive its thermal model by the researcher Yun *et al*. [11].

The IGBT models published are reviewed, analyzed, compared and classified into different categories according to mathematical type, objectives, complexity, accuracy and speed in some literatures [12-15]. In published literatures, few researchers considered IGBT power losses, thermal model, and thermal management with its control rules.

In this paper, an IGBT module power loss was evaluated by Hefner's electrical model and the switching control rules with considering the dependency of the switching losses on various factors, such as the switching voltage, switching current, stray inductance, and the reverse recovery process of the free-wheeling diode (FWD). Validation of the model was conducted by comparisons with published characteristic curves by the manufacturers.

The thermal model of IGBT PWM inverter composed of six IGBT modules is established in this paper, and their thermal management system is designed and simulated. To verify the simulation results, the experimental tests were also conducted in this paper.

The electrical model of the IGBT modules

As well known, the IGBT modules can be regarded as a Darlington structural component which consists of bipolar junction transistor (BJT) and metal-oxide-semiconductor field-effect transistor (MOSFET), where BJT is the conduction element, MOSFET is the driving element. Accordingly, its electrical model [16] can be established in the PSPICE software as shown in fig. 1, where R_s is the parasitic resistance for MOS; R_G, R_C, and R_E are resistances which service for the conductions of the device, H is controlled power, D_{BE} and D_{SD} are diodes, respectively. Then, its transfer characteristics and output characteristics (shown as fig. 2) can be obtained by simulations. Figure 3 presents the data sheet of the characteristic curves.

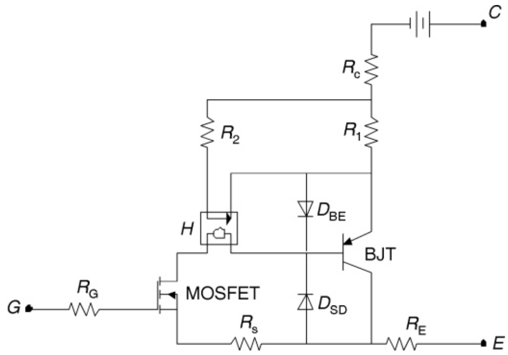

Figure 1. The electrical model of the IGBT in the simulation software

As can be seen that the tendencies of simulation curves agree with those from the data sheet, and the differences between the simulations and data sheet were not significant. Therefore, the electrical model was used to simulate the switching process of the IGBT modules and the thermal loss of the IGBT modules was calculated according to its working condition in this paper.

Thermal model of the IGBT modules

The power losses of IGBT modules come from the IGBT chip and the paralleled FWD chip, and IGBT chip losses include conduction losses and switching loss, and the freewheeling diode losses include the conduction loss and turn-off loss. Based on its electrical model and control rule, these losses can be evaluated [17]:

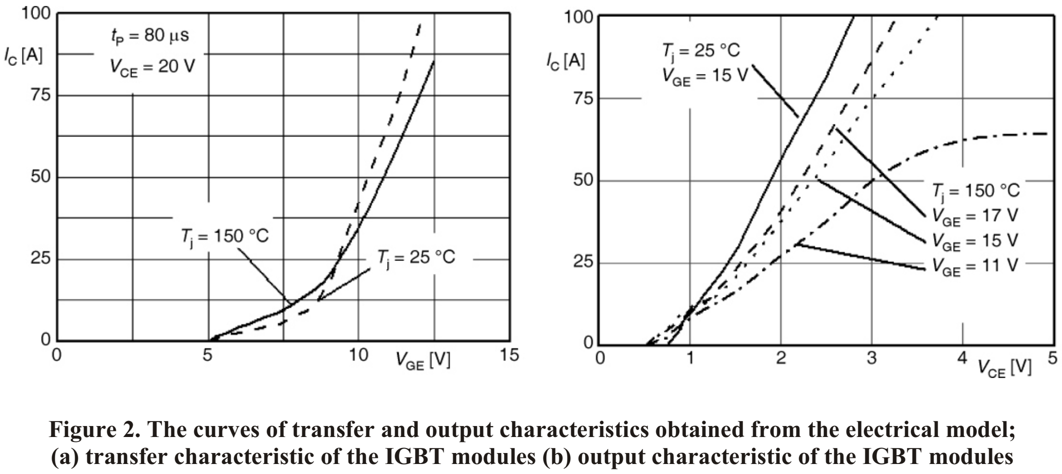

Figure 2. The curves of transfer and output characteristics obtained from the electrical model; (a) transfer characteristic of the IGBT modules (b) output characteristic of the IGBT modules

