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Emitter Turn-off Thyristor (ETO) - A High Power Semiconductor Switch

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Abstract **- In today's electric power system, solid state power electronics technology plays more and more important roles and the demand for mega-watt level power ratings is increasing. The development of mega-watt power converters strongly depends on the state-of-the-art of power semiconductor technology. The Emitter Turn-off Thyristor (ETO) is a new emerging high power semiconductor switch which combines the advantages of Gate Turn-off Thyristor's (GTO) high voltage and current capability and MOS easy gate control. Its superior control characteristics combined with its high speed, wider RBSOA, higher controllable maximum current, forward current saturation capability, its on-device current sensing and low cost make the ET0 the most promising power device in high power, smart control applications. Future, ETO switches under development will also pack with additional features that no-competing technologies offer, including built-in voltage, current and temperature sensing capability, control-power self-generation capability and high-voltage current saturation capability. These capabilities make ETO a very promising power semiconductor device to reduce the cost of converter-based transmission controllers while improving the controller output power, dynamic performance, and operating reliability.**

Index Terms **- Semi Conductor Switches, ETO, GTO, IGBT, IGCT**

I. INTRODUCTION

Advancements in the power electronics systems have been directly related to the availability of improved power semiconductor devices. The device performance greatly determines the efficiency, reliability, volume, and cost of the power electronics system. Thyristor technology has long been the only solution to megawatt power applications. The combined index of its forward voltage drop, blocking voltage and conducting current is the best among power semiconductor devices. However, its major drawback is the inability to control the current except through self-commutation. The need for a controllable high power switch has resulted in the development of Gate Turn-off Thyristor (GTO) and Insulated Gate Bipolar Transistor (IGBT).

Recent developments of high power IGBTs are challenging the leadership position of GTOs in megawatt applications due to its high speed, large safe operating area (SOA) and easy control. But compared to IGBT, the GTO still has the advantage of much high power handling capability. However the GTO has several drawbacks in applications.

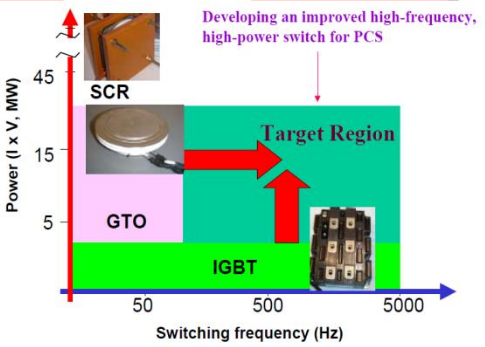

Fig 1.1: Targeted to improve the limitations of the Present High Power Devices [1]

The major drawbacks of the GTO device are the requirement for a complex gate drive circuit due to its current control characteristic, and its relatively poor reverse bias safe operating area (RBSOA) due to the uncontrollable current filamentation among GTO cells during device turn-off. These gate drivers are usually bulky and have very slow transient response, resulting in a very long storage time and a turn-off gain between three to five. The operation frequency of the GTO is therefore limited to less than one kilo-Hertz. This poor RBSOA capability is also the main reason for employing a dv/dt snubber in the GTO turn-off circuit so as to avoid simultaneous high voltage and high current across the device. The inhomogeneous current distribution during the turn-on transient results in the di/dt problem and demands a turn-on di/dt limiting snubber. Effective solutions to these two problems are critical to maintain GTO's superiority in high power applications.

High-power converters are increasingly used in drives for heavy-duty traction, power quality management and magnetic energy storage systems. Figure-1.1 shows targeted to improve the limitations of the present high power devices [1]. To meet the demand for advanced high power semiconductor devices, renewed efforts have been made to improve a GTO-oriented device in the past few years. Based on fundamental analysis regarding the RBSOA and control of the GTO, The Emitter Turn-off Thyristor (ETO) is developed. The Emitter Turn-off Thyristor (ET0) is major stride in the development of GTO technology based superior high power semiconductor devices. The emitter turn-off thyristor (ETO) is a new type of superior high-power semiconductor device that is suitable for use in high-frequency and high-power converters. Theoretical analysis and experimental results suggest that the ET0 has the combined advantages of both the GTO and the IGBT:

- GTOs' high voltage and current ratings
- IGBTs' voltage control
- High switching speed, wider RBSOA and high reliability.
- Built-in device voltage, current and temperature sensors
- Control power self-generation capability
- Low forward voltage drop

