

Series and Parallel Operation of the Emitter Turn-Off (ETO) Thyristor

Yuxin Li, *Member, IEEE*, Alex Q. Huang, *Senior Member, IEEE*, and Kevin Motto

Abstract—By dramatically decreasing the storage time, the emitter turn-off thyristor (ETO) has a very good match in storage time. Storage time dispersion of less than ± 100 ns is normal for ETOs and can be further reduced through adjustment of the emitter switch gate resistance. Thus, the capacitance required for dynamic voltage balancing in the ETO series connection is significantly reduced. Uniform current sharing for parallel-connected ETOs is also guaranteed at the device level through the open-base p-n-p turn-off mechanism. The current-balancing inductance can be essentially removed. Theoretical analysis and experimental results of 53-mm ETOs are presented.

Index Terms—Emitter turn-off, emitter turn-off thyristor, gate turn-off thyristor, integrated gate-commutated thyristor, MOS turn-off thyristor, thyristor, unity gain turn-off.

I. INTRODUCTION

DEVICE-LEVEL series connection has been the most popular practice in industry to boost system power output. For a system equipped with series-connected devices, the operating voltage is increased so the current can be reduced to save connections. The stray inductance becomes less critical, allowing simpler system layout design.

The key issue in series connection is how to ensure uniform dynamic voltage sharing at both turn-off and turn-on transition. For insulated gate bipolar transistors (IGBTs), the dynamic voltage sharing can be achieved through active gate control without additional component [1]. However, because there is no forward-biased safe operation area (FBSOA), series-connected gate turn-off thyristors (GTOs) have to use passive voltage-balancing capacitor C_S as shown in Fig. 1. Under inductive load turn-off condition, the voltage difference between these two GTOs due to the storage time difference $2\Delta t_S$ is given by

$$\Delta V = \frac{2I_A \Delta t_S}{C_S}. \quad (1)$$

The storage time of a traditional GTO is about $20 \mu\text{s}$ [4], which is determined by the gate driver and the GTO's parameters such

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Y. Li is with Analog Devices, Inc., San Jose, CA 95134 USA (e-mail: yuxin.li@analog.com).

A. Q. Huang is with the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA (e-mail: huang@vt.edu).

K. L. Motto is with Northrop Grumman Corporation, Sykesville, MD 21784-5101 USA (e-mail: Kevin_l_motto@md.northgrum.com).

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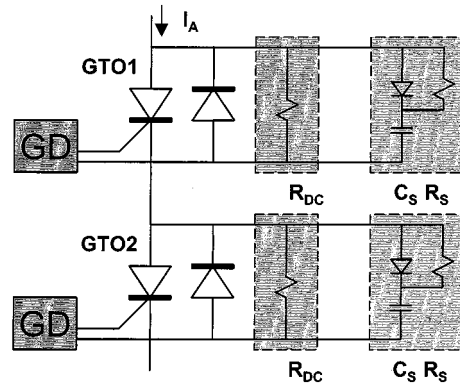


Fig. 1. Two GTOs series connection topology.

as wafer thickness, doping, etc. A storage time spread of $\pm 10\%$ is reasonable for GTOs made from the same process [2]. Thus, to maintain a maximum voltage difference of $\pm 10\%$ of their rated voltage during turn-off phase for two 1-kA/4.5-kV GTOs, the voltage-balancing capacitance required will be $4 \mu\text{F}$. This big capacitor should be avoided for the following three reasons. First, this high-voltage high-speed capacitor is very expensive. Second, a big C_S increases the energy trapped every time during turn-off ($0.5C_S V^2$), leading to the increased power dissipation in the discharge resistor. Third, a big C_S requires more switching transient time and limits the applicable switching frequency.

To alleviate these problems, a group of devices with much less storage time dispersion is required.

Device paralleling is another device-level option to increase the power handling capability of a system. Parallel connection can significantly increase a device's current capability, which is required in some applications such as circuit breakers where no single device can handle the current. The GTO is by far the gate-controllable device with the highest current handling capability. The state-of-the-art 6-in GTO has a maximum turn-off current capability of 6.0 kA. However, the parallel operation of a traditional GTO is very hard. In the case of two GTOs in parallel, the current will try to crowd to the slower device during the turn-off transient. With more current, the cathode injection of the slower device becomes stronger so the critical gate current to turn off the device also increases, which leads to a further delayed turn-off process for the slower device. This is, therefore, a positive feedback process. The slower GTO can easily enter a state that is beyond its turn-off capability. Traditionally, a dynamic current-balancing inductor L_B is required for each paralleled device to prevent current crowding as shown in Fig. 2. Large L_B increases voltage spike applied on the device and increases switching losses as well as cost and size of the system.

