Series Connection of IGBT's with Active Voltage Balancing

Soonwook Hong, Venkatesh Chitta, *Member, IEEE*, and David A. Torrey, *Member, IEEE*

***Abstract*—This paper describes an active gate drive circuit for series-connected insulated gate bipolar transistors (IGBT's) with voltage balancing in high-voltage applications. The gate drive circuit not only amplifies the gate signal, but also actively limits the overvoltage during switching transients, while minimizing the switching transients and losses. In order to achieve the control objective, an analog closed-loop control scheme is adopted. The closed-loop control injects current to an IGBT gate as required to limit the IGBT collector–emitter voltage to a predefined level. The performance of the gate drive circuit is examined experimentally by the series connection of three IGBT's with conventional snubber circuits. The experimental results show the voltage balancing by an active control with wide variations in loads and imbalance conditions.**

***Index Terms*—Insulated gate bipolar transistor, insulated gate bipolar transistor gate drive, overvoltage control.**

I. Introduction

SERIES connection of thyristors and gate-turn-off thyristors (GTO's) has been widely used in high-voltage dc (HVDC) systems, static var compensators (SVC's) and high-voltage source inverters. The reasons for using series-connected power devices are to achieve high efficiency in power converters and to minimize the system size.

In order to eliminate device overvoltages, a passive voltage-balancing technique is typically used. This passive control generates excessive power losses in snubber circuitry and slows down the switching transients in order to balance the voltages in the series-connected devices. In the series connection of GTO's, these losses and slow switching characteristics prevent the device from being applied to pulsewidth modulation (PWM) inverters. If it is possible to use insulated gate bipolar transistors (IGBT's), PWM techniques can be used so that following advantages can be realized:

- increased system operation frequency;
- compactness in the power circuit;
- reduced power losses in the snubber circuit;
- simple driving circuitry.

However, the techniques used for the series connection of thyristors and GTO's cannot be directly applied to IGBT's because of entirely different device characteristics. The transient switching characteristics of IGBT's are normally in the 0.3–0.5-μs range, so that conventional transient voltage balancing by using passive elements is not possible. The purpose of voltage balancing in series-connected IGBT's is to achieve an equivalent switching transient comparable with the transients obtained when one large-rating IGBT is used by using active transient voltage balancing.

Therefore, the voltage control scheme must be fast, so that it does not create much loss nor degrade the switching frequency of the system. It should also be economical so that it is useful in practical applications. Steady-state voltage balancing should be used to equalize stresses among series-connected devices. This steady-state balancing can be achieved by using balancing resistors that can also serve as a voltage sensor for an active transient voltage-balancing controller.

In the last few years, high-voltage and high-power IGBT's and emerging devices like insulated gate commutated thyristors (IGCT's) have been introduced, but they are applied in only limited applications because of the high cost or limited availability of very-high-voltage devices. In order to make these devices cost effective, series connection is a viable solution. Many papers have been published on the series connection of IGBT's in recent years. Their main concerns are to balance the dynamic and steady-state voltage imbalances due to the gate driver delay and mismatches of IGBT's and snubber circuitry.

Gate voltage slope control [1] is a good way of controlling the overvoltage in IGBT's. The control scheme is to limit the voltage slope of the gate signal according to the IGBT transient voltage, so that it does not create any voltage overshoot during active control transients, thereby generating an exact amount of control input to the gate driver. However, in order to achieve voltage balancing without any overshoot for all of the series-connected IGBT's, the control slope should be very much slower than the device with the slowest characteristics. Because this slope control creates a long transient during the switching action, it can generate excessive power loss during transients, and the switching frequency of the system must be reduced because of these slow transient characteristics. The device must also be used well below its ratings, due to the

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excessive heating of the devices. The other disadvantage of this control is that the gate voltage slope control is applied to all the switching devices during the balanced voltage condition, so that it can create excessive power losses during normal operations.

