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A new method to extract stray inductance in IGBTs' Dynamic testing platform

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Abstract: Stray inductance in IGBTs' dynamic testing platform has great influence on switching characteristics, such as switching speed, switching loss, voltage overshoot, and so on. Conventional methods are analyzed in this paper, which cannot extract stray inductance accurately due to existence of resistance in power stage current path. A new method is proposed in this paper to extract stray inductance based on turn-off transient waveform and a following turn-on transient waveform. In this method, it is assumed that capacitor voltage and load current are constants during turn-off transient and the following turn-on transient, and then the stray inductance is extracted accurately by using gradients of both turn-off current and turn-on current at a given current value. The new method eliminates the influence of resistance in current path. To verify the proposed method, circuit simulation is carried out by using Synopsys Saber; furthermore, an IGBT dynamic testing platform is developed, stray inductance of the testing platform is extracted under different voltage levels. Simulation and measurement results prove the effectiveness of the new method. Insulated gate bipolar transistors, electronic equipment testing, inductance measurement

1. Introduction

INsulated Gate Bipolar Transistors (IGBTs) are increasingly used in the transmission and distribution field due to advantageous features of high power cycling, high thermal capability and especially suited for series connection[1]-[3]. New designed IGBT modules have to be tested, which helps to make a comprehensive understanding of dynamic switching characteristics of IGBTs under different working conditions . Hence, a dynamic testing platform is needed to evaluate the dynamic characteristics of IGBTs[4].

Stray inductance of dynamic testing platform is a key factor that affects dynamic characteristics of IGBTs [5]-[6]. Thus, Dynamic parameters of IGBT are tested with a special dynamic testing platform, and the stray inductance of the testing platform is always specified. For instance, datasheets of IGBTs which produced by Westcode Corporation indicate that dynamic parameters are extracted under specified condition; the stray inductance of dynamic testing platform is 200nH. Meanwhile, datasheets of StakPak IGBT of ABB Corporation also specify that the stray inductance of dynamic testing platform is 200nH.

Parasitic inductances of IGBT dynamic testing platform exist in power device modules, capacitor, copper interconnects, and busbars, etc. Much research effort has been reported on methods of extracting stray inductances and these methods can be divided into two categories. One is to extract parasitic inductance of each component separately by using mathematical computation or simulation approaches, which is based on three-dimensional (3-D) finite element analysis[7]-[9] or partial element equivalent circuit (PEEC) method [10]-[13]. In addition, parasitic inductance of each part can be extracted by impedance analyzer [14]-[15], time domain reflectometry [16] or by using an extra oscillating circuit [17]. However, methods mentioned above can extract parasitic inductance of each part accurately, but mutual inductance between each part is not mentioned. Hence, extracting separately is inappropriate in identify total stray inductance of testing platform.

2. Stray inductance calculation based on conventional method

Fig. 1 shows the schematic circuit of dynamic testing platform. Stray inductance is extracted by using voltage and current waveforms of turn-off and turn-on. DUT (Device under Test) in Fig. 1 is Press Pack IGBT under test, Diode is freewheeling diode.

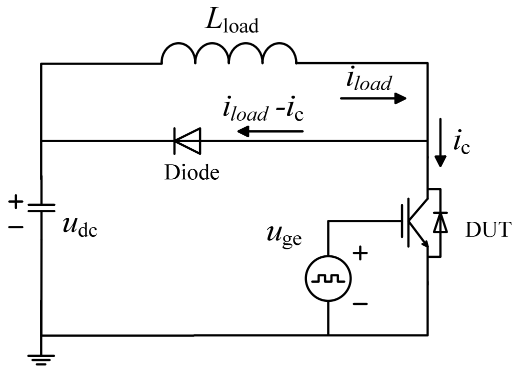

Fig.1 Schematic of test circuit

2.1 Method 1

Stray inductance in current path can be calculated by using turn-off waveforms. Figure 2 shows the turn-off waveforms of IGBT. In the turn-off transient of IGBT, free-wheeling diode is in big current forward bias, and then the voltage drop of diode can be ignored. Hence, the voltage of IGBT is described as

