Performance Characterization of 1-kA/4.5-kV Symmetrical Emitter Turn-Off Thyristor (ETO)

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Abstract - **The Emitter Turn-Off Thyristor (ETO) is a hybrid power semiconductor device that turns off the Gate Turn-Off Thyristor (GTO) under the unity turn-off gain condition. This paper presents for the first time test results of a symmetrical ETO. The on-state voltage drops, snubberless forced turn-off losses, and load-commutated turn-off losses are characterized. The results show that the symmetrical ETO is suitable for applications that need high current and high reverse voltage blocking capability, such as a current source inverter (CSI).**

I. INTRODUCTION

High power converters are increasingly used in drives for heavy-duty traction, power quality management, and magnetic energy storage systems. For medium-voltage (2300V-6900V) large ac-drive applications, pulsewidth modulation (PWM) current source inverters with symmetrical GTOs have been successfully implemented [1-2]. However, the GTO has several disadvantages in applications [3-5]. During the turn-off transient, the P-N-P-N four-layer structure causes inhomogeneous transient current distribution that results in a small Reverse Biased Safe Operation Area (RBSOA). A dv/dt snubber is needed to ensure the GTO operates within the RBSOA during the turn-off process. During the turn-on transient, the P-N-P-N four-layer structure also causes the current crowding problem and therefore a turn-on di/dt limiting snubber is demanded. Furthermore, since the GTO is a current-control device, its gate driver is bulky and dissipates hundreds of watts in a typical application. The complicated GTO gate drivers usually result in a very long storage time and a turn-off gain between three and five. The operation frequency of the GTO is therefore limited to less than 500 Hz.

The dominant position of GTOs in megawatt applications is recently challenged by high power Insulated Gate Bipolar Transistors (IGBTs) that have high speed, large SOA and are easy to control. However, the conduction loss of the high power IGBTs is still much higher than that of the GTO. The IGBTs' high conduction loss results in lower system efficiency. Furthermore, since no symmetrical IGBTs are available now, the IGBT CSI is not attractive. This situation will continue in the near future. In the past few years, a lot of efforts have been made to improve the switching performance of the GTO-oriented devices. Two types of the GTO-based semiconductor device with wide RBSOA are developed at present. They are the MOS Turn-Off Thyristor (MTO) and the Integrated Gate Commutated Thyristor (IGCT) [6-7]. With dramatically improved switching performance, these GTO-based devices will help maintain the domination of GTO technology in high power areas.

The Emitter Turn-off Thyristor (ETO) [3] is another type of GTO technology based superior high power semiconductor devices. Based on the mature technology of the GTO and power MOSFET, the ETO provides a low cost and superior solution to megawatt applications. Theoretical analysis and experimental results suggest that the ETO has the combined advantages of both the GTO and the IGBT: GTOs' high voltage and current ratings, low forward voltage drop; IGBTs' voltage control; high switching speed; and wide RBSOA.

High power asymmetrical ETOs with current ratings of 1-kA to 4-kA, and voltage ratings of 1-kV to 6-kV have already been demonstrated by the authors [3, 8]. In this paper, the operation principles and characterization results of a 1-kA/4.5-KV symmetrical ETO are presented for the first time.

II. OPERATION PRINCIPLE OF THE ETO

According to the GTO theory [7], hard-driven technique can substantially improve the RBSOA and speed of the GTO. Under the hard-driven turn-off condition, the entire cathode current is quickly commutated to its gate before the anode voltage starts to rise. In this way, the thyrisor latch-up is interrupted and the whole turn-off process is like that of an open-base PNP transistor. This process is also called unity-gain turn-off.

