The Techniques of the Serial and Paralleled IGBTs

Jiann-Fuh Chen
Power Electronics Lab.
Department of Electrical Engineering
National Chen Kung Univ.
Taiwan, R.O.C.

Jiunn-Nan Lin
Power Electronics Lab.
Department of Electrical Engineering
National Chen Kung Univ.
Taiwan, R.O.C

Tsu-Hua Ai
Power Electronics Lab.
Department of Electrical Engineering
National Chen Kung Univ.
Taiwan, R.O.C

Abstract—To extent the rating ranges of current and voltage of IGBT, the serial and parallel methods are presented in this paper. For serial techniques, it is found that the voltage sharing can be got to balance by adding a RCD snubber and an adequate balancing resistor in each IGBT in series. For parallel method, a parallel scheme using current feedback method is proposed in this paper. The above serial and parallel techniques are proved that the currents of paralleled IGBTs and the voltages of IGBTs in series can be balanced by experiments.

I. INTRODUCTION

BJTs have lower conduction losses in the on-state, but have longer switching times, especially at turn-off. MOSFETs can be turned on and off much faster, but their on-state conduction losses are larger. The IGBT is a hybrid power device that combines the advantages of a MOSFET (fast switching and low drive power) and a BJT (low conduction losses). Because of the advantages of IGBTs, they have wide applications in many fields.

In particular, due to its large current-handling capability, the IGBT is especially suitable in applications of high frequency (20kHz) medium power (1 to 100kW) PWM inverters and motor drives. If we need larger power of IGBTs, it will be necessary to extent the capacities of IGBTs. There are two methods to get the large power for semiconductor devices, that is, making devices high current density and high voltage. It is not difficult to get to high current density and high voltage for devices in manufacturing, but we have to think about the costs. Generally speaking, the costs will be lower to get to large power when devices in series or paralleled than get to large power by the single device. So, they are important techniques for IGBTs to get to high current density by parallel and high voltage by series[1,2].

Power devices can not tolerate the surges over the rating ranges in short time, and can not be protected by general fuses and breakers. Because of the differences of the parameters of power devices, they will result in the unbalances of the voltages or currents when devices in series or paralleled. Besides, the switching losses of power devices are larger than the on-state losses in high frequency operation. We have to consider the switching time and oscillations as the results of threshold voltages, on-state resistance, off-state resistance and the lines in experiments. Because of the unbalances of devices, we have to solve the problems.

The authors are with the Department of Electrical Engineering National Chen Kung University, Tainan, Taiwan, R.O.C.
886-6-2757575-62353(phone) 886-6-2345482(FAX)

II. TECHNIQUES OF IGBTS IN SERIES

A. RCD Snubber

The RCD snubber is composed of a resistor(R), a capacitor(C) and an diode(D), as shown in Fig.1. When the IGBT is switched off, the capacitor C_S will be charged. When the IGBT is switched on, the capacitor will discharge along the original path that it was charged, and the value of "di/dt", will increase. In order to limit this, a resistor R_S is connected in series as indicated in Fig.2. The diode D_S in Fig.2 provides a low impedance only for the charging path for the capacitor.

The resistor R_S should be chosen small enough to ensure that the capacitor C_S can discharge fully during the switching transition time. But R_S can not be chosen too small, it will damage the devices because of large current. The capacitor C_S is used to fight with the steep change of the voltages. It will cause the voltages to rise slowly, so it can prevent the surges. If C_S is chosen too large, it will effect the switching time. If C_S is chosen too small, it can not fight with the steep change of the voltage. The suitable values of C_S and R_S should be designed carefully by rules[3,4].

B. Design Criteria of The Capacitance and Inductance of The Snubber

Fig.2 shows the switching waveform of the voltage of the capacitor C_S and the load current when the IGBT is being off. Assuming a linear decrease of the load current during its turn-off interval t_{fi}, the voltage across the capacitor at any time t is calculated as follows:

0-7803-2775-6/96 $4.00 © 1996 IEEE

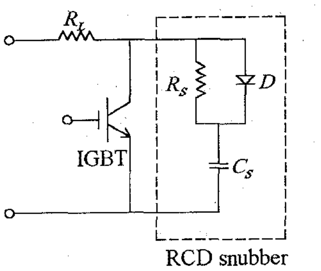


Fig.2. IGBT with a RCD snubber.

