

The Gen-3 Emitter Turn-Off Thyristor

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The emitter turn-off thyristor (ETO) is the first in a new family of high power devices that are suitable for high-performance power conversion systems (PCS), which are an important part of energy storage systems (ESS) [1,2,3]. Benefiting from the ETO's snubberless turn-off capability and low switching times, systems using the ETO device can have high switching frequencies and low snubber requirements, which can increase a system's dynamic response as well as reduce the system's cost and size.

The ETO consists of an emitter switch (low voltage metal-oxide semiconductor field effect transistor, MOSFET) in series with a gate turn-off thyristor (GTO). By turning off the emitter switch MOSFETs, a high voltage pulse is applied between the cathode and gate of the GTO. If this voltage is high enough compared to the gate loop inductance of the ETO, the GTO gate current will increase rapidly to the anode current level and the cathode current will decrease to zero before the anode voltage starts to rise. In this condition, the positive feedback loop of the GTO is broken. The npn-transistor turns off first and the main GTO turns off in the rugged open-base pnp-transistor mode. At this time, the ETO achieves the so-called unity turn-off gain. The turn-off in true open-base pnp mode is the key to achieving high speed and large turn-off current capability. It is also clear that the ETO uses the anode current to provide the turn-off energy; hence it dramatically saves drive power needed in high frequency operation when compared to competing technologies like the Integrated Gate Commutated Thyristor (IGCT) [4].

Recently, a new generation of the ETO, Gen-3 ETO, has been developed [4]. Gen-3 ETO employs a 91mm buffered layer GTO for low conduction and switching losses. New circuit and housing designs have been applied to the Gen-3 ETO to achieve high current, snubberless turn-off, high reliability, efficient manufacturability, and low cost.

Fig. 1 shows a diagram of the Gen-3 ETO. The Gen-3 ETO includes a commercial GTO, a printed circuit board (PCB) where all the electronic components are placed, and metal plates to connect the GTO and the PCB. In the ETO, an emitter switch Q_E is placed in series with the GTO, and a gate switch, Q_G , is connected to the GTO's gate. There is a current source between the gate and cathode of the GTO. The Q_E , Q_G , and the current source are controlled by the drive circuit. The logic circuit gets the turn-on and turn-off signals from the controller through optical fiber. When the ETO is commanded to turn on, the emitter switch Q_E is turned on and the gate switch Q_G is turned off. At the same time, a high current firing pulse is injected into the GTO's gate by a current source, just like turning on a conventional GTO. Since Q_E has a very low conduction drop, the ETO has low conduction losses with its forward drop determined primarily by the GTO. When the ETO is commanded to turn off, the emitter switch Q_E is turned off and the gate switch Q_G is turned on. The GTO's cathode current path is cut off and the cathode current has to commute to the gate switch, Q_G , via the GTO's gate, which finally turns off the GTO; hence the ETO.

During the ETO's on-state, all the anode current will go through the MOSFETs. The emitter switch of the ETO acts as a small linear resistor in the normal conduction mode; hence the voltage drop across the emitter switch Q_E reflects the current through the device and can therefore be used for feedback and protection purposes [5]. Additionally, a temperature sensor is employed to obtain ETO case temperature information. Combining the voltage drop and temperature information, a logic circuit is provided to obtain precise current information from the ETO. This current information is used for the system's closed-loop current control and it significantly reduces the ETO cost. It can also be used for over-current protection purposes. The logic circuit generates a pulse-width modulation (PWM) waveform whose duty cycle is proportional to the ETO's current. The PWM signal is sent by an optical transmitter to the outside controller for current control purposes.

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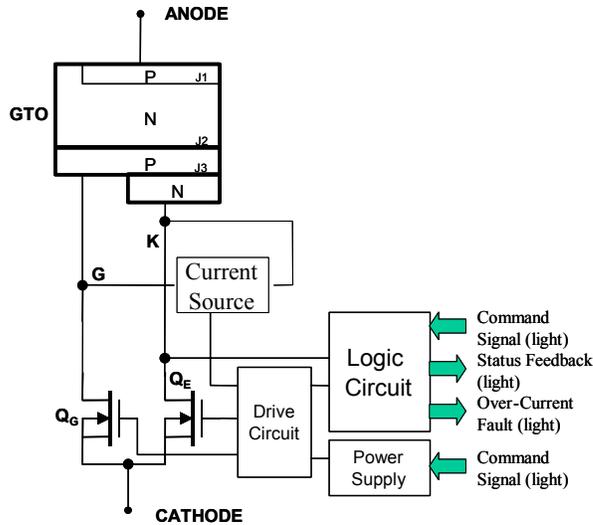


Fig. 1. Block diagram of the Gen-3 ETO.