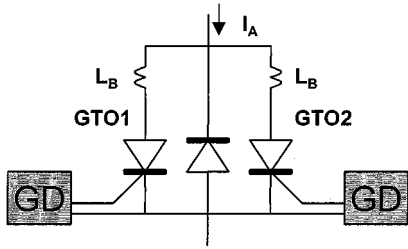


Fig. 2. Two GTOs parallel connection topology.

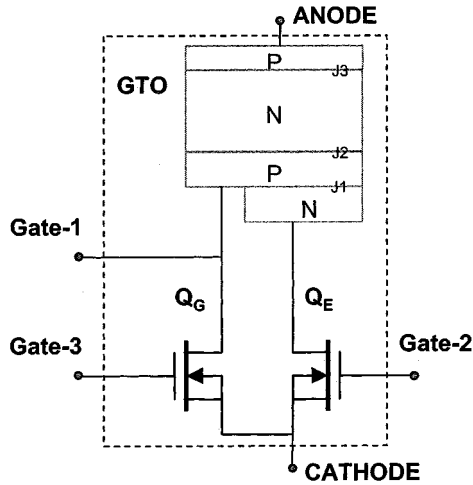


Fig. 3. Schematic diagram showing the operation principle of the ETO.

Issues of paralleling devices include ensuring dc current sharing and dynamic current sharing. Devices with uniform, resistive, and positive temperature coefficient $I-V$ characteristics will give a good dc current sharing (this is the case for MOSFETs). The parameter uniformity of paralleled devices, on the other hand, dominates the dynamic current sharing.

Devices with less storage time spread are also required to solve current crowding for parallel-connected devices.

The emitter turn-off thyristor (ETO) [3], [6] is a newly introduced high-power device with a significantly shrunken storage time and, thus, much smaller storage time dispersion. Also, in the ETO's turn-off transient, the traditional GTO's p-n-p-n latch-up mechanism is changed to an open-base p-n-p process, which implies better current sharing. This paper investigates the performance of the ETO under series and parallel connections.

II. PERFORMANCE OF THE ETO

The ETO is a GTO-MOSFET hybrid device as shown in Fig. 3. The two MOSFETs are operating as a complementary pair to help the GTOs turn off. Once the emitter switch Q_E is turned off and the gate switch Q_G is turned on, the GTO cathode current will be diverted to its gate almost instantly, realizing so-called “unity gain” turn-off condition, which means the GTO gate current equals the anode current. The benefit of the unity gain turn-off is twofold. First, the storage time, which is the time needed for the gate current to remove all minority charges in the p-base region, is now significantly decreased to about $1 \mu s$. Second, unlike the traditional GTO, the turn-off of an ETO is changed to an open-base p-n-p process that further ensures the

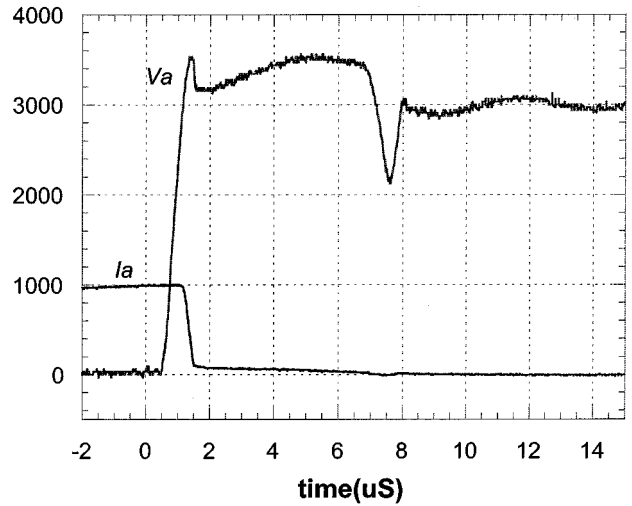


Fig. 4. 1-kA/4.5-kV ETO1045S snubberless turn-off at 25 C.



Fig. 5. Photograph of ETO1045S.

TABLE I
ETO STORAGE TIME AT 125C

| | ETO1 | ETO2 | ETO3 | ETO4 | ETO5 | ETO6 |
|---------------------|------|------|------|------|------|------|
| t_s (μsec) | 1.3 | 1.4 | 1.3 | 1.4 | 1.2 | 1.2 |

current uniform distribution among GTO cells over the turn-off transient. Consequently, the snubberless turn-off capability of the ETO has been demonstrated as shown in Fig. 4 [5]. Fig. 5 is a picture of the developed 53-mm 1-kA/4.5-kV ETO1045S, which is also used for this study.

III. ETOS IN SERIES CONNECTION

A. Dynamic Voltage Sharing During Turn-On and Turn-Off

With significantly decreased storage time, ETOS have much better storage time dispersion than that of the GTO. A storage time survey of six ETOS from the same batch is shown in Table I. The difference is within $\pm 10\%$ and the absolute value of $\Delta t_{S(max)}$ is reduced to about ± 100 ns.

