High Power Energy Storage System Application Utilizing Emitter Turn-Off (ETO) Thyristor

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Abstract- this paper presents new advancement of the high power, high frequency Emitter Turn-off (ETO) Thyristor, and its application in the high power energy storage systems. The homogenous switching capability in the ETO due to guaranteed unity-gain turn-off enlarges the safe operation area of the ETO to full dynamic avalanche limitation, hence basically reaching the physical limit of silicon material. This enlarged safe operation area results in an ETO that is basically only limited by its thermal handling capability. Therefore ETO is well suited for high-power high-frequency power conversion applications. We will show for the first time the 10 kHz pulse switching capability of the ETO demonstrating the homogenous switching capability. Furthermore, thermal analysis of the cooling options for the ETO device are examined with the aim to increase the thermal handling capability. The result of longer time testing at sustained high power levels will be discussed and presented. Technology development in the area of modular high-power converter design and modular control system will also be discussed that are important to high-power energy storage system demonstration.

I. Introduction

In the high power energy storage systems, the power gate turn-off thyristor traditionally plays a major role. Due to the GTO's inhomogeneous turn-on and turn-off transients, GTO converter needs bulky and costly dv/dt and di/di snubber circuits, and the switching frequency is low. The power consumed by the GTO gate driver is also enormous and increases with the increase of the turn-off current and the switching frequency. The power consumption associated with the dv/dt snubber and the gate driver is a huge burden to the thermal management system, and hence limits the switching frequency. Traditionally, power converter equipped with GTOs operates at frequencies lower than 500Hz or even at line frequency.

The emitter turn-off (ETO) thyristor [1,2,3] dramatically improves the switching performance of the GTO by driving the GTO gate current to equal the anode current during turn-off, achieving so-called "unity gain turn-off" [2]. ETO can be safely turned off without any dv/dt snubber due to the much more uniform turn-off process, and the minimum on/off time can also be reduced due to its uniformly temperature distribution across the junction during switching. The power consumption of the ETO drive unit is also significantly reduced and is almost independent of the turn-off current and frequency. Due to the short turn-off storage time and the low gate drive unit power consumption, the ETO converter can operate at kHz range. This paper presents the high power, high frequency performance of the ETO and its application in the high power energy storage systems.

II. The Characteristics and Performance of the ETO

Fig. 1 shows the picture of the 4.5 kV, 5 kA ETO. Fig. 2 shows the turn-off waveform of the ETO at 5000A, 2200V DC bus voltage without dv/dt snubber. From fig. 2 it can be calculated that the maximum silicon power density reaches 238.7kW/cm^2, and the maximum current density reaches 100A/cm^2. These data show that the ETO's Safe Operation Area (SOA) is basically enlarged to that of an open base PNP transistor and is only limited by the dynamic avalanche, approaching the physical limits of silicon [8]. This test also shows that the ETO turn-off storage time is about 1.2 μs, which is reduced to about one twentieth of that of GTO (25 μs).

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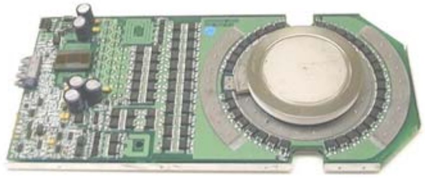