$$u_{ce} - u_{dc} = L_s \cdot \mathrm{d}i_c / \mathrm{d}t\text{-}i_c R_s \tag{1}$$

where Rs is the loop resistance in current path. If the value of loop resistance is negligible, then the stray inductance is

$$L_s = \frac{u_{ce}\text{-}u_{dc}}{\mathrm{d}i_c / \mathrm{d}t} \tag{2}$$

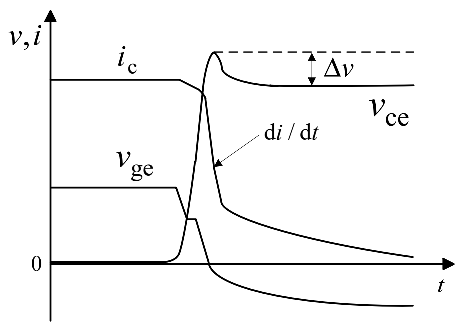

Fig.2 Turn-off waveforms of IGBT

2.2 Method 2

Stray inductance of power circuit can be calculated by using turn-on waveforms. Figure 3(a) shows the turn-on waveforms of IGBT; figure 3(b) shows the reverse recovery of freewheeling diode. Similarly, diode is operation in the big current forward bias when collector current is lower than load current.

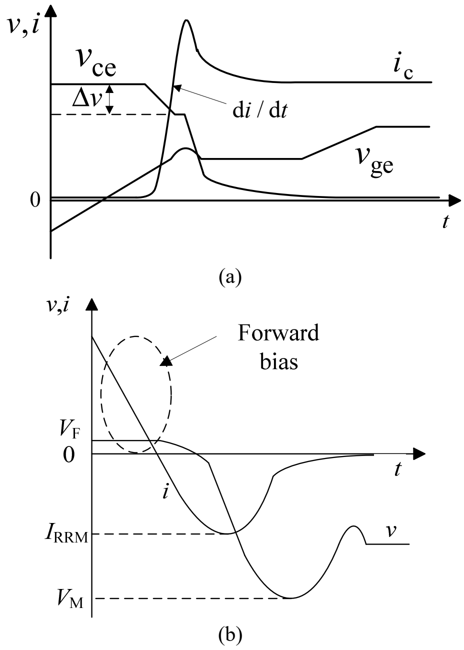

Fig.3 Switching waveforms during turn-on transient. (a)turn-off waveforms of IGBT. (b) Reverse recovery of free-wheeling diode.

From figure 3(a), the collector-emitter voltage of IGBT can described as

$$u_{\mathrm{dc}} - u_{\mathrm{ce}} = L_{\mathrm{s}} \cdot \mathrm{d}i_{\mathrm{c}} / \mathrm{d}t + i_{\mathrm{c}} R_{\mathrm{s}} \tag{3}$$

Also, if the resistor is negligible, then

$$L_{\mathrm{s}} = \frac{u_{\mathrm{dc}} - u_{\mathrm{ce}}}{\mathrm{d}i_{\mathrm{c}} / \mathrm{d}t} \tag{4}$$

Through these methods, one can calculate the stray inductance by measuring only capacitor voltage, collector-emitter voltage and the collector current of DUT. However, limitation of this method is that impacts of loop resistance is ignored, causing a certain degree of error as a result.

3. Extraction of stray inductance based on experiment

3.1 Circuit analysis of dynamic testing platform

Freewheeling diode can be simplified as series of a voltage source, a resistance and an inductance, the equivalent circuit of dynamic testing platform is depicted in Fig. 4. As shown in Fig. 4, Udc is the no-load voltage of capacitor, rc is the parasitic resistance of capacitor, Lc is the parasitic inductance of capacitor and bus bar. Lload is the load inductance; r1 and L1 are the resistance and inductance of copper interconnects between bus bar and anode terminal of freewheeling diode. Ubi is forward threshold voltage of pin diode, rd is equivalent resistance of diode, Ld is parasitic inductance inside diode module; r2 and L2 are resistance and inductance of copper interconnects between cathode terminal of freewheeling diode and collector terminal of IGBT. Current ic is collector current of IGBT under test, Uce is collector-emitter voltage of IGBT, Uge is gate driver output voltage. r3 and L3 are resistance and inductance of copper interconnects between emitter terminal of IGBT and bus bar. re and le are emitter resistance and emitter inductance. Effects of mutual inductance between the various parts

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are all considered in the inductance of each copper interconnects. Then, voltage drop of each component in equivalent circuit during switching performance is depicted in Fig. 5.