Two 1.0-kA/4.5-kV ETO1045Ss with a storage time difference of 100 ns were used to demonstrate the improved series connection performance. The current is measured by a Rogowski coil. The dynamic voltage balancing capacitance is reduced to $0.5 \mu F$ due to the reduced Δt_S . Figs. 6 and 7 show the dynamic voltage on these two devices during turn-off and turn-on, respectively. The voltage difference during turn-off is only 0.2 kV, which is less than 5% of their rated voltage, when they are turned off at their rated current (1.0 kA). The

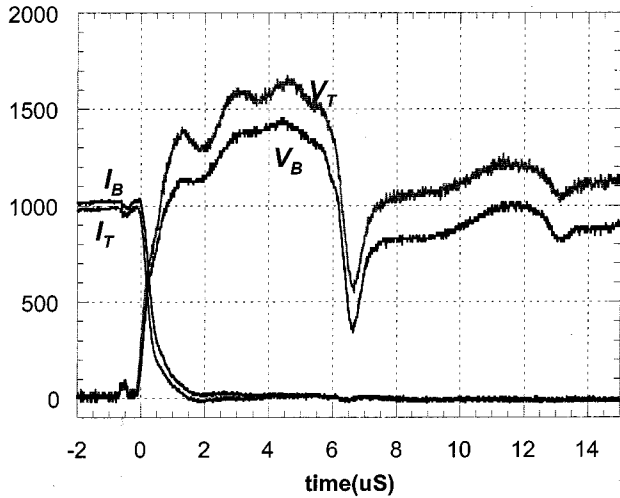


Fig. 6. Turn-off of two series-connected ETOs at 0.5 μF voltage balancing capacitance (V_T —top switch voltage; I_T —top switch current; V_B —bottom switch voltage; I_B —bottom switch current).

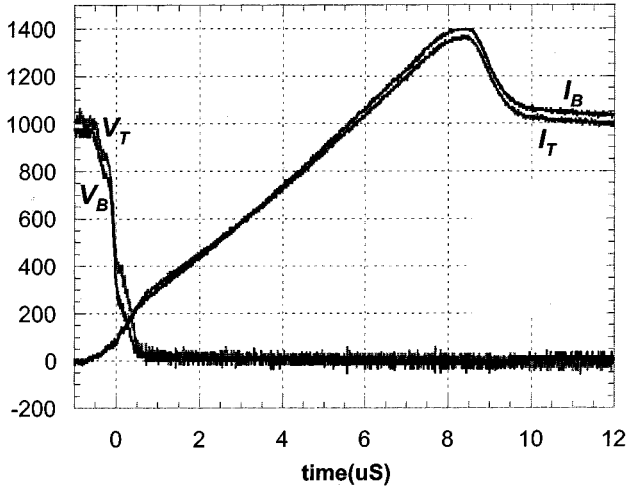


Fig. 7. Turn-on of two series-connected ETOs at 0.5 μF voltage balancing capacitance (V_T —top switch voltage; I_T —top switch current; V_B —bottom switch voltage; I_B —bottom switch current).

observed turn-on delay time difference is essentially nothing. Since a di/dt snubber is normally required to control the reverse recovery of the diode, turn-on is not a practical concern in series connection.

B. Storage Time Adjustment

The storage time of the ETO can be further adjusted by inserting a resistor in the gate of the emitter switch of the ETO, similarly to the case of the IGBT. This gate resistor will delay the turn-off process of the emitter switch and eventually delay the turn-off process of the ETO. Since this resistor stays with the device instead of with the gate driver, the ETO's storage time can be calibrated easily. Fig. 8 shows the experimental waveforms and Table II is a summary of the relationship between the storage time and the gate resistance for one specific ETO. With tightly matched storage time, ETOs can even do series connection without the help of a dv/dt snubber with an acceptable voltage-sharing performance.

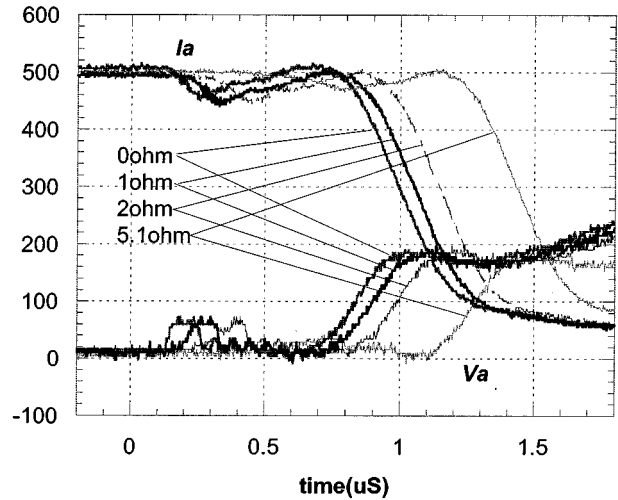


Fig. 8. ETOs storage time dependency on the gate resistance of the emitter switch.

