Emitter Turn-Off Thyristor (ETO) based converters for Energy Storage

Kevin Motto[1], Yuxin Li, Aaron Xu, and Alex Q. Huang

Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061 USA
Phone: (540) 231-5494

For power electronic systems operating in the high power region, the conventional semiconductor switches available have been the Silicon Controlled Rectifier (SCR) and the Gate Turn-Off (GTO) thyristor. The SCR has the highest ratings of any semiconductor switch available but cannot be turned off by means of its control terminal. This prevents the use of SCRs in many applications where a switching frequency much higher than the fundamental AC line frequency is necessary in order to reduce filter size or improve performance. The SCR is therefore not suitable to many energy storage systems where high frequency are required such as STATic var COMpensators (STATCOMs) and SMES interfaces. The GTO is essentially an SCR with the ability to be turned off by means of its gate, hence the name. The GTO has traditionally been the only option for high power converters which require forced commutation capabilities. This gives the advantage of higher switching frequency which allows the construction of active filters for the utility and high power DC/DC converters such as needed to interface a SMES coil to the inverter if the common voltage-fed inverter topology is desired. Funded by DOE Energy Storage Systems Program and made use of ERC shared facilities supported by the National Science Foundation under award number EEC-9731677.

Unfortunately, the GTO is far from an ideal solution. Turning the GTO off requires a significant fraction (1/5 to 1/3) of the current being turned off which must be provided by the gate driver. This leads to expensive and bulky gate drivers which consume excessive power. There is also a long delay (20-30 µs) between the beginning of the turn-off command and the actual turn-off response from the GTO. Due to its large die size (up to 6 inches) the GTO has a tendency towards uneven current distribution throughout the die during turn-on, which requires the use of a snubbing inductor to allow the die time to come into uniform conduction. The GTO also suffers from a poor turn-off characteristic which requires the use of a large snubber capacitor connected in parallel to limit the rate of rise of voltage when it turns off. The energy in this capacitor must be either dissipated or circulated by some auxiliary resonant circuit, which increase the complexity of the power converter. Due to the high switching loss, the limited dI/dt and dV/dt, and long transition times, the GTO cannot achieve a switching frequency much above 500 Hz.

It has been shown that the GTO's problems can be eliminated by forcing the gate current to be equal to the anode current during turn off [1]. This condition, known as unity gain, allows the thyristor to be decoupled into two transistors which turn off separately. When the positive feedback loop within the thyristor is gone, the current distribution tends to be uniform throughout the die, which dramatically improves the turn-off capability of the device. A GTO operated in the unity gain condition can operate without the snubber capacitor usually required and also has its delay time reduced to only 1 µs. In order to meet unity gain, the gate current must rise to the anode current within 1 µs, or the GTO will begin to turn off in the conventional way with the positive feedback loop still present. Due to the package inductance and the gate junction breakdown, it is not easy to realize unity gain with conventional GTO drive techniques for high current devices, but several new devices have been introduced which utilize new techniques to achieve unity gain. These devices include the Integrated Gate Commutated Thyristor (IGCT) [2] and the Emitter Turn-Off (ETO) thyristor [3].

The ETO[1] combines a GTO with a parallel group of low voltage, high current MOSFETs to synthesize a high power, high-speed semiconductor switch. The MOSFETs are placed in series with the ETO's cathode (emitter) and are used to control the GTO as shown in figure 1(left). When the series MOSFETs (Q_e) turn off and the gate MOSFETs (Q_g) turn on, all of the current flowing through the GTO is immediately commutated into the GTO's

[1] Email: mkevin@vpec.vt.edu

gate. This large gate current results in termination of the thyristor's positive feedback loop, so the turn off process is like that of a PNP transistor. This transistor turn off is very fast and very robust, without the dV/dt induced problems found in thyristor turn-off. Because of the transistor turn-off mechanism, the ETO has even current distribution throughout the large area die so there is no current crowding problem. A family of ETOs has been developed, with the largest being the ETO 4060, which is a 4kA/ 6kV device shown with its driver in figure 1(right).

