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The Switching Characteristic of Igbt

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Abstract: *Since insulator gate bipolar transistor (IGBT) devices emerges, the switching characteristic of IGBT is important in converter performance, efficiency and lifetime improvement. With the development of voltage source converter based high voltage direct current (VSC-HVDC) technology to high voltage rating and high power capacity, the converter value and hybrid direct current breaker have put forward higher requirements on IGBT package feature and electrical performance. Compared with the solder plastic IGBT modules, the press-pack IGBT modules is the preferred device of VSC-HVDC which feature faster switching speed, high power density, double sided heat dissipation and more easily to be connected in series. Based on the dual pulse test principle, the paper designed a test platform of switching performance for press-pack IGBT modules. The effects of the different external mechanical mounting force, load parameters and junction temperature on switching performance across to the test results are analyzed. Then we discussed preliminarily variation mechanism of switching performance for press-pack IGBT from the view of module`s package feature and semiconductor knowledge in order to provide preference for using and popularizing in the high power conversion field*.

Keyword: *press-pack IGBT, double pulse test, switching performance*

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Since the 21st century, with the increasingly prominent problems such as energy shortages and environmental pollution, the demand for new technology of large-scaled clean power transmission,wide area power supply and demand balance and high-capacity, and high-efficient and large-capacity flow have emerge one after another, giving birth to the transformation of transmission methods. The VSC-HVDC technology based on voltage source converter and IGBT is widely used in renewable energy grid connection, island power supply, urban center power supply, and large-capacity and long-distance power grid interconnection, etc.,because of more flexible operation mode and better controllability. And it continues to develop toward high voltage levels and greater system capacity.

Converter values and hybrid DC circuit breaker, which are key devices for flexible DC transmission technologies, place high requirements on the packing characteristics and electrical performance of high-power IGBT devices [6]. In the soldered IGBT module package design, the bonding wires are used to achieve the electrical connection between the internal chip and the external circuit, making the bonding wire the most vulnerable part of the solderingIGBT module and limiting the increase in the power level of the IGBT module [8].The press-pack IGBT modules are similar to IGCT package designs. They have no bonding wire and feature low thermal resistance and small spurious parameters. So they are suitable for power conversion application with high power levels and faster switching speeds. The press-pack IGBT modules has a short-circuit pass-through failure mode, which is an ideal device for series connection of power modules and is a core component of the hybrid DC circuit breaker.

At present, multinational companies such as ABB, Toshiba, and Westcode have successively introduced press-pack IGBT modules. University and research institutes at home and abroad have conducted preliminary tests and analysis of crimped IGBT modules.In this paper, ABB`s StakPak-type press-pack IGBT module is taken an the research object, and a test of double-pulse measurement is built. The test platform focused on the influence of external mechanical mounting force, load parameters and junction temperature on switching performance.Then we discussed preliminarily variation mechanism of switching performance for press-pack IGBT from the view of module`s package feature and semiconductor knowledge.

I. PRESS-PACK IGBT MODULES DUAL PULSE TEST PLATFORM

1.1 Test platform introduction

The object of this paper is ABB's StakPak IGBT module, model 5SNA 2000K451300. Based on the electrical parameters and package characteristics of the module, designed Crimp type IGBT double pulse test circuit as shown in Figure 1.

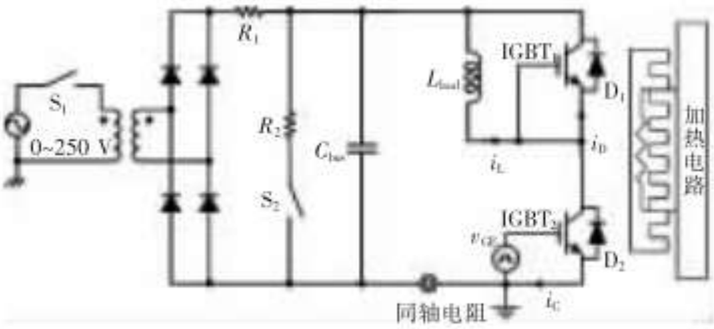


Figure 1 circuit of double-pulse test platform

The double-pulse test circuit is divided into a charge-discharge circuit and a half-bridge circuit with an inductive load.The input power of the charge and discharge circuit is a single phase 0~250 V adjustable AC source, and the step-up transformer ratio is 1:13.$S_1$is the charging relay switch, S_2 is the discharging relay switch, R_1 is the charging current limiting resistor with resistance of 5 kΩ and power of 500 W, and R_2 is the resistance of two resistances with 5 kΩ and power of 500 W in series.The bus capacitance of the half-bridge circuit consists of 15 1.3 kV/1.8 mF film capacitors in the form of 5 strings of 3 parallels. Each capacitor is connected in parallel with 3 200 kΩ resistors with a power of 5 W as the voltage equalization resistor.Test circuit hardware parameters are shown in Table 1.

