Letters

Accurate Evaluation of Cooling System Capability of Three-phase IGBT-based Inverter*

Dan Zheng[1], *Puqi Ning*[1, 2*], *Xiaoguang Chai*[1, 2], *Wei Sun*[1], *Zhijie Qiu*[1], *Yuhui Kang*[1], *Han Cao*[1, 2] *and Tao Fan*[1, 2]

(1. Institute of Electrical Engineering Chinese Academy of Sciences, Beijing 100190, China;
2. School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: In this paper, an offline evaluation method for the cooling capability of three-phase insulated-gate bipolar transistor (IGBT) inverters is presented, which can better emulate real working conditions. With a properly designed sudden-stop control sequence, the conventional junction temperature monitoring method at a low current is used to calculate the junction temperature before the sudden stop of an inverter. This can solve the challenging switching loss calculation issue in conventional methods. Finally, the feasibility, control sequence, and electrical behaviors of the proposed method are validated through experimental tests.

Keywords: Junction temperature monitoring, IGBT, conduction voltage

1 Introduction

Cooling capability evaluation is a core step in three-phase inverter design and development [1-2]. In most studies, the junction temperature of the device is estimated using the loss model and thermal network model, as shown in Fig. 1. An accurate evaluation of the thermal dynamics can help to predict the stability of inverter systems [3-5]. In some conventional methods, the thermal impedance is derived from the datasheets of power modules and cooling systems; hence, an accurate calculation of the power loss is required. As an alternative method, a simplified working condition is assumed, and a detailed finite-element method simulation is used. However, currently, these methods are not sufficient for high-power-density inverters [6-7].

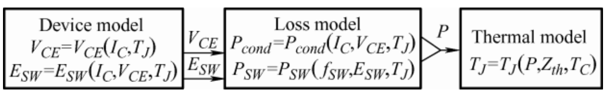


Fig. 1 Conventional junction temperature estimation methods

In a high-power-density inverter, the cooling system usually operates in the saturation mode, and the accuracy of thermal behavior estimated at the lower power may significantly decreases at the rated power. The non-ideal thermal imbalance, limited pump capability, and complex dynamic electrical load influence the loss calculation [8-9]. Therefore, it is important to explore a more advanced characterization method at the rated power, which does not involve too many assumptions in the thermal path and loss calculation.

A method evaluates the junction temperature of insulated-gate bipolar transistors (IGBTs) under light load, half load, rated power, and overload conditions gradually is preferred, to prevent damage to power devices by directly operating at the maximum allowed power. Commonly used junction temperature monitoring methods can be classified as conduction contact-based, electro-thermal model-based, optical, and temperature-sensitive electrical parameter (TSEP)-based methods [10-13]. The TSEP-based method uses the chip itself as a temperature sensor, which has advantages in terms of accuracy, control modification, and hardware invasion [10-13].

The method based on the on-state voltage at low current is widely used in junction temperature measurement, and the basic circuit is shown in Fig. 2. Among other TSEP methods, the peak gate current,

Manuscript received January 22, 2021; revised February 1, 2021; accepted March 1, 2021. Date of publication March 31, 2021; date of current version March 8, 2021.
* Corresponding Author, E-mail: npq@mail.iee.ac.cn
* Supported by the National Key Research and Development Program of China (2016YFB0100600).
Digital Object Identifier: 10.23919/CJEE.2021.000007

leakage current, and overshoot voltage methods have relatively low resolutions, therefore requiring special sensors. In contrast, the threshold voltage, turn-off time, and turn-off delay methods have high nonlinearity, requiring complex calibration. Furthermore, the short-current and breakdown voltage methods may directly damage devices [10]. Owing to cost, linearity, complexity, and stability advantages, the on-state voltage at low current is the recommended method in the JESD51-14 and other standards when conducting thermal resistance tests.

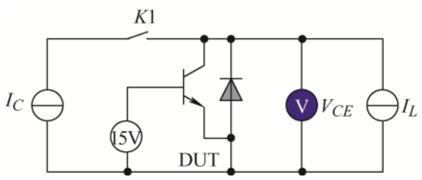


Fig. 2 Traditional cooling system capability evaluation using the method based on the on-state voltage at low current

To evaluate the thermal impedance of regular power modules, a widely used testing method is based on the on-state voltage with a very low current injection. However, the device under test (DUT) remains conductive in the heating phase, and the switching loss in real working conditions can only be estimated. To compensate for the issue of switching loss estimation, the heating current is usually set to a higher value [14]. This calculation-based setting may result in inaccuracies when operating at the rated power.

Ref. [15] introduced a method to estimate the junction temperature of an single-phase inverter under the switching mode, resulting in a thermal characterization that is closer to that of real operation cases. An H-bridge testing circuit and its corresponding control methods were presented. However, it is difficult to apply this method to a three-phase inverter system owing to control and current cutting reasons.

To solve the above issues, this paper presents an accurate and feasible offline cooling capability evaluation method for an IGBT-based inverter. A control sequence is used to rapidly cut off all three-phase currents; thus, an approximate ideal sudden-stop situation can be formed. This contributes to a more accurate evaluation of thermal impedance.

2 Sudden-stop and cooling down procedure

2.1 Sudden-stop control procedure

In this study, a three-phase inverter is loaded with three-phase inductors and resistors, as shown in Fig. 3. As indicated, T6 at the bottom of phase C represents the DUT IGBT. For motor drives and other three-phase power sources, the equivalent inductance (L) and resistance (R) must be carefully calculated and used. The switching frequency, power factor angle, and other working conditions must be considered. As current sensors are usually present in most inverters, only an on-state voltage sampling unit is required in this method.

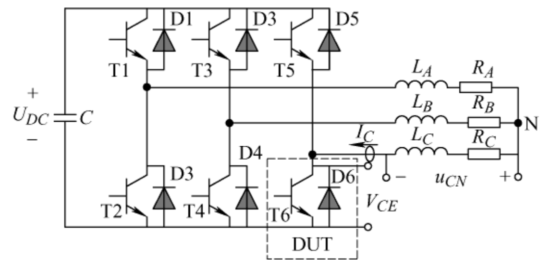
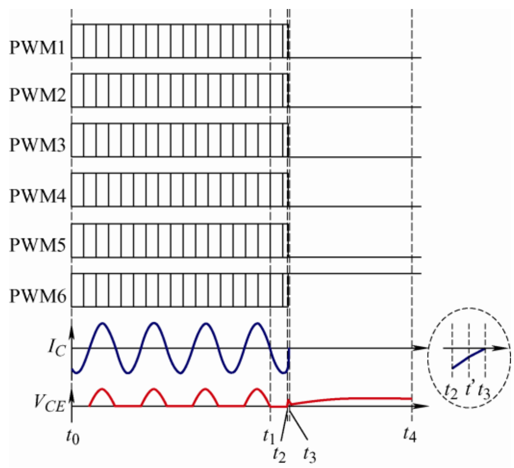


Fig. 3 Inverter topology

Fig. 4 shows the sudden-stop control sequence. Based on a set power target, all three phases can be powered with a regular control algorithm. After thermal equilibrium is reached, the load current is interrupted at time t_2, without any further auxiliary switches. In this state, the DUT (T6) is activated and all the other IGBTs (T1–T5) are turned off.



t_0-t_3: run time; t_3-t_4: stop time; t_2-t_3: shutdown process;

t_3-t_4: T_J measurement; t_1-t_3: compensate time;

t_2-t': stage 1; t'-t_3: stage 2.

Fig. 4 Sudden-stop control sequence

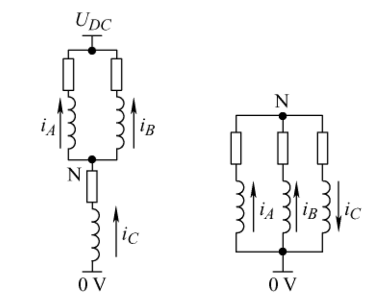
If the phase C current (I_C) flows from the IGBT module and its amplitude is larger than those of the currents of the other two phases at time t_2, the load currents would flow through D1, D3, and D6. In this scenario, the inverter enters a forced discharge mode, as shown in Fig. 5a. In this mode, reverse voltages are applied to inductive loads. All phase currents quickly return to 0 A following a two-stage slope, generally within several milliseconds. The current discharge rate (di/dt) of the inductor L_C is determined by Eq. (1).

$$\frac{\mathrm{d}i_L}{\mathrm{d}t}=\frac{u_{CN}-i_L\times R}{L} \tag{1}$$

where u_{CN} is the instantaneous voltage of the phase C load, i_L is the current flowing through the load, L is the inductance of L_C, and R is the resistance of R_C. In the first stage, u_{CN} is $2/3U_{DC}$, where U_{DC} is the DC-link voltage. When the minor currents of phases A and B return to 0 A, the current path will be disconnected instead of having a damped oscillation behavior due to the shutdown of T1–T5.

The second stage is thereafter initiated, and u_{CN} is set to $1/2U_{DC}$. The energy stored in the inductors is transferred to the DC-link capacitor as reactive power, resulting in a voltage increase (ΔU). Usually, the reactive power is already considered in the power stage design; therefore, ΔU is not sufficient to cause any damage.

When the control sequence does not conform to the forced discharge mode, the natural discharge mode of the converter is activated, as shown in Fig. 5b. In this mode, the current flows between the three-phase loads, and the energy is only consumed by resistors. This process is relatively slow, usually performed in several seconds, and should be avoided during cooling evaluation procedures.



(a) Forced discharge (b) Natural discharge

Fig. 5 Inductor discharge mode

In a real test, the forced discharge mode can be controlled by monitoring and comparing the phase currents. Every phase leg can be evaluated by repeatedly changing the control sequence and low-current injection circuit connection.

2.2 Cooling down procedure

To evaluate the impact of the shutdown process on the junction temperature, the FOSTER model of the inverter system, shown in Fig. 6, was established and is commonly used. Usually, the datasheet provides only the thermal impedance from the junction to the case. Therefore, the thermal impedance between the junction and fluid should be derived from experiments. When the cooling fluid is water with a flow rate of 70 L/min, the junction-to-fluid thermal impedance of a ABB module 5SNG1000X170300 is shown in Tab. 1, where R_i and τ_i are the thermal resistance and time constant pairs, respectively.

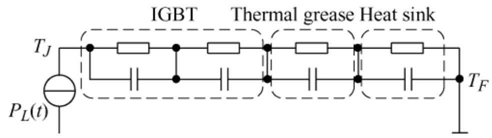


Fig. 6 FOSTER network model of a thermal impedance

Tab. 1 Transient thermal impedance of an IGBT module

i	R_i/(K/kW)	τ_i/s
1	6.16	0.036
2	20.08	0.555
3	43.12	2.271
4	1.80	1.017

Fig. 7 shows the relationship between the IGBT junction temperature and time based on a simulation. The IGBT was heated by an AC current flowing through it alternately. The heating power was set to 560 W. The junction temperature stabilized in approximately 10 s, and the fluctuation was approximately 3 ℃. The heating current was then interrupted at 15 s. In the following 10 ms, the temperature change was less than 0.5 ℃. Therefore, in this procedure, the junction temperature can be measured by the conduction voltage with a low current within 5 ms of the current interruption. The sampling time in this study was selected as 100 to 1 000 μs.

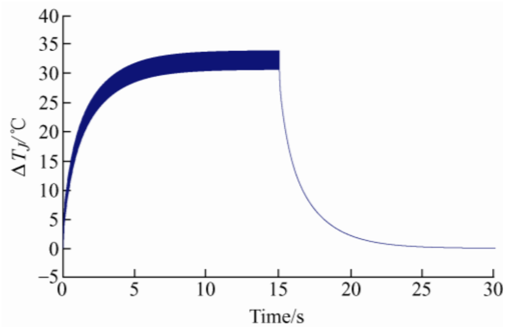


Fig. 7 Simulation results of IGBT cooling curve

Furthermore, using the sudden-stop control procedure described in Section 2.1, the current after the cut-off moment is forced to flow through T5 instead of T6. Thus, the time between t_1 and t_3 can be measured. The IGBT junction temperature immediately before the cut-off can also be accurately calculated using a typical compensation algorithm, such as the square root t method [16] shown in Fig. 8. The relationship between ΔT_J and $\sqrt{t}$ is linear during the initial period of the shutdown. This period, which is approximately hundreds of milliseconds, is related to the thermal characteristics of the module. Although this relationship is still based on some ideal assumptions, the error in practical applications is acceptable.

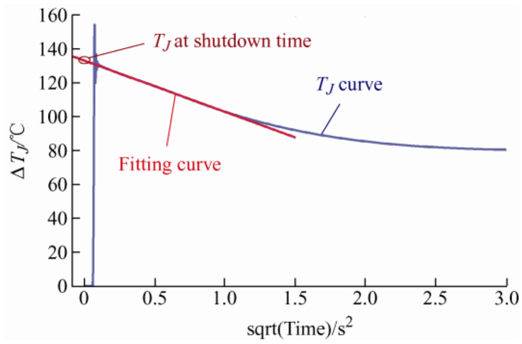


Fig. 8 Temperature compensation method

3 On-state voltage measurement and a junction temperature estimation case

3.1 Junction temperature estimation with a very low current

The junction temperature of IGBTs can be estimated using the on-state voltage under a very low current. As shown in Fig. 9, a very low current (I_L) is injected into the DUT; therefore, its power loss can be neglected. To obtain the relation between the junction temperature (T_J) and on-state voltage (V_{CE}), T_J was controlled by an ambient testing cabinet.

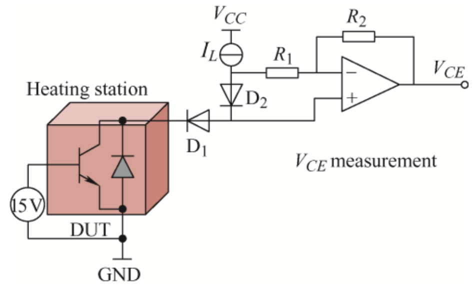


Fig. 9 T_J-V_{CE} calibration schematic

In this study, an ABB module (5SNG1000X170300) was tested considering I_L ranging from 5 mA to 100 mA. The linear relation between T_J and V_{CE} was confirmed for each I_L, as shown in Fig. 10. From the data analysis, the slope is approximately –2.5 mV/℃.

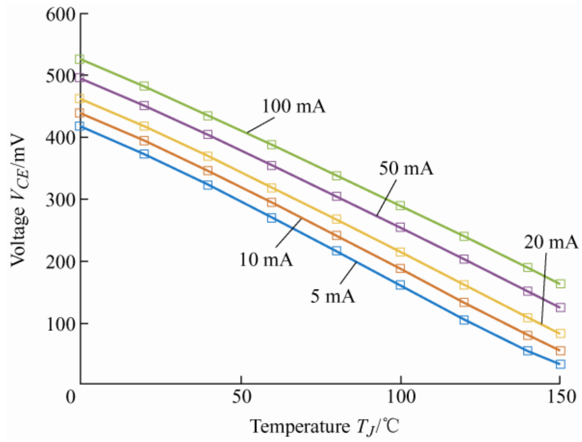


Fig. 10 T_J-V_{CE} relationship at low current injection

3.2 Cooling capability evaluation case

To demonstrate the feasibility of the cooling capability estimation, a comparison test was conducted, as shown in Fig. 11. The inverter was composed of ABB modules (5SNG1000X170300), and its main parameters are listed in Tab. 2. A three-phase RL test bank was used as the load. After estimating the ambient temperature and module rating, the inverter was safely tested using a DC bus voltage of up to 600 V and a peak current of 1 000 A.

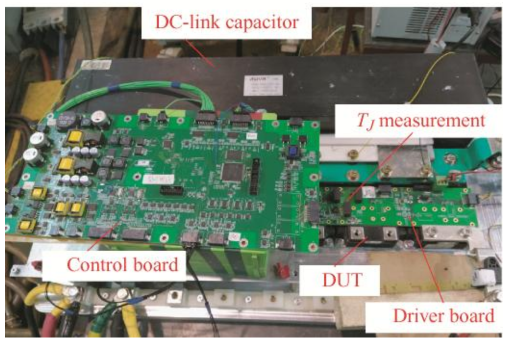


Fig. 11 Cooling capability evaluation experimental platform

Tab. 2 Experimental platform parameters

Parameter	Value
IGBT module	1 700 V/1 000 A
DC-link capacitor	1 200 V/2 500 μF
Load inductor/mH	0.36
Load resistor/mΩ	3
DC-link voltage/V	600
Fundamental frequency/Hz	50
Switching frequency/kHz	1.8-4.5
Flow rate/(L/min)	70

As shown in Fig. 12, a peak current of 900 A was used, and then the inverter was suddenly stopped at 1.5 ms by performing the sudden-stop control sequence. Then, a very low current (6.25 mA) was injected into the IGBT T6 in phase C. The on-state voltage of T6 was measured at a sampling rate of 1.8 kHz.

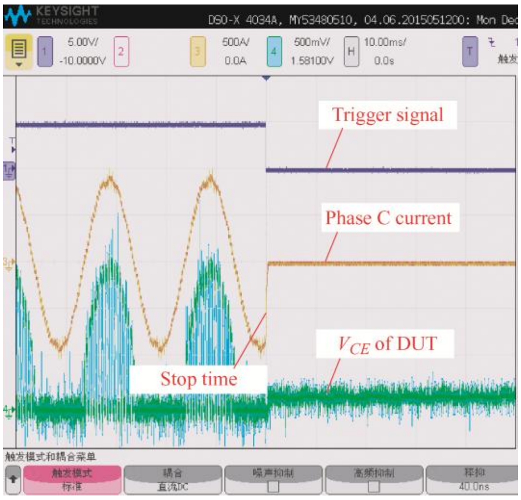


Fig. 12 Sudden-stop process

Fig. 13 shows T_J obtained after the shutdown procedure. T_J at the shutdown moment was calculated by the $\sqrt{t}$ method. Although all other IGBTs were turned off, V_{CE} on T6 was still affected by the noise from the DC side. The V_{CE} noise coupling path is shown in Fig. 14. The on-resistor of the bottom IGBT T6 and the parasitic capacitor of the top IGBT T5 form a high-pass filter. Therefore, the high-frequency noise from the grid side is transmitted to the measuring circuit. It can be eliminated using a digital low-pass filter.

The maximum allowed junction temperature of the IGBT module in the datasheet was 175 ℃. For safe and feasible operation, the average junction temperature was set to 140 ℃. In this experiment, the cooling fluid was water, the maximum flow rate was 70 L/min, and the ambient temperature was limited to 80 ℃. The proposed method was used considering different currents and switching frequencies to evaluate whether the cooling capability satisfied the design requirements. Furthermore, a commonly used thermal impedance method was selected for comparison of the measurements. The results are presented in Tab. 3, where T_F is the fluid temperature, f_Z is the switching frequency, and I_F is the current amplitude. The results of the two methods agree with each other, and their errors are less than 5 ℃. Thus, the proposed cooling capability estimation method shows a good evaluation potential and can be used in future design and development of converters.

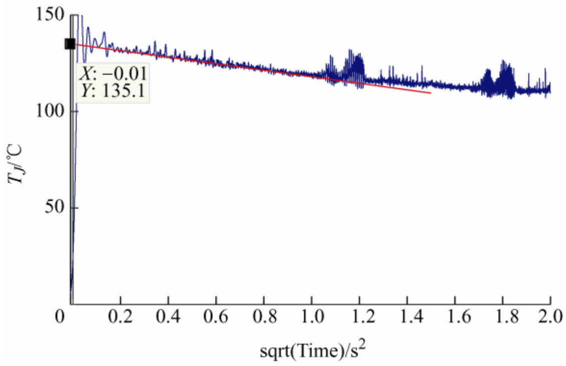


Fig. 13 T_J test value after shutting down

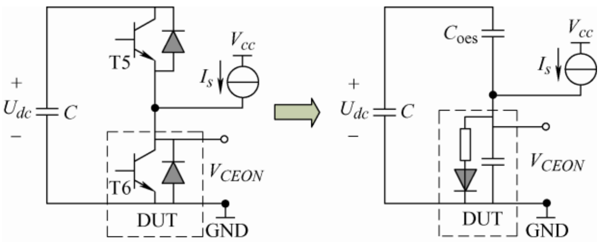


Fig. 14 V_{CE} measurement noise coupling path

Tab. 3 Comparison of temperature monitoring

T_F/℃	f_Z/Hz	I_F/A	T_J/℃	T_J/℃
			Test	Thermal impedance method
80	1.8	1 000	133	131
80	2.5	900	134	132
80	4.5	700	139	136
70	2.5	1 000	130	130
50	4.5	1 000	138	135

4 Summary and conclusion

An offline cooling capability evaluation method for three-phase IGBT inverters was proposed, which can emulate the working conditions of switching-mode devices. A current control sequence was used to stop all heating currents in a short time. Using the conventional method based on the on-state voltage at a low current and a related compensation method, the junction temperature could be accurately calculated to evaluate the cooling capacity of the inverter system. Compared with the traditional method, the proposed method can more accurately represent the actual working condition of the inverter. On the basis of the existing controller, only a simple voltage measuring unit was added, resulting in a low cost, small size, and simple operation. The proposed method can also be utilized in light load and overload conditions, as well as for single-phase inverters. Furthermore, it can be used to validate an online junction temperature monitoring system.

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