Systems constructed using the ETO device will benefit from the increased switching frequency which is possible due to the reduced switching times and the low snubber requirements. The use of higher switching frequency allows a reduction in the size of input and output filters for the systems as well as better dynamic response. Dynamic response is important for energy storage systems which are supplying power for a pulsed load, such as an electromagnetic launcher. In addition, the ETO's low driving power requirement simplifies the auxiliary power supplies needed for a large converter.

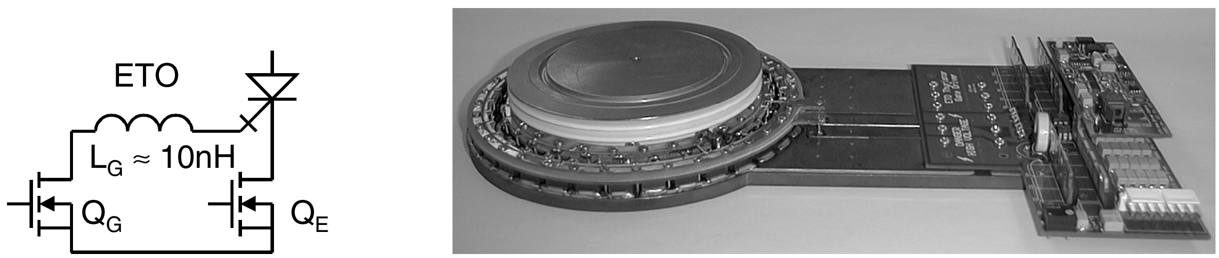

Figure 1: ETO circuit (left) and 4 kA/6kV ETO (right)

Based on the ETO devices developed at CPES, a power converter capable of operating at 1 MVA has been developed. This converter uses the smallest ETO, the 1 kA/ 4.5kV ETO1045, switching at 1.5 kHz without any dV/dt snubbers using a 2.5 kV DC bus voltage. This converter has shown the advantages expected from the ETO such as high frequency operation (relative to other high voltage devices) and low driving power. The driving power for the ETO at 2 kHz is less than 10% of the driving power for a GTO at 500 Hz. A photograph of this converter is shown following in figure 2, and a schematic of the power circuit is shown in figure 3.

