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Research of Voltage-Balancing Methods of Series-Connected IGBTs

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Abstract: Voltage-balancing method is the key to the application of series-connected Insulated-Gate Bipolar Transistor(IGBT). In this paper the voltage-balancing process is divided into 4 stages: dynamic turning-on process, dynamic turning-off process, the tail current state and steady state, whose voltage-balancing methods are then proposed respectively: gate compensation capacitor network for dynamic process; resistance capacitance(RC) voltage-balancing circuit designed for tail current state with the capacitance given by a formula; and parallel-connected voltage-balancing resistance for the steady state. Based on the work above, power module of two series-connected IGBTs is designed and tested under high voltage and high current condition. The result shows that under the series total voltage 2kV (1.85kV maximum peak voltage for each IGBT) and 2kA current, the power module balanced the voltage of the whole period of an turning on and off process, and both of the voltage-unbalance-rate of dynamic and steady state are less than 5%.

Keywords: IGBT Series, Power Module, Dynamic Voltage Balancing, Tail Current

1. Introduction

With the development of power electronic technology, high voltage and high power equipments put forward higher request to the IGBT. However, because the structure and material of semiconductor devices, the voltage level of IGBT is the highest in 6.5kV, which cannot reach the voltage level on many occasions in the power system, so IGBT series is an inevitable choice for IGBT high voltage applications. The press pack IGBT has double side heat dissipation, and the current density is higher under the same voltage level, especially for use in series [1-3]. As the speed of IGBT is very fast and the device parameters cannot be completely consistent, voltage balancing is the key to the application of series-connected IGBTs [4-6].

The key reasons of series-connected IGBTs voltage unbalancing are the gate electrode driver signal is not synchronous or the parameter is difference. As shown in Figure 1, with two series-connected IGBTs (Q_1, Q_2) as an example, U_n is the average steady-state voltage of each series-connected IGBTs. You can achieve voltage balancing if each series-connected IGBTs collector emitter voltage changes at the same time and the slope is the same, that is, to minimize Δt_{on}, Δt_{off} and the slope of $\Delta\frac{dv}{dt}\Big|_{Q_1\text{-}Q_2}$ between collector and emitter. The dynamic voltage unbalancing of series devices [7] can be expressed as $\alpha_{off}=\frac{\Delta U_n}{U_n}\times 100\%$.

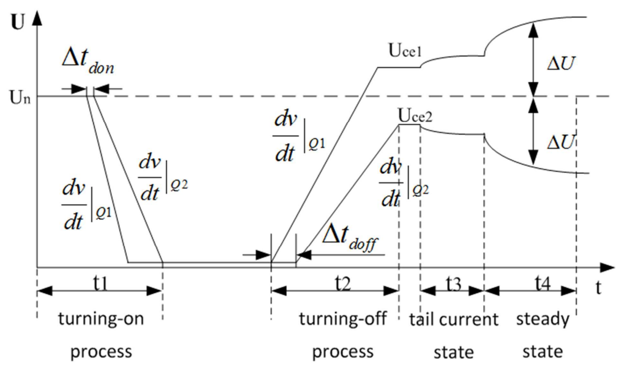


Figure 1. Diagram of voltage unbalance during the whole turning on and off period of IGBT.

As the IGBT series is mainly focused on the dynamic process of turn-off, but not the whole process. The control strategies including the passive buffer circuit [8], gate electrode signal delay control [9], gate electrode synchronous control [10], gate electrode voltage control [11], IGBT gate electrode balanced nuclear complex control circuit [12], IGBT Miller effect control voltage balancing technology [13]. These methods can be divided into active control directly and passive control indirectly. Active controlthrough bya closed-loop feedback control circuitofcollector emitter and gate electrode drive signal, which is complicated and high cost. Passive control through by introduction of RCDbuffer circuit in the peripheral IGBT, but cost greatly and efficiency low in the high frequency.

With the development of digital technology and high-speed optical transmission technology, the difference gate electrode drive between the synchronous signal is further reduced, and IGBT parameters are the main factors to IGBT series voltage balancing. Therefore, a new gate electrode control circuit is required to achieve the series-connected IGBTs voltage balancing.