II. Basic Concept of The ETO

Three main characteristics of the traditional GTO have to be improved in order to compete with the IGBT and maintain their dominance in high power applications. First, the bulky high current gate driver has to be eliminated. This can be achieved if a voltage-controlled device can be made. Second, the RBSOA of the GTO has to be improved. The RBSOA of traditional GTOs is limited by the current filamentation and crowding problems because each of the GTO's cell has a different storage time. Non-uniform current distribution happens during device turn-off. Significant de-rating is therefore required resulting in a small RBSOSA. Third, the speed of the GTO has to improve. This requires the reduction of the storage time, current fall time and tail time and improvement in dV/dt capability.

According to the GTO theory, the RBSOA and speed of the GTO can be improved dramatically by utilizing the so called hard-driven technique. Under the hard-driven turn-off condition, the GTO's cathode current is almost instantly commutated to its gate before the anode voltage starts to rise. In this way, the GTO's emitter junction is totally reverse biased during the turn-off transient and the whole turn-off process is like an open-base PNP transistor turn-off. This process is also known as unity-gain turn-off. The hard-driven turn off process benefits the GTO in several ways. The maximum current of the GTO is dramatically increased while the limitation for each GTO cell remains unchanged. A hard-driven GTO therefore has wider RBSOA than conventional GTOs. Hard-driven GTOs also have improved speed because of the rapid removal of charges by a very large gate current.

The ET0 is a GTO-MOSFET hybrid device as shown in Figure-2.1 [2]. The two MOSFETs are operating as a complementary pair to help the GTO's turn-off. In the ETO, a GTO is in series with an emitter switch Qe, and another switch Qg is connected to its gate. The turn-off of the emitter switch cuts off the GTO's cathode current path and the entire cathode currents are transferred to the gate path. In this way, the latch-up mechanism of the GTO is broken and the ETO is turned off under a unity-gain turn-off condition (also known as a hard driven turn-off condition).Therefore, the ETO has a wide RBSOA and snuberless turn-off capability. It is important to note that the turn-off process is a voltage controlled process. A traditional gate-2 is used to turn-on the ETO.

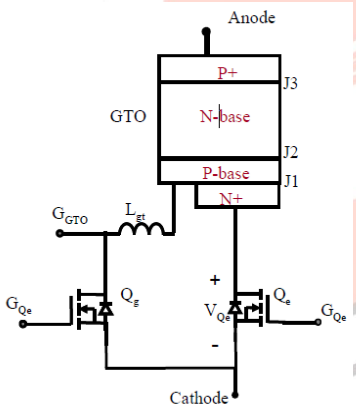

Fig 2.1: ETO equivalent circuit [2]

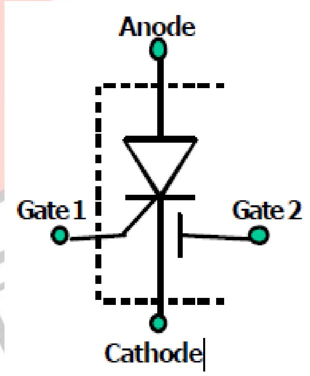

Fig 2.2: ETO symbol [2]

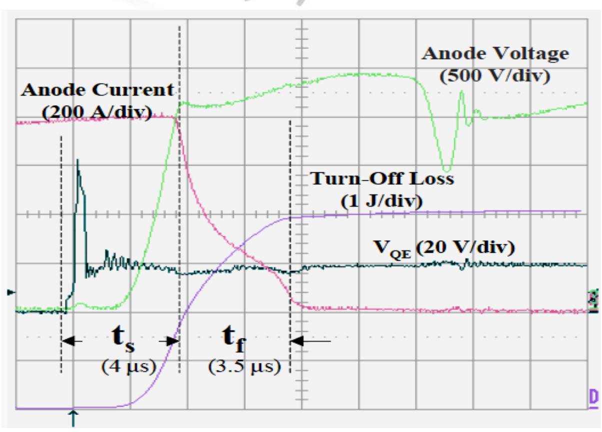

Fig 2.3: Snubberless Turn-off waveform of ETO [2]