Figure 2: ETO-based 1 MVA inverter

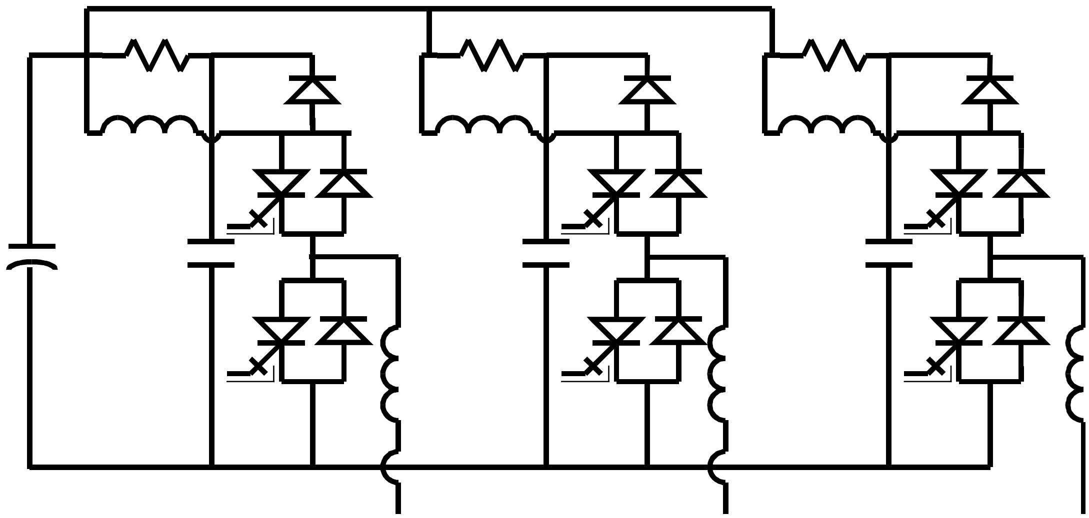

Figure 3: ETO-based three-phase inverter

This converter is comprised of a DC link bulk capacitor as well as three identical phase legs. As shown in figure 4, each phase leg consists of two main switches and their anti-parallel connected diodes, as well as an integrated voltage clamp and dI/dt limiting snubber. Unlike a snubber, the voltage clamping capacitor C_C does not discharge every switching cycle, so it does not lead to much power loss. This capacitor absorbs the energy in the parasitic inductance of the bus and limits the peak voltage applied to the semiconductors. When a diode is conducting and the opposite switch turns on, the reverse recovery current from the diode would be enormous without the inductor L_S, which limits the outgoing dI/dt rate in the diodes thus reducing the reverse recovery dramatically. When the switches turn off, the load current in inductor L must continue. Therefore the diode opposite the switch (top diode for the bottom switch) turns on and the resistor R forces the current into the snubbing inductor. The time necessary for this transition is related to the L/R time constant, and can be reduced at the expense of additional voltage stress by increasing the resistance. This snubber is required because of the poor characteristics of the high voltage diode and is not a requirement of the ETO.

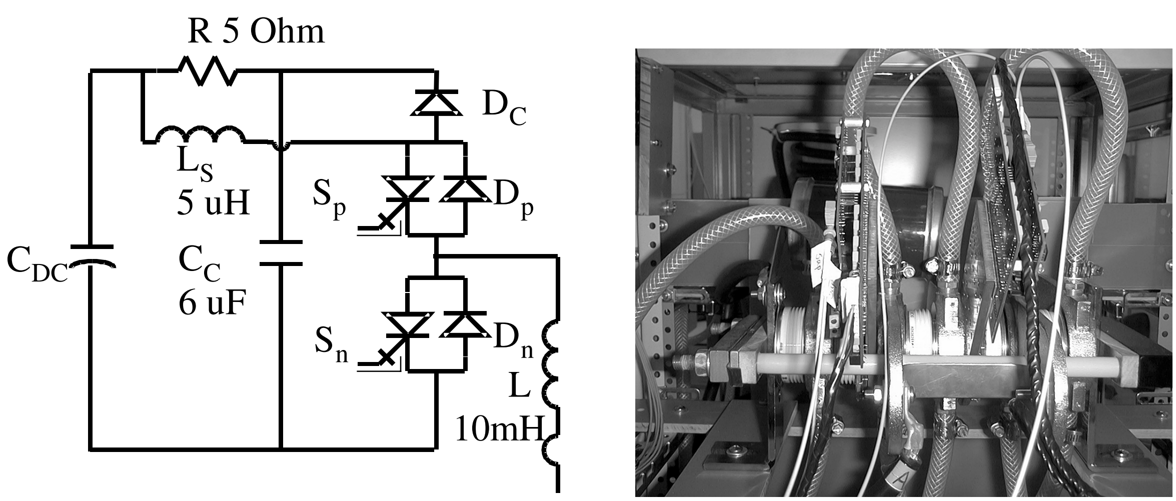

Figure 4: ETO phase leg schematic (left) and photo (right)

The ETO-based inverter has been tested with a reactive load up to 200 Amps of phase current. Due to the higher switching frequency the output waveforms have very low distortion and minimal switching ripple current. The three-phase output current waveforms are shown in figure 3. The three currents are slightly imbalanced because this test was performed with the control loop open and the three filter inductors are not perfectly matched. The anode voltage and anode current of one ETO are also shown from this inverter test. As can be seen, the ETO is operated without dV/dt snubbers and the voltage overshoot is very small compared to the device's 4500 V breakdown. This test was performed with 900 V DC voltage due to the limitations of the power supply used, but the output current is at the rated value, so the voltage overshoot will not increase at higher link voltages.