In this paper the voltage balancing process is divided into 4 stages: dynamic turning-on process, dynamic turning-off process, the tail current state and steady state, whose voltage-balancing methods are then proposed respectively: gate compensation capacitor network for dynamic process; RC voltage-balancing circuit designed for tail current state with the capacitance given by a formula; and parallel-connected voltage-balancing resistance for the steady state. Based on the work above, power module of two series-connected IGBTs is designed and tested under high voltage and high current condition. The result shows that under the series total voltage 2kV (1.85kV maximum peak voltage for each IGBT) and 2kA current, the power module balanced the voltage of the whole period of an turning on and off process, and both of the voltage unbalance-rate of dynamic and steady state are less than 5%.

2. The Voltage Unbalancing Factor of Series IGBT in the Switching Cycle

The voltage unbalancing process of the series-connected IGBTs can be divided into 4 stages in the whole period of a turning on and off process. As shown in Figure 1, the main reason of voltage unbalancing is t_{on} and the down slope of $\frac{dv}{dt}$ are not the same in t_1. The main reason of voltage unbalancing is t_{off} and the rising slope of $\frac{dv}{dt}$ are not the same in t_2.The main reason is RC for the tail current state not the same in t_3. The main reason is leakage current is not consistent for the steady state in t_4.

2.1. Voltage Unbalancing of Dynamic Turning-on Process

The main reason of voltage unbalancing is t_{on} and the down slope of $\frac{dv}{dt}$ are not the same in dynamic turning-on process.

Input capacitance of gate electrode is charged by the driving power supply in the turning-on process, the turning-on time is [14]:

$$t_{\rm don} = R_{\rm gon} \times (C_{\rm ge} + C_{\rm gc}) \times \ln \frac{U_{\rm cc}}{U_{\rm cc} - U_{\rm ge(th)}} \quad (1)$$

To the IGBT and the driver selected, the threshold voltage $U_{ge(th)}$ and the amplitude of the driving power supply U_{cc} can be fixed, so ton is affected by the gate electrode drive resistance R_{gon}, g-e capacitance C_{ge} and g-c capacitance C_{gc} and so on. Then to reduce the difference betweenC_{ge} and C_{gc} of IGBT as soon as possible can ensure t_{don} is basically synchronous.

When the U_{ce} of IGBT rapidly dropped, C_{gc} changed with U_{ce} can be approximate equivalent as shown in Figure 2 below [15]:

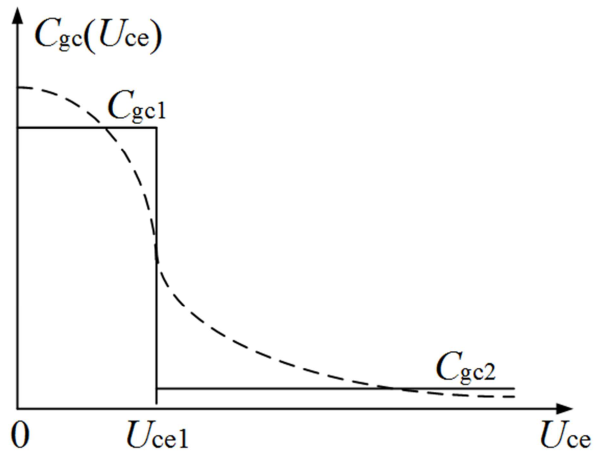


Figure 2. *Principle of the C_{gc} with U_{ce}.*

At the same time, the approximate expression of the down slope of U_{ce} is as follows [16]:

$$\frac{dU_{\rm ce}}{dt} \approx \begin{cases} -\dfrac{U_{\rm cc} - U_{\rm mill\_on}(I_c)}{R_{\rm gon} \times C_{\rm gc2}} & U_{\rm ce} \geq U_{\rm ce1} \\ -\dfrac{U_{\rm cc} - U_{\rm mill\_on}(I_c)}{R_{\rm gon} \times C_{\rm gc1}} & U_{\rm ce} < U_{\rm ce1} \end{cases} \quad (2)$$

As shown above, $U_{mill\_on\ (Ic)}$ is the amplitude of the gate Miller level in the turning-on process, which is related with I_c. For the series of IGBT, I_c is equal, so it can be considered that $U_{mill\_on\ (Ic)}$ is the equal. Then voltage decline rate is mainly affected by R_{gon} and C_{gc} in the dynamic turning-on process.