The Gen-3 ETO also has a built-in protection system as shown in Fig. 2. The temperature of the GTO and the power MOSFETs are measured constantly. If the temperature exceeds the safe operating range, an over-temperature signal can be generated. The ETO's power supply voltages are also monitored in time. An abnormal voltage output can trigger a voltage-abnormal signal. Taking advantage of the sensed current signal, the Gen-3 ETO can generate an over-current signal when the ETO's current reaches the abnormal range. All of the protection signals are analyzed by the control network. The control network can shut down the ETO or just send out a fault signal to the external controller according to the user's setting. The control network also sends the state signal to the external controller, indicating the ETO is in the on- or off-state. All the output signals are sent to the controller through optical fibers. With the built-in protection system and the fast turn-off mechanism, the ETO can turn-off before a fault has risen beyond the controllable level. This advantage is very important for the converters that provide energy to the electric utility grid. And when a system fault is cleared, the ETO can begin operating again. The ETO's over-current function can also be used as a solid-state breaker in power system protection applications.

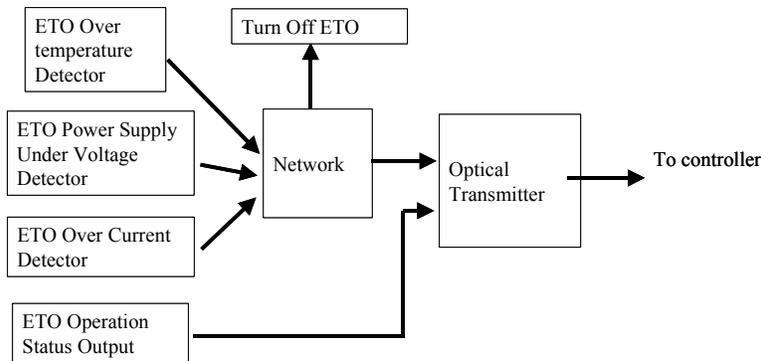


Fig. 2. The Gen-3 ETO's built-in protection system

Fig. 3 shows a picture of the Gen-3 ETO. The power MOSFETs are on both sides and in a ring shape to increase the current and thermal handling ability that ensures the 1500A RMS current and 4000A snubberless switching capability. A planar PCB-based transformer and inductor are employed to increase the manufacturability and reliability. The optical fiber interface with status feedback and built-in ETO current sensing output make it easy to use and is compatible with IGCTs. The AC supply voltage input makes the ETO easy to use for transformer isolation.

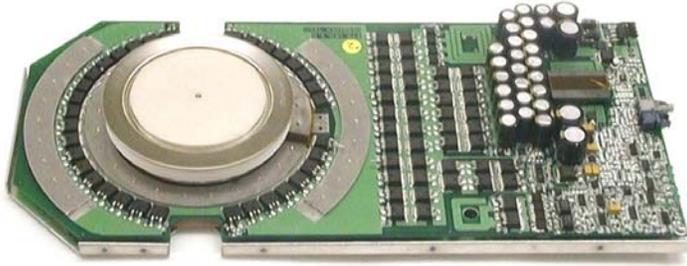


Fig. 3. The picture of the Gen-3 ETO.