Tab.1 Parameters of double-pulse test platform

Main Components	Parameters
Bus capacitance	6.5kV/1.08mF
Absorption capacitance	6kV/8uF
Capacitance pressure balance resistor	67kΩ/15W
Transformer ratio	1:13
Charging current limiting resistor	5kΩ/500W
Discharge leakage resistance	10kΩ/1 000W
Load inductance	100~200uH

In the half bridge test circuit, the gate of $IGBT_1$ is short-circuited, the anti-parallel diode is used as the freewheeling diode, and $IGBT_2$ is used as the device under test. The collector-emitter voltage v_{ce} is measured by a differential probe, and the collector current i_c is determined by coaxial resistance measured.This coaxial resistor model is 1M-2 with a 200 MHz bandwidth and high linearity.The maximum number of joules is 125 J. The detailed parameters are shown in Table 2.

Tab.2 Parameters of coaxial resistor

Model	Bandwidth/MHz	Rise time/ns	Resistor/Ω	J_{max}
1M-2	200	2	0.01	125

Both the $IGBT_1$ and the $IGBT_2$ are crimped together at intervals with the heating plate. The size of the crimping force is controlled by an external hydraulic press.The heating plate uniformly heats the IGBT module and maintains a stable temperature to change the test junction temperature.The structure of the pressure-bonded IGBT double-pulse test platform is shown in Figure 2.

Fig.2 Press-pack IGBT test platform

1.2 Dual pulse test principle

The timing waveform of the double-pulse test circuit is shown in Figure 3.The waveforms include the gate drive voltage v_{GE}, the load current i_L, the collector-emitter voltage v_{CE} of the device under test, the collector current i_C, and the freewheeling diode current i_D.Before the experiment started, the AC source was rectified by the diode rectifier bridge after the step-up transformer. After charging the current limiting resistor R_1, the bus capacitor was charged. After the bus voltage reached the set test voltage V_1, S_1 was disconnected. Remember that this time is t_0, at this moment, the $IGBT_2$ of the device under test is turned on, and the bus line capacitor discharges $IGBT_2$ through the load inductanceL_{Load} .After the time ΔT_1, i_C reaches the set test current value I_1, $IGBT_2$turns off. Remember that this time is t_1 and the voltage and current waveforms of the $IGBT_2$ turn-off process are obtained. After t_1, the load inductance continues to flow through diode D_2, and after a time ΔT_2 , $IGBT_2$ turns on again. Since ΔT_2 is very short and the load inductance is large, it can be assumed that the currents I_1 and I_2 of the $IGBT_2$ are turned off and on at the two moments. This is t_2 and the voltage and current waveforms during the on-time of the $IGBT_2$ are obtained.After ΔT_3 to t_3, $IGBT_2$ turns off again, and the load inductance continues to freewheel by diode D_1 until the load inductor current drops to zero.At the same time, the discharge relay S_2 is closed and the bus capacitor discharges through R_2 until the voltage is 0 and the test is completed[13].

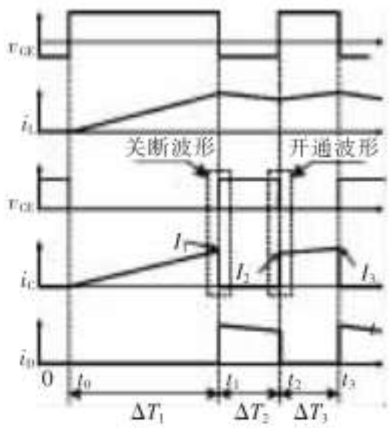


Fig.3 Sequential signal of double-pulse test

1.3 Switching waveforms of pressure-pack IGBT modules in typical conditions

At bus voltage 2 000 V, collector current 1 000 A, crimp force 40 kN, and junction temperature 25°C, the key waveforms for the off and on times were measured, as shown in Figure 4, including v_{GE}, v_{CE},i_C and switching loss power P_{off} /P_{on} .Unlike the ideal turn-off and turn-on waveforms in Figure 3, due to stray inductance [14] in the turn-off process, the voltage v_{CE} has a turn-off overshoot, and the overshoot ratio is approximately 20%; During the IGBT on-time, the reverse recovery current of the freewheeling diode is superimposed on the collector current, and the current overshoot is about 1.5 times the collector current to be measured.At the same time, due to non-ideal switching of IGBT devices, the voltage and current waveforms partially overlap, and the two are multiplied together to generate switching power losses. If they are time-integrated, the amount of IGBT losses during turn-on or turn-off can be calculated.