Digital deadbeat control for voltage balancing [2], [3] is also a good approach to balance the voltages during the switching transient. The deadbeat control is a state observer that can control the voltage balancing precisely. The result shows comparatively small voltage overshoot during the control transients and generates small power losses due to the control. However, the digital control has many stages for sensing, converting analog signals to digital, and control decisions, so that it has its own delay. In addition, the control is discrete. In order to minimize the control delay, the sensing part and controller should be fast, so that it might not be an economical solution for practical applications.

Gate current pulse control [4] is a straightforward approach to balance the transient voltages. This control is very effective, in that it can control the overvoltage with minimized control path and generate small power losses. The results show the balancing action in the IGBT voltage with comparatively small voltage overshoot during the control transient. However, the transient during control action is determined by the capacitor value in the active controller, so that it cannot generate the exact amount of positive gate pulse in variable-load cases. This control generates a discrete pulse of charge to the gate, so that it does not respond to continuous overvoltage.

Most papers previously written concentrated on the delay in gate signals for series-connected IGBT's. The delay can greatly influence the voltage imbalance. The different gate delays during the turn-on transient can produce spike voltages across the slowest device. The leading gate turn-off transient also produces an overvoltage across one device, and it can create steady-state voltage imbalance for the device. However, if these delayed or leading gate signals can be limited to less than 0.3 μs, they do not create significant overvoltage problems. Carefully designed gate drive circuits can generate less than 0.1-μs delays, so that they do not create significant overvoltage. However, if these delays are applied in the series-connected IGBT's, overvoltage conditions are inevitable, so that they must be considered.

Other major causes of overvoltage are the stray inductance of the bus bar and the different characteristics of the snubber circuit for each device in the series connection. The inductance of the bus bar can be different for the different IGBT's, and this may cause different switching characteristics and voltage spikes. The dv/dt's of the switching transients are mostly dominated by the snubber capacitor. Because the tolerance of the capacitance is expected to be 5%–10%, the dv/dt of each series-connected IGBT is slightly different. The difference in capacitances does not create a significant voltage spike because the transients due to the snubber capacitor are continuous rather than discrete, as is the case with the delayed gate signals. However, if many IGBT's are connected in series for a high-voltage application, these differences in capacitance can produce a significant overvoltage across the IGBT with the smallest snubber capacitance.

By considering previous studies, the following constraints should be considered in designing and testing the active voltage balancing controller.

- It should not create power losses during balanced voltage operation.
- It should be practical.
- The overvoltage transient controller should be fast.
- It should perform well with different loads and causes of overvoltages.

This paper presents an analog active controller that overcomes some of the disadvantages of earlier approaches. It proposes a feedback control with the comparable power loss and switching speed to a perfectly balanced string of IGBT's. Experimental results are provided with different causes of voltage imbalance and different load cases.

II. CONTROL FOR VOLTAGE BALANCING

The voltage imbalance during switching is prevented from destroying the device by actively clamping the voltage across the device. If the voltage of the device with the highest voltage is controlled to be clamped to a reference voltage which is less than the voltage rating of the IGBT, the overvoltage naturally distributes across the other devices in the series connection. This ensures safe operation of power devices without reducing the speed of the IGBT's, since the device voltage is limited only when it exceeds the voltage reference. It also acts only on those devices which have overvoltages. The devices subjected to an overvoltage see increased losses; those devices not subjected to overvoltages will not see a reduction in efficiency. In addition, the control does not act when the voltages are balanced, which is also important, because devices that are already balanced should not be slowed down.

In order to overcome disadvantages of the conventional series connection of power devices, the control criteria used here is to minimize the additional switching time and power loss due to the series connection. The linear control must also continuously control the imbalance voltage. Therefore, a local closed-loop feedback control is introduced in this paper. Fig. 1 shows the control scheme used in this paper.