The Emitter Turn-off Thyristor (ETO) is a MOS-GTO hybrid device that makes the GTO operating under the hard-driven condition. The equivalent circuits of the asymmetrical and symmetrical ETO are shown in Fig. 1(a) and (b), respectively. A symmetrical ETO can be easily realized by using a symmetrical GTO in series with an emitter switch Q_E and connecting gate switch Q_G to the GTO s gate. Compared to asymmetrical ETO, the symmetrical ETO has no N+ region in the anode side to short junction J3 so it can block reverse voltage. During normal forced turn-off transient, Q_E is turned off and Q_G is turned on. The GTO s cathode current is totally bypassed via switch Q_G before the anode voltage begins to rise. In this way, the thyristor latch-up is broken and the ETO is turned off under unity turn-off gain condition. It should be stress that the turn-off process is a voltage-controlled process. So the gate driver of the ETO is very compact and dissipates much less power. During turn-on transient, Q_E is turned on and Q_G is turned off. A high current pulse is injected

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into the GTO gate to reduce the turn-on delay time and improve the turn-on di/dt rating.

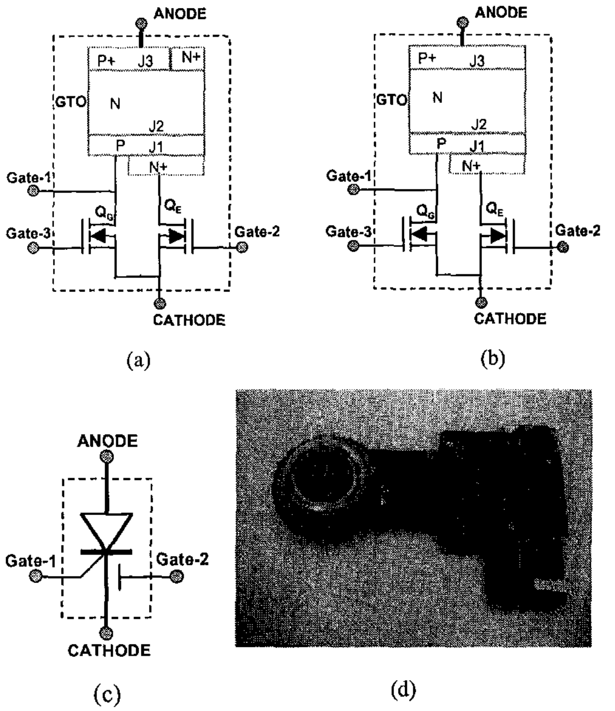

Fig. 1. (a) Asymmetrical ETO equivalent circuit, (b) Symmetrical ETO equivalent circuit, (c) Circuit symbol and (d) Picture of 1-kA/4.5-kV symmetrical ETO with its gate driver.

III. Experimental Setup And Results

Experimental results are obtained on a 53-mm 1-kA/4.5-kV symmetrical ETO (ETO1045). Results are then compared with asymmetrical ETO with the same rating. A 53-mm fast-recovery diode (SM60CXC574) is also tested for its reverse recovery characteristics in order to establish benchmark result for the symmetrical ETO.

A. On-state Characteristics

The on-state voltage drop of the ETOs was measured by turning on the device to discharge a charged capacitor. The ETO current will first increase to the rated current value and then decrease to zero while the capacitor is discharged. The I-V curve of the device can then be obtained by monitoring the current and voltage drop of the ETO during this discharging process. The discharging time constant in the test circuit is about 80 μs. Test results for the symmetrical ETO, asymmetrical ETO and the diode are shown in Fig. 2. The on-state voltage drop of the asymmetrical ETO is higher than that of the symmetrical ETO due to its anode-short structure that results in less conductivity modulation.

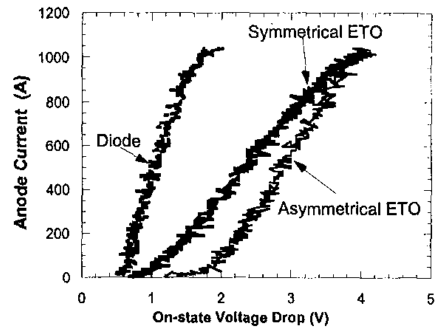

Fig. 2. On-state voltage drop comparison.