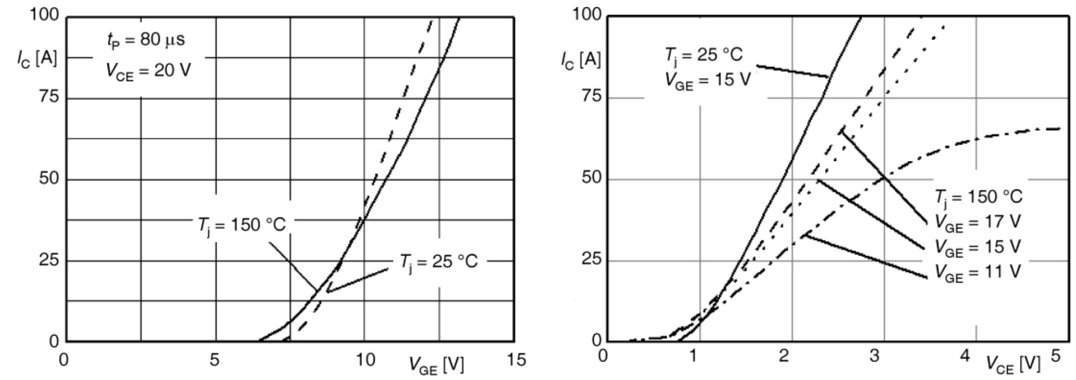

Figure 3. The curves of transfer and output characteristics given by the data sheet; (a) transfer characteristic curve of data sheet (b) output characteristic curves of data sheet

The IGBT modules conduction losses

The conduction losses comes from the saturation voltage drop, its general formula is:

$$P_{\text{cond-igbt}} = \frac{1}{2}\left(V_{\text{ce}}\frac{I_{\text{p}}}{\pi} + r_{\text{ce}}\frac{I_p^2}{4}\right) + M\cos\phi\left(V_{\text{ce}}\frac{I_{\text{p}}}{8} + r_{\text{ce}}\frac{I_p^2}{3\pi}\right) \tag{1}$$

where $P_{\text{cond-igbt}}$ is conduction losses, V_{ce} – the saturation voltage drop, I_{p} – the peak value of the output current, r_{ce} – the conduction equivalent resistance, M – the duty cycle of the PWM modulation output, $\cos\phi$ – the PWM output power factor.

The IGBT modules switching loss

The switching loss comes from power losses during turn on and off, and it can be calculated:

$$P_{\text{sw-igbt}} = \frac{1}{\pi}f(E_{\text{on}} + E_{\text{off}}) \tag{2}$$

where $P_{\text{sw-igbt}}$ is switching loss, f – the switching frequency, E_{on} – the single pulse turn-on power consumption under the rated condition, and E_{off} – the single pulse turn-off power consumption under the rated condition.

Conduction loss of FWD

Similar to IGBT modules chips, the conduction loss of FWD comes from the conduction voltage drop and junction thermal resistance, and it can be calculated:

$$P_{\text{cond-diode}} = \frac{1}{2}\left(V_{\text{f}}\frac{I_{\text{p}}}{\pi} + r_{\text{f}}\frac{I_p^2}{4}\right) - M\cos\phi\left(V_{\text{f}}\frac{I_{\text{p}}}{8} + r_{\text{f}}\frac{I_p^2}{3\pi}\right) \tag{3}$$

where $P_{\text{cond-diode}}$ is conduction loss, V_{f} – the saturation voltage drop, I_{p} – the peak value of the output current, r_{f} – the conduction equivalent resistance, M – the PWM modulation output duty cycle, $\cos\phi$ – the PWM output power factor.

Turn-off loss of FWD

The turn-off loss of the FWD is caused by its recovery off state, and it can be calculated:

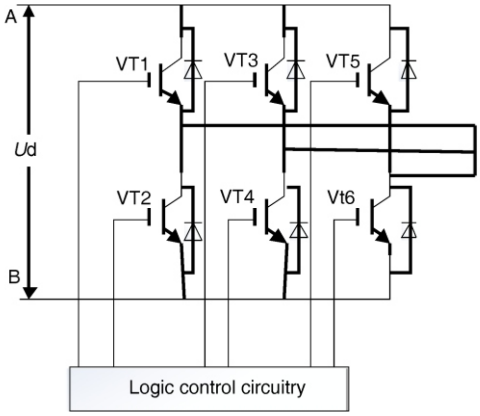

Figure 4. The PWM inverter

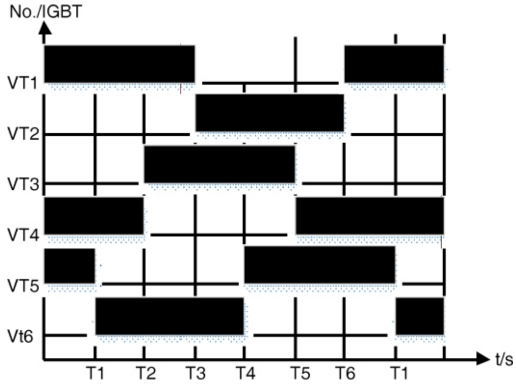

Figure 5. The state of the IGBT module for one cycle

$$P_{\text{sw-diode}} = \frac{1}{\pi} f E_{\text{rr}} \tag{4}$$

where $P_{\text{sw-diode}}$ – the turn-off loss, f – the switching frequency, E_{rr} – the single pulse turn-off power consumption under the rated condition.

Then, the total power losses of the IGBT modules are:

$$P_{\text{total}} = P_{\text{cond-igbt}} + P_{\text{sw-igbt}} + P_{\text{cond-diode}} + P_{\text{sw-diode}} \tag{5}$$

It can be seen that the power losses can be evaluated according to the IGBT modules control rule, such as working frequency, collector current, duty cycle and so on. When the IGBT modules are used in the PWM inverter, its heat transfer model can be described in the fig. 4. Here, totally six IGBT modules are used in the inverter, and there are three IGBT modules working together in every phase. Switching rule of the IGBT modules at every phase is shown in fig. 5. VT1-VT6 denotes the six IGBT modules.

The previous power losses need to be estimated according to the IGBT modules electrical model and control rule. When the IGBT modules are used in a PWM inverter, there are six IGBT modules (VT1~VT6) working together as shown in fig. 4. However, not all IGBT modules are working at a time, and only three IGBT modules need to be worked in every working stage as shown in fig. 5, and there are six working stages (T1~T6) in one cycle. VT1, VT4, and VT5 are working for T1; and VT1, VT4, and VT6 for T2; VT1, VT3, and VT6 for T3; VT2, VT3, and VT6 for T4; VT2, VT3, and VT5 for T5; VT2, VT4, and VT5 for T6.

Thermal management of the IGBT modules in the inverter

According to the control rule and eqs. (1)-(5), their power losses can be estimated as 260 W for one IGBT modules, so one thermal management system with forced air cooling was designed to guarantee the working temperature in every stage, and the related design parameters are listed in tab. 1. To verify the thermal management system, a simulation model was built in the FEM as shown in fig. 6.

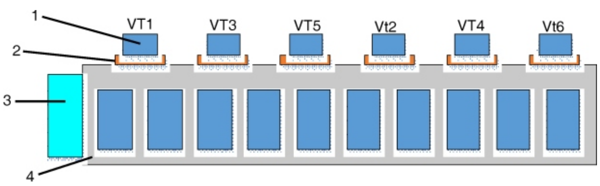

Figure 6. The simulation model of IGBT modules used in the inverter with the cooling system; *1 – IGBT module; 2 – substrate; 3 – fan; 4 – heat sink*

Table 1. The attribute parameters of each part of the simulation model in Icepak software

Name	Material	Size [mm]	Power	Thermal conductivity [$Wm^{-1}K^{-1}$]	Type
IGBT modules	Si	122 62 17	260 W	148	SKM50GB12T4
Substrate	Cu	122 62	–	377	–
Thermal interface material	Grease	122 62 0.3	–	4.5	–
Heat sink	Aluminum nitride	600 125 135	–	180	DXC-616