The IGBT voltage $V_{\mathrm{ce,fb}}$ is sensed by using a potential divider across the collector–emitter junction, and this voltage is compared with the reference voltage. The voltage generated as a result of this comparison is

$$V_{\mathrm{out}} = \frac{(R_i + R_f)V_{\mathrm{ce,fb}} - R_f V_{\mathrm{ref}}}{R_i}. \tag{1}$$

When $V_{\mathrm{ce,fb}}$ is greater than the V_{ref}, the overvoltage is converted into positive gate current with appropriate feedback gain. This positive current is applied to the gate as long as there is an overvoltage across the IGBT. The IGBT collector–emitter voltage is decreased by virtue of the additional positive charge on the gate. To ensure that the transients are controlled in time, the op-amp and *TR3* and *TR4* should have wide bandwidth. During the control transients, if any overvoltage is applied to the IGBT again by the external circuit, the feedback acts to control the IGBT voltage to the reference and the voltage distributes among the other devices. It should be noted that

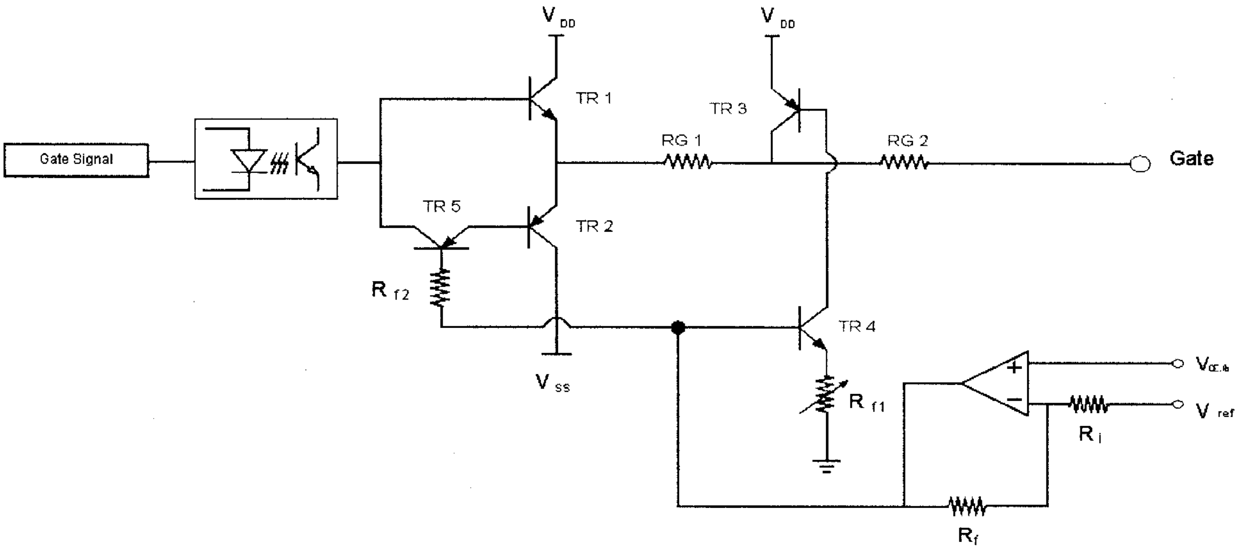


Fig. 1. The active voltage-balancing control scheme.

TR3 and *TR4* operate in the active region, suggesting faster operation comes at the expense of increased heating of these devices.

The static voltage limiter forces the gate to turn on the device with a small delay when a steady-state overvoltage is applied to the IGBT. This is very important when a very long delay is applied to the IGBT during the turn-on transient.

III. Experimental Setup

In order to test the overvoltage phenomena in IGBT series connections, a general chopper circuit is used. The series-connected IGBT's used in the test are MG75J2YS91(600 V, 75 A), MG50J2YS1(600 V, 50 A), and MG25Q2YS91(1200 V, 25 A) manufactured by Toshiba. The reason for using different rating IGBT's is to observe different characteristics of the switching devices and demonstrate that devices of different characteristics can be connected in series.