B. Forced Commutation Characteristics

In a current source inverter (CSI), the symmetrical ETO can be used as an active switch to perform the forced turn-off and normal turn-on action. Since the symmetrical ETO has high dv/dt capability due to its unity-gain turn-off, the turn-off tests are performed without a dv/dt snubber (snubberless turn-off). The forced turn-off loss of the symmetrical ETO increases when the anode current or anode voltage (V_{bus}) increases as shown in Fig. 3. The forced turn-off loss of the asymmetrical ETO is lower than that of the symmetrical ETO due to its anode-short structure that results in less current tail. The turn-off time (t_{off}) of the symmetrical ETO is almost constant (2.2 μs) when the anode current or anode voltage increases, where t_{off} is defined as the time between the start of the turn-off signal and the beginning of the current tail (see Fig. 4). Furthermore, the storage time, t_s, is only about 0.9 μs and does not change when the voltage and current vary, where t_s is defined as the time between the start of turn-off signal and the increase in anode voltage, as described in Fig. 4. The small and un-varying storage time make the ETO suitable for series or parallel connection which is usually required by high power systems. A typical snubberless forced turn-off waveform of the symmetrical ETO is displayed in Fig. 4.

The turn-on process of the symmetrical ETO is similar to that of a classical GTO and is affected by the regenerative action of the two transistors embedded in the four P-N-P-N layers. The di/dt rating of the ETO can be much higher than that of a GTO because the ETO gate driver is much more closely placed to the gate than the GTO case [see Fig. 1 (d)]. However, in order to limit the reverse recovery stress of the freewheeling diode or load-commutated ETO, a di/dt snubber is used in our test to limit the turn-on di/dt to about 80 A/μs. The turn-on loss will increase with the anode current increasing, as shown in Fig. 5. The turn-on loss is small compared to the snubberless forced turn-off loss because the di/dt limiting snubber minimizes the voltage and current overlapping area. The turn-on delay time keeps almost constant (0.3μs) at different turn-on current levels. A typical turn-on waveform is shown in Fig. 6.

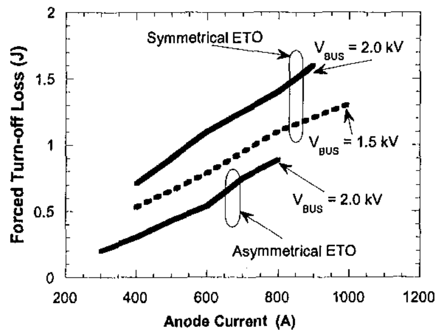

Fig. 3. Snubberless forced turn-off losses.

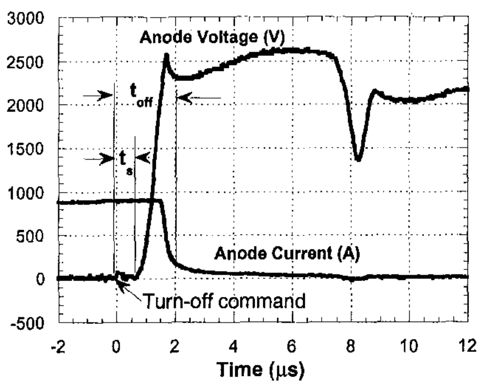

Fig. 4. Snubberless forced turn-off waveforms.

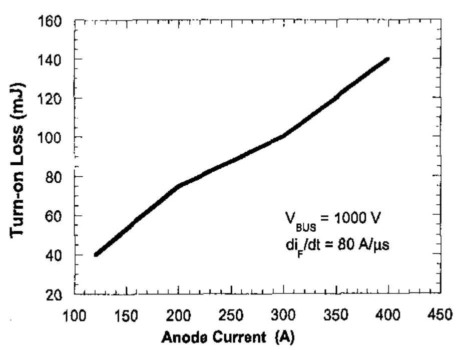

Fig. 5. Turn-on losses with di/dt snubber.

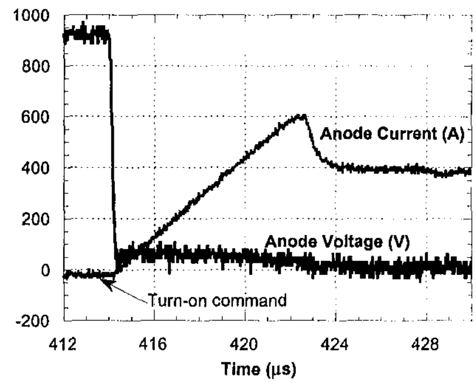

Fig. 6. Turn-on waveforms.