TABLE II
ETO STORAGE TIME INCREASE WITH RESPECT TO ITS GATE RESISTANCE

| $R_G(\Omega)$ | 0 | 1 | 2 | 5.1 |
|---------------------|---|------|------|------|
| Δt_S (usec) | 0 | 0.06 | 0.15 | 0.42 |

C. System Savings Due to the Reduced Δt_S

The reduced storage time difference Δt_S implies big savings at the system level. For a system employing series-connected devices, if:

- devices' storage time dispersion is $t_S \pm \Delta t_S$;
- maximum designed static voltage for each device is V_S ;
- dynamic voltage balancing capacitance is C_S ;
- maximum turn-off current is I_M ;

then the maximum voltage sharing difference is

$$\Delta V_M = 2I_M \left(\frac{\Delta t_S}{C_S} \right). \quad (2)$$

ΔV_M can also be related to the maximum permitted static voltage V_S through

$$\Delta V_M \equiv kV_S \quad (3)$$

where k is the voltage-sharing index. From (2), k can be expressed as

$$k = 2 \left(\frac{I_M}{V_S} \right) \left(\frac{\Delta t_S}{C_S} \right). \quad (4)$$

For n devices in series connection, the worst case is that $(n-1)$ devices are having a longest storage time ($t_S + \Delta t_S$) and only one device has a shortest storage time ($t_S - \Delta t_S$). Then, the total voltage V_{DC} that these n devices can handle is

$$\begin{aligned} V_{DC} &= V_S + (n-1)(V_S - \Delta V_M) \\ &= nV_S - (n-1)\Delta V_M. \end{aligned} \quad (5)$$

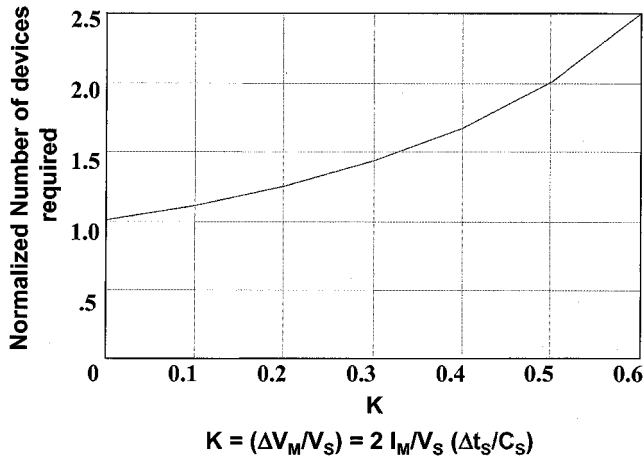


Fig. 9. Normalized number of series-connected devices needed to handle a certain voltage.

Thus, the number of devices needed to handle V_{DC} is

$$\begin{aligned} n &= \frac{V_{DC} - \Delta V_M}{V_S - \Delta V_M} \\ &\approx \frac{V_{DC}}{V_S - \Delta V_M} \\ &= \left(\frac{1}{1-k} \right) \left(\frac{V_{DC}}{V_S} \right). \end{aligned} \quad (6)$$

In an ideal case where all devices have the same storage time and share the same voltage during turn-off transient, k is, thus, zero so the number of devices needed is minimum (V_{DC}/V_S). When the sharing difference k is increasing, the normalized number of devices needed is increasing according to (6), as depicted in Fig. 9.

For a system employing GTOs in series, if the voltage-sharing index k is selected as 0.5, then twice as many as the minimum number devices is needed from Fig. 9. If the devices are replaced with the ETO, which has only one-twentieth the storage time difference, then the voltage-sharing index k will be 0.025—essentially the ideal case, so the number of devices needed is the minimum number. If the snubber capacitance is cut to one-tenth, then the voltage-sharing index k will be 0.25, which then requires a $1.4\times$ minimum device number. For high-voltage applications, the snubber capacitor means cost, size, and thermal management. A $10\times$ smaller snubber capacitance has great impact on the system.

IV. ETOS IN PARALLEL CONNECTION

A. DC Current Sharing

High-voltage GTOs are more likely to have a resistive $I-V$ characteristic that is good for dc current sharing. The series-connected MOSFET, which behaves like a ballast resistor, makes the ETOS $I-V$ even more resistive.