Major causes of voltage imbalances in the power circuits and device characteristics can be modeled by the following:

- using IGBT's of different ratings;
- using different snubber capacitors;
- applying delays in gate signals;
- using different parameters in individual gate drive circuits.

In order to observe different characteristics due to load conditions, the system is tested with resistive loads and inductive loads. Fig. 2 shows the circuit diagram used in the test. The dc-bus voltage is set to 1.1 kV. The voltage reference in the active controller is set to 370 V, so that even in the unbalanced condition, each IGBT blocks 370 V with the active controller. The load current for both resistive loads and inductive loads is set to 20 A, so that the smallest IGBT is operated within its rated current. For the snubber circuit, combinations of snubber capacitors are used to generate voltage imbalance. Delay control circuits are needed for test purposes only in order to create forced delays among the gate signal inputs.

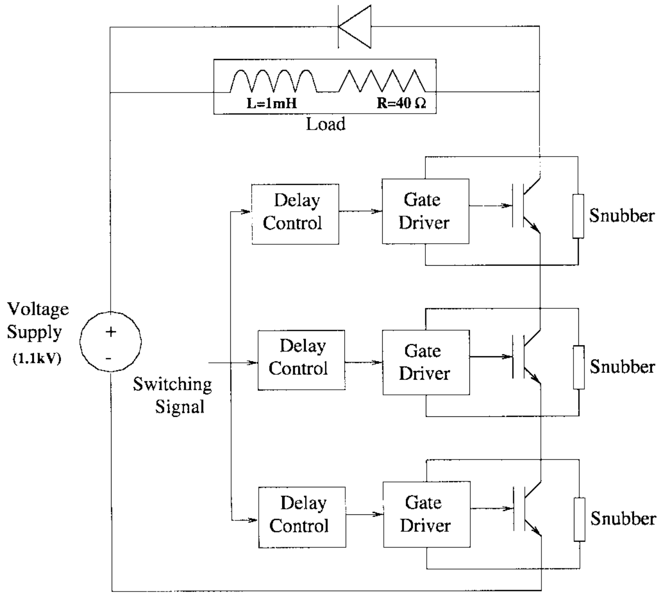


Fig. 2. The experimental setup used to evaluate the control scheme of Fig. 1.

Even though inductive loads are practical, the resistive load is also considered. In the case of an inductive load, the current commutates from the switch to the diode, while in a resistive load case, the current is just proportional to the load voltage. Thus, the switching process is entirely different. The purpose of this test is to demonstrate that the active voltage control acts well, even under such varied switching transients.

For the testing of using different parameters in the gate drive circuit, different gate resistors are used. Even with a 100% increase in the gate resistance in normal operation, the switching characteristics do not change. For voltage imbalance conditions, the feedback action with the higher gate resistor has a slightly slower control action. The use of different gate resistors causes the switching transients to be slow, but the effect is similar to the effect of the snubber capacitance. The result of using different parameters in the gate drive circuit neither generates significant voltage imbalance, nor are the results very different from other test results, so they are not presented in this paper. The nominal value of gate resistance is 33 Ω. This value was considered to be a reasonable compromise between switching speed and stress on *TR3* and *TR4*.

IV. RESULTS

In the experiments, two major causes of voltage imbalances are considered. One is the voltage imbalance caused by external snubber capacitors and the other is the voltage imbalance caused by gate signal delays. For the imbalances caused by the delays, turn-on transients and the turn-off transients are considered separately because of their different characteristics.