C. Load Commutation Characteristics

The symmetrical ETO has the reverse blocking capability and can therefore be used in circuits requiring to block reverse voltage. The load-commutated turn-off (reverse recovery) can be realized in the circuit when the voltage across the ETO changes polarity. This situation is typically encountered in a CSI. The turn-off process in this case is similar to a diode reverse-recovery. The symmetrical ETO was tested in this case by using it as a freewheeling diode. During the test, the turn-on signal is fed to the gate of the symmetrical ETO all the time. First, a positive anode-cathode voltage is applied and the load current will go through the tested ETO. Then the anode-cathode voltage changes to negative and the symmetrical ETO is load-commutated turned off. The test results are shown in Figs. 7-9, where I_{rr}, E_{rec}, t_{rr} and Q_{rr} are reverse recovery current, reverse recovery loss, reverse recovery time and storage charge, respectively. The reverse recovery current and storage charge of the symmetrical ETO are lager than those of the standard diode, because the symmetrical ETO is designed for optimized active switching purpose instead of the reverse blocking performance. Also during the reverse recovery process, the ETO behaves like an open-base PNP transistor and there is an additional amount of holes injected into n-drift region from the p-base region on the cathode side. The reverse recovery loss is much higher than the forced turn-off loss because although the two processes are very similar, the charge stored in ETO is favorable to a forced turn-off than a load-commutated turn-off. This can be observed by comparing the dv/dt rate (2.5 kV/μs) in Fig. 4 with the dv/dt rate (1.0 kV/μs) in Fig. 9.

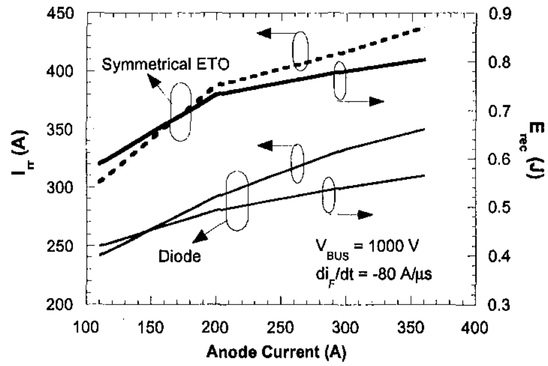

Fig. 7. Reverse recovery currents and reverse recovery losses.

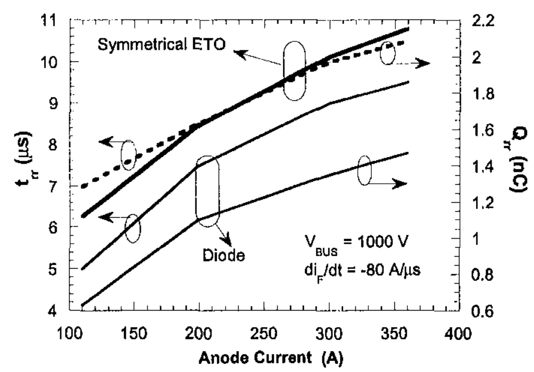

Fig. 8. Storage charge and reverse recovery time.

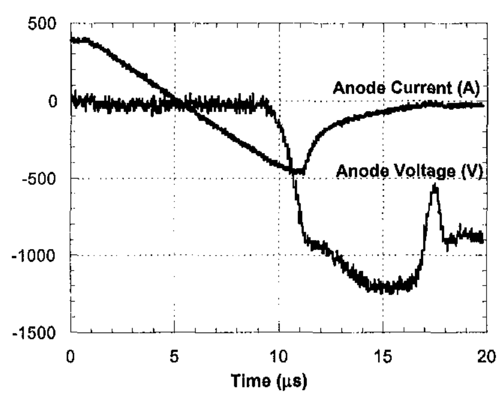

Fig. 9. Load-commutated turn-off (reverse recovery) waveforms.