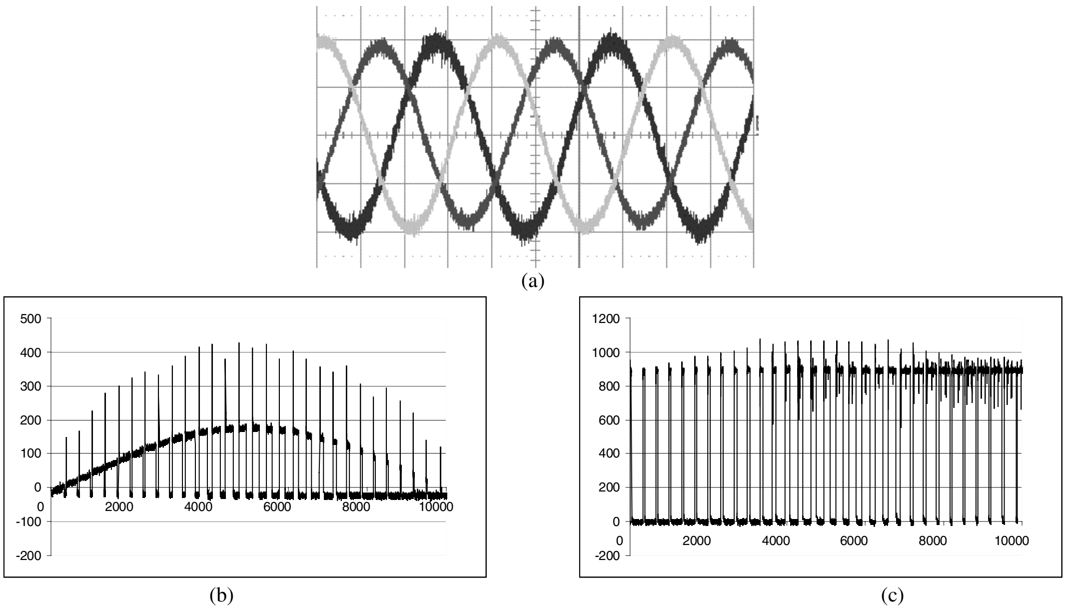

Figure 4: Three-phase currents (a), switch current (b), and switch voltage (c)

One energy storage application where the ETO is particularly well suited is utility grid active filters. In these applications slow switching devices such as SCRs and GTOs are not suitable because they cannot achieve response fast enough to filter higher order harmonics such as the 11th and 13th, which are troublesome for the power system. The power level of these systems makes devices such as IGBTs impractical due to the large number of devices required in order to achieve the required current and voltage limits. The largest IGBTs currently available have a power handling capability of about one-fourth that of the largest ETO, the ETO4060. In addition, these IGBTs have very high conduction losses which lead to poor system efficiencies, although the IGBTs do have the benefit of ease of use.

Systems that must directly interface to utility distribution voltages require high voltage, high performance devices in order to avoid bulky and expensive transformers. When slow devices such as GTOs are used in these applications, their voltage rating is adequate but they still require transformers. Because the performance is too slow, several inverters are connected in parallel through phase-shifting transformers so that they add up to produce good waveforms. However, higher performance devices such as ETOs and IGCTs can switch fast enough to synthesize good output currents using single inverters, so phase-shift transformers are not necessary. If more power is required, multiple inverters can be used connected directly in parallel.

The performance of all high power systems can be improved through the use of better circuit topologies [4]. Multi-level inverters such as the diode clamped converter and the flying capacitor converter simultaneously increase the voltage capacity and the effective switching frequency, which reduces the filter requirements without increasing the actual frequency of any switch. However, both of these topologies become very complicated when scaled beyond three-level. A cascaded bridge converter can be scaled to a high number of levels very easily as shown in figure 6. The drawback with this type of converter is that they require separate power supplies for each of the cascaded bridges. Although this makes these converters very cumbersome for applications such as motor drives, this topology is very well suited for use in energy storage. If each bridge has its own energy storage element such as a capacitor, there is no need for the separate power supplies. This topology is therefore particularly well suited to STATCOMs and similar applications which store energy for short times, where a capacitor is adequate for the storage. If the number of levels in a cascaded bridge converter is made high enough, then the semiconductor switches can operate at the AC line frequency and still synthesize very good output waveforms.