2.2. Voltage Unbalancing of Dynamic Turning-off Process

Similar to the turning-on process, total input capacitance of gate electrode is charged by the driving power supply in the turning-off process, the turning-off time is[14]:

$$t_{\mathrm{doff}} \approx R_{\mathrm{goff}} \times (C_{\mathrm{ge}} + C_{\mathrm{gc}}) \times \ln\left(\frac{U_{\mathrm{cc}} - U_{\mathrm{gg-}}}{U_{\mathrm{mill\_off}(I_c)} - U_{\mathrm{gg-}}}\right) \quad (3)$$

U_{gg-} is the driver's turn off voltage. Toff is affected by the gate electrode drive resistance R_{goff}, g-e capacitance C_{ge} and g-c capacitance C_{gc} and so on.

At the same time, the approximate expression of the rising slope of U_{ce} is as follows:

$$\frac{\mathrm{d}U_{\mathrm{ce}}}{\mathrm{d}t} \approx \begin{cases} \dfrac{U_{\mathrm{mill\_off}(I_c)} - U_{\mathrm{gg-}}}{R_{\mathrm{goff}} \times C_{\mathrm{gc1}}} & U_{\mathrm{ce}} \le U_{\mathrm{ce1}} \\ \dfrac{U_{\mathrm{mill\_off}(I_c)} - U_{\mathrm{gg-}}}{R_{\mathrm{goff}} \times C_{\mathrm{gc2}}} & U_{\mathrm{ce}} > U_{\mathrm{ce1}} \end{cases} \quad (4)$$

Then voltage rising rate is mainly affected by R_{goff} and C_{gc} in the dynamic turning-off process.

In summary, the main factors that affect the dynamic voltage balancing of IGBT are shown in Table 1:

Table 1. *Factors affecting the dynamic voltage-balancing process of IGBT.*

variable		influence factor
turning-on	t_{don}	R_{gon}, C_{ge}, C_{gc}
	$\frac{dv}{dt}$	R_{gon}, C_{gc}
		R_{gon}, C_{gc}
turning-off	t_{doff}	R_{goff}, C_{ge}, C_{gc}
	$\frac{dv}{dt}$	R_{goff}, C_{gc}
		R_{goff}, C_{gc}

According to the analysis above, the dynamic parameters that affect the IGBT in the turning-off process can be divided into two types of external parameters and internal parameters. The external parameters include I_c, drive voltage U_{cc} and U_{gg-}, gate electrode resistance R_g. The internal parameters include C_{ge} and C_{gc}. Further, I_c, U_{cc} and U_{gg-} can be considered equal. Both R_{gon} and R_{goff} are adjustable. Then the key factor affect the dynamic voltage unbalancing is the difference of C_{ge} and C_{gc} of IGBT.

Gate compensation capacitor network for dynamic process then proposed, that is parallel-connected voltage-balancing capacitor between gate electrode and emitter to weaken the inconsistency of the C_{ge} of the IGBT, and parallel-connected voltage-balancing capacitor between gate electrode and collector to weaken the inconsistency of the C_{gc} of the IGBT. Because the parallel capacitor will cause IGBT turn-on and turn-off time longer, the need for the dynamic characteristics optimization is reduce driving resistance of R_{gon} and R_{goff} in order to make ton and toff unchanged.

2.3. Voltage Unbalancing of the Tail Current State

When the gate voltage of U_{ge} is reduced to below the threshold voltage, the collector current I_c get into the tail current stage.

As the IGBT parameters may not be completely consistent, the current stage of tail attenuation also cannot be exactly the same, which result in voltage unbalancing of IGBT series. As two series-connected IGBTs as an example, the voltage unbalancing of the tail current state as shown in figure 3.