D. Loss Comparison in CSI

Due to the reverse voltage blocking capability, the symmetrical ETO is very suitable for applying to CSI to make the circuit simple. Fig. 10 shows the simplified power circuit of the CSI using symmetrical ETOs. Compared to the asymmetrical ETO CSI shown in Fig. 11, the symmetrical ETO CSI uses less semiconductor devices. The conduction loss and cost of the CSI therefore is reduced.

The converter loss is compared between the CSI composed of symmetrical ETOs and the CSI using asymmetrical ETOs in series with diodes. The CSI conditions are as follow: DC link current I_{dc} = 500 A; the maximum line-to-line output voltage is 2 kV; di/dt = 100 A/μs; Modulation index M = 0.8; Load power factor is 0.8; the control strategy is space-vector PWM control. The loss comparison results are shown in Fig. 12, where E_{on}, E_{off}, E_{rec} and E_{cond} are the turn-on loss, forced turn-off loss, load-commutated turn-off loss and conduction loss. The asymmetrical ETO CSI has lower switching loss due to the lower forced turn-off loss and reverse recovery loss. However, the symmetrical ETO CSI has much lower conduction loss that results in a 5.7% decrease of the total loss.

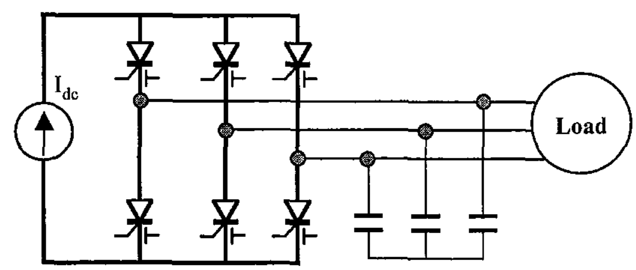

Fig. 10. The simplified power circuit of symmetrical ETO CSI.

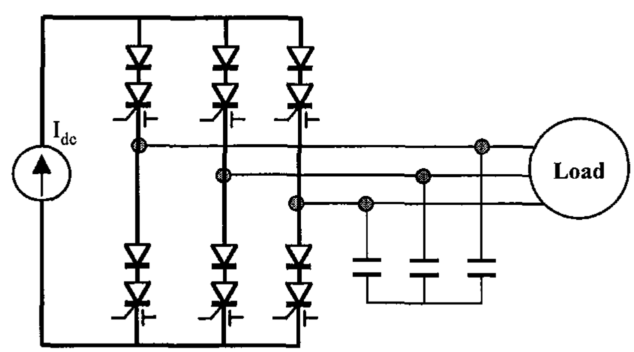

Fig. 11. The simplified power circuit of asymmetrical ETO CSI.

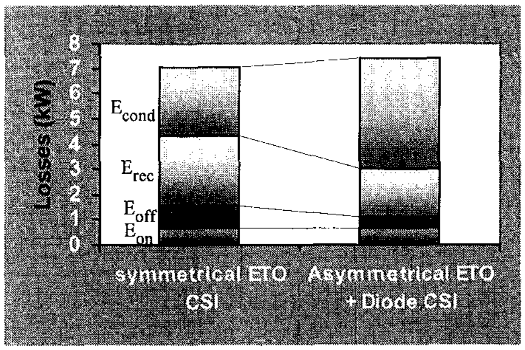

Fig. 12. Loss comparison.

IV. CONCLUSIONS

This paper experimentally characterizes the symmetrical ETO for the first time. The on-state voltage drops, the active turn-on and turn-off loss, and the load-commutated turn-off loss are measured. The results show that the symmetrical ETO has lower on-state voltage drops than that of the asymmetrical ETO. The symmetrical ETO also has the snubberless turn-off capability. Although the load-commuted turn-off loss is higher than that of a commercial diode, the symmetrical ETO is still suitable to apply in the high power circuits that need reverse voltage blocking capability, due to the lower conduction loss and simplicity of the circuit without dv/dt snubber.

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