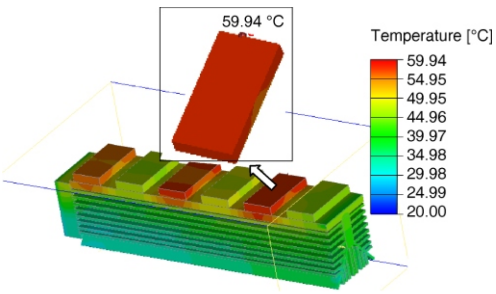

Figure 7. Temperature distribution for T1

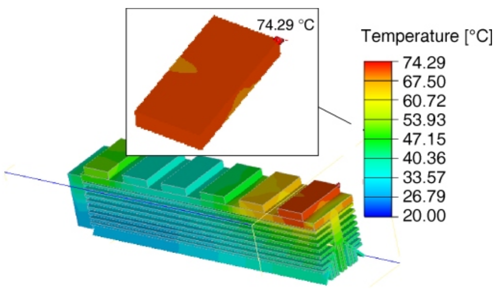

Figure 8. Temperature distribution for T2

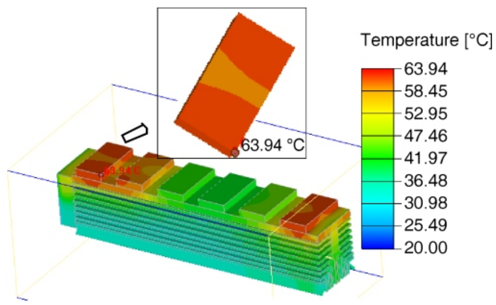

Figure 9. Temperature distribution for T3

According to the working principle of the inverter, there are six working state, and three IGBT modules working together in every stage. The IGBT modules are placed on the different position of the heat sink, therefore, its temperature distribution is different at every stage. Figures 7-12 shows the temperature simulation results at different stage.

For T1 phase, VT1, VT4, and VT5 are working and have power losses, the temperature distribution is shown in fig. 7. At this time the three IGBT modules are placed uniformly on the heat sink, the heat produced does not affect each other, so the cooling result is relatively ideal.

For T2 phase, VT1, VT4, and VT6 are working, the temperature distribution is shown in fig. 8. At this time, VT4 and VT6 are neighbor, and farthest from the fan simultaneously, so the cooling effect of this phase relative to several other stages is poorer, but the maximum temperature is below 80 °C.

For T3 phase, VT1, VT3, and VT6 are working, the temperature distribution is shown in fig. 9. At this time, compared with fig. 8, although the VT1 and VT3 are neighbor, they are close to the fan, so the highest temperature of the stage is lower than the T2 stage.

For T4 phase, VT2, VT3, and VT6 are working, the temperature distribution is shown in fig. 10. At this time, the three IGBT are placed uniformly, but they are far away from the fan compared with phase T1, so the overall temperature increases a little.

For T5 phase, VT2, VT3, and VT5 are working, the temperature distribution is shown in fig. 11. At this time, the three IGBT modules are neighbor, so the temperature at this phase is high.

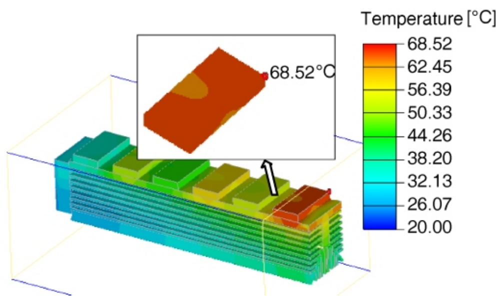

Figure 10. Temperature distribution for T4

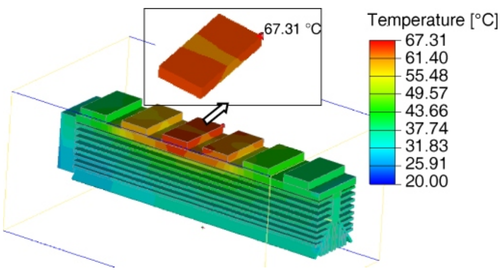

Figure 11. Temperature distribution for T5

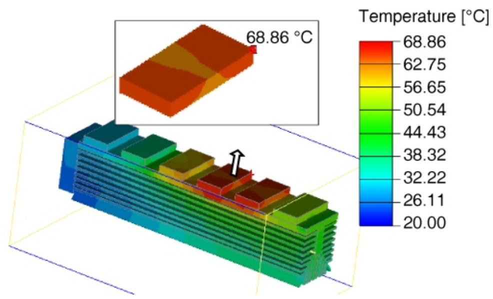

Figure 12. Temperature distribution for T6

For T6 phase, VT2, VT4, and VT5 are working, the temperature distribution is shown in fig. 12. At this time compared with fig. 11, under the two phases, the three IGBT modules which are adjacent each other are operating at the same time, but since the three IGBT modules in fig. 12 are farer than the three IGBT modules in fig. 11, so the temperature under this phase is slightly higher than phase T5.

According to the simulation results, it can be found that the thermal management system can guarantee the IGBT modules are working temperature lower than 80 °C. Compared with other thermal management system, which allocated one heat sink for every IGBT module and used six heat sinks totally. The total power losses of PWM inverter adopted six IGBT modules losses; the volume of the PWM inverter is more compact, and the performance is more reliable.

Experimental set-up

The experimental set-up of the thermal management system is constructed as shown in fig. 13. As shown in the figure, the experimental set-up includes temperature acquisition unit, oscilloscope, the electrolytic capacitor, load resistance, circuit breaker, IGBT modules and cooling system, and driver circuit. Two large series of resistances are used as the load. When the experiment is carried out, the driver circuit runs the compiled program to control the IGBT modules' driver, and the driver generates the PWM wave to control the turn-on and turn-off of the IGBT modules. When the PWM inverter is working steadily, their temperatures are recorded by the temperature acquisition device. The specifications for the temperature sensors are Pt100, operating range –100~280 °C, precision 0.5 °C. The temperature acquisition device records the temperature from the temperature sensor every a few seconds.