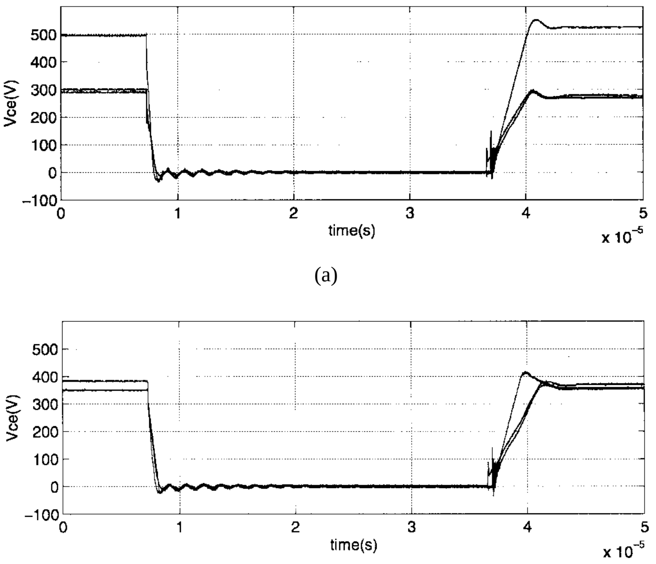
A. Snubber Capacitor Imbalance

The snubber circuits are the most influential elements that affect transient characteristics of the IGBT by the external power circuit. The turn-on and turn-off transients are dominated by the capacitor values. If every snubber capacitor is the same and only one snubber capacitor is small, the IGBT with smaller capacitor switches faster than the other devices. During the turn-on transient, switching transients are so fast that any overvoltages are not observed. During the turn-off transient, the dv/dt of the smaller snubber capacitor is faster than the other devices, so that it blocks higher voltage than other devices.

For test purposes, one IGBT has 50% of the snubber capacitance (0.1 μF) compared with other snubber capacitors (0.2 μF), so that dv/dt of the device with a small capacitor is twice the dv/dt of the rest of the devices. The dv/dt during the turn-off transients for the IGBT with a smaller snubber capacitance is fastest, so that it blocks the highest voltage. When the total voltage across the IGBT series connection reaches the dc voltage, the IGBT with smallest snubber capacitor blocks the highest voltage and the rest of the voltage is equally shared by the remaining devices. The snubber resistor for all IGBT's is 2 Ω.

Fig. 3(a) shows the voltage imbalance caused by different snubber capacitor values with an inductive load. Without active control, one device has an overvoltage near the device voltage rating because of the high dv/dt during turn-off transient. Since the balancing resistors are not used, the voltage imbalance during turn-off transients creates steady-state voltage imbalance. The bottom part of Fig. 3 shows the voltage balancing with active control. The voltages are well balanced to the reference for transient and steady states. During the turn-off transient, a slight voltage overshoot is observed due to the transient response of the controller.

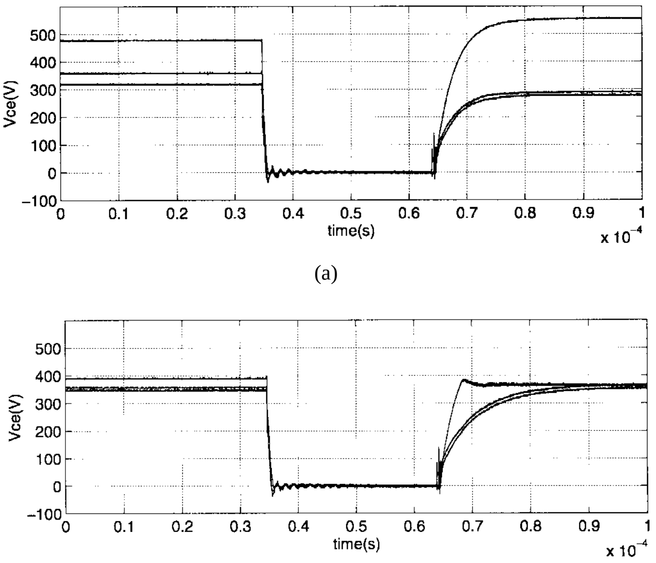
Fig. 4 shows the same results with a resistive load. A negligible overshoot is observed by the active control transient. Although voltage overshoot is not large, the active control lasts longer than in the inductive load case. The *RC* transient characteristics of the turn-off transient for the slower device make the active control response slow.