At this time, the gate driver lost control of the IGBT, only can through RC voltage-balancing circuit designed for tail current state to improve voltage unbalancing.

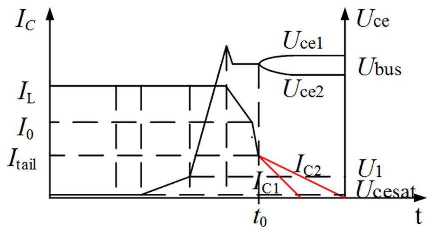


Figure 3. *Diagram of voltage unbalance during tail current process of series-connected IGBTs.*

Assume that the decay rate of Q_1 is greater than Q_2, and the voltage U_{ce1} of Q_1 being to rise and U_{ce2} of Q_2 being to decline, and the decline of the tail current decay is approximate to exponential function, and the tail current time constant is τ_1 and τ_2 of the two series-connected IGBTs respectively.

Assume that the current is I_0 flows through the IGBT when the t_0 time, and voltage unbalancing all absorbing by capacitance C caused by the tail current. Ignore limiting current resistor R_s, the relationship between the voltage and current of the series IGBT is expressed as follows after Δt.

$$C \times [U_1(t_0 + \Delta t) - U_1(t_0)] = I_0 \times (e^{-\frac{t_0}{\tau_2}} - e^{-\frac{t_0}{\tau_1}}) \times \Delta t + C \times [U_2(t_0 + \Delta t) - U_2(t_0)] \quad (5)$$

simplify as:

$$C \times U_1' = I_0 \times (e^{-\frac{t_0}{\tau_2}} - e^{-\frac{t_0}{\tau_1}}) + C \times U_2' \quad (6)$$

And:

$$U_1 + U_2 = U_{dc}$$

The voltage difference in the tail state of the series IGBT is:

$$\Delta U = U_1 - U_2 = \frac{I_0}{C} \times (\int e^{-\frac{t_0}{\tau_2}} \mathrm{d}t - \int e^{-\frac{t_0}{\tau_1}} \mathrm{d}t)$$

Assumed that the current decays to zero after (4~5)τ, absorption capacity expressed as follows:

$$C = \frac{I_0}{\Delta U} \times (\tau_2 - \tau_1) \quad (7)$$

2.4. Voltage Unbalancing of the Steady State

Parallel-connected voltage balancing resistance for the steady state in order to solve the static voltage of series IGBT imbalance when the IGBT is completely turned off.

According to the following formula select resistance [17]:

$$R = \frac{1}{10} \times R_{\mathrm{off}} \quad (8)$$

3. Voltage Balancing Test of Series-Connected IGBTs Power Module

3.1. Parameters of Series-Connected IGBTs Power Module

The power module number of the two series-connected IGBTs is 5SNA2000K451300 of ABB, rated voltage is 4500V, rated current is 2000A.

1) Selected for Cge and Cgc

According to the IGBT datasheet [18], combined with the analysis of the 2.2 section, select C_{ge_ext}=300nF and C_{gc_ext}=1.5nF.

2) Selected for Rs and C

According to IEC 60747-9:2007, the continuous time of the tail current of the IGBT comes from 0.1Ic to 0.02Ic. Then the start of the tail current time I_{tail}=125A. Assumed that the difference of the tail current time constant is 0.5 us~1.0 us, andU_{dc} is 2000V. In order to the voltage-unbalance-rate of dynamic and steady state are less than 5%, as the formula (7), can calculate C=0.5μF or 1μF. In practice, select C=0.56 uF.

Considering the loss and so on, select R_s=36Ω.

3) Selected for voltage balancing resistance R

According to the IGBT datasheet [18], the maximum leakage current is 100mA at 125 C. According to the formula (8), the voltage balancing resistance R=450kΩ.

As to the parameters mentioned above, the power module of the IGBT series is shown in Figure 4:

Figure 4. *Equipment of series-connected IGBTs.*

3.2. Voltage Balancing Test of Series-Connected IGBTs Power Module

The schematic of two series-connected IGBTs is shown in Figure 5. The bus voltage U_{dc}=2000V, the load inductance L=141uH, and the two series-connected IGBTs are Q_1 and Q_2, and Q_3 is used as parallel-connected diode.