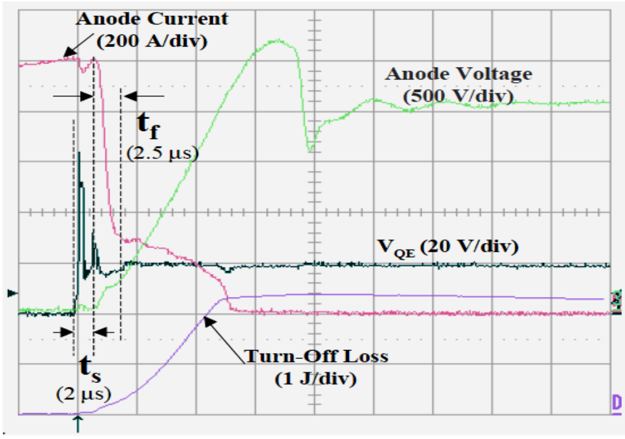

Fig 2.4: ETO Turn-off waveform with dV/dt Snubber [2]

It is very important to mention that both the emitter switch Qe and the gate switch Qg are not subject to high voltages, no matter how high the voltage is applied to the ETO. Qg is connected with gate-drain shorted; hence it always operates along its transfer characteristic. The voltage across Qg is clamped at a value slightly higher than its threshold voltage. And because the inner structure of the GTO's gate-cathode is a PN junction, the maximum voltage applied to the emitter switch Qe can't exceed that of Qg.

In real applications, a dV/dt turn-off snubber is usually applied to reduce the device's turn-off loss and to improve its reliability. With a dV/dt snubber, compared to the snuberless case, the ETO has a lower storage time and current fall time since the device current starts to drop once the anode voltage begins to rise, as indicated in next page. Figure-2.3 shows the snuberless turn-off waveform of ETO [2] and Figure-2.4 shows the ETO turn-off waveform with dV/dt snubber [2].

During the turn-on transient, Qe is turned on and Qg is turned off. A high current pulse is injected into the GTO's gate by the integrated gate driver in order to reduce the turn-on delay time and to improve the turn-on di/dt rating. The built-in PNP and NPN transistors inside the GTO latch up quickly and the anode voltage of the ETO collapses to a low voltage. So the turn-on process of the ETO is similar to that of a GTO. The ETO's compact structure and low gate loop inductance (about 10 nH), a gate current pulse with high amplitude and rise rate can be applied; therefore an ETO can be uniformly turned on without current crowding problems.

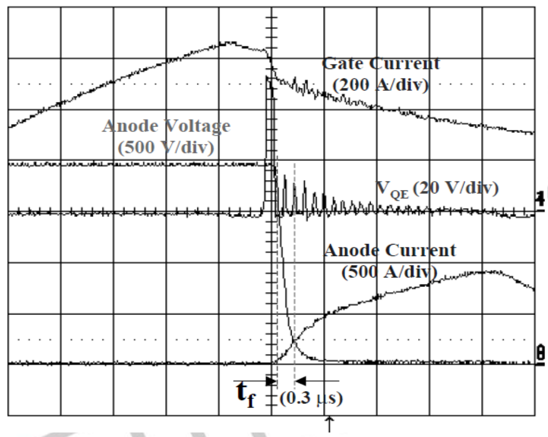

Fig 2.5: Turn-on waveforms of the ETO [2]

Figure-2.5 shows the uniform turn-on waveforms of the ETO [2]. By applying a pulsed gate current (IGM = 500A, diG/dt = 4 kA/μs, pulse width = 20 μs), the device voltage collapses quickly from 2 kV to about 200 V within 0.3 μs and continuously decreases despite the fast-rising anode current. This means that the built-in NPN transistor part of the GTO is turned on first and goes through its linear region to its quasi-saturation region before regenerative switching begins. So the ETO's turn-on process is similar to that of a transistor with uniform current distribution. The maximum device current rise rate is improved; the turn-on loss is very small, and therefore is negligible.

III. The Built-In Current Sensor And Over Current Protection of The ETO

The current sensor is an important element in the power electronics systems for the measurement, protection, and control purposes. In ETO, built-in current sensor, this can measure the ETO current during its on-state. The sensed current information is sent out by an optical PWM signal which can be easily received and used for control purpose. The built-in current sensing function can also be used in the over-current protection purpose.