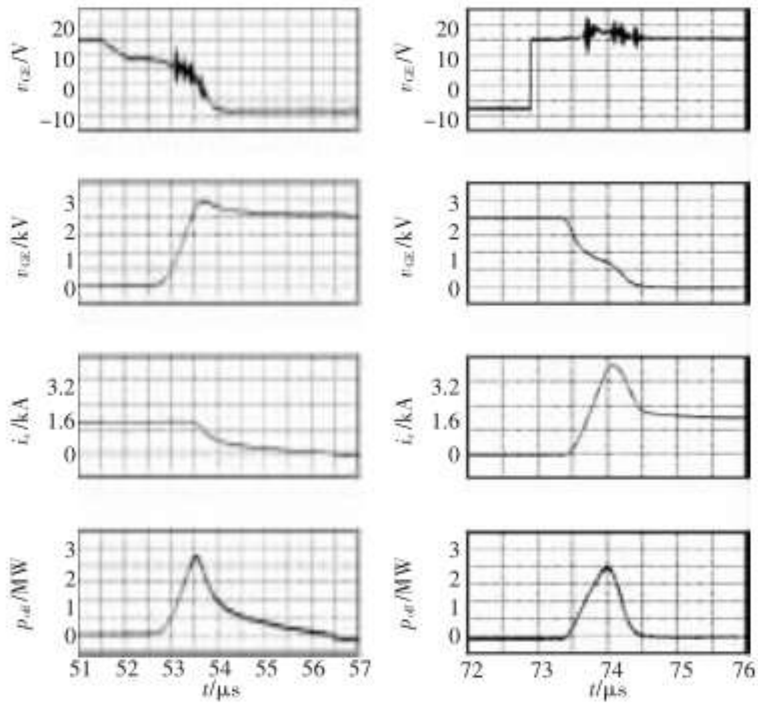


Fig.4 Switching waveforms in typical working condition

With reference to the definition of the IGBT switch characteristic parameters in the international standard IEC 60747-9, by changing the test parameters, the corresponding switch characteristics are extracted to analyze the impact mechanism of the mechanical crimping force, load parameters and junction temperature on the switch characteristics of the crimped IGBT.

II. EFFECT OF MECHANICAL CRIMP ON SWITCHING CHARACTERISTICS OF MODULE

Press-pack IGBT modules require a mechanical crimp force during the installation process to ensure proper module usage [15-16].The test module's requirement for the crimping force is between 60~75 kN, and the crimped surface should be guaranteed to be smooth and even.The actual crimping device is easily deformed under high mechanical stress, so that the module is not stressed uniformly.At the same time, due to the effects of thermal expansion and contraction, when the external ambient temperature or the internal junction temperature of the module changes, the mechanical stress of the crimping device also changes, which in turn affects the force of the module.To study the relationship between the mechanical stress and the switching characteristics of the module, under the working conditions of bus voltage 2 000 V and load current 1 000 A, the influence of mechanical pressure on the switching characteristic parameters was tested and analyzed.The experimental results are shown in Table 3.

Tab.3 Switching parameters of press-pack IGBT module with variable mounting forces and temperatures