To avoid positive feedback of current crowding, a positive temperature coefficient $I-V$ is very important. Typical high-voltage GTOs have this feature above a critical current value. This critical current point, however, moves toward a lower current direction for the ETO because of the strong positive tem-

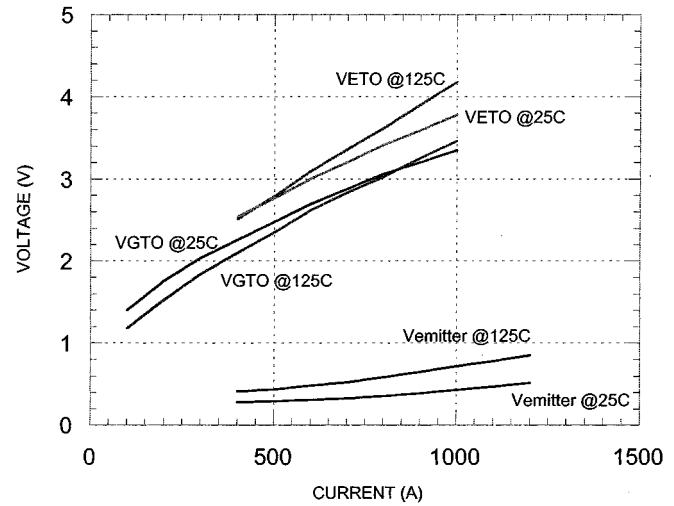


Fig. 10. Relationship of forward voltage drop versus temperature for ETO1045S.

perature coefficient of the series connected MOSFETs. Fig. 10 shows the ETO's measured forward $I-V$ characteristics.

B. Dynamic Current Sharing During Turn-Off Transient

The current sharing is a big problem for traditional GTOs operating in parallel connection because of their p-n-p-n latch-up mechanism. However, this mechanism is broken in the ETO turn-off operation. Due to the unity turn-off gain, the cathode injection is terminated quickly and the device functions like an open-base p-n-p transistor.

Under unity gain turn-off, the storage time is the time needed to remove all the minority carriers in the p-base layer. Since the cathode injection is cut off, minority carriers in the p-base will simply decrease from its initial density before turn-off. The current to remove p-base minority carriers is the device's gate current, which equals its anode current under the unity turn-off gain condition.

The ETO's storage time is almost a constant value over a wide current range. The minority carrier quantity in the p-base is in proportion to the anode current before turn-off process, and under unity turn-off gain, the minority carrier removing speed being the anode current.

Unlike the GTO, the storage time difference of the parallel-connected ETO will decrease. In the case of two ETOS in parallel, the current will crowd to the slower device with a longer storage time right after the faster ETO finishes its storage phase. However, more anode current means faster minority carrier removing speed, which makes the slower ETO's storage time shorter. This is a negative feedback process that alleviates current crowding.

Another feature of the ETOS' parallel operation is that the uniform current distribution among devices can be reestablished after the slowest device finishes its storage phase.

For the case of two ETOS in parallel as shown in Fig. 2 with a dv/dt snubber, the predicted minority carrier distribution in the GTO is illustrated in Fig. 11, and the current and voltage waveforms are shown in Fig. 12. The turn-off process starts from t_0 and at t_1 , both ETOS gain their unity turn-off gain. By t_2 ,

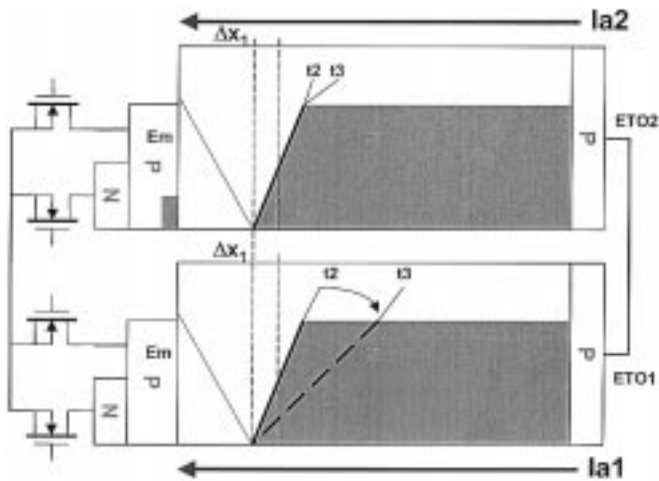


Fig. 11. GTOs parallel turn-off under unity-gain condition.

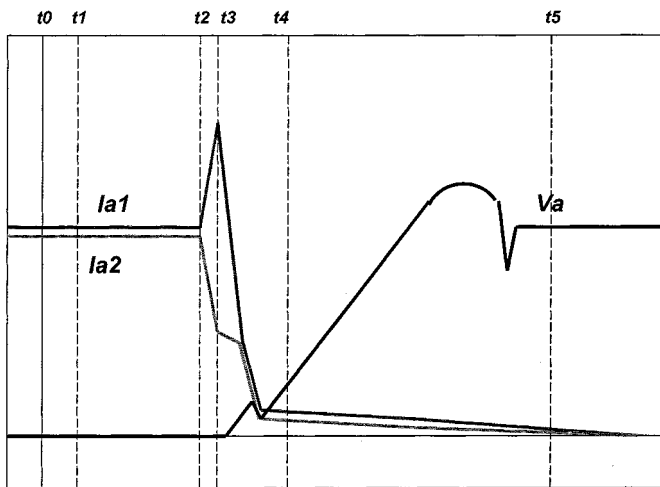


Fig. 12. Current-sharing process for ETO parallel connection.