A boost type converter is employed for the Gen-3 ETO testing. Fig. 4 shows the test circuit for the Gen-3 ETO and Fig. 5 shows a picture of the test circuit for the Gen-3 ETO. In a typical test, the ETO (DUT) is initially off, and the high voltage capacitor bank C_{DC} is charged to the voltage that the ETO will experience during switching. When the testing begins, the ETO is turned on and C_{DC} charges the load inductor L_L . When the current flowing through the ETO reaches the desired value, the ETO is commanded to turn off. The total load current will still go through the ETO until its anode voltage V_a reaches the bus voltage V_b . Then the ETO's anode current begins to be commutated to the free-wheeling diode and the clamp circuit. The ETO will see a voltage spike due to the stray inductance of the circuits. However, this spike is limited to a safe value by the clamp circuit. The ETO has the highest stress during the interval, when the current and voltage are simultaneously high.

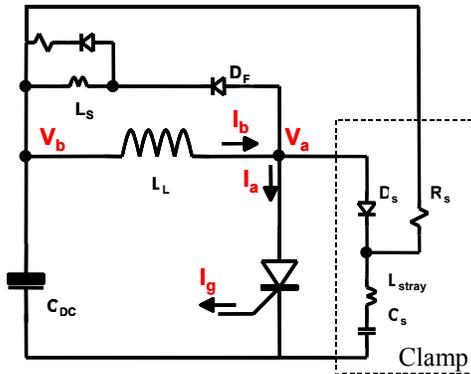


Fig. 4. The test circuit for the Gen-3 ETO.

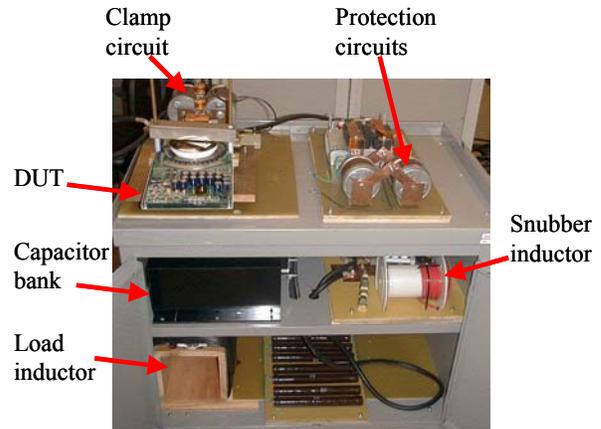


Fig. 5. A picture of the test circuit for the Gen-3 ETO.

Fig. 6 shows the turn-off waveform of the Gen-3 ETO at 4000A on a 2200V DC bus without snubber. The turn-off operation begins with the emitter switch Q_e turning-off and the gate switch Q_g turning-on. After the Q_e turns off, the voltage on Q_e will rise. This voltage will force the GTO's cathode current to be commutated to the GTO's gate until the cathode current becomes zero, to achieve so-called unity turn-off gain. From the time the ETO begins turning off to the unity turn-off gain point, it takes about 600ns to transfer 4000A to the gate. So it can be calculated that the turn-off gate current rate of increase is about 7000A/us. After the unity turn-off gain, the anode current remains constant, flowing through the PNP transistor to the GTO gate. The minority carriers in the P-base region are pulled out by this current until the main junction J_2 is recovered. It takes about another 600ns until the storage time finishes. Then the voltage increases to the DC link voltage value and the minority carriers in the n- region are swept out. After this time, the anode voltage has a spike and the anode current falls rapidly to its tail value. Finally, the anode current decreases slowly, determined by the minority carrier recombination in the undepleted n- region. The ETO takes only 5us after receiving the turn-off signal until the anode current reaches zero.

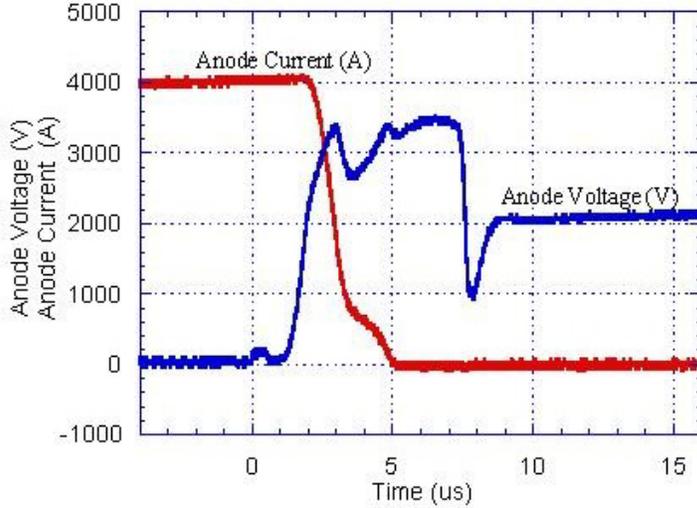


Fig. 6. The snubberless turn-off waveform of the Gen-3 ETO at $I_a=4000A$, $V_{dc}=2200V$, and $T_j=25\text{ C}$.