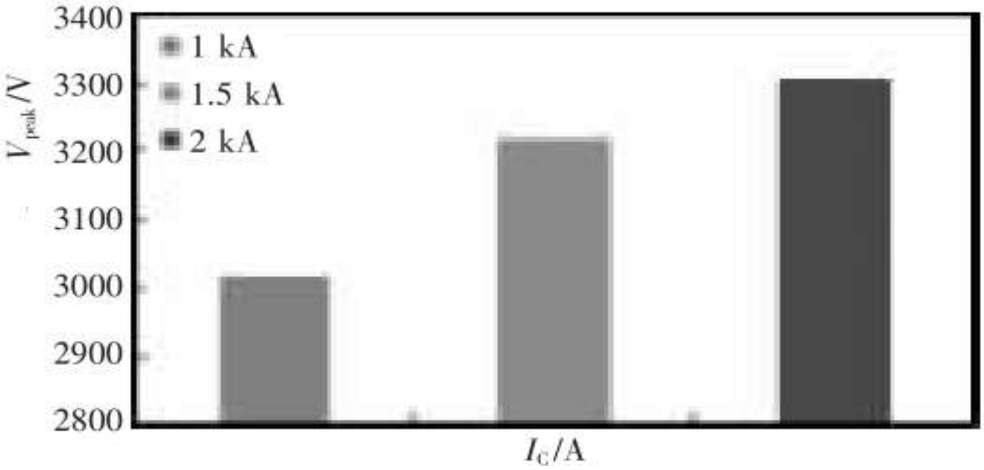
T_{jt}/℃	P/kN	V_{PEAK}/N	I_{PEAK}/N	t_{on}/ns	t_{off}/ns	E_{on}/mJ	E_{off}/mJ
25	30	2500	2900	786	4016.4	1053.7	1489.9
	40	2500	2910	783	4015.3	1061.4	1491.8
	50	2510	2910	782	4012.0	1064.2	1503.1
125	30	2440	3030	750	4162.4	1745.7	2111.4
	40	2430	3020	754	4155.2	1755.2	2113.0
	50	2430	3020	754	4151.0	1771.3	2131.5

From the data in Table 3, it can be seen that when the temperature, bus voltage, and load current are constant, the switching characteristic parameters of the pressure-bonded IGBT module change very little by changing the mechanical pressure. The difference between the values of the same switch characteristics under different crimping forces is within 5%.According to the internal structure of the StakPak type IGBT module[17], the collector and emitter of the module are electrically connected by a crimping pin made of a copper sheet, and the inside of the crimping pin is a disc spring subjected to a crimping force.Therefore, there is no obvious coupling relationship between the switching characteristics of this type of pressure-bonded IGBT module and the mechanical crimping force of the module.In order to ensure that the IGBT module under test meets the basic requirements, the module withstand pressure is maintained at 50 kN in subsequent experiments.

III. EFFECT OF LOAD PARAMETERS ON SWITCHING CHARACTERISTICS OF MODULES

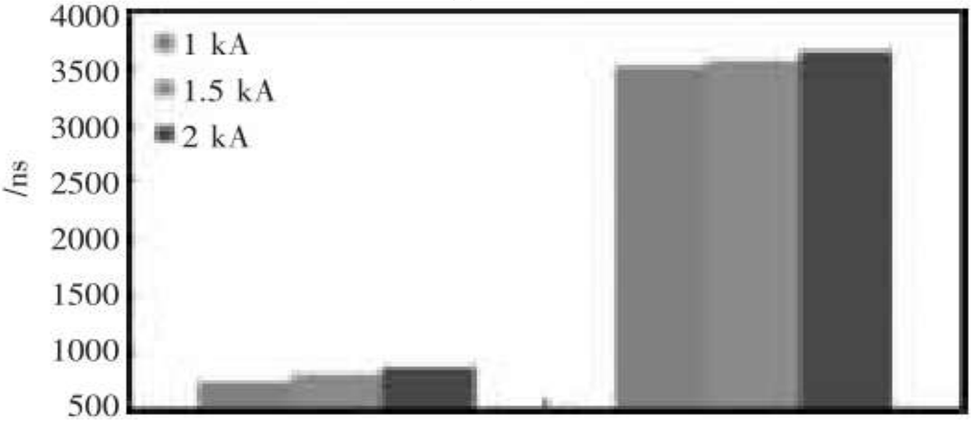
The drive resistance R_G used in this article is 1.8 Ω. When the driving parameters are fixed, the influence of the changes in bus voltage and load current on the switching characteristics of the module is mainly studied.

Figure 5 shows the influence of the change in load current (1 kA, 1.5 kA, and 2 kA) on the switching characteristics at a junction temperature of 25°C and a bus voltage of 2 500 V.As can be seen from Figure 5, the peak turn-off voltage, turn-on/turn-off time, and rate of change of the turn-on/turn-off current are all positively correlated with current.This is due to the fact that when the operating voltage and junction temperature are fixed, the collector current determines the number of minority cells accumulated in the drift region during forward conduction. When the collector current increases, the number of accumulated minor ions increases, making the turn-on and turn-off times longer.The increase in the collector current also increases the current density in the carrier extraction region [18], which increases the rate of change of the turn-on and turn-off currents.With the increase in the rate of change of the off current and the parasitic inductance of the loop, the peak value of the off voltage experienced by the module is also increased.Figure 6 shows the effect of the bus voltage (1 kV, 1.5 kV, 2 kV) at a junction temperature of 25°C and a load current of 1 000 A on the switching characteristics.The difference from the situation in Fig. 5 is that as the bus voltage rises, not all switching characteristic parameters increase, and the turn-on time decreases.From the semiconductor physics level analysis, when the bus voltage rises, the carrier concentration at the edge of the carrier extraction region becomes higher [18], which increases the rate of change of the current at the time of turn-on and increases the peak value of the turn-on current at the time of reverse recovery.But it also speeds up the extraction of carriers, making the turn-on time smaller.