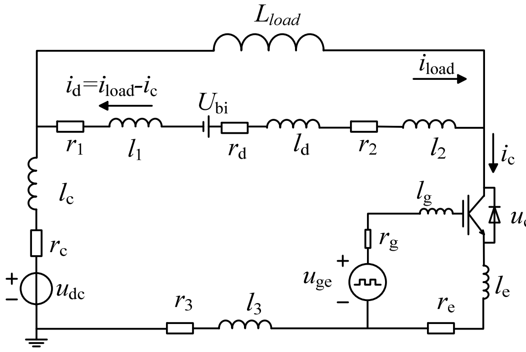


Fig. 4 Equivalent circuit of dynamic testing platform

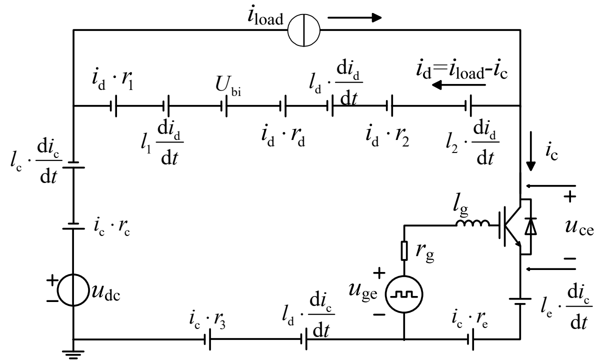


Fig. 5 Voltage distribution in dynamic testing platform

Now according Kirchhoff's law, the following equations are always true whether DUT is turning on or turning off

$$u_{dc} + (l_d + l_1 + l_2) \times \frac{di_d}{dt} + i_d (r_1 + r_2 + r_d) + U_{bi}$$
$$= u_{ce} + i_c (r_e + r_3 + r_c) + (l_e + l_3 + l_c) \times \frac{di_c}{dt} \quad (5)$$

$$i_c + i_d = i_{load} \quad (6)$$

Designating the stray inductance of dynamic testing platform is

$$L_s = l_d + l_1 + l_2 + l_e + l_3 + l_c \quad (7)$$

$$R_s = r_1 + r_2 + r_3 + r_c + r_d + r_e \quad (8)$$

Then, in the switching off transient of DUT,

$$u_{dcf} + i_{off} (r_1 + r_2 + r_d) + U_{bi}$$
$$= u_{cef} + i_{cf} R_s - L_s \cdot \frac{di_{cf}}{dt} \quad (9)$$

Meanwhile, in the switching on transient of DUT,

$$u_{dcr} + i_{on} (r_1 + r_2 + r_d) + U_{bi}$$
$$= u_{cer} + i_{cr} R_s + L_s \cdot \frac{di_{cr}}{dt} \quad (10)$$

Specifically, udcf is the no-load voltage of capacitor when collector current of DUT is icf, the collector-emitter voltage is ucef and the load current is ioff in the same time. udcr is the no-load voltage of capacitor when collector current of DUT is icr, ucer is the collector-emitter voltage and ion is the load current at the very same time.

3.2 Novel method to calculate stray inductance of dynamic testing platform

Based on the analysis above, the tray inductance of dynamic testing platform can be calculated accurately by eliminating the impacts of loop resistance.

Switching transient waveforms of voltage and current of DUT are measured, as shown in Fig. 6. Specifically, δt is time interval between two samples on Oscilloscope, t means testing time. Meanwhile, tf is corresponding to the time when collector current of DUT is i0 in turn-off process; tr is corresponding to the time when collector current of DUT is also i0 in turn-on process.