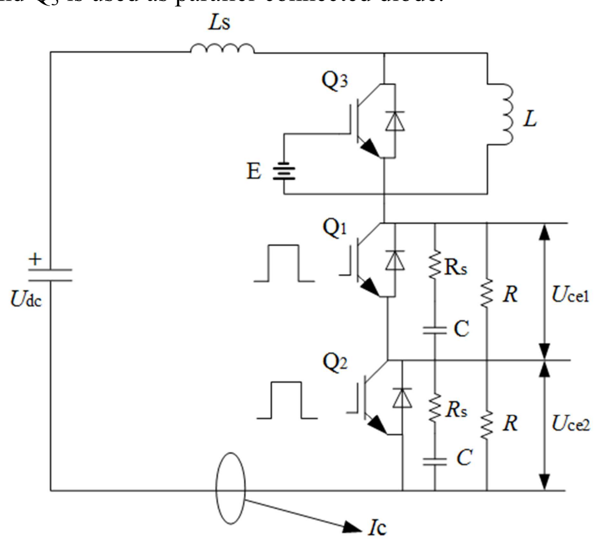
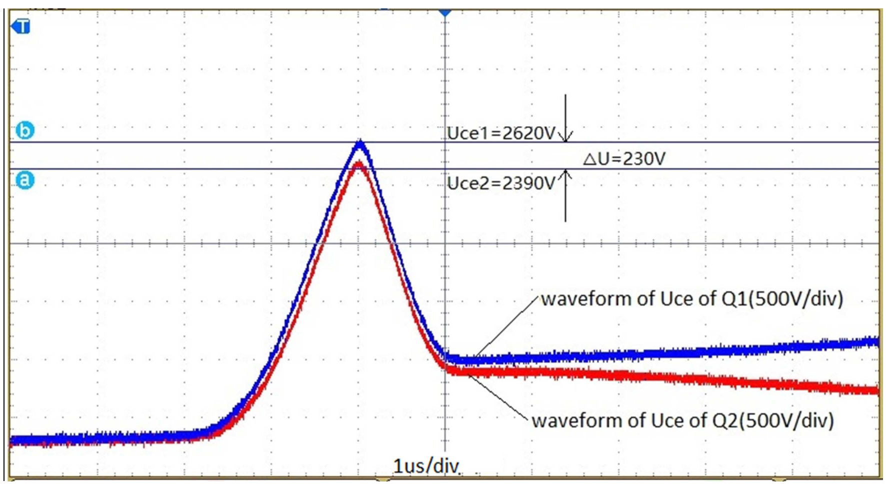
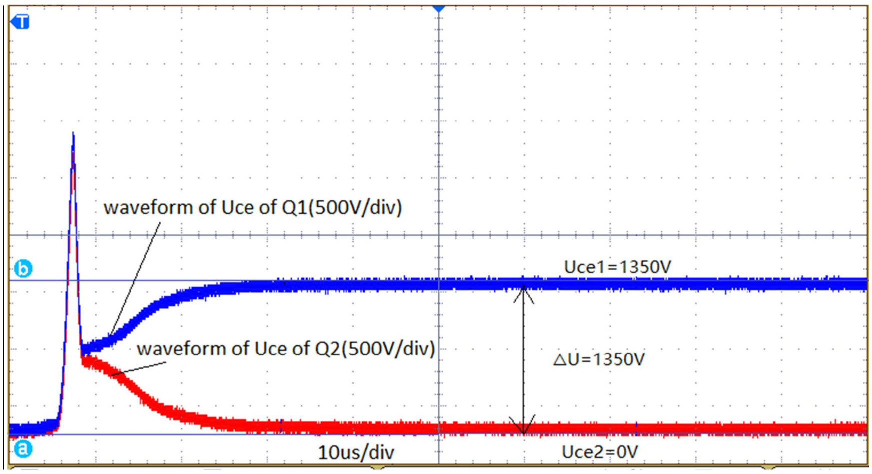