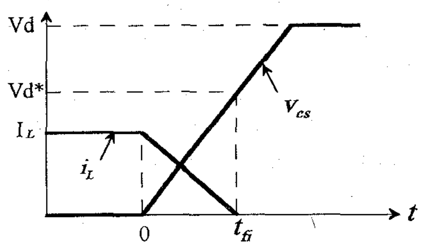


Fig.2. Capacitor voltage and load current during the turn-off transition interval.

$$V_{CS} = \frac{1}{C_s}\int_0^t i_L dt \;\Rightarrow\; V_{CS} = \frac{1}{C_s}\int_0^t \frac{I_L}{t_{fi}} t\, dt$$

where i_L means the load current.

The capacitor voltage gets to a designed value V_d* at time $t{=}t_{fi}$:

$$V_d^* = 0.5(I_L t_{fi})/C_S \tag{1}$$

where V_d* is a fraction of the voltage source V_d.

According to (1), the capacitor C_S can be chosen from (2):

$$C_S > (I_L t_{fi})/2\,V_d^* \tag{2}$$

the minimum of C_S can be derived from (2).

In the resonant RLC circuits, the damping ratio is defined by (3):

If damping ratio is chosen to be small enough, the peaks

$$\xi = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{3}$$

of voltage will not be too large. But it can not be too small, because the large surges will damage the devices. We do not want the damping ratio to be larger than unity, for it will takes more time to attain the stable situation, and slow down the switching time. The damping ratio should be chosen smaller enough than unity as (4) :

$$\xi = \frac{R_{load}}{2}\sqrt{\frac{C_s}{L_{load}}} < 1 \tag{4}$$

where R_{load} means the resistance of the load and L_{load} means the inductance of the load. Rearranging (4), the maximum of C_S can now be calculated from (5):

Hence, combining (2) and (5), (6) is obtained:

$$C_s < \frac{4L_{load}}{R_{load}^2} \tag{5}$$

At the turn-on interval of the IGBT, the resistor R_S should

$$\frac{I_L t_{fi}}{2V_d^*} < C_s < \frac{4L_{load}}{R_{load}^2} \tag{6}$$

limit the peak discharge current through the IGBT to a safe value. The choice of R_S is mainly decided by the minimum on-time $T_{on(\min)}$ of the IGBT. The minimum on-time can be designed to be at least five times of the time constant $R_S C_S$:

$$T_{on(\min)} > 5R_s C_s \tag{7}$$

(7) can be reformed as

$$R_s < T_{on(\min)} / 5C_s \tag{8}$$

This means that R_S should be chosen suitably for the quick discharge of C_S.

Using the above equations, all the component values of the snubber connected to the IGBT can be calculated.

C. Blancing Resistor

The output off-state resistance of the IGBTs are not often the same because of the variance of the device parameters. Fig.3 shows the IGBTs with snubbers and balancing resistors. The off-state resistance for each IGBT are R_{off1} and R_{off2} and the balancing resistor is R_B. Fig.4 indicates the equivalent circuit of the off-state serial IGBTs where the capacitor of the snubber will be ignored foe it can be taken as open circuit in the straight line of the input square waveform. The value of the equivalent output off-state resistance for each IGBTs in series will be closer if R_B is put in the circuit. The R_B is often chosen roughly as one-tenth of the IGBT output off-state resistance that is calculated from (9):

$$R_B \cong \frac{1}{10} R_{off} \tag{9}$$

According to the above descriptions, the unbalance of the voltages of the serial IGBTs can be improved by putting a RCD snubber and a balancing resistor R_B in each IGBT in series.