Since the exact maximum temperatures are hard to get by experiments because of the limit of test conditions, temperatures of four points of each IGBT were measured in experimental tests and the maximum test results of these four points were adopted as the final measurement value. The locations of four measuring points for each IGBT were shown in fig. 14.

The measurement values and simulation values are compared in tab. 2 and fig. 15. It can be seen that all of the predictions of maximum temperatures are higher than those of test results. The biggest error is 6.47% and the smallest one is 0.91%. These should be caused by the differ-

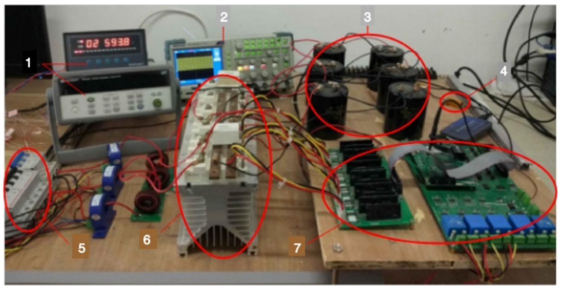

Figure 13. Experimental set-up of the IGBT PWM inverter thermal management system:
1 – temperature acquisition unit, 2 – oscilloscope, 3 – electrolytic capacitor, 4 – load resistance, 5 – circuit breaker, 6 – IGBT modules and cooling system, 7 – driven circuit

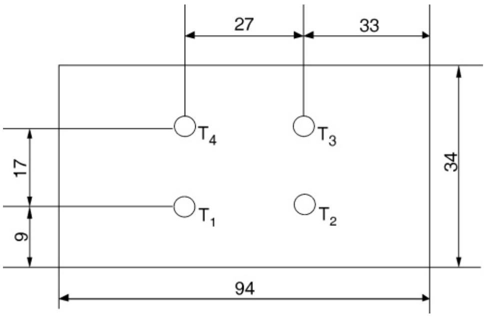

Figure 14. The position of the temperature sensor for every IGBT module

Table 2. Experimental data for the IGBT modules

Stage	Temperature [°C]		Error [%]
	Test results	Simulation results	
T1	56.3	59.94	6.47
T2	71.7	74.29	3.61
T3	61.8	63.94	3.46
T4	66	68.52	3.82
T5	66.7	67.31	0.91
T6	66.2	68.86	4.02

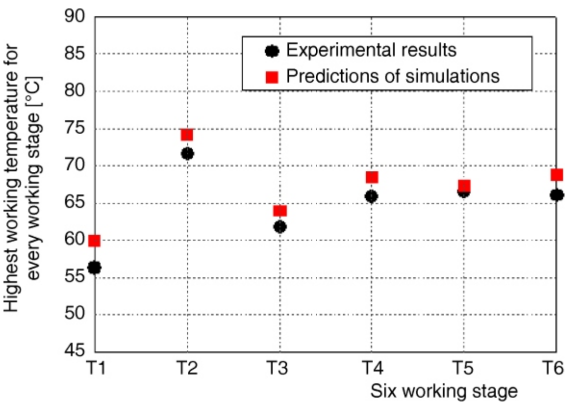

Figure 15. Comparison of experimental results and simulation results

ences of the measurement point. For the experiments, the highest temperature position is difficult to be tested, thereby, its values are lower than the predictions of simulations. Also, it can be seen that the highest temperatures of six phases are all lower than 80 °C. These results showed that the thermal management system satisfies the heat dissipation requirement of the IGBT modules PWM inverter, and can ensure the working reliability.

Conclusions

The main work and conclusions of this paper are summarized as follows. Firstly, based on the circuit equivalent method and the control rule, the IGBT modules electrical model is built, which is relevant to their switching frequency, switching voltage, switching current, and the reverse recovery process of FWD, and the power losses are estimated. Then, for a given inverter with six IGBT modules, its thermal resistance network model and thermal simulation model with forced air cooling are established, and the transient temperature field for six working stage are obtained. These results showed that the thermal management system is feasible, and can guarantee their working temperature lower than 80 °C. Lastly, a thermal management system of IGBT modules PWM inverter is constructed and tested, and the simulation results agree with the experimental results. The previously results showed that the thermal management system which adopted one heat sink for six IGBT modules are feasible and compact, and also could ensure their working temperature in every working stage.

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