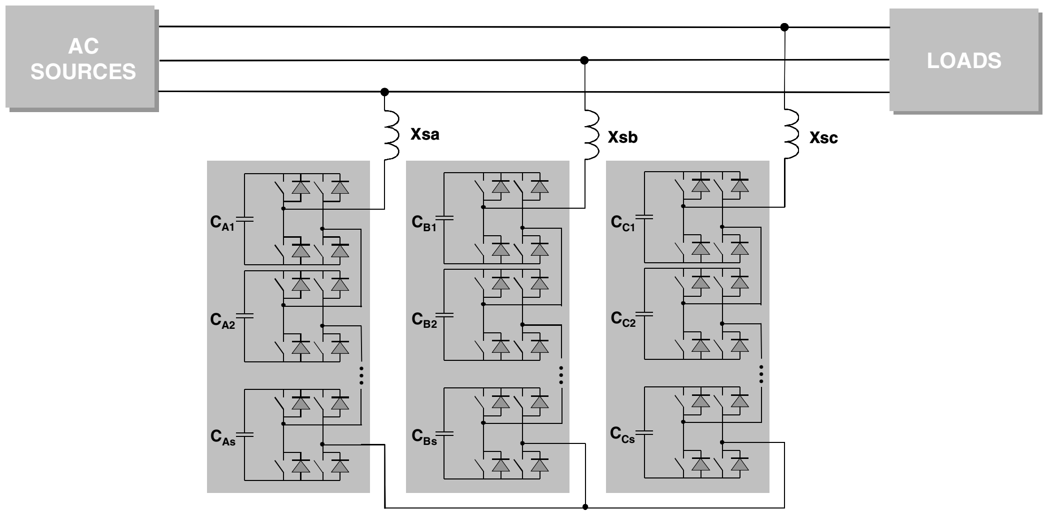

Figure 6: Cascaded Bridge STATCTOM

This topology is also well suited to battery energy storage systems used for uninterruptible power supplies because each bridge can use a separate battery pack. The total battery storage required is no greater than with other inverter topologies, so there is no penalty for using this type of converter.

One very important advantage of fast switches such as ETOs is in system protection when a fault occurs. With slow devices such as GTOs the device cannot turn off before a fault current has risen beyond the controllable level. Even if the fault is detected as soon as it occurs, a GTO has at least 20 µs before the device begins to turn off. In this time the current is rising constantly, and even though there is a dI/dt limiting snubber, the current will be very high by the time the GTO turns off. However, and ETO begins to turn off within 1 µs of the command. Therefore the dI/dt snubber will have only allowed the current to rise about 500 Amps during this time, so an ETO or IGCT can still easily interrupt this current level. The improvement in protection is a very important advantage even if a topology is selected which will reduce the switching frequency requirement. With conventional GTO based systems the only means of fault management is to turn all switches on and wait for the protective fuses to open. Although this technique can protect the inverter hardware adequately, this is not a graceful solution because all fuses must be replaced after any fault occurs. Most power system faults are cleared very quickly (within several line cycles) so it is important for any converter providing energy to the grid to come back online as quickly as possible, which is much easier if no parts need to be replaced. An ETO based system can begin operating again immediately in order to see if the fault is still present.

In conclusion, high-speed semiconductor devices such as the ETO can provide many advantages in the power electronic converters associated with many energy storage applications. They offer the advantage of better output waveforms due to their higher switching frequencies, which can dramatically reduce the cost and size of the output filters necessary in order to meet power quality specifications. The higher frequency operation also allows faster control response so that high order harmonics can be cancelled and the converters can respond quickly to transients on the external systems. One additional benefit is easier protection of power conversion systems due to the rapid response and good turn-off capability. Advanced topologies can improve the performance of the systems with reduced stress on the semiconductor switches, but better switches are always beneficial for better systems.

References:
1. H. E. Gruning, A. Zuckerberger, "Hard Drive of High Power GTOs: Better Switching Capability obtained through Improved Gate-Units", *Conf. Rec. IEEE-IAS* Oct. 1996, pp. 1474-1480
2. P. K. Steimer, H. E. Gruning, J. Werninger, E. Carrol, S. Klaka, S. Linder, "IGCT – A New Emerging Technology for High Power, Low Cost Inverters", *Conf. Rec. IEEE-IAS*, 1997, pp. 1592-1599
3. Y. Li, A. Q. Huang, and K. Motto, "Experimental and Numerical Study of the Emitter Turn-Off Thyrsitor (ETO)", *IEEE Transaction on Power Electronics*, May 2000, pp. 561-574
4. J.-S. Lai and F. Z. Peng, "Multilevel Converters – A New Breed of Power Converters", *IEEE Transactions on Industry Applications*, May/June 1996, pp. 509-517