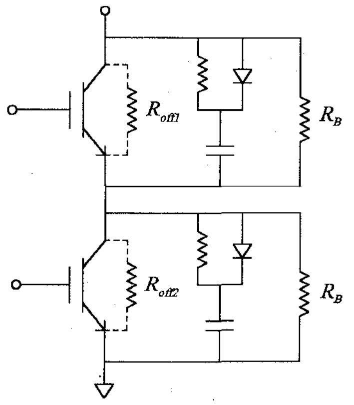


Fig.3. The IGBTs in series with snubbers and balancing resistors

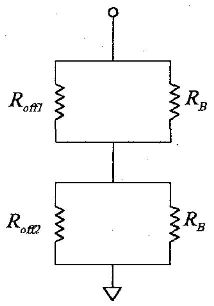


Fig.4. The equivalent circuit when the IGBTs are off

Ⅲ. TECHNIQUES OF PARALLELED IGBTS

MOSFETs are easily paralleled because their on-state resistance has a positive temperature coefficient. IGBTs are more difficult to be paralleled because of their negative temperature coefficient of the on-state resistance.

IGBT is a voltage-controlled device. It is fully on and approximates a closed switch when gate-source voltage is sufficiently large. The IGBT is off when the gate-source voltage is below the threshold value, V_{GS}. IGBTs require the continuous application of a gate-source voltage of appropriate magnitude in order to be in the on-state. The source current is controlled by the gate-source voltage, V_{GS}. If V_{GS} increases, the source current I_D will increase, or vice versa. The linear relationship between V_G and I_D will be used in the load current balance for the paralleled IGBTs. The simplified block diagram of the paralleled IGBTs is shown in Fig.5. The output currents of paralleled IGBTs, I_D, can be detected by a current transducer and transferred as a voltage signal. To reduce the high frequency noise, the voltage signal will be passed a low-pass filter to grid the noise and modify the signal waveform. The controller voltage signal is fed through the signal which is filtered for generating a series of voltage trigger signal. The trigger control block is next applied to the paralleled module to control the output current to follow the controller voltage signal.

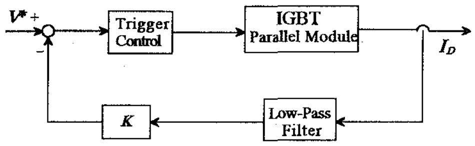


Fig.5. control block diagram of the paralleled IGBTs

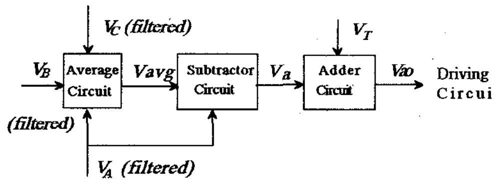


Fig.6. The computation block diagram of the three paralleled IGBTs

Three Paralleled IGBTs

The simplified controlled block diagram of the three paralleled IGBTs is shown in Fig.6. The IGBT can be detected by a current transducer as a voltage signal. The voltage signal is used as the controller input signal that the voltage signal will be passed through low-pass filter to grid noise and modify the waveform. The filtered voltages are V_A, V_B and V_C, respectively, as indicated in Fig.6. To regulated the load current, the trigger voltage will be modified by the reference voltage which is come from the average value of the filtered voltage of the three IGBTs. The modifiable magnitude of the trigger control voltage for the three IGBTs is the sum of the average voltage value and the voltage difference value. The voltage difference is performed by the average voltage value minus the filtered voltage value, for example, V_A as indicated in Fig.6. There is a problem here, that is, no feedback signal to apply to the driving circuit initially. Therefore, we apply the initial voltage V_T to the driving circuit continuously. To explain