The over-current caused by the short circuit, malfunction, or the component failure is severe fault situation that can result in further failure of the power converter if appropriate remedial action is not taken in time. The over-current protection of the conventional GTO based converter is more complicated and difficult than that of the MOSFET, BJT, or IGBT based converters. For the MOSFET, BJT, or the IGBT, the accidental over-current can cause the device to go out of the saturation region and enter the active region, and the rising voltage of the device will limit the current. In this situation, the converter can be protected if the device is commanded to shut down quickly. However, the latching devices such as GTO cannot enter such active region to limit the current. On contrary, the large fault current will make the GTO to latch more strongly. GTO takes relatively longer time to turn off due to its longer storage time, which also increases with the current. If the rising rate of the fault current is too fast, the current will exceed the maximum controllable current of the GTO during the storage time, and cause the GTO turn-off failure. In conventional technology, when over-current situation happens, the GTO will be kept on and let the fault current be cut off by the protection elements such as fuses.

- **The ETO Built-in Current Sensor**

The emitter turn-off thyristor (ETO) is a MOS-GTO hybrid high power device. Inside the ETO, the GTO is connected in series with the MOSFET's. When ETO is conducting current, the total current will go through both the GTO and the MOSFET's. In this situation, the MOSFET's act as a small linear resistor whose voltage drops is proportional to the current through it. Based on this principle, the ETO's built-in current sensor is designed.

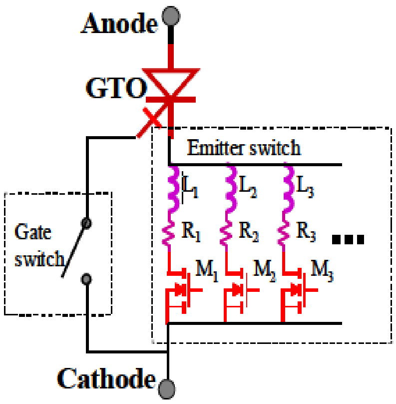

Fig 3.1: ETO equivalent circuit (for built-in current sensor) [5]

Figure-3.1 shows the ETO equivalent circuit [5]. The emitter switch consists of many MOSFET's in parallel. These MOSFET's have very good current sharing capability due to their strong positive temperature coefficient. As shown in Figure-3.1, the parasitic resistance and inductance R1, L1, R2, L2, etc, which caused by the layout of the MOSFET's and the circuit routing, may affect the current sharing of the MOSFET's and increase the ETO current conduction loss. To reduce these parasitic effects, the circuits are put in a multi-layer PCB, and these MOSFET's are arranged in a ring shape and put very close around the GTO. By following this approach, the parasitic effects are minimized and can be ignored for the current sensing. So we can get the simplified equivalent circuit shown in Figure-3.2 [5]. During the on-state as shown in Figure-3.2, the gate switch is off and the emitter switch is on. The ETO current will go through both the GTO and the emitter switch MOSFET's, which are also used for the current sensing purpose since voltage drop across MOSFETs reflect current through them. In the off-state as shown in Figure-3.3, the emitter switch is kept off and gate switch is on [5]. The voltage across the emitter switch MOSFETs does not reflect (zero current) through them.

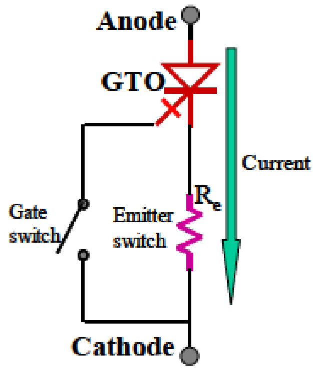

Fig 3.2: ETO Simplified Equivalent Circuit (ON State) [5]

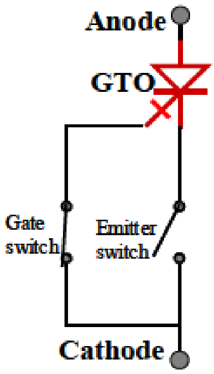

Fig 3.3: ETO Simplified Equivalent Circuit (OFF State) [5]