(a)

(b)

Fig. 3. Capacitor unbalance. Inductive loads (a) without and (b) with active control.



(a)

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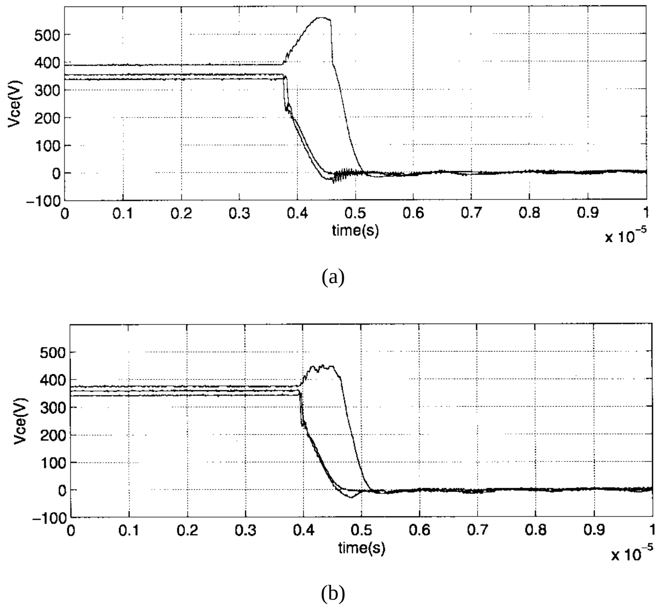
Fig. 4. Capacitor unbalance. Resistive loads (a) without and (b) with active control.

In both cases, a small amount of the overvoltage is monitored by the active control. Because of the delay in the active control itself, a proper margin should be applied for the reference. The way of setting the proper margin is discussed in Section V. Because such a large capacitance difference is an extreme case, the overvoltage in a practical application can be expected to be much smaller than the test results.

B. Turn-On Delay Imbalance

Even though turn-on delay does not create any voltage imbalance in steady state, a small delay during turn-on can create a voltage spike across the delayed IGBT. A high-voltage



(a)

(b)

Fig. 5. Turn-on transient. Inductive loads (a) without and (b) with active control.

spike is not observed with a delay of less than 0.3 μs because each IGBT is not fully saturated. In order to clearly observe the overvoltage, a 1-μs delay is created for one IGBT gate signal.

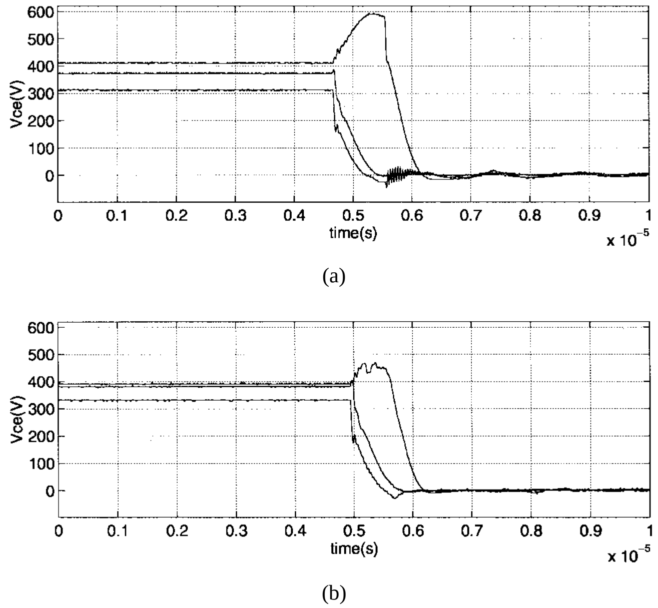
The top part of Fig. 5 shows the voltage spike during the turn-on transient in the inductive loads. The delayed gate drive signal generates a transient voltage spike across the device. Although this does not create steady-state voltage imbalance, power loss during the delay can generate local heating inside the device. Fig. 5(b) shows the active voltage balancing during transients. During the active control, a slightly larger voltage overshoot is observed than the unbalanced capacitor cases because of the fast switching during turn-on transients.