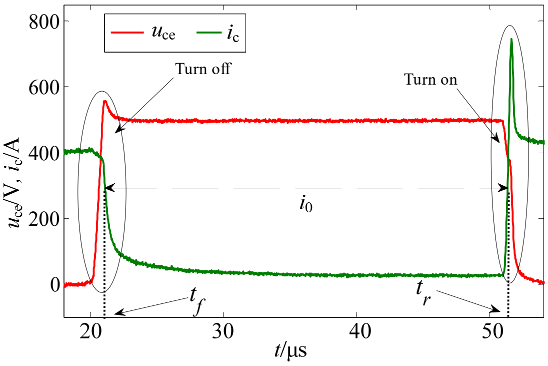


Fig.6 Switching waveforms

Since the load current is constant and the voltage drop of capacitor is negligible, based on the analysis above, it can be summarized that, magnitude of load currents equal at time tr and tf, which means ioff = ion; no-load voltage of capacitor and load current show no change from tr to tf, which means udcf = udcr; then one can calculate the stray inductance by solving (9) and (10)

$$L_s = (U_{cef} - U_{cer}) / \left(\frac{di_{cr}}{dt} + \frac{di_{cf}}{dt} \right) \tag{11}$$

Advantage of this new method is that errors caused by loop resistance are eliminated.

4. Method comparison based on simulation

In this part, conventional method and new method are compared in calculating stray inductance based on circuit simulation.

4.1 Stray inductance extracting based on conventional method

IGBT switching characteristic is analyzed by using Synopsys Saber, model of IGBT derived from 1700V/75A IGBT chip of ABB Corporation; model of freewheeling diode derived from 2500V/108A Fast-Diode chip of ABB Corporation.

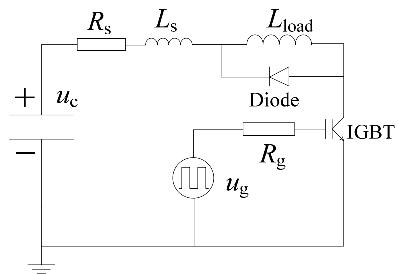


Fig.7 Simulation circuit with resistance

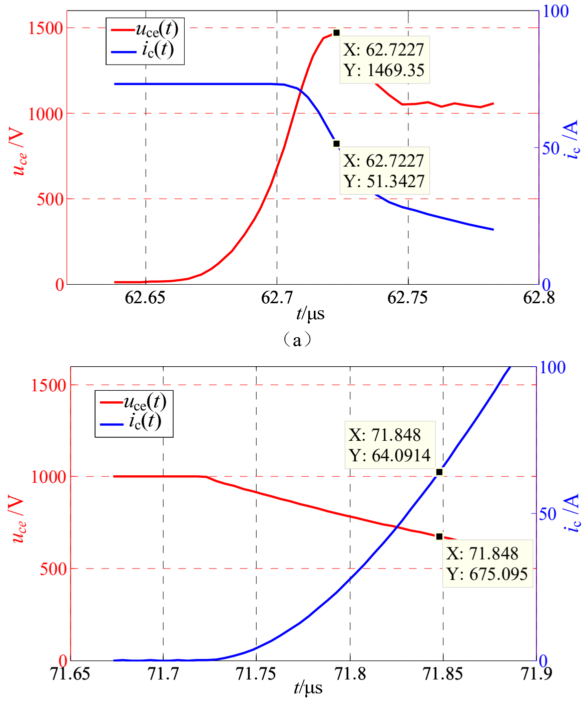


Fig.8 Switching waveforms. (a)turn-off waveforms. (b)turn-on waveforms.

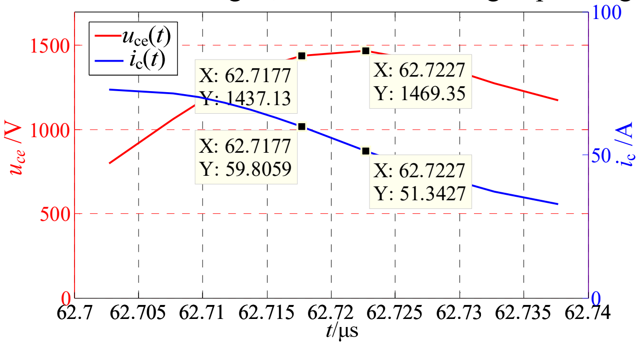
To verify the resistance has a non-negligible impact on stray inductance extracting, a simulation circuit with loop resistance is given in Fig. 7, and the resistance is 1Ω. Simulation results are shown in Fig. 8.