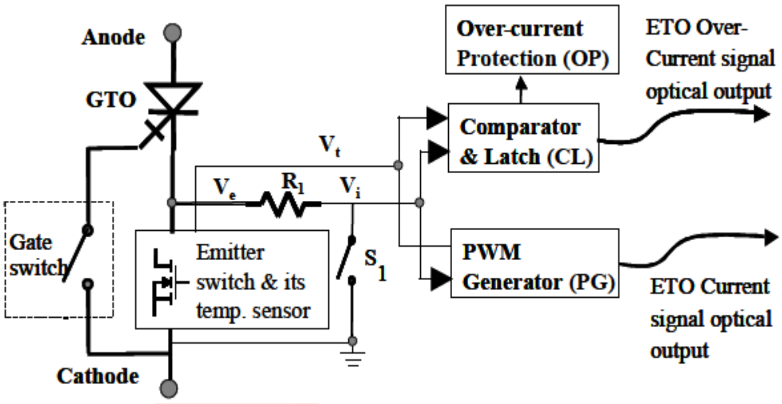

Fig 3.4: The block diagram of the ETO built-in current sensor and over-current protection [5]

Figure-3.4 shows the block diagram of the ETO built-in current sensor and over-current protection [5]. The voltage across the emitter switch Ve is sensed, and sent across a resistorR1 to the PWM generator (PG) and the comparator and latch (CL). There is a switch S1connecting R1 and electrical ground. In addition, the temperature of the ETO emitter switch is also sensed and transferred to a voltage signal Vt. Vt is also sent to the PG and the CL. In the ETO on state, S1 is opened and the Ve, which is proportional to the current through the emitter switch, equals to Vi. In the ETO off state, S1 is closed and the zero voltage, which means that the current through the emitter switch is zero, equals to Vi. Vi is received by PG and CL. The PG generates a PWM signal whose duty-cycle is proportional to Vi. Then the PWM signal is transformed to the optical signal and sent out through the optical fiber.

- **The ETO Over-Current Protection**

The ETO can shut down the over-current fast and automatically due to its built-in current sensing function, fast turn off speed, and high current turn off capability. Based on the ETO built-in current sensor, the ETO over-current protection circuit was built. In CL, Vi is constantly compared to a trigger voltage by a fast comparator. Once this voltage is bigger than the trigger voltage, the comparator will trigger the latch, and an over-current warning signal will be generated and locked. This signal is also sent to the over-current protection block to turn off the ETO. The ETO emitter switch temperature information Vt is also sent to CL. The trigger voltage can be adjusted by Vt. Then the over-current trigger value will not be affected by the temperature. The over-current warning signal is also sent out by the optical fiber. In some applications, the ETO may not be desired to turn off when over-current happens. In these situations, the over-current warning signal can be used by the controller to freeze all the ETO's or trigger the circuit breaker to shut down the fault current.

The ETO dramatically reduces its storage time to about 1μs through the unity gain turn-off. Therefore, the ETO has a much faster turn-off speed than that of the conventional GTO. Combining with the built-in current sensor, the ETO can detect the over-current and trigger the turn-off very fast and shut down the ETO before the fault current reaches the maximum ETO controllable turn-off value.

The device over-current is usually caused by the short circuit, the malfunction, or the component failure. When these fault conditions happen, the current will lose control and rise until the over-current protection of the ETO triggers. In fault conditions, the current rising rate is limited by the di/dt snubber or the stray inductors of the circuit. If the current is below the maximum ETO turn-off current after the over-current protection delay, the ETO and the system can be safely protected.

The ETO built-in current sensor is a low cost, high precision, and convenient to use function. This function can be easily used for the current control purpose. Due to its built-in current sensor, fast switching speed, and high current turn off capability, the ETO can shut down the fault over-current within a very short time. The ETO's built-in current sensor and over-current protection function can be used to improve the performance, and reliability, as well as reduce the cost of the high power electronics systems.

COMPARISON OF ETO, IGCT AND IGBT

The ETO is a hybrid power semiconductor device that turns off the Gate Turn-off Thyristor (GTO) under the unity turn-off gain condition. To meet the demand for advanced high power semiconductor switches, renewed efforts have been made to improve thyristor based devices in the past few years. If the GTO can be turned off under the so called unity-gain condition or hard driven turn-off, the SOA capability of GTO can be largely improved. The Integrated Gate Commutating Thyristor (IGCT), a specially developed GTO that has very low gate loop stray inductance is connected to a negative power supply through a low on-resistance MOSFET. Once the MOSFET is turned on, the negative power supply will force the cathode current communicate to the gate so that the unity turn-off gain can be achieved. Recent developments of high power Insulated Gate Bi-polar Transistor (IGBT) are challenging the dominant position of GTOs in megawatt applications due to its higher speed, wider SOA and easy control. However, IGBT’s voltage/current rating is still much lower than that of GTOs.