ETO2 finishes its storage phase and enters the turn-off process while ETO1 is still in its storage phase. Between t_2 and t_3 , the voltage on ETO1 remains low at its forward voltage drop, which basically clamps the voltage on ETO2. Therefore, the depletion region length Δx_1 in the n^- layer of ETO2 cannot expand. In the steady state before t_2 , the minority carrier in the n^- region is almost a constant. Without further injection from the p-base after t_2 , these minority carriers will be gradually removed by the anode to cathode current. The current of ETO2 between t_2 and t_3 is the diffusion current determined by the minority carrier density gradient in the n^- region. Because there is no minority carrier injection at the cathode side, a portion of this current, namely, the electron current, acts as net minority carrier extraction current, and the gradient is decreasing, which reduces the current in ETO2. The extra current is transferred to ETO1. To overcome the loop stray inductance between the two devices, a little voltage is built up on ETO2.

By t_3 , ETO1 finishes its storage phase, too. From now on, until t_4 , both of the ETOs' currents are mainly their diffusion current determined by their minority carrier gradient in their n^- region. At t_3 instant, the gradient in ETO1 is higher so its

minority carrier removing speed is also higher. ETO1's anode current will decrease at a higher rate. On the other hand, the minority carrier gradient in ETO2 is lower after the previous process, so its minority carrier removing speed is lower, so is the anode current of ETO2. This process can be viewed as the faster device waiting for the slower device. In a short period after t_2 , uniform current distribution is established again.

Experimental results support the above theory. Two 1-kA/4.5-kV ETOs (ETO1 and ETO2) are used for the experiment. ETO1 has a 70-ns longer storage time than ETO2. The two ETOs are arranged 6 in away from each other with two bus bars across them. The stray inductance in the two devices' loop is about 100 nH.

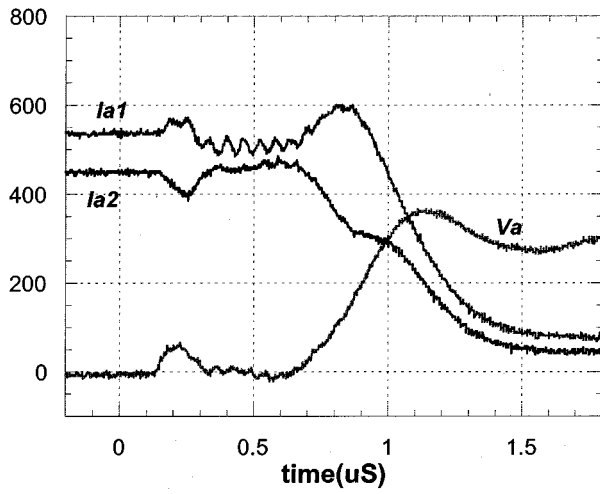
Fig. 13(a) shows these two ETOs' current-sharing characteristics under snubbed turn-off condition. The current transfer between time instant (0.15–0.3 μ s) is due to their gate driver difference. Because ETO2's gate driver is inherently 30 ns faster, the anode voltage of ETO2 has a net increase of its turn-off voltage (about 60 V) before ETO1 does. This set a voltage difference on the two devices' anode and introduces a small current commutation. However, this current crowding is harmless because this period is short and the voltage on the devices is still low.

The current crowding due to the storage time difference happens after time instant $t = 0.55 \mu$ s in Fig. 13(a). The anode voltage on ETO2 increases to overcome the two devices' loop stray inductance. The probing point (center point between the two devices) voltage as shown is, thus, also increased. After ETO1 enters its turn-off phase, ETO1's anode current decreases rapidly while ETO2's anode current is almost waiting (decreases very slowly). These two devices' anode currents decrease in a similar pattern after the current sharing is restored.