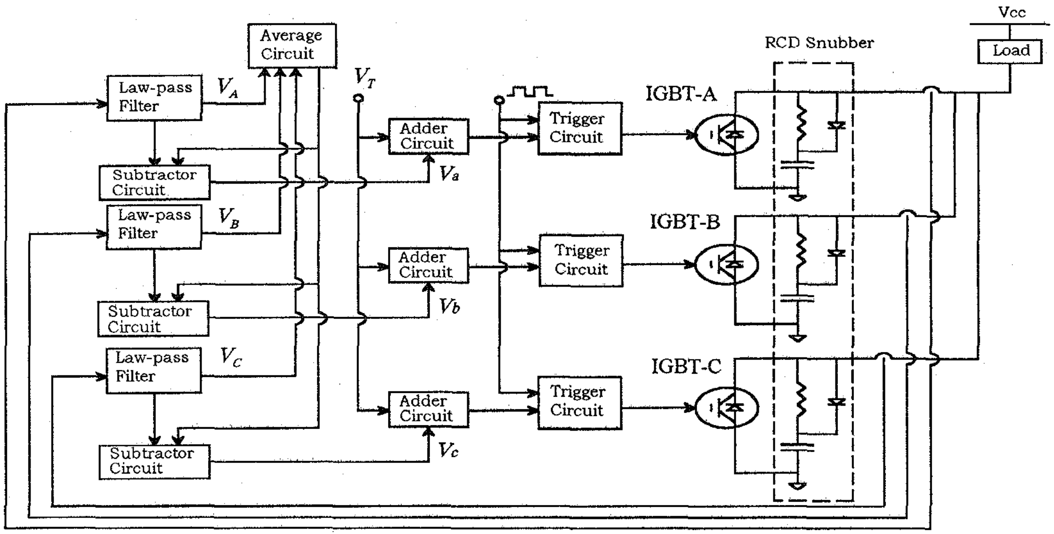


Fig.7. The detailed control block diagram and hardware configuration of the three paralleled IGBTs.

the principles of the computation block diagram, we take the following example.

(i) When the system starts instantaneously,

$$V_A = V_B = V_C = 0$$
$$\Rightarrow V_{avg} = \frac{V_A + V_B + V_C}{3} = 0$$
$$\Rightarrow V_a = V_{avg} - V_A = 0$$
$$\Rightarrow V_{ao} = V_T \cdots\cdots \textit{the initial input voltage}$$

(ii)After the system starts,

$$V_A \neq 0,\ V_B \neq 0,\ \textit{and}\ V_C \neq 0$$
$$\Rightarrow V_{avg} = \frac{V_A + V_B + V_C}{3} \neq 0$$
$$\Rightarrow V_a = V_{avg} - V_A$$
$$\Rightarrow V_{ao} = V_T \cdots \textit{the input voltage after starting}$$

Therefore, the more high load current, the more high translation filtered voltage. If the filtered voltage value V_A is higher than the average voltage value, the difference voltage V_a is negative, or vice versa.

IV.EXPERIMENTAL RESULTS

Subject to the above descriptions, the experimental results of the serial and paralleled techniques are discussed, respectively.

Experimental Results of Serial Technique

To prove the accuracy of the above serial theory, the following parameter values for NIEC PDMB506 IGBT are used for the experiments:

$$R_{off1}(IGBT1) = 621K\Omega$$
$$R_{off2}(IGBT2) = 700K\Omega$$

The value of R_{off} is roughly taken as 650K. The R_B is calculated from (9):

$$R_B \cong \frac{1}{10} \times 650K\Omega = 65K\Omega$$

Test Condition:

$$R_{load} = 47\Omega,\ L_{load} = 200\mu H$$

$$V_d = 120\,V,\ V_{cd}(IGBT1) \cong V_{cd}(IGBT2) = \frac{V_d/2}{10} = 6\,V$$

$$I_L = 2.5A,\ t_f = 1\mu s,\ T_{on} = 50\mu s$$

The C_s is decided by (6):

$$0.21\mu F < C_s < 0.36\mu F$$

Here, we choose $C_s = 0.33\,\mu F$ as the parameter of the experiment. The R_s is decided by (8):

$$R_s < 30.3\Omega$$

Here, we choose R_s=20

Fig.8 show the experimental results of the two serial IGBTs without RCD snubber and RB at 10Khz frequency.