According to the turn-off waveforms in figure 8(a) and equation (2), the stray inductance is calculated to be 293.3nH; while the calculated result is 324.6 nH if using turn-on waveform in figure 8(b) and equation (4).

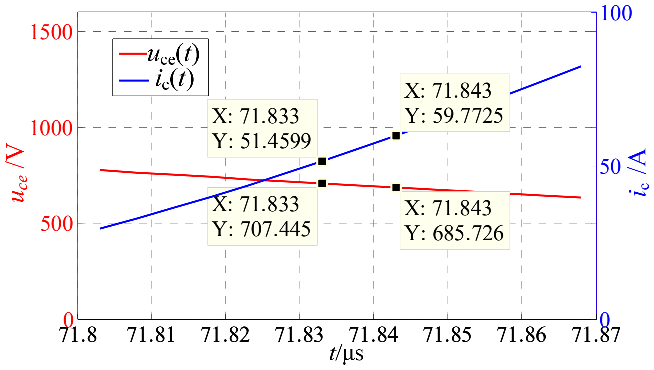
Hence, stray inductance extracted by conventional method shows obvious deviation with true stray inductance when resistance exists in commutation loop. When extracting stray inductance by using turn-off waveform data, the deviation is -2.7%, a negative value indicates the calculated value is less than true value; the deviation is 14.9% when turn-on waveform data is used to extract stray inductance, a positive value indicates the calculated value is larger than true value. Therefore, conventional method has limitation in extracting stray inductance when current path exist resistance and diode.

4.2 Stray inductance extracting based on new method

Simulation circuit is the same as depicted in Fig. 7, software settings keep the same, turn off/on waveforms are also the same as shown in Fig. 9, which is an enlarged partial graphic.



(a)



(b)

Fig.9 Calculation of stray inductance based on switching waveform. (a)turn-off waveforms, (b)turn-on waveforms

When turn-off and turn-on current are both 56A, careful high magnification observation of these switching waveforms are shown in Fig. 9, which also shows the results processed by Synopsys Saber software. When turn-off current is 56 A, collector-emitter voltage is 1451.4 V, current gradient is -1.6907 kA/μs; meanwhile, when turn-on current is 56 A, collector-emitter voltage is 694.72 V, current gradient is 0.83933 kA/μs, then the stray inductance is calculated to be 299.1 nH according (11).

The deviation between calculation result and true value is about 0.3%, which means the method proposed in this paper can accurately extract the stray inductance in the commutation loop.

4.3 Comparison of calculation result based on different methods

Changing the resistance in current path, stray inductance is calculated based on conventional method and new method proposed in this paper. Still, stray inductance in simulation circuit is 300 nH, relative error between calculating results and true value shown in Fig.10, where Lcal is the calculation results and Ltrue is the true value of stray inductance.

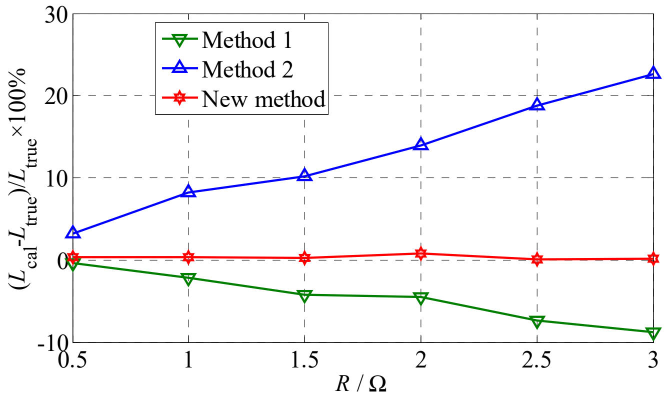


Fig.10 Relative error in calculating stray inductance

The conventional method mentioned above extracts stray inductance based on turn-off waveforms or turn-on waveforms separately. From (1), the calculated results are smaller than the true value, as shown the green line in Fig.10. From (3), the calculated results are larger than the true value, as shown the blue line in Fig.10. Moreover, the smaller of ic/(dic/dt), the smaller the relative error.