Fig. 6 shows the same results during a turn-on transient with a resistive load. During the turn-on transient, switching characteristics for resistive loads and inductive loads are similar.

C. Turn-Off Delay Imbalance

When there is a delay in the turn-off gate signal, there should be voltage imbalance among the series-connected IGBT's. The highest voltage imbalance is observed when one gate turn-off signal leads the rest of the turn-off signals. The delay in turn-off transients can create voltage imbalance, both during transients and steady state. In that case, the fastest device starts to block higher voltage in steady state than the delayed devices. For the test of the turn-off delay unbalancing, one device is turned off 1 μs earlier than other devices.

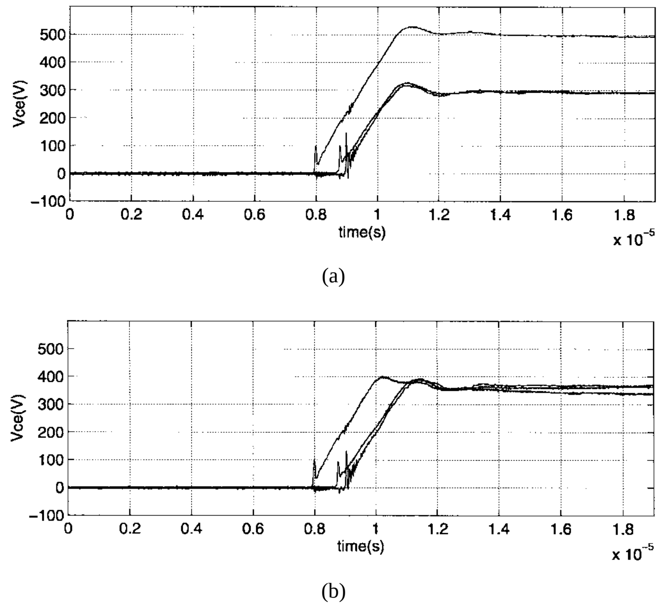
Fig. 7(a) shows the overvoltage during turn-off transient with an inductive load. The turn-off transient is longer than the 1-μs delay, so that the device voltage with fastest gate signal does not reach its steady-state value and the delay generates overvoltage across the device. Fig. 7(b) shows the voltage balancing created by the active control. The results show a negligible voltage overshoot during active control.



(a)

(b)

Fig. 6. Turn-on transient. Resistive loads (a) without and (b) with active control.



(a)

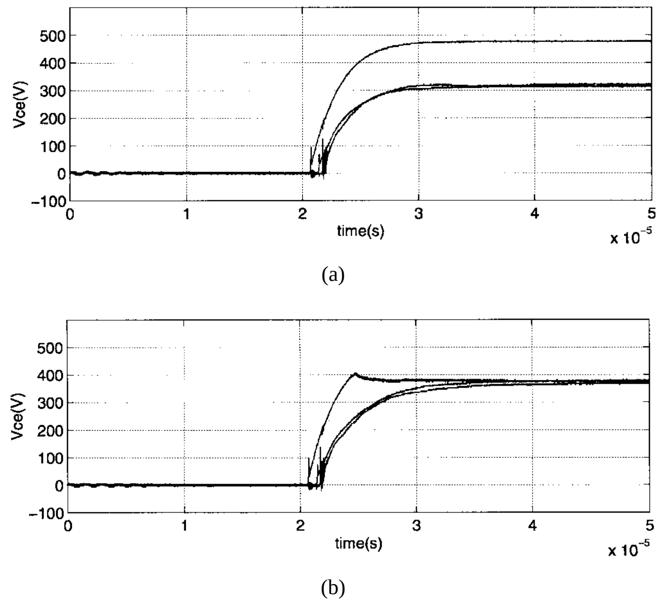
(b)

Fig. 7. Turn-off transient. Inductive loads (a) without and (b) with active control.