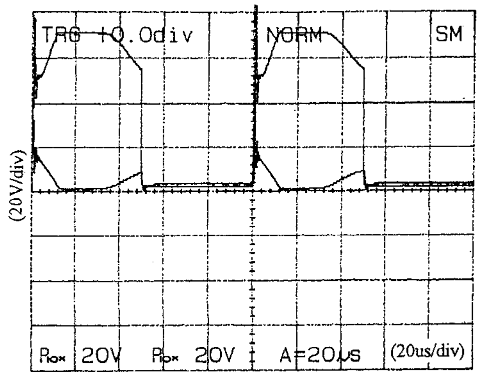


Fig.8. the serial experimental waveform at 10Khz without RCD snubber and R_B (two serial IGBTs)

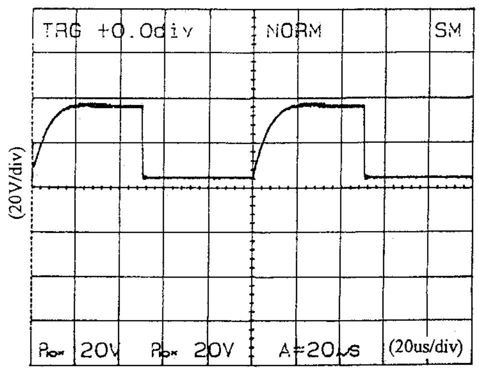
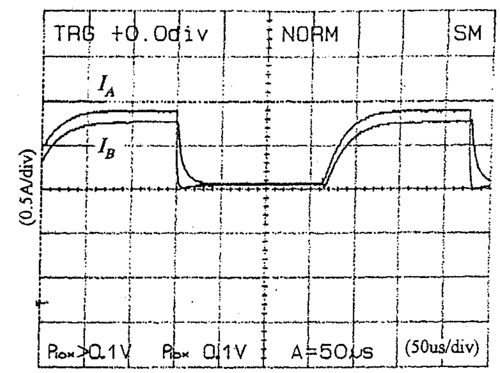


Fig.9. the serial experimental waveform at 10Khz with RCD snubber and RB (two serial IGBTs)

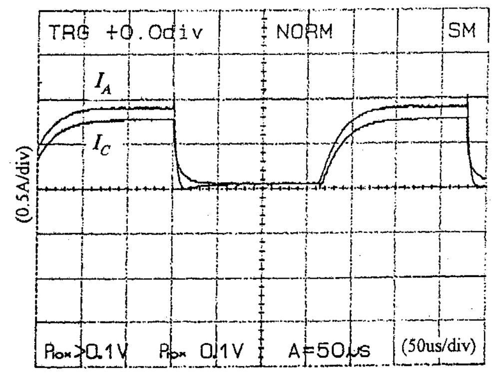
Fig.9 show the experimental results of the two serial IGBTs with RCD snubber and RB in the above test condition at 10KHz frequency. Hence, the assumptions made for the analysis of the IGBT serial techniques are in conformity with the experimental results.

Experimental Results of The Parallel Technique

The whole control block diagram of the three paralleled IGBTs and the more detail information for hardware configuration are as shown in Fig.7. The main circuits in Fig.7 contain driving circuits, control circuits, snubber circuits and starting source V_T. The snubber circuits are the same as the ones in serial techniques. The IGBTs are mounted on the same heatsink. The device circuit connected to the drain, gate and source terminals are made via the screw tracks with resulting minimum stray inductance. The load used for



(a) the currents of IGBT-A and IGBT-B



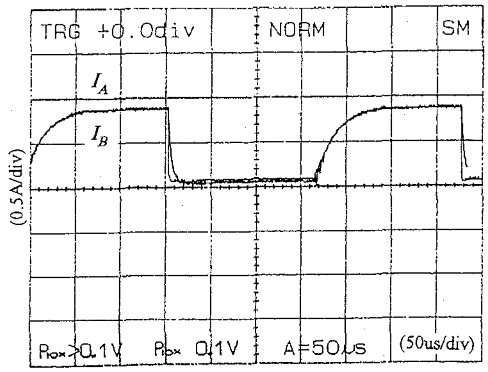
(b) the currents of IGBT-A and IGBT-C

Fig.10. the parallel waveform when using one gate resistance for gate drive at 3Khz (three paralleled IGBTs)
(a) the currents of IGBT-A and IGBT-B
(b) the currents of IGBT-A and IGBT-C

