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ORIGINAL ARTICLE

Thermal management implementation method for IGBT modules of inverters based on junction temperature estimation

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Abstract
Insulated gate bipolar transistors (IGBTs) are widely used in grid-connected renewable energy generation. Junction temperature fluctuation is an important factor affecting the operating lifetime of IGBT modules. Many active thermal management methods for suppressing junction temperature fluctuation exist, but research on the implementation of thermal management in converters is limited. Junction temperature extraction is the basis of implementing thermal management. In this study, a thermal network model method and a temperature-sensitive electrical parameter (TSEP) method for junction temperature estimation are analyzed first. Aiming to limit the maximum junction temperature of IGBTs, a thermal management method is proposed by changing switching frequency. Then, for a three-phase two-level inverter, the effectiveness of the proposed thermal management method is analyzed by offline simulation based on the thermal network model method. Lastly, the IGBT junction temperature in the inverter is estimated online by using the TSEP method and the feasibility of the thermal management implementation method is verified on an experimental platform.

Keywords Insulated gate bipolar transistor · Junction temperature estimation · Thermal management · Inverter

1 Introduction

With the development of renewable energy generation technology, many power electronic converters are used in grid-connected systems. The output of renewable energy generation is characterized by volatility and uncertainty, especially a wind power converter that operates in a constantly changing state with the variation in wind speed. In this case, the components in the power converter are always under the action of alternating thermal stress, thus accelerating the aging process of some devices. According to a survey based on more than 200 products from 80 companies, power semiconductor devices account for 21% of failure rates in power electronic devices [1]. The reliability of power semiconductor devices has been greatly improved in recent years with the advancement of manufacturing processes. However, high-power insulated gate bipolar transistor (IGBT) modules remain at a high risk of aging failure when applied in variable operating conditions because of their packaging structure [2].

Temperature and its cycle are the main stress sources that affect reliability performance [3], and this effect becomes evident with the trend of high power density and high temperature in power electronic systems [4]. When the operating condition of an IGBT changes, because the module package is a multilayer structure and the thermal expansion coefficient of adjacent layers is inconsistent [5], alternating thermal–mechanical stress will occur with the change in semiconductor chip temperature. The material will creep fatigue under the repeated action of alternating thermal–mechanical stress. Through a power cycle test in [6], M. Held proposed that the number of cycles to IGBT failure is negatively correlated with the average junction temperature and the junction temperature fluctuation amplitude.

Therefore, an effective way to increase the service lifetime of an IGBT module and improve its reliability is to reduce the junction temperature fluctuation during the device operation. Thermal management reduces the thermal stress on the device by enhancing heat dissipation or lowering device losses to decrease the amplitude or average of chip temperature fluctuations [7]. Thermal management can

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extend the replacement cycle of power modules and reduce equipment maintenance costs.

At present, many active thermal management methods, including increasing the cooling fan speed or liquid cooling system flow [8], changing the switching frequency [9], and exchanging the modulation strategy [10], exist. In [9], for the grid-side converter of a wind power generation system, Qin analyzed the relationship of junction temperature and total harmonic distortion (THD) with switching frequency and operating power and studied the feasibility of thermal management by changing switching frequency but did not explain how to select the control target of junction temperature fluctuation. For grid-connected converters, the THD of injected current is an important parameter, which has been studied in different types of inverters [11, 12]. In [13], for grid-side converters, Zhang proposed to take increased THD as input, the extended lifetime of thermal management as return, and the return on investment as a quantitative index to guide the selection of junction temperature control targets. However, junction temperature is directly measured using an infrared camera in [13], and this method is difficult to be applied in practice because of its high cost [14]. Therefore, the most important aspects in implementing thermal management are the selection of junction temperature control target and the online evaluation of junction temperature.

The thermal management method usually takes the IGBT junction temperature as the control target, so the junction temperature information must be obtained first. The methods commonly used for junction temperature estimation include thermal network model method [15, 16] and temperature-sensitive electrical parameter (TSEP) method [17, 18]. The thermal network model method is based on the electrothermal analogy and uses the Cauer or Foster network to establish the equivalent thermal model of the device [19]. The thermal network model method requires several iterative calculations, and many parameters need to be identified in the loss calculation and thermal network models; thus, this method is usually used to simulate the IGBT junction temperature offline. The TSEP method measures the electrical parameters of the terminal of the device, which are closely related to junction temperature as the temperature sensor. This method estimates junction temperature in accordance with the precalibrated relationship between junction temperature and electrical parameters, which can realize online junction temperature evaluation. In [20], Dianov used on-state resistance as TSEP to estimate the device junction temperature.

In this study, a thermal management method is designed by changing switching frequency for three-phase two-level inverters. Through limiting the maximum junction temperature of the IGBT as the control target, the appropriate switching frequency threshold is selected in consideration of the constraint of the harmonic content of the inverter output current. Then, the thermal network model method is used to estimate the junction temperature offline, and the effectiveness of the thermal management method in suppressing the IGBT junction temperature fluctuation is analyzed by the simulation of a two-level grid-connected inverter. Lastly, the IGBT junction temperature in the inverter is estimated online by using the TSEP method based on on-state voltage drop, and the feasibility of the proposed thermal management method is verified on an experimental platform.

2 Design of a junction temperature estimation and thermal management method

2.1 Thermal network model method

The thermal network model method is often used to estimate the junction temperature of an IGBT in a converter offline. The junction temperature is calculated by establishing the power loss model and the thermal network model of the device. The principle block diagram of the thermal network model method for the calculation of junction temperature is shown in Fig. 1. Parameters, such as the collector current I_c of the device in the converter, are input into the loss calculation module to obtain the power loss P_T of a single device under the current operating condition. The loss value is input into the Foster thermal network model, and the voltage at both ends of the current source is the junction temperature T_j of the device.