According to the simulation results, deviation of calculation results and true value increases along with the increasing loop resistance. While using the method proposed in this paper, deviation almost has no relationship with loop resistance.

Based on the novel method, a testing platform is developed, and stray inductance of IGBTs dynamic testing platform is measured and calculated.

5. Extraction of stray inductance of IGBTs dynamic testing platform

5.1 Dynamic testing platform

An IGBT dynamic testing platform is built based on double pulse method. The device under test(DUT) is T0600TB45A (4.5kV/600A) produced by Westcode Corporation, clamping force is 20kN and relative error is 3%. Experiments are carried out at room temperature, discharge capacitor is a metal film capacitor, and its capacitance is 6000µF. Load inductance is 250µH. Using the diode in IGBT module as a freewheeling diode; the IGBT module is DIM800NSM33-A000 produced by DYNEX.

Testing Oscilloscope is Tektronix DPO4104B, voltage probe for gate voltage measurement is TPP0500, time delay is 5.2ns; high voltage differential probe for collector-emitter voltage measurement is THDP0100, time delay is 16.7ns, current sensor is Rogowski coil, time delay is 30.2ns. All probes have been calibrated before test. Turn-on gate resistance is 8Ω, turn-off gate resistance is 11Ω, and gate voltage pulse interval is 30µs, and the time is long enough to turn off the IGBT completely.

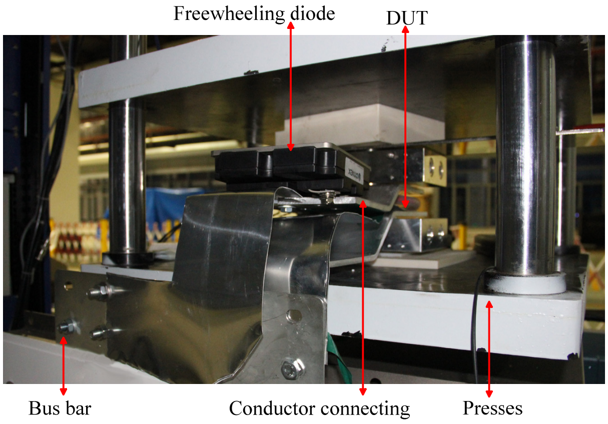


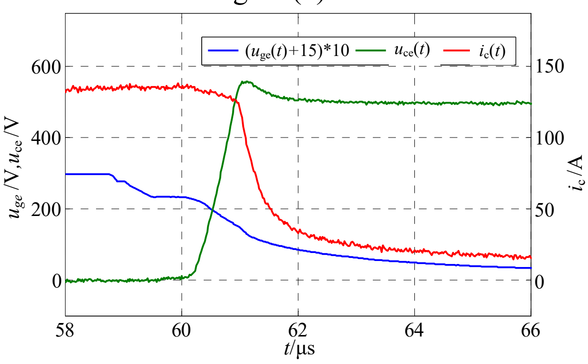
Fig.11 Dynamic test bench for PPIs

5.2 Experiment results

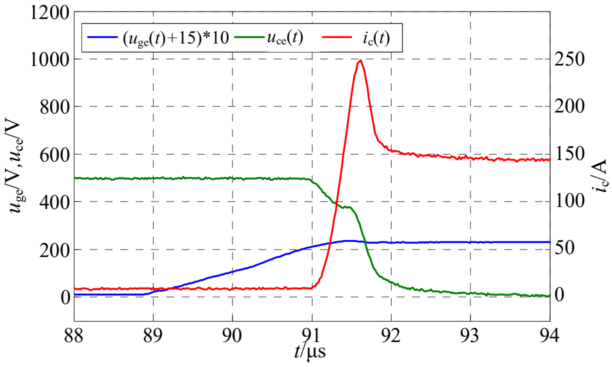
Using the dynamic testing platform as shown in Fig. 11, waveforms are measured in two different voltage levels, since experiment in different voltage offers comparable results; and then the stray inductance is calculated individually.