A. Device Losses

The loss of a switching device is one of the most important characteristics. The total device losses include the conduction losses and the switching losses, between which there are always tradeoffs. Figure-4.1 shows the on-state voltages of IGBT, IGCT and ETO [3] and Figure-4.2 shows the switching losses characteristics of IGBT, IGCT and ETO [3].

Due to the existence of a di/dt snubber, the turn-on losses of the IGCT and ETO are very small and can be neglected. Based on the losses shown in Figures-4.1 and Figure-4.2, the total device loss of ETO, IGCT and IGBT can be calculated. Figure-4.3 shows the device total losses at 500Hz switching frequency [3] and Figure-4.4 shows the device total losses at 1 kHz switching frequency [3].

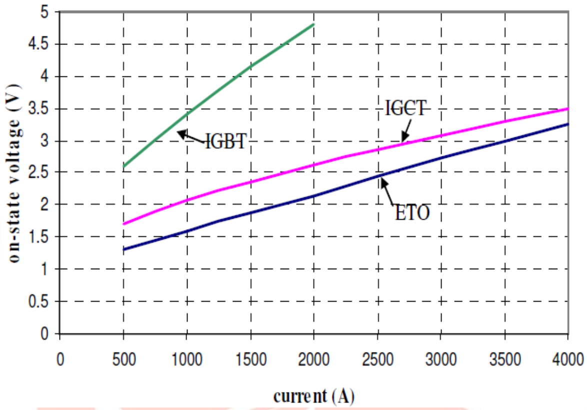

Fig 4.1: On-State Voltages of IGBT, IGCT and ETO [3]

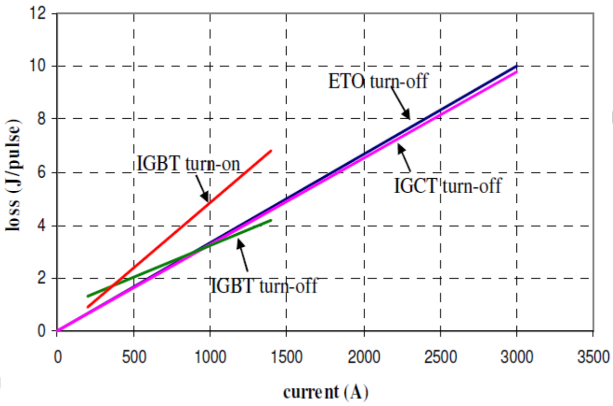

Fig 4.2: Switching losses Characteristics of IGBT, IGCT and ETO [3]

From Figures-4.3 and Figure-4.4, it can be seen that ETO and IGCT have similar total losses but much lower than that of the IGBT. This comparison demonstrates the need to use devices based on thyristor technology for very high power applications. ETO and IGCT are superior in this regard.

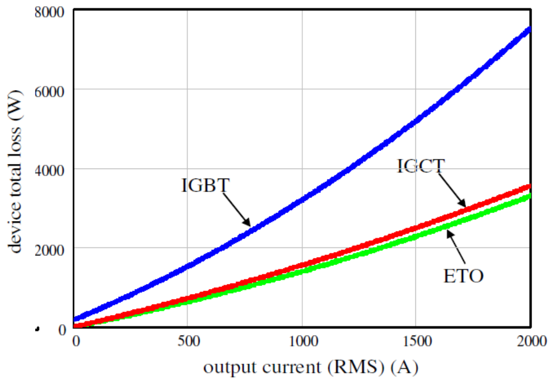

Fig 4.3: Device total losses at 500Hz switching frequency [3]

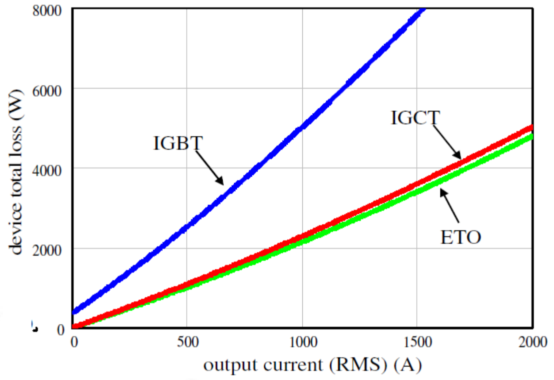

Fig 4.4: Device total losses at 1 kHz switching frequency [3]

Table 1: Comparison among ETO, IGCT and IGBT [7]