Figure 5. *Schematic of two series-connected IGBTs.*

The waveform of turning off process without voltage balancing measures as shown in Figure 6 below. As Figure 6 (a) can be seen, the voltage difference of two series IGBT in the turning-off process is 230V without any voltage balancing measures, and the voltage-unbalance-rate of dynamic is 4.5%. The inconsistent dynamic voltage exacerbates the voltage unbalancing in the tail current stage. Figure 6 (b) says that the voltage difference of two series IGBT in steady state is 1350V, and Q_1 bear all voltage drop, Q_2 turning-off failure, the voltage-unbalance-rate of steady state is as high as 100%.



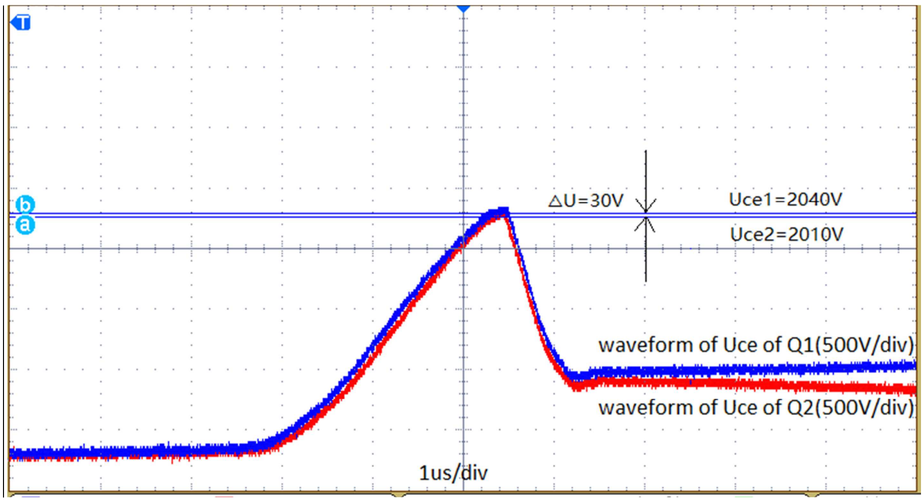
(a) Waveform of turning off process



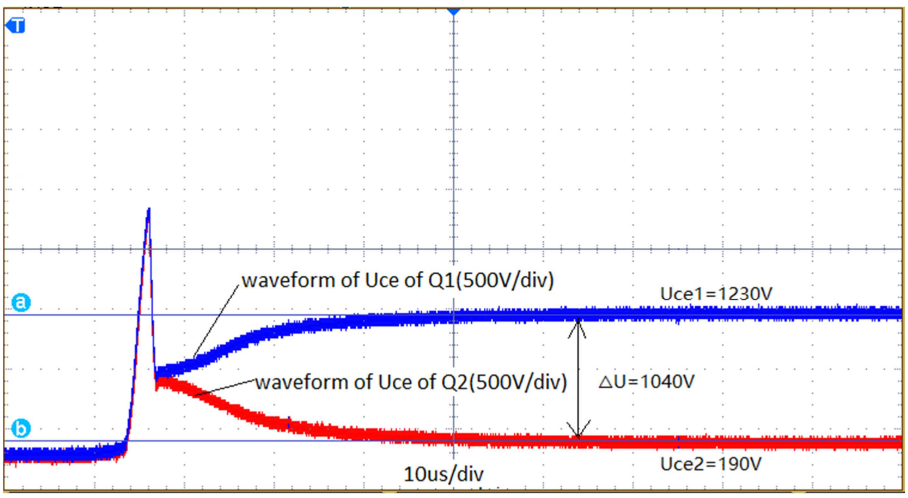
(b) Expanded waveform of turning off process

Figure 6. *Waveform of turning off process without voltage balancing measures.*

Waveform of turning off process of IGBT with gate compensation capacitor network when C_{ge_ext}=300nF and C_{gc_ext}=1.5nF but without voltage balancing resistance R.