5.3 Testing voltage 500 V

Gate voltage, collector-emitter voltage and collector current during switching off are shown in Fig. 12(a); switching on waveforms is shown in Fig. 12(b).



(a)



（b）

Fig.12 Switching waveforms of IGBTs. (a) turn-off waveforms, (b) turn-on waveforms

By using curve fitting, when turn-off current of IGBT is 90.5 A, collector current gradient is - 0.179 kA/μs, voltage of collector-emitter is 554.7V. Additionally, when IGBT turn-on current is 90.5 A, collector current gradient is 0.531 kA/μs; voltage of collector-emitter is 394.5 V.

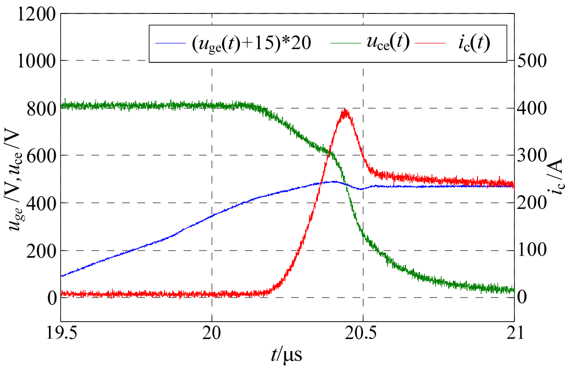
According to conventional method, calculation result of stray inductance of dynamic testing platform is 305.6 nH if using turn-off current waveform and equation (2); or the result is 198.7 nH if using turn-on current waveform and equation (4). Based on the method proposed in this paper, stray inductance is calculated to be 225.6 nH.

5.4 Testing voltage 808 V

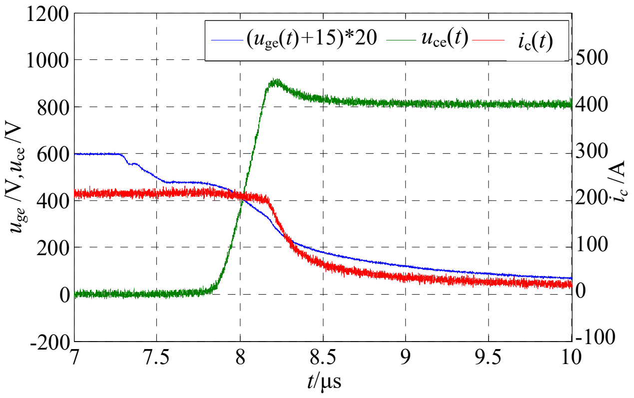
Experimental waveforms are shown in Fig. 13. Based on curve fitting, when turn-off current of IGBT is 105A, current gradient is - 0.1829 kA/μs; at the very same time, voltage of collector-emitter is 863 V.

Additionally, when turn-on current of IGBT is 105A, current gradient is 0.6318 kA/μs; and the collector-emitter voltage is 679 V.

According to conventional method, calculated result of stray inductance is 300.7 nH if using turn-off current waveform and equation (2); or the result is 204.3 nH if using turn-on current waveform and equation (4). Based on the method proposed in this paper, the calculated result is 225.8 nH.



（a）



（b）

Fig.13 Switching waveforms of IGBTs. (a)turn-off waveforms, (b)turn-on waveforms

6. conclusion

Stray inductance in IGBT dynamic testing platform has great influence on dynamic test results of IGBTs. To achieve accurate switching characteristics of IGBT devices, stray inductance must be extracted accurately. Many works have been done to extract stray inductance based on simulation or experiment, but these methods are not accurate in extracting stray inductance of testing platform. Based on circuit analysis of IGBT switching transient, a new method is proposed in this paper to extract stray inductance, which use both turn-off transient waveform and the following turn-on transient waveform. Compared to the conventional method, this method is superior because mutual inductance of each part in testing platform is included and the impact of resistor in current path is excluded. The experimental results show that the stray inductance value extracted does not change along with test voltage level, current level and rate of current change. Thus, the proposed method is effective to extract stray inductance of IGBT dynamic testing platform.

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