Characteristics	ETO	IGCT	IGBT
Total loss	Low	Low	High
Turn Off Capability	High	High	Low
Switching time	Fast	Fast	Medium
Current sensing capability	Yes	No	No
Voltage Scalability	Good	Good	Best
Positive Temperature Co-efficient	Best	Poor	Good
Cost per kW	Lowest	Low	High
Control Power Needed	Low	High	Low

B. Voltage and Current Scalability

As the development of HVDC and FACTS applications, the converter with higher output voltage is demanded. To achieve higher output voltage, the series connection of devices is necessary. The most important aspect in series connection of switching devices is to balance the static and dynamic voltage sharing. The static voltage balancing can be simply achieved by connecting resistor in parallel with each device. The dynamic voltage balancing during turn-on and turn-off transients are more difficult to achieve. Two dynamic voltage balancing techniques are currently used in the industry: the load side balancing and the gate side balancing, also called active gate control. The load side balancing uses snubber circuit and/or clamp circuit to limit the voltage rising (dV/dt) and/or to clamp the peak voltage. The main disadvantage of the load side control is the additional loss involved in the snubber and clamp circuits. The active gate control is to use the control function of the gate drive to achieve the voltage balancing. The active gate control approach is more attractive due to its high efficiency.

Currently, it is not possible for ETO and IGCT to achieve voltage balancing by the active gate control approach, because of their latching thyristor structure. Load side balancing approach is necessary for the series connection of ETO and IGCT. Fortunately, their high switching speed greatly reduces the turn-off storage time delay and results in very well defined identical switching transients compared with the GTO. Thus, comparing with GTO, a much smaller snubber can be used to achieve the voltage balancing, leading to relatively small additional losses. Next generations of ETO are currently under development which will enable active voltage balancing, further simplification for the high power system applications, and an increase of ETO's advantage over the IGCT.

To increase the output current capability of a converter, the parallel operation of the devices is necessary. Due to the emitter switch MOSFET's, ETO has very strong positive temperature coefficient than IGCT and IGBT. Therefore, ETO has the best current sharing in the parallel operation than that of IGCT and IGBT.

C. Protection

The over-current caused by the short circuit, malfunction or the component failure can result in further failure of the power converter if no appropriate timely protection action is taken. Both, IGBT and ETO have over-current protection capability. IGBT and ETO can detect the fault current condition and turn off automatically. For IGBT, over-current can cause the device to go out of the saturation region and enter the active region, and the rising voltage of the device will limit the current. For the ETO, the rising rate of the fault current is limited by the di/dt snubber. IGCT have a poorer over-current protection capability due to the much longer turn-off delay time compared with ETO. If the over-current not be turned off for any reason, the switching device will be destroyed. IGCT will short circuit under all worst case failure conditions due to its press-pack package. On contrary, IGBT will act as an open circuit due to its wire bond package. When switching devices are series connected, short circuit failure is desirable, since the converter may still able to operate with one or more switching devices fail short circuited.

D. Component Cost and Complexity

For the IGBT and IGCT converters, the auxiliary power supply and the isolation transformers are required to provide power for the device gate drivers. Those auxiliary power supplies, isolation transformers, and their wiring greatly increase the complexity and cost of the system. In those situations, tens or even hundreds of high power devices are required to build the system. Auxiliary power supplies, isolation transformers, and their wiring for the device gate drivers will be very complex. The total power consumption of all the gate drivers will be very large, especially for the IGCTs whose gate drivers require large power to turn off and turn on the device. It is also difficult to implement the reliable insulation design for the transformers in the high voltage applications. Therefore, the auxiliary power supplies, transformers, and their wiring greatly increase the cost and reduce the reliability of the system. For the ETO, those challenges are dramatically relieved by the ETO's control-power self-generation function. ETO can obtain the power for its gate drive directly from the DC-bus. The auxiliary power supplies and transformers are not required.

IV. Recent Development In ETO

In recent years, the ETO technology has been continuously improved with great efforts. The new Generation was designed to improve the ETO's turn-off, turn-on and high frequency switching capabilities. The design was targeted to increase the manufacturability and reduce the cost as well.

- **The Limitations of the First Generation ETO**

Fig 5.1: The picture of the first generation ETO [2]

The picture of the first generation ETO is shown in Figure-5.1 [2]. Although the ETO concept was demonstrated, the first generation ETO has limitations which prevent it from handling the real high power.