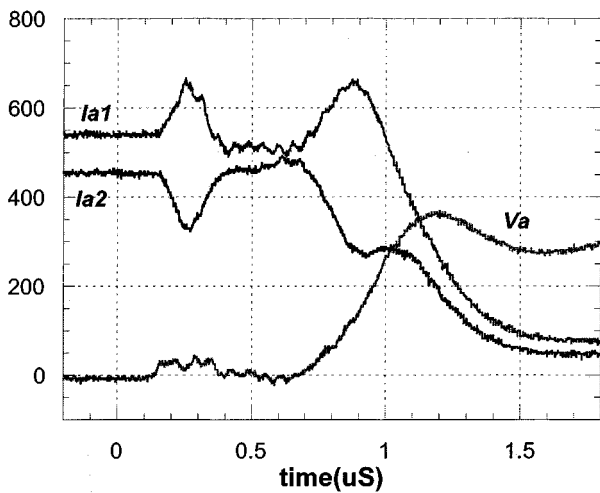
As discussed previously, the ETO's storage time can be adjusted through the gate resistance of its emitter switch. By inserting a 1- Ω resistor into the gate, ETO1 will have about 60 ns more delay, and the current crowding should be exaggerated. Fig. 13(b) shows the current sharing of this case. Stronger current crowding is observed. However, uniform current distribution is eventually restored. On the contrary, the current crowding will be improved by well-matched parallel devices. Fig. 13(c) shows the current sharing between the same two ETOs when a 1- Ω resistor is inserted into the gate of ETO2.

Current crowding during turn-off significantly increases the current stress of the slower device. However, the instant power stress is not that bad. For the case of Fig. 13(b), even the peak current of ETO1 is more than twice as much as the current in ETO2 at that time, their peak instant power, as shown in Fig. 14, is only 1.5 \times as high. The peak instant power of the slower device ETO1 appears very close to the point when the uniform current distribution is regained. Since ETOs can stand very high instant power (200–300 W/cm²) [5], current crowding toward the slower device does not threaten the device's safe operation area.

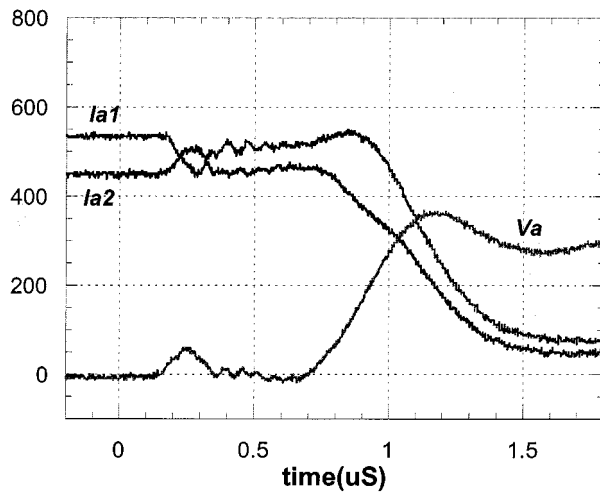
Since the device-level mechanism can prevent the current crowding and restore uniform current sharing after the storage phase, paralleled ETOs should also be capable of snubberless turn-off. Fig. 15 shows the current sharing at 2-kV snubberless turn-off condition. In the anode voltage rising phase, the anode



(a)



(b)



(c)

Fig. 13. Current sharing between two ETOs during turn-off ($V_{DC} = 1.0$ kV, $3 \mu\text{F}$ snubber, 25°C). (a) $t_{s1}-t_{s2} \sim 70$ ns. (b) $t_{s1}-t_{s2} \sim 130$ ns. (c) $t_{s1}-t_{s2} \sim 10$ ns.

currents of both the ETOs are due to the expansion of their depletion region. Since the devices' initial conditions, which determine minority carrier distributions in the n^- layer, are identical for the two ETOs, their displacement currents should also equal

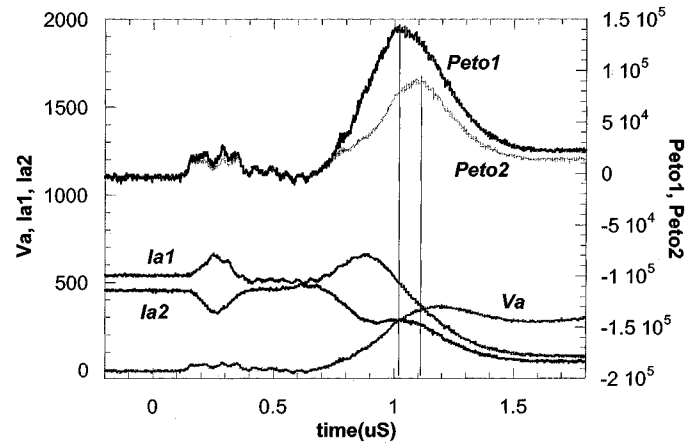


Fig. 14. Instant power stress on the parallel-connected ETOs during turn-off transient.