(a)Waveform of turning off process



(b)Expanded waveform of turning off process

Figure 7. *Waveform of turning off process of IGBT with gate compensation capacitor network.*

As Figure 7 (a) can be seen, the voltage difference of two series IGBT in steady state come from 230V to 30V, and the voltage-unbalance-rate of dynamic is is less than 1%. which improve the consistency of the delay time and the rising voltage rate when the gate compensation capacitor network used. Because of the increase of the dynamic voltage consistency weaken the influence of the voltage unbalancing of the steady state, the voltage difference of two series IGBT in steady state comes from 1350V to 1040V as Figure 7 (b), and the voltage-unbalance-rate of dynamic decline to 73.2%. Waveform of turning off process with gate compensation capacitor network and RC circuit as shown in Figure 8. As can be seen, Waveform of dynamic peak voltage of two series-connected IGBTs is consistent, and voltage imbalance degree in steady state from 73.2% decline to 6.1%.

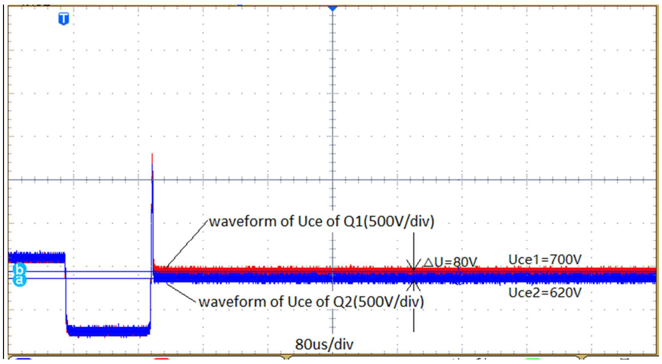


Figure 8. *Waveform of turning off process with gate compensation capacitor network and RC circuit.*

When the power module balanced the voltage of the whole turning on and off process is implemented, double pulse test the voltage balancing of the whole period of the IGBT, and voltage balancing resistance R used. Double pulse drive test waveform select 80us, 30us, 30us, bus voltage U_{dc}=2000V, double pulse waveforms of IGBT series are shown in figure 9.

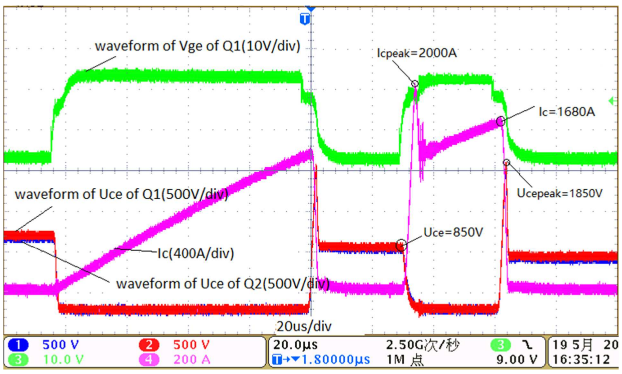


Figure 9. *Waveform of the whole turning on and off process of series-connected IGBTs.*

As can be seen figure 9 above, the current peak of the second turning-on time is 2000A, voltage Uce of each IGBT is 850V, and the turning-on waveform of the two series-connected IGBTs completely coincide. The voltage peak of the second turning-off time is 1850V and the current of the second turning-off time is 1680A, and the turning-off waveform of the two series-connected IGBTs completely coincide. Considering the error of the high-voltage test is about 3%, as can be seen above, the voltage and current of the series-connected IGBTs in the whole turning on and off process is completely coincident, and the voltage and current dynamic unbalance-rate are less than 5%.

4. Conclusion

In this paper the voltage-balancing process is divided into 4 stages, the influence factors of each stage are summarized, and voltage-balancing methods are then proposed respectively. Based on the work above, power module of two series-connected IGBTs is designed and tested under high voltage and high current condition. The result shows that the power module balanced the voltage of the whole period of a turning on and off process according to the analysis and selected above, and both of the voltage-unbalance-rate of dynamic and steady state are less than 5%. The method cost low and volume compact, which can improve the consistency of dynamic voltage of series IGBT significantly, and provides reference value for engineering application.

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