The maximum unity-gain turn-off current is limited by MOSFET voltage, and gate loop inductance. For the old design, Qe and Qg are placed on two copper plates, leading to a large gate loop inductance. The old design includes many copper plates, discrete components, and many PCB boards. The emitter switch MOSFET's and gate switch MOSFET's are soldered on the multi-layer copper plates and connected by multiple PCB boards. The gate driver is on another PCB board. The emitter switch, gate switch and gate driver board are connected by the copper plates and the screws. The mechanical design of the old generation ETO has poor manufacturability and reliability.

- **The New Generation ETO**

Recently a new generation emitter turn-off thyristor with power self-generation and sensors integration functions and it has high performance, high reliability, and high manufacturability. An important improvement of the new generation ETO is that all the reverse current conduction path, which is from cathode of the ETO to the anode of the ETO, are blocked or limited. Figure-5.2 shows the picture of the new generation ETO [7]. In the new design, all the components except GTO are put on a PCB circuit board. The GTO and the circuit board are connected by copper plates. The heat generated by the GTO can be easily removed by double side cooling. The Qe MOSFET's are arranged in a ring shape around the GTO to reduce the gate loop inductance. The snubberless turn-off capability of the ETO is highly improved. Since the gate drive circuits, emitter switch, and gate switch are all put on the PCB board, the manufacturability and reliability is improved. Figure-5.3 shows its typical turn-off waveform without snubber [7].

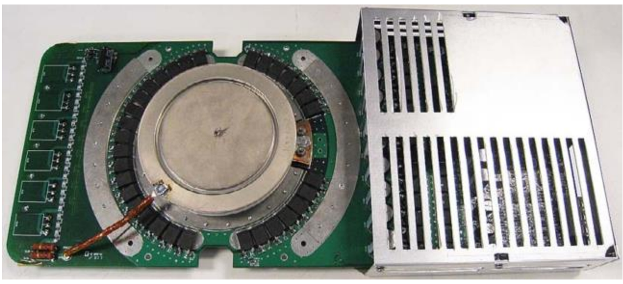

Fig 5.2: The New Generation ETO [7]

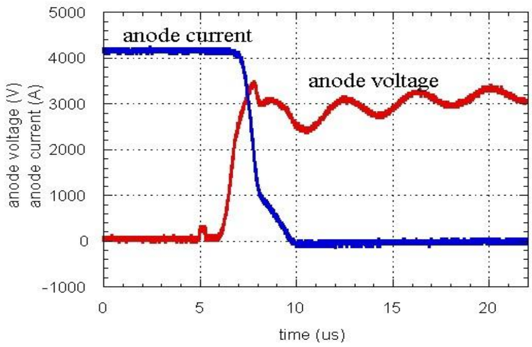

Fig 5.3: Turn-off waveform of the New Generation ETO [7]

Since the di/dt snubber is greatly reduced, the dv/dt snubber is not required, and the power consumption of the gate drive is very low. With self power, built-in sensor and protection functions, large gate drive power can be saved, the system cost can be reduced and the reliability can be greatly improved. Due to these benefits, the ETO technology is promising for high power application.

New Generation ETO also has the following features:

- Built-in device voltage, current and temperature sensors and protection function.
- Control power self-generation capability to remove external auxiliary power supply system for control.

V. CONCLUSION

In today's electric power system, solid state power electronics technology plays more and more important roles and the demand for mega-watt level power ratings is increasing. The development of megawatt power converters strongly depends on the state-of-the-art of power semiconductor technology, in the development of the Emitter Turn-Off (ETO) thyristor, an emerging power semiconductor switch for high power applications.

The ETO is a hybrid power semiconductor device that turns off the Gate Turn-off Thyristor (GTO) under the unity turn-off gain condition. The unity gain for the device's turn-off is realized with the combination of two independent MOSFET switches, thus avoiding the usage of capacitors and thus lifting the temperature limitations of the IGCT concept. The ETO also requires a low inductance and low resistance commutation path at the gate terminal, leading to bulky driver stages comparable to the IGCT's. Due to its fast switching speed, snuberless turn-off capability, voltage control and built-in current sensing, it is superior high power semiconductor device.

Realizations of the ETO are still in experimental status and are not introduced to the market yet. Packed with advanced features as well as superior performance, ETO based power electronics systems are very attractive for various grid applications.

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