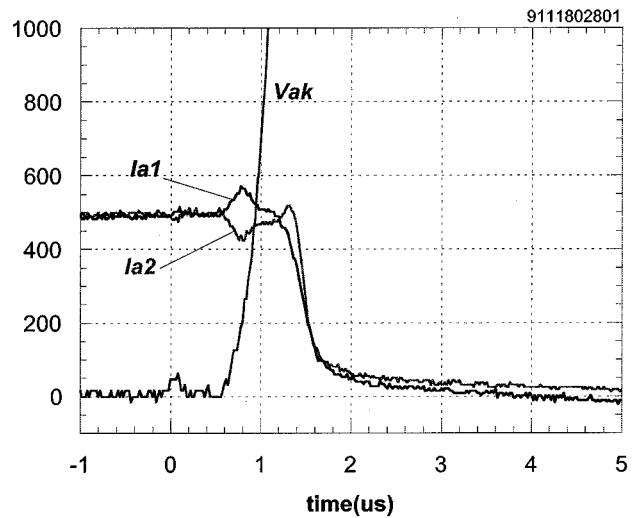


Fig. 15. Current sharing between two ETOs during snubberless turn-off ($V_{DC} = 2$ kV, 25°C).

to each other. This guarantees uniform stress on both of the ETOs at the point of highest instant power point. The tendency of restoring uniform current sharing is also obviously shown in Fig. 15. It can also be observed that there is a little current crowding right before the current fall. This is because of the minor difference of the devices' doping and physical parameters. The current nonuniform distribution caused by this is very small but the di/dt of one device is significantly increased. The increased di/dt is a threat to the snubberless turn-off capability of the ETO [5].

V. DISCUSSION

Most of the above-discussed theory can apply to other kinds of hard-driven GTOs such as MOS turn-off thyristors (MTOs), integrated gate-commutated thyristors (IGCTs), etc. They all have the merit of short storage time distribution, as does the ETO in series connection. Although their storage times cannot be adjusted simply through a gate resistor, it can be achieved at the gate-driver level or even on the controller level.

Without the series-connected MOSFET, the resistive forward $I-V$ characteristics of the MTO and the IGCT is not as good

as that of the ETO. However, this can be improved at the device-level design tradeoff. Both the MTO and the IGCT have the same negative feedback mechanism toward current crowding during the turn-off transient as the ETO because of the same open-base p-n-p turn-off nature. Compared to the ETO, the IGCT should be better at handling snubberless turn-off in parallel connection because it has no dependency on the anode falling di/dt [5].

VI. CONCLUSION

By dramatically decreasing the storage time, ETOs have a very good storage time agreement. Storage time dispersion of less than ± 100 ns is normal for ETOs and can be further reduced through adjustment of the emitter switch gate resistance. The capacitance required for dynamic voltage balancing in series connection is significantly reduced. The current sharing for paralleled ETOs is guaranteed at the device level through the open-base p-n-p turn-off mechanism. The required current-balancing inductance can be reduced or eliminated.

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Yuxin Li (S'98–M'01) was born in Hunan, China, in 1964. He received the B.Eng. degree in radio and electronics engineering in 1985 from Zhejiang University, Hangzhou, China, the M.Eng. degree in semiconductor devices in 1990 from Nanjing Electronic Devices Research Institute, Nanjing, China, and Zhengzhou University, Zhengzhou, China, and the Ph.D. degree in power electronics in 2000 from Virginia Polytechnic Institute and State University, Blacksburg.

He has been with the Power Management Product Line, Analog Devices, Inc., San Jose, CA, since 2000. From 1996 to 2000, he was with the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University. His research interests include power management of battery-powered systems, computing power solutions, switching-mode power supplies, medium-voltage power converters/inverters, and power semiconductor device characterization.



Alex Q. Huang (S'91–M'94–SM'97) received the B.Sc. degree in electronic engineering from Zhejiang University, Hangzhou, China, the M.Sc. degree in electronic engineering from Chengdu Institute of Radio Engineering, Chengdu, China, and the Ph.D. degree from Cambridge University, Cambridge, U.K., in 1983, 1986, and 1992, respectively.

He is currently an Associate Professor in the Center for Power Electronics Systems, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg. Since 1983, he has been involved in the development of modern power semiconductor devices and power integrated circuits. He fabricated the first IGBT power device in China in 1985. While at Cambridge University, he developed a high-voltage power IC process to integrate power devices and advanced CMOS devices using conventional CMOS technology. His current research interests are novel power devices and power ICs, monolithically integrated power management, and high-power solid-state devices and their applications in electric power regulation and motor drives. He has authored more than 80 papers published in international conference proceedings and journals and is the holder of six U.S. patents.

Dr. Huang was the recipient of a National Science Foundation Presidential Career Award.



Kevin Motto was born in Petersburg, VA, in 1975. He received the B.S. and M.S. degrees in electrical engineering from Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, in 1997 and 2000, respectively.

From 1998 to 2000, he was with the Center for Power Electronics System, Virginia Tech, as a Graduate Research Assistant. He researched high-power semiconductor devices and their application to medium-voltage inverters. Since 2000, he has been with Northrop Grumman Power/Control Systems, Sykesville, MD. His work is with high-power converters for military applications.