Fig. 8 shows the same results during the turn-off transient for a resistive load. Because of the slow *RC* transient during turn-off, the settling time of active control is longer than the inductive load case. In both cases, the voltage overshoot is controlled to within 10% of the reference voltage.

V. DISCUSSION

An active voltage-limiting gate driver has been designed and evaluated with different causes of voltage imbalance. The results show very fast overvoltage limiting control. In the design of the active voltage limiter, the following points



(a)

(b)

Fig. 8. Turn-off transient. Resistive loads (a) without and (b) with active control.

should be carefully considered in order to optimize the voltage limiting.

- *Overvoltage Reference*: It is customary to apply a voltage margin of 1.5–2.0 to IGBT's according to the application. In this case, the sum of the total overvoltage reference to each IGBT can be set between the system maximum voltage and the sum of the IGBT ratings for the series connection. If all of the IGBT's connected in series have overvoltages with active voltage control, the voltage is limited to the sum of the reference voltages, so that during the turn-off state, current can flow though the IGBT's, where the excess voltage is dropped across the load. In this case, all of the IGBT's are operated in active region and the power loss during the active control transient can create local heating inside the IGBT's. In order to prevent power device failure by local heating, the sum of the reference voltages should be larger than the maximum dc system voltage. Also, the active controller has its own transient voltage overshoot by its control delay, so that it is necessary to set the reference smaller than the IGBT rated voltage. Considering each IGBT is operated at 50%–70% of its voltage rating in practical applications, it is reasonable to set the voltage limit to 80%–85% of rated voltage of IGBT's.
- *Feedback Gain*: The transient characteristics of the voltage limiter is dominated by the feedback gain, which determines the current injected into the gate for a given overvoltage. If the feedback gain is too small, the feedback current is small, so that slow operation of voltage control can be expected and overvoltages can be large enough to reach the voltage rating of the IGBT. If the feedback gain is too high, abrupt current changes during its active region can generate excessive power losses, which might cause device failure. Therefore, the feedback gain should be set according to the overvoltage and power circuits. Care must be taken to use a comparator with a switching speed consistent with the intended response time. Comparator speed and dissipation in *TR3* and *TR4* suggest that response times much faster than 1 μs will be expensive to implement.

The overvoltage reference and feedback gain are closely related, because the active controller operates according to the feedback gain and the voltage error. It is a reasonable approach to set the reference voltage according to the system load condition and dc voltage variance. The feedback gain can be calculated according to the voltage error and margin between voltage reference and device voltage rating.

In order to maximize the speed of the active controller, the components in the active control should be selected, so that their frequency response should be much faster than the IGBT transient response. The merits of the proposed active control are as follows.

- For a voltage smaller than the reference, the active controller does not operate and create any delay or power losses in the IGBT operation.
- The active control does not use any digital logic, so it has continuous control and is fast.
- Each device is controlled independently, so that each IGBT can be treated as a module with voltage clamping. This modular nature enables stacking IGBT's without posing limitations. It also eliminates the need for comparing the voltages across the other series connected devices, thus simplifying the hardware and avoiding isolation problems.

VI. CONCLUSION

This paper has shown that it is possible to practically use series-connected IGBT's in very-high-voltage applications, with the following advantages.

- The power electronic system can be compact.
- Precise control can be achieved.
- Harmonics can be much reduced.
- Losses can be reduced.

In order to meet the system requirements in using series-connected IGBT's, voltage balancing should be well controlled with minimum cost and maximum efficiency. The proposed new method to control the voltage distribution by active control allows very-high-voltage application of IGBT's without slowing down switching speed or increasing the significant power losses by load-side voltage balancing.

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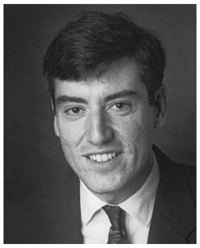

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