From Fig. 6, it also can be calculated that the maximum power of the DUT during turn-off is about 10MW. So it can be calculated that the maximum power density during turn-off of the Gen-3 ETO reaches approximately:

$$\frac{P_{\max}}{\pi * \left(\frac{9.1cm}{2}\right)^2} = 1.538 * 10^5 W / cm^2$$

The current density reaches:

$$\frac{I_{\max}}{\pi * \left(\frac{9.1cm}{2}\right)^2} = 61.5 A / cm^2$$

Fig. 7 shows the on-state characteristics of the Gen-3 ETO at $T_j=25\text{ C}$. Fig. 8 shows the turn-off losses of Gen-3 ETO at the 3uf snubber and snubberless conditions as a function of anode current and bus voltage at $T_j=25\text{ C}$.

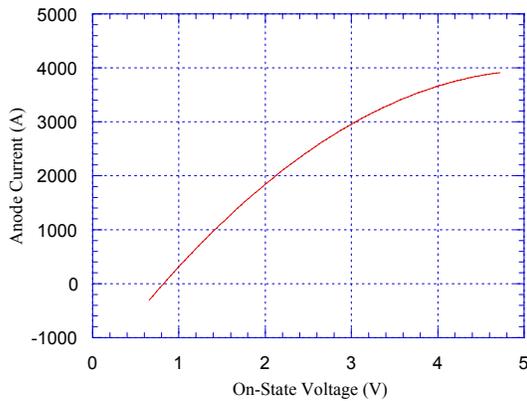


Fig. 7. The on-state characteristics of Gen-3 ETO at 25C.

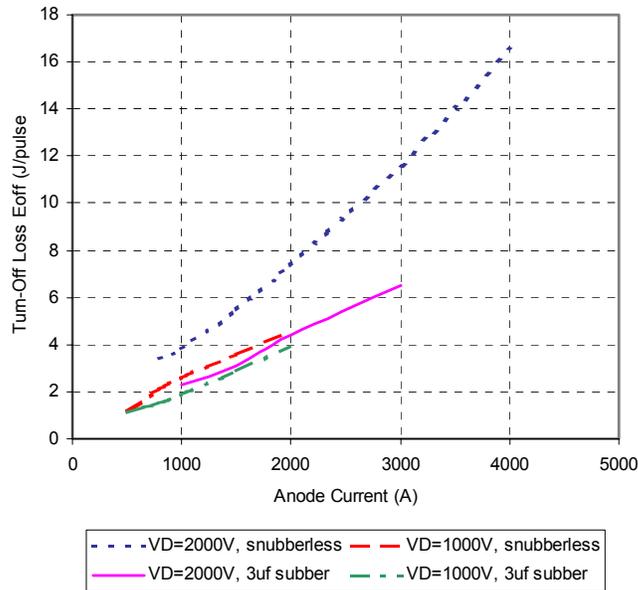


Fig. 8. Measured turn-off losses of Gen-3 ETO

From Fig. 8, it can be seen that the turn-off losses increase almost linearly as the anode current increases at a given bus voltage. Due to the high turn-off speed, the snubberless turn-off loss is only slightly higher than that with the snubber.

From the design and the experimental results of the Gen-3 ETO, it can be seen that the Gen-3 ETO has advantages such as 4000A capability, snubberless turn-off capability, low conduction loss, fast switching speed, built-in current sensing, high reliability, low control power, and easy manufacturability. Using the Gen-3 ETO as the switch, a power converter can have higher switching frequency, higher efficiency, smaller size and lower cost than it would using the traditional GTO. The Gen-3 ETO is suitable for the applications in distributed energy resources, energy storage systems, FACTs, and power system protection.

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