The thermal model of an IGBT module usually adopts the fourth-order Foster thermal network equivalent. The IGBT module analyzed in this study is a half-bridge module of BSM50GB120, with rated voltage and current of 1200 V and 50 A, respectively. The thermal resistance and capacity of each order of IGBT given in the data manual are shown in Table 1. In the table, R_{th5} and C_{th5} are the thermal network parameters of the heatsink, which are derived from a typical forced air cooling heatsink in the power simulation tool IPOSIM.

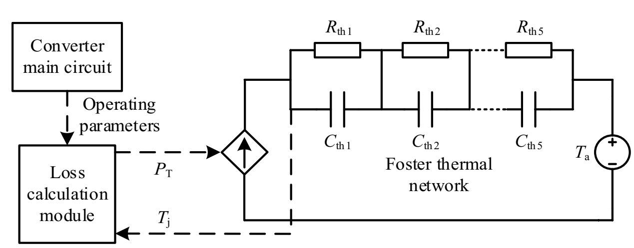


Fig. 1 Schematic of calculating the junction temperature by the thermal network model method

Table 1 Parameters of the foster thermal network

Order N	1	2	3	4	5
R_{thN} (K/W)	0.0527	0.177	0.0141	0.0258	0.3
C_{thN} (J/K)	0.171	0.254	5.18	8.88	100

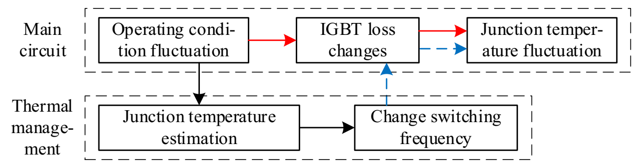


Fig. 3 Schematic of the thermal management method by changing switching frequency

2.2 TSEP method based on on-state voltage drop

In this study, the junction temperature of the IGBT is estimated online by taking the on-state voltage drop of the IGBT under the current of the converter as the TSEP. The three-dimensional relationship between on-state voltage drop V_{ce_on}, junction temperature T_j, and collector current I_c is obtained through a single-pulse Calorstat experiment, and the junction temperature is estimated by on-state voltage drop in reverse.

After the data of on-state voltage drop are obtained, the nonlinear relationship of junction temperature with on-state voltage drop and collector current should be fitted to evaluate junction temperature in reverse. In this study, the back propagation (BP) neural network algorithm is used to fit the relationship between them. The structure of the junction temperature fitting model is shown in Fig. 2, with V_{ce_on} and I_c as inputs and T_j as output. The BP neural network does not need to specify the functional relationship between input and output, and the model obtained by data training can calculate a result close to the expected output in accordance with the input value, which has a strong nonlinear mapping ability.

2.3 Design of a thermal management method

In this study, a thermal management method is designed by changing switching frequency. As shown in Fig. 3, the fluctuation in the operating condition of the inverter causes a fluctuation in the junction temperature of the IGBT. The junction temperature is estimated on the basis of an evaluation model. When the maximum junction temperature exceeds the predetermined range, the switching frequency is reduced to decrease the amplitude of the junction temperature fluctuation under the same operating condition. Reducing the switching frequency can directly lower the switching loss of the IGBT, but it also increases the harmonic content of the output current of the inverter. This condition must be considered comprehensively when selecting the threshold of switching frequency.

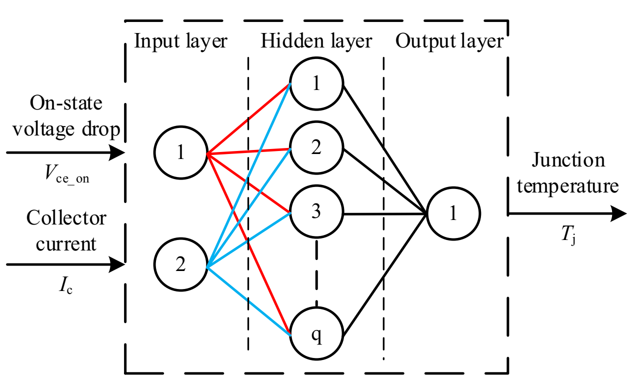


Fig. 2 Structure diagram of the junction temperature fitting model

A complex relationship exists between the maximum junction temperature of the IGBT and the THD of current and switching frequency, and the thermal management approach needs to select suitable maximum junction temperature limit and switching frequency threshold. For preventing THD from exceeding the relevant standards, the switching frequency cannot be adjusted too low when the junction temperature is high, but the switching frequency can be adjusted to a higher value when the junction temperature is low. In addition, ambient temperature, as a benchmark for temperature rise, must be considered when designing the thermal management method.

When the IGBT module is operating, the chip junction temperature will at least be higher than the ambient temperature T_a, and the maximum junction temperature T_{jmax} in the process of junction temperature fluctuation can be expressed as

$$T_{jmax} = T_a + \Delta T_j, \tag{1}$$

where ΔT_j represents the difference between the maximum junction temperature and the ambient temperature, which is determined by the power loss of the device. The loss is determined by the operating conditions and the ambient temperature. Under the same operating conditions, the higher the ambient temperature, the higher the junction temperature of the IGBT. After thermal management is added, the lower the T_{jmax} value is, the more beneficial it is to prolong the operating lifetime of the power module. The higher the ambient temperature, for making the maximum junction temperature be less than a certain value, the smaller the value of ΔT_j is required, so the switching frequency needs to be adjusted to a lower value. When the switching frequency is considerably low, the THD of current cannot meet the requirements.

When other conditions are constant, the IGBT junction temperature is highest when the ambient temperature and the operating current of the converter are highest, which is the most serious condition when designing the parameters for thermal management. Therefore, the values of the upper limit of junction temperature T_{jh} and the lower limit of switching frequency f_{swth} are determined in accordance with the junction temperature fluctuation of the IGBT under the maximum ambient temperature T_{amax}. The selection principle is T_{amax}, and the converter operates under the maximum current condition so that the THD of output current does not exceed a certain limit value to determine f_{swth}. Then, T_{jh} is determined in accordance with the maximum junction temperature under f_{swth}. IEEE Std 519 recommends that the THD of the maximum current be less than 5%. T_{jh} for thermal management to reduce the switching frequency can be expressed as

$$T_{jh} = T_{amax} + \Delta T_{jh}, \tag{2}$$

where ΔT_{jh} is the expected maximum junction temperature fluctuation after thermal management is added.

The relationship between switching loss and current is quadratic. When the current is small, the maximum junction temperature does not change much with the change in switching frequency, whereas THD changes greatly. Therefore, THD is preferred when the current is small, so the switching frequency is directly adjusted to the rated value when the junction temperature is low. The value of the lower limit of junction temperature T_{jl}, which returns to the rated switching frequency for thermal management, is determined by the maximum junction temperature under f_{swth} and the rated current condition, which can be expressed as

$$T_{jl} = T_{amax} + \Delta T_{jl}. \tag{3}$$

In this study, the thermal management method by changing switching frequency is discrete frequency control, which takes the fundamental current period (i.e., junction temperature period) as the control step. This method determines whether the thermal management adjusts the switching frequency in accordance with the value of the maximum junction temperature. In one control step, the process of thermal management judgment is shown in Fig. 4. When the maximum junction temperature T_{jmax} of the IGBT exceeds T_{jh} and the switching frequency is greater than f_{swth} at a certain ambient temperature, the switching frequency reduces by 1 kHz. When T_{jmax} is less than T_{jl}, the switching frequency returns to the rated value.

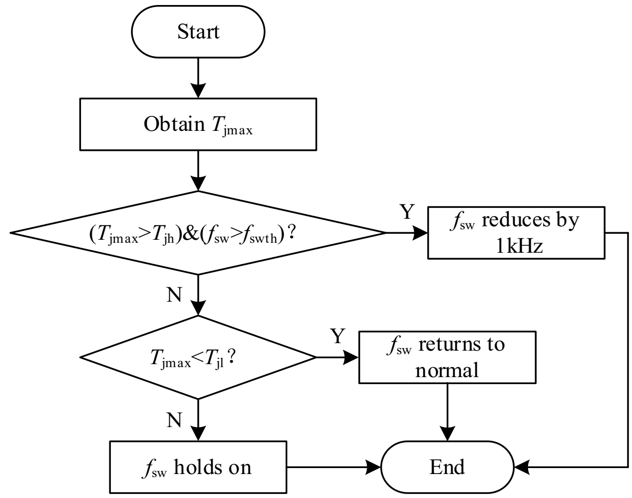


Fig. 4 Judgment process of the thermal management method

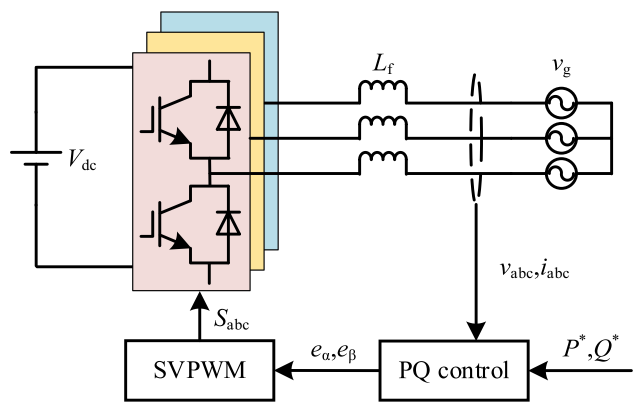


Fig. 5 Block diagram of the grid-connected inverter system

3 Simulation analysis

3.1 Junction temperature estimation by the thermal network model method

This study takes the common three-phase two-level grid-connected inverter in renewable energy generation as a simulation case and analyzes the junction temperature of the IGBT and the thermal management method. The control strategy adopts PQ control, which mainly has two applications: one is current-type grid-connected equipment tracked by maximum power, such as wind energy and solar energy, and the other is an energy storage inverter with constant active and reactive power output.

As shown in Fig. 5, the inverter system is connected to the grid through L filter. In the figure, V_{dc} is the DC-side voltage; L_f is the filter inductance; v_g is the grid voltage;

Table 2 Parameters of the inverter system

Parameters	Value	Parameters	Value
DC-side voltage	600 V	Filter inductance	5 mH
Grid voltage	380 V	Rated output power	23 kW

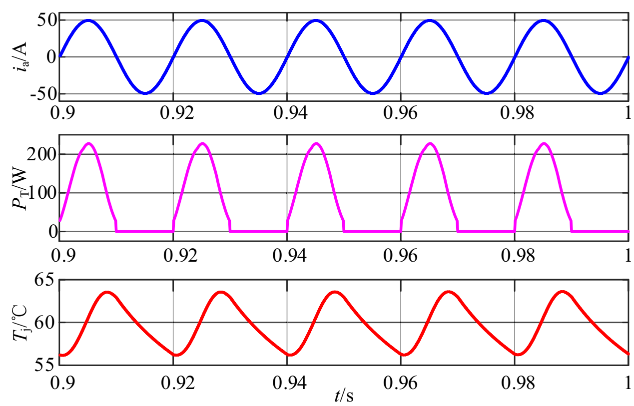


Fig. 6 Simulation waveform of the IGBT in the inverter

P^* and Q^* are the active and reactive power references, respectively; v_{abc} and i_{abc} represent three-phase voltage and current, respectively; e_α and e_β are voltage modulation waves; S_{abc} is the IGBT switching signal. The simulation parameters are shown in Table 2.

The grid-connected inverter model and thermal network model of the IGBT are built in MATLAB. The simulated output phase current i_a, IGBT power loss P_T, and junction temperature T_j of the inverter are shown in Fig. 6. The IGBT on the upper bridge arm of a-phase only has current flowing in the positive half period of i_a; hence, the loss changes periodically with the amplitude of the current and causes junction temperature fluctuation.

3.2 Feasibility analysis of changing switching frequency

For the grid-connected inverter shown in Fig. 5, the relationship of the maximum junction temperature T_{jmax} of the IGBT with the RMS value I_a of the phase current and the switching frequency f_{sw} is shown in Fig. 7. With an increase in I_a and f_{sw}, T_{jmax} also presents an increasing trend.

The relationship of the THD of grid-connected current with I_a and f_{sw} is shown in Fig. 8. Decreasing switching frequency will lead to an increase in THD, whereas THD will decrease with an increase in current RMS value. This condition provides feasibility for thermal management by changing switching frequency. When the operating current of the converter increases, the maximum junction temperature can be reduced by decreasing the switching frequency,

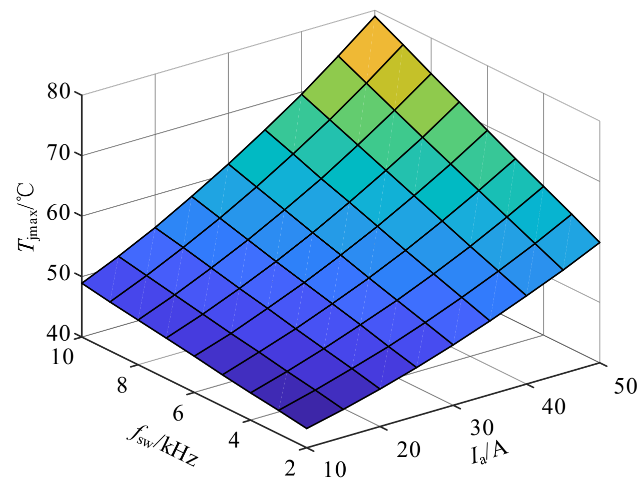


Fig. 7 Diagram of maximum junction temperature in relation with switching frequency and phase current

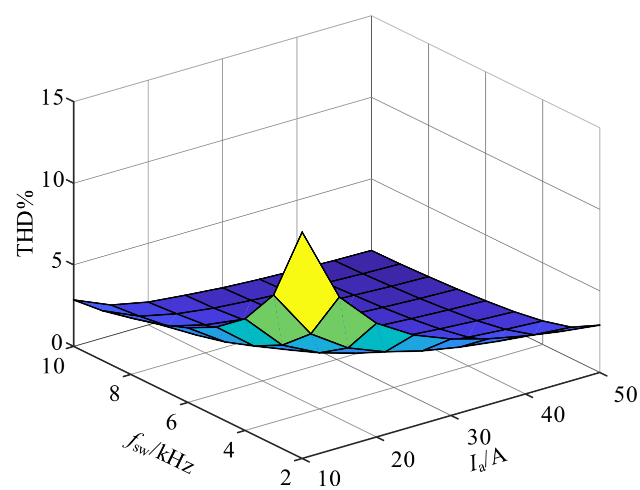


Fig. 8 Diagram of the THD of grid-connected current in relation with switching frequency and phase current

and the THD of the current will not increase excessively. When the operating current decreases, the switching frequency is increased to avoid excessive THD of the current. In this way, after the addition of thermal management, the maximum junction temperature of the IGBT and the THD of grid-connected current are basically stable at moderate values.

3.3 Simulation verification of thermal management

The thermal management method is verified in the inverter model established above. The ambient temperature T_a is set to 40 °C, which is the maximum ambient temperature, and the rated switching frequency is 10 kHz. The lower limit of switching frequency f_{swth} is 2 kHz, the maximum junction temperature under the condition that the THD of grid-connected current is 2.9% is determined to set the value of T_{jh} to 61 °C, and the value of T_{jl} is set to 51 °C. The fluctuation in junction temperature with multiple changes in given active power before and after the addition of thermal management is simulated.

For simulating the power fluctuation in renewable energy generation, four operating conditions are set during the simulation, and the given active power under each operating condition is as follows: I (10 kW), II (23 kW), III (33 kW), and IV (15 kW). Under different operating conditions, the given reactive power is always 0 kVar. The output active and reactive powers of the inverter are shown in Fig. 9, and the output powers can efficiently track the given values.

The RMS values of phase current I_a under each steady-state condition are as follows: I (15.15 A), II (34.85 A), III (50 A), and IV (22.73 A). The junction temperature fluctuation of the IGBT when thermal management is not adopted is shown in Fig. 10a. The maximum junction temperature T_{jmax} is 76.15 °C, the maximum junction temperature fluctuation ΔT_j is 36.15 °C, and the average junction temperature T_m is 57.56 °C. The RMS value of a-phase current under variable operating conditions is shown in Fig. 10b, and the switching frequency is constant at 10 kHz.

The change in switching frequency after the addition of thermal management is shown in Fig. 11b. The initial switching frequency is 10 kHz. In condition II, with an increase in the RMS value of phase current, the IGBT junction temperature exceeds the upper limit T_{jh}. As a result, the switching frequency becomes 9 kHz at 0.63 s and stabilizes at 8 kHz after 0.69 s. After 1 s, the switching frequency is continuously reduced and finally stabilized at the lower limit of switching frequency at 2 kHz, at which the current is maximum. With a decrease in current, the maximum junction temperature becomes lower than the lower limit T_{jl}; consequently, the switching frequency at 1.59 s returns to 10 kHz.

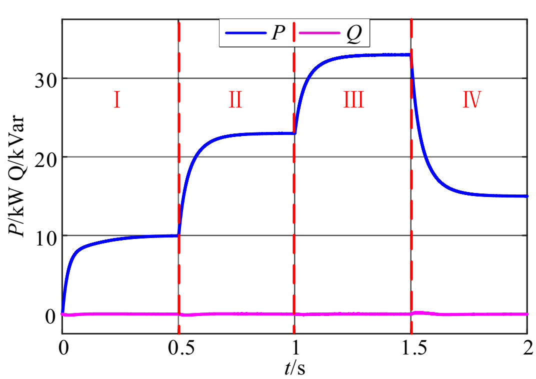


Fig. 9 Output power of the inverter under variable operating conditions

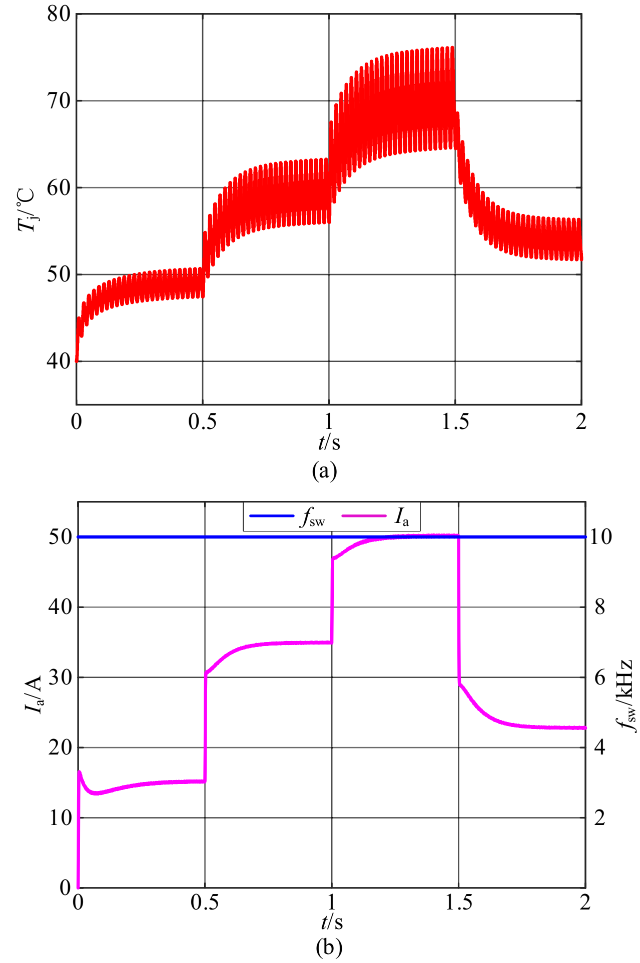
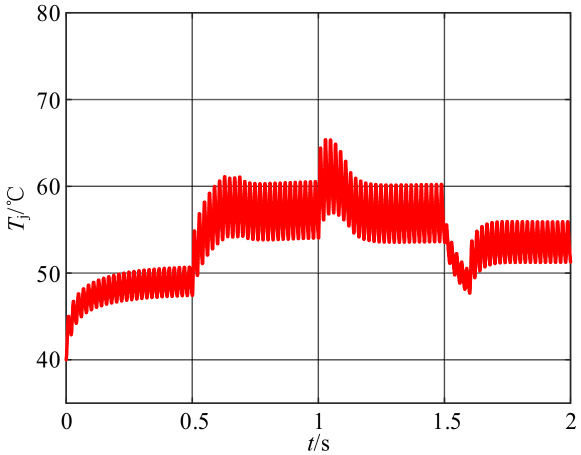


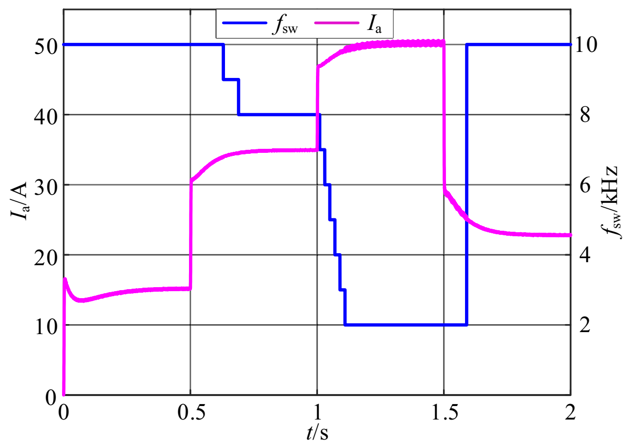
Fig. 10 Simulation waveforms under variable operating conditions: **a** junction temperature; **b** switching frequency and phase current (without thermal management)

In Fig. 11a, T_{jmax} is 65.36 °C, ΔT_j is 25.36 °C, and T_m is 53.72 °C. Table 3 indicates that after thermal management is added, the maximum junction temperature fluctuation ΔT_j is reduced by 29.85%, the average junction temperature T_m is decreased by 6.67%, and the amplitude and average value of the IGBT junction temperature fluctuation are effectively reduced.

For the inverter with L filter, the THD of grid-connected current in a steady state with thermal management by changing switching frequency is shown in Table 4. Compared with the THD when the switching frequency is constant at 2 kHz, the maximum THD of current is only 2.9% with changing switching frequency; the switching frequency is reduced to 2 kHz, and the current is maximum. When the switching frequency is constant at 2 kHz, the maximum value of THD is 9.21%, and the current is minimum. After the addition of thermal management, the THD is generally less than the condition in which the switching frequency is constant at 2 kHz. That is, while the thermal management reduces the



(a)



(b)

Fig. 11 Simulation waveforms after adding thermal management: **a** junction temperature; **b** switching frequency and phase current

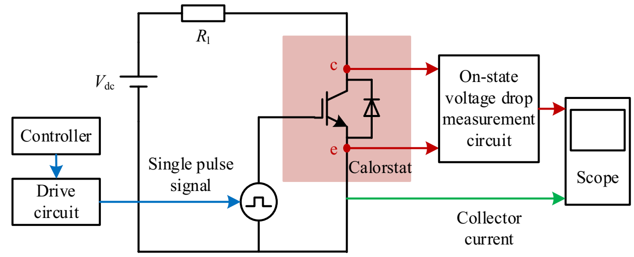


Fig. 12 Schematic of the single-pulse Calorstat experiment

Table 3 Effect of thermal management on the junction temperature of the IGBT

Thermal management	T_{jmax} (°C)	ΔT_j (°C)	T_m (°C)
No	76.15	36.15	57.56
Yes	65.36	25.36	53.72

Table 4 THD of grid-connected current at different switching frequencies

RMS of current (*A*)	15.15	34.85	50.00	22.73
THD of 2 kHz f_{sw}	9.21%	4.06%	2.9%	6.14%
THD of changing f_{sw}	1.87%	1.34%	2.9%	1.23%

junction temperature fluctuation, the switching frequency is increased under low current to avoid excessive THD to meet the power quality requirements of the converter.

The simulation analysis shows that the proposed thermal management method by changing switching frequency can effectively reduce the amplitude and average value of IGBT junction temperature fluctuation in grid-connected inverters, decrease thermal stress, and improve the reliability of power modules.

4 Experimental verification

4.1 Demonstration of the junction temperature fitting model

Given the difference between the actual environment and simulation, the inaccuracy of the loss model and the thermal network model of IGBT will lead to an inconsistency between the junction temperature estimated by the thermal network model method and the actual junction temperature of the device. Although the online estimation method is not superior in terms of cost [21, 22], this study still uses the TSEP method to estimate the actual junction temperature online. The key to applying the TSEP method based on on-state voltage drop is to establish a junction temperature fitting model.

The single-pulse Calorstat experiment circuit adopted to calibrate the relationship between on-state voltage drop and junction temperature is shown in Fig. 12. The controller sends a single-pulse signal, and the DC power supply provides collector current to the IGBT in the BSM50GB120 module through the circuit composed of resistor R_1. The on-state voltage drop is measured by a lead wire, and waveform data are collected using an oscilloscope. This study adopts the on-state voltage drop measurement circuit proposed by U.M. Choi in [23]. The measurement instruments used in the experiment are shown in Table 5. During the experiment, the IGBT module is placed in the Calorstat for a period, so that the IGBT junction temperature is approximately equal to the temperature set by the Calorstat. The width of the

Table 5 Measurement instruments

Instruments	Range	Accuracy
On-state voltage drop measurement circuit	0–5 V	1.04%
A622 current probe	50 mA–100 A	±50 mA
TBS2204B oscilloscope	Maximum 300VRMS	8-bit

single-pulse is set to 1 ms, and the self-heating temperature rise caused by the current for this length of time can be ignored.

The junction temperature varies from 20 °C to 95 °C and the collector current varies from 1 to 17 A in the single-pulse Calorstat experiment. The on-state voltage drop under different collector currents and junction temperatures is shown in Fig. 13. The points in the figure are the measured on-state voltage drop under corresponding conditions, and the surface is the polynomial fitting according to the primary relationship between on-state voltage drop and junction temperature and the quadratic relationship between on-state voltage drop and current. From Fig. 13, at a small current, the on-state voltage drop decreases with an increase in junction temperature, and the two are negatively correlated. At a large current, the on-state voltage drop increases with an increase in junction temperature, and the two are positively correlated. When the current is about 10 A, the on-state voltage drop is basically unchanged despite varying junction temperature.

When the current is around 10 A, the junction temperature of the IGBT cannot be evaluated by the on-state voltage drop because the relationship between them is not obvious. Therefore, the TSEP method based on on-state voltage drop should also be divided into small and large current ranges on the basis of the value of the collector current, and different neural network models should be established accordingly.

The collector current varies from 1 to 4 A in the small current range. The junction temperature fitting model is trained using the BP neural network fitting toolbox nftool in MATLAB, and the training results are shown in Fig. 14. The horizontal axis is the measured junction temperature, and the longitudinal axis is the fitting value of the neural network under the same conditions. The value of correlation coefficient R of the dataset is 0.984. The results show that the trained neural network model has a good fitting effect on junction temperature.

4.2 Estimation of IGBT junction temperature in an inverter platform

The experimental platform of a three-phase two-level inverter, as shown in Fig. 15, is composed of DC power supply, RL load, three-phase inverter, drive circuit, control circuit, and on-state voltage drop measurement circuit. The IGBT half-bridge module in the inverter is BSM50GB120, and the modulation mode is SVPWM in the control circuit.

The experimental parameters are shown in Table 6. When the ambient temperature is 20 °C, the junction temperature of the IGBT is estimated using the experimental data including the phase current i_a and IGBT on-state voltage drop V_{ce_on} collected under the operating conditions in Table 6. The waveform of i_a is shown in Fig. 16. The peak value of current is 3.92 A, and the phase current is the filtered data;

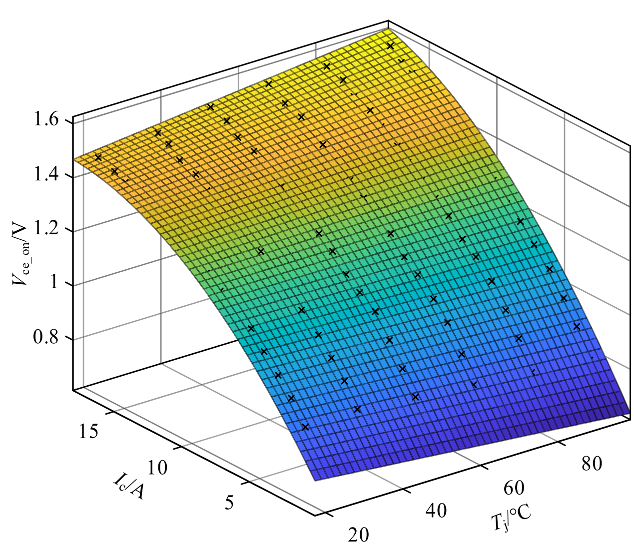


Fig. 13 Distribution of on-state voltage drop at different currents and junction temperatures

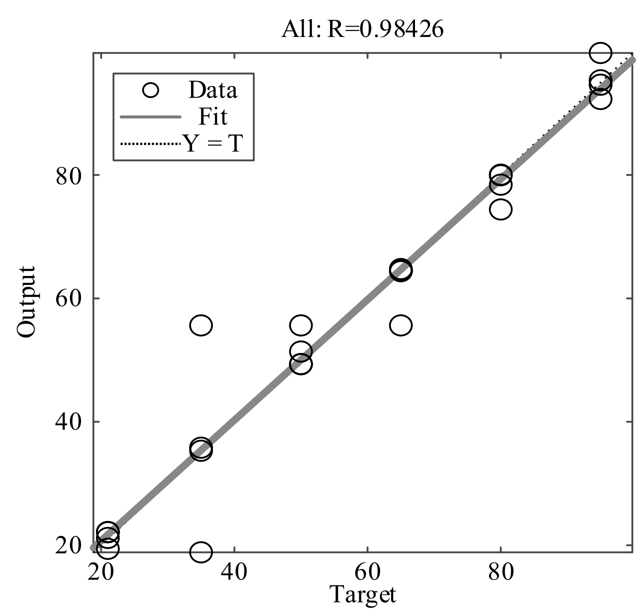


Fig. 14 Correlation between predicted and actual values

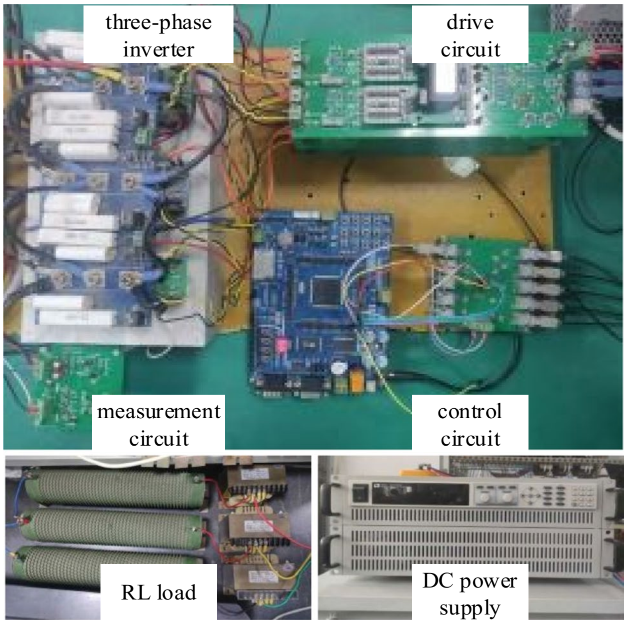


Fig. 15 Diagram of the three-phase two-level inverter platform

Table 6 Inverter experimental parameters

Parameters	Value
DC-side voltage	180 V
Modulation ratio	0.8
Switching frequency	8 kHz
Fundamental frequency	50 Hz
Load resistance	20 Ω
Load inductance	5 mH
Switching device	BSM50GB120
Drive circuit	2SD315AI

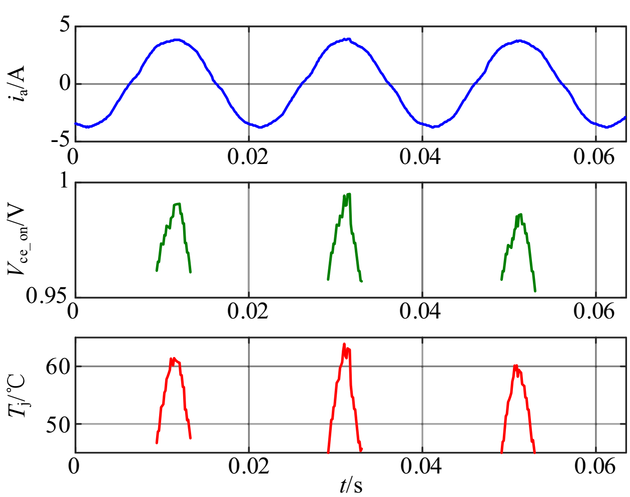


Fig. 16 Results of junction temperature estimated by the TSEP method

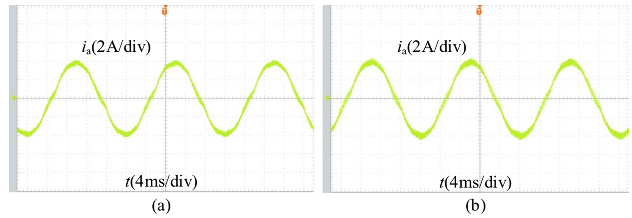


Fig. 17 Waveforms of the phase current of the inverter at different switching frequencies: **a** 8 kHz; **b** 5 kHz

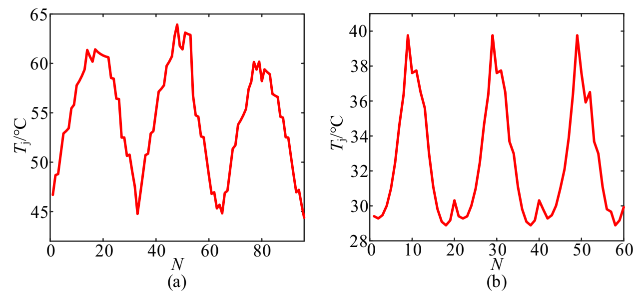


Fig. 18 Waveforms of the IGBT junction temperature of the inverter at different switching frequencies: **a** 8 kHz; **b** 5 kHz

thus, the waveform is relatively smooth. For implementing the proposed thermal management method, the on-state voltage drop near the peak current is selected to estimate the maximum junction temperature. In Fig. 16, the junction temperature T_j of the IGBT near the peak current fluctuates between 45 °C and 65 °C, estimated by the TSEP method. When the phase current is positive, the IGBT on the lower bridge arm is turned-on, so the junction temperature waveform is concentrated near the positive peak current.

4.3 Experimental verification of thermal management feasibility

The waveforms of phase current i_a in the experiment when the switching frequency of the inverter is reduced from 8 to 5 kHz are shown in Fig. 17a–b, respectively.

The waveforms of junction temperature T_j near the peak current of the IGBT in the inverter at 8 and 5 kHz switching frequencies estimated by the TSEP method are shown in Fig. 18a–b, respectively. Each figure contains the junction temperature of three current cycles. The number of switching cycles near the current peak at different switching frequencies varies, so the junction temperature data points differ. The maximum junction temperature of the IGBT at 8 kHz switching frequency is about 60 °C, whereas the maximum junction temperature at 5 kHz is about 40 °C.

The experimental results indicate that reducing the switching frequency can significantly decrease the maximum junction temperature of the IGBT. This finding verifies the

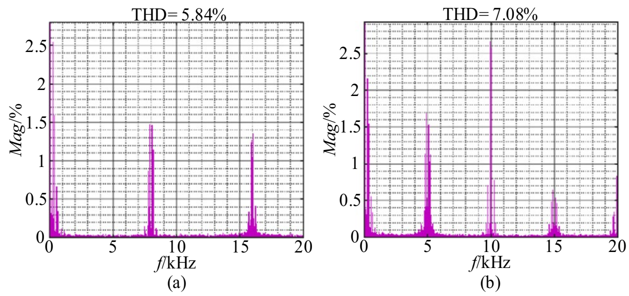


Fig. 19 THD distribution of the inverter current at different switching frequencies: **a** 8 kHz; **b** 5 kHz

effectiveness of thermal management by changing switching frequency.

The THD distributions of the phase current of the inverter at 8 and 5 kHz switching frequencies are shown in Fig. 19. The THD of the phase current at 8 kHz is 5.84%, whereas the THD at 5 kHz is 7.08%.

Figure 19 demonstrates that reducing the switching frequency will increase the THD of the current, which is the shortcoming of the thermal management method by changing switching frequency. Given that the amplitude of current in the experiment is only about 3.9 A, which is a small current, THD can also meet the requirements of IEEE Std 519 at low switching frequency with increasing current.

In summary, combined with the TSEP method based on on-state voltage drop and the proposed thermal management method, an implementation method of IGBT thermal management in an inverter is formed. The feasibility of the method is verified by experiments.

5 Conclusion

Junction temperature evaluation is the basis of IGBT thermal management in converters. This paper presents a method of IGBT thermal management for inverters based on junction temperature estimation. In consideration of the constraints of junction temperature and power quality, the fluctuation in IGBT junction temperature is suppressed by changing switching frequency. The effectiveness of the proposed method is verified by simulation and experiment, and the conclusions are as follows:

1. According to a simulation based on the thermal network model method, the proposed thermal management method can limit the maximum junction temperature of IGBTs below the set upper limit, effectively reduce the thermal stress of devices, and improve the reliability of IGBT modules. The power quality of inverter output current can also be ensured.
2. The TSEP method based on on-state voltage drop can estimate the maximum junction temperature of devices online in accordance with the phase current of inverters and the on-state voltage drop of IGBTs. Then, on the basis of the actual operating condition of the inverters, the method can determine whether the switching frequency needs to be changed to implement IGBT thermal management.

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Data availability All data are provided in the theoretical analysis and experimental verifcation sections of this paper.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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