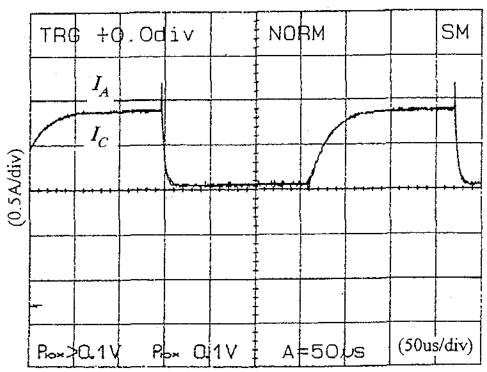
loading test is composed with inductors and resistors. The power IGBT modules, PDMB506 (50A/600V, NIEC), are used in the experimental tests. Fig.10 shows the measurement results when using the one gate resistance for gate drive at 3Khz. The unbalance current is very high. In Fig.11, the same measurement results are shown when using the feedback control loop at 3Khz. It is shown that the paralleled IGBTs with feedback control loop are satisfactory.

V. CONCLUSIONS

Owing to the optimal device characteristics of the IGBT, the application of serial and parallel operation and large voltage and current capacity have been caused many adverse



(a) the currents of IGBT-A and IGBT-B



(b) the currents of IGBT-A and IGBT-C

Fig.11. the parallel waveform when using the feedback control loop at 3Khz (three paralleled IGBTs)
(a) the currents of IGBT-A and IGBT-B
(b) the currents of IGBT-A and IGBT-C

notice to the power electronic range. In this paper, the new schemes for serial and parallel IGBTs are developed.

(1)Serial techniques : It is found that the voltage sharing can be balanced by adding a RCD snubber and an adequate balancing resistor R_B in each IGBT in series by suitable designation of the parameters. And, the experimental waveforms show that the oscillations for IGBTs in series without RCD snubbers and balancing resistors can be eliminated by this serial method.

(2)Parallel techniques : A new schemes for paralleled IGBTs is developed. Using the characteristics of linear relationship of V_G and I_D , the balance load current can be obtained by the value of change of the gate-source voltage in the IGBT. The feedback control loop for paralleled IGBTs is constructed. From comparing the difference of with and without feedback control loop, the experimental results for load current balance of paralleled IGBTs are presented. It is shown that the paralleled IGBTs with feedback control loop are satisfactory.

But the above experimental results show that the best operational frequency is not high. The reasons are as follows. For serial techniques, the snubbers will effect the switching speed. For parallel techniques, the low-pass filters will slow down the operational time. Hence, the frequency range can not attain high level. However, if the switching frequency increases, the switching losses will increase, too. The switching frequency is generally chosen in the low range to reach high efficiency.

From the experimental results, the necessity to extent the capacity will be easily accomplished at low frequency by using the developed serial and paralleled IGBTs techniques in this paper.

VI. REFERENCES

[1] R. Gvidini, D. Chatroux, Y. Guyon, D. Lafore, and B. Hennevin, "15KV Switch Made of Semiconductor Power MOSFETs Devices in Series, " Power Conversion Proceedings in France, pp.235-239, June 1994.

[2] A. Jaafari, D. Bergogne, and J. P. Picard,"Low Energy for High Power 300A-1000V IGBT," IEEE Ind. Appl. Soc. Meet., Conf. Rec. pp.943-945, 1990.

[3] A. R. Hefner, "An Improved Understanding for the Transient Operation of the Power Insulated Gate Bipolar Transistor(IGBT)," IEEE Transactions on Power Electronics, vol.5, no.4, pp.459-468, 1990.

[4] K. S. Rajashekara, Joseph Vithyathil, and V. Rajagopalan, "Protection and Switching-Aid Networks for Transistor Bridge Inverters," IEEE Transactions on Industrial Electronics, vol.IE-33, no.2, pp.185-192, 1986.