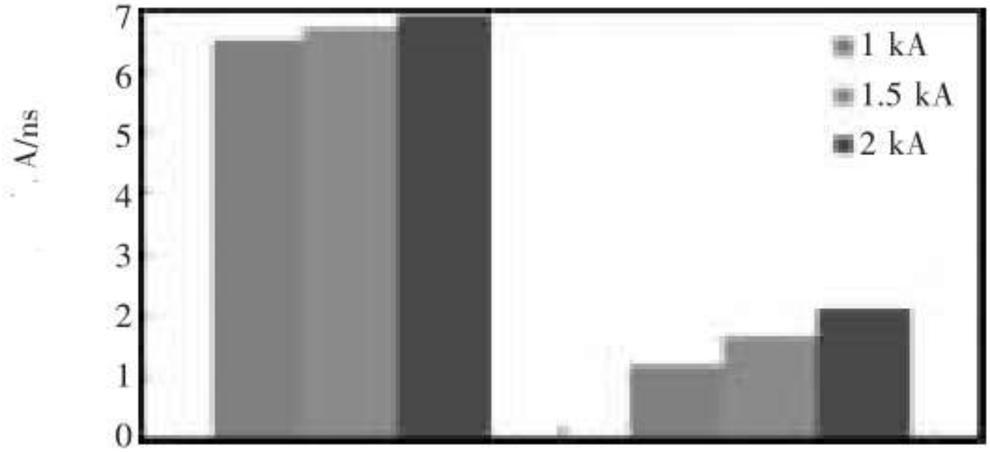
(a) Turn-on voltage peak comparison

(b)



Turn-ontime turn-off time

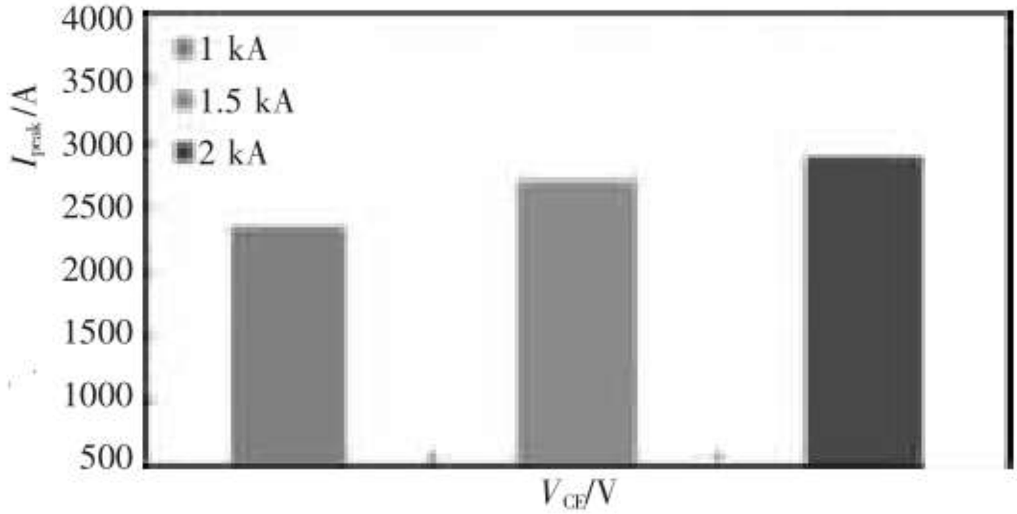
(c) Turn-on or turn-off time comparison



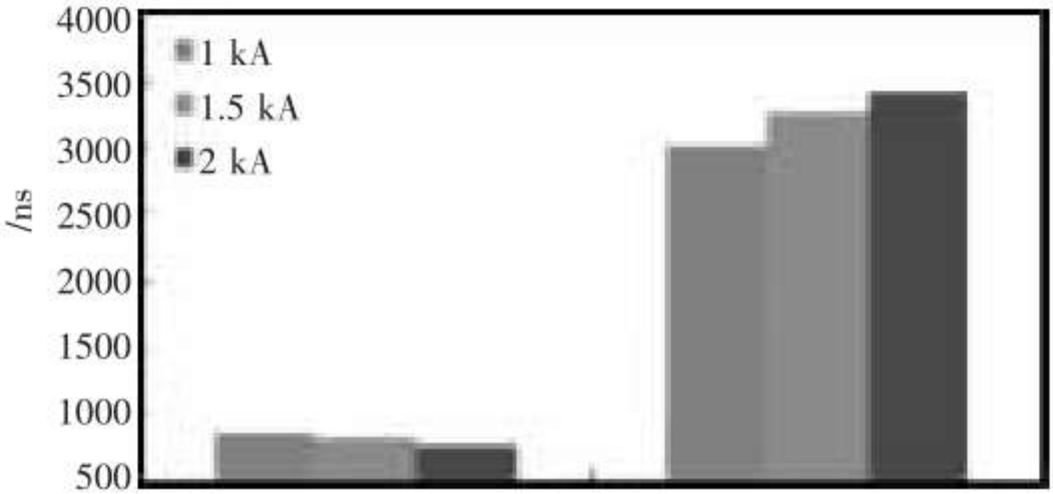
turn-on current turn-off current

(d) Comparison of current change rate

Fig.5 Switching parameters of press-pack IGBT module with variable load current at 25°C /2 500 V

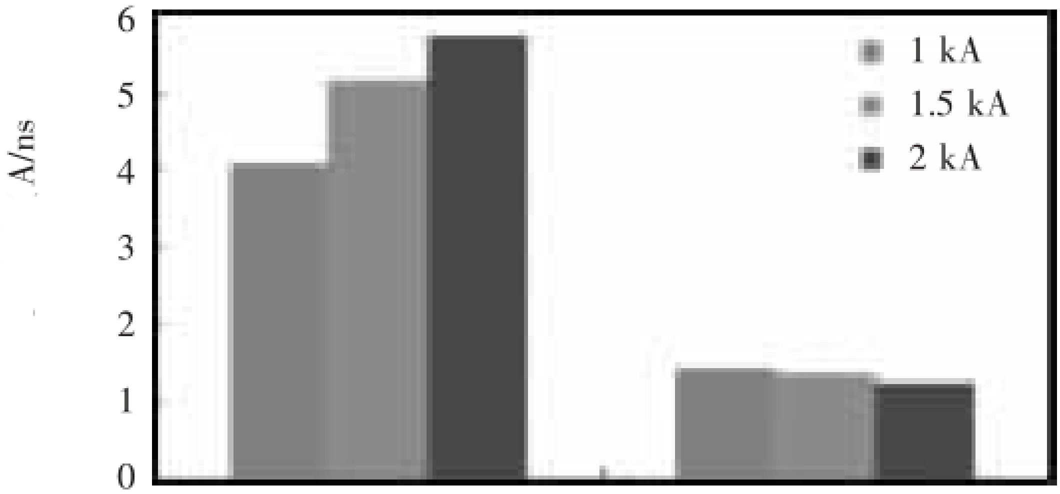


(a) Turn-on current peak comparison



turn-on time turn-off time

(b) Turn-on or turn-off time comparison



turn-on currentturn-off current

(c) Comparison of current change rate

Fig.6 Switching parameters of press-pack IGBT module with variable bus voltage at 25°C /1 000 A

IV. EFFECT OF JUNCTION TEMPERATURE ON SWITCHING CHARACTERISTICS OF MODULE

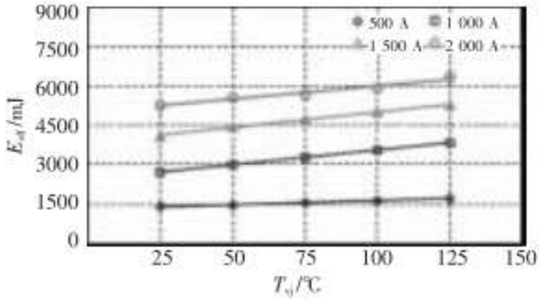
In the practical application of IGBT modules, the junction temperature of IGBT modules is constantly changing due to the self-heating effect of high-frequency on-off switching of the chip and the change of the external environment.The working nature of the IGBT module is the carrier transport, which is closely related to the carrier mobility and lifetime. The junction temperature has a direct impact on the carrier mobility and lifetime.Therefore, in order to analyze the relationship between switching characteristics of the module and the junction temperature, the switching characteristic parameters of the pressure-coupled IGBT module at different temperatures T_{vj} (25°C, 50°C, 75°C, 100°C, 125°C) are tested.The results are shown in Figure 7 and Figure 8, respectively.

From Fig. 7 (a), (b) and Fig. 8 (a) and (b), when the load parameters are constant, the turn-off loss E off and turn-on loss E on increase as the junction temperature rises.The increase of the switching loss will further promote the rise of the junction temperature and form a positive feedback of thermal effect.This shows that as the junction temperature rises, the module's trajectory moves closer and may even exceed its safe operating area (SOA).

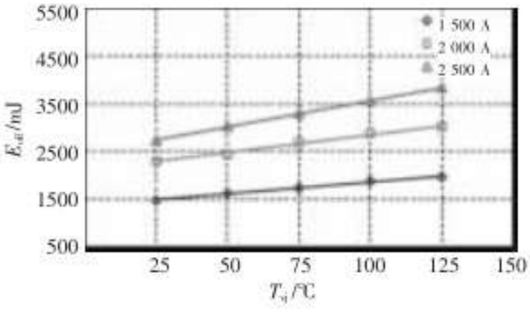
From Fig. 7 (c) and Fig. 8 (c), it can be seen that with the rise of the junction temperature, the module turn-off delay time increases because the Miller capacitance C_{gc} of the IGBT and the Miller plateau voltage u_{gp} are influenced by the junction temperature change. The turn off delay time t_{doff} and the relationship between the two[19] are expressed as

$$t_{doff} = R_g\left(C_{ge} + C_{gc}\right)\ln\left(\frac{U_{gon}}{U_{gp}}\right) + \frac{R_g C_{gc}\left(U_{dc} - U_{gon}\right)}{U_{gp}}$$

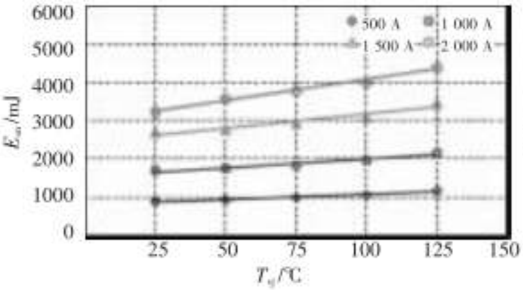
The change of the junction temperature mainly affects the Miller capacitance C_{gc}, the Miller plateau voltage u_{gp}, and the turn-on voltage u_{on}. Since the bus voltage u_{dc} is much larger than the turn-on voltage u_{on}, the junction temperature has a negligible effect on the turn-on voltage.When the junction temperature rises, the Miller capacitance C_{gc} increases and the Miller plateau voltage u_{gp} decreases, both of which make the turn-off delay time t_{doff} increase.Therefore, when the load parameters are constant, the turn-off delay time is positively correlated with the junction temperature.

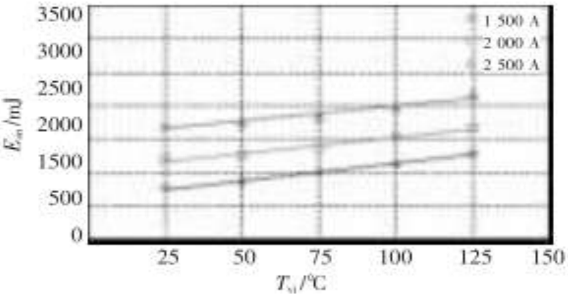


(a)turn-off loss

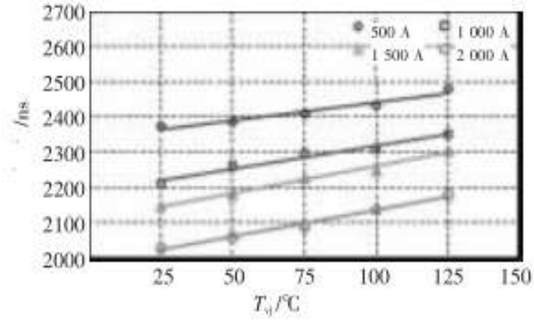


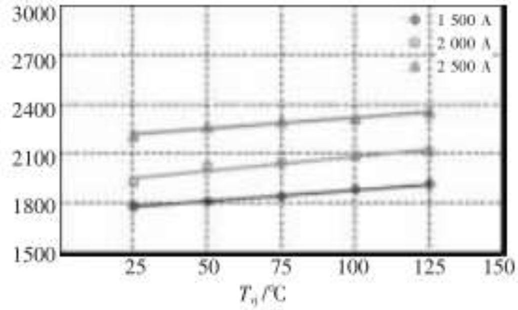
(a)turn-off loss



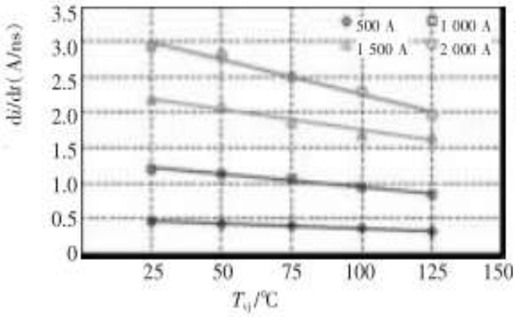


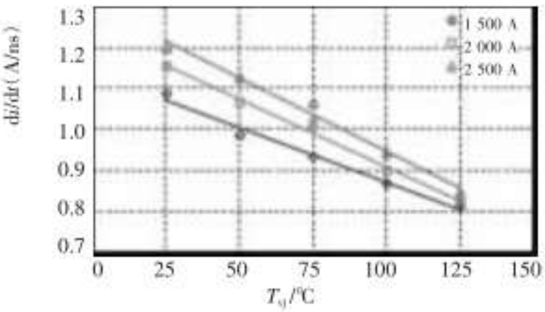
(b)turn-on loss (b)turn-on loss



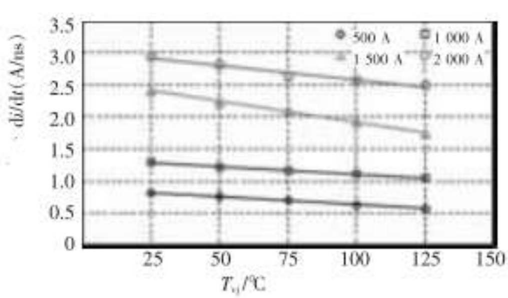


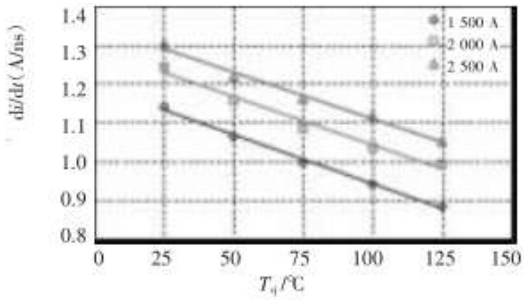
(c)turn-off delay time (c)turn-off delay time





(d)current change rate at turn-off time(d)current change rate at turn-off time





(d)current change rate at turn-on time(d)current change rate at turn-on time

Fig.8 Switching parameters of press-pack IGBT module in 2 500 A **Fig.8 Switching parameters of press-pack IGBT module in 1 000 A**

From Fig. 7(d) and Fig. 8(d), it can be seen that the maximum current change rate of the module at the moment of turning off decreases as the junction temperature increases.When the junction temperature of the module increases, the carrier diffusion coefficient inside the device will decrease, making the current change rate at the initial time of turn-off slow, and the current change rate at the initial time of turn-off is the maximum change rate of the current at turn-off time.Therefore, the maximum change rate of the module shutdown current decreases as the junction temperature increases.

From Fig. 7(e) and Fig. 8(e), it can be concluded that the maximum rate of change of current at the time of turn-on is negatively related to the junction temperature.The maximum change rate of current at the moment of turn-on is the maximum change rate of reverse recovery current.When the junction temperature increases, the carrier lifetime increases, the reverse recovery storage charge increases, and the reverse recovery softness increases, causing the current change rate to decrease at the time of reverse recovery [20].Therefore, the maximum rate of current change at the moment of module on-off decreases as the junction temperature increases.

V. CONCLUSION

This article takes ABB's StakPak type press-pack IGBT module as the research object, designs and builds a switching characteristic test platform based on the double pulse principle.On the basis of this platform, the switch characteristics of the press-pack IGBT module were tested, and the influence of the mechanical crimping force, load parameters, and junction temperature on the switching characteristics of the press-pack IGBT module was analyzed.Studies have shown that the special package design of the StakPakpress-pack IGBT module does not have a direct coupling relationship between the mechanical crimping force and the switching characteristics of the module;At the same time, the influence rules of load parameters and junction temperature on the switching characteristics and safe operating conditions of the module are also obtained, and the switching characteristics of the module are analyzed from the physical level of the semiconductor device.This paper provides a reference for the future more efficient and safer application of press-pack IGBT modules in flexible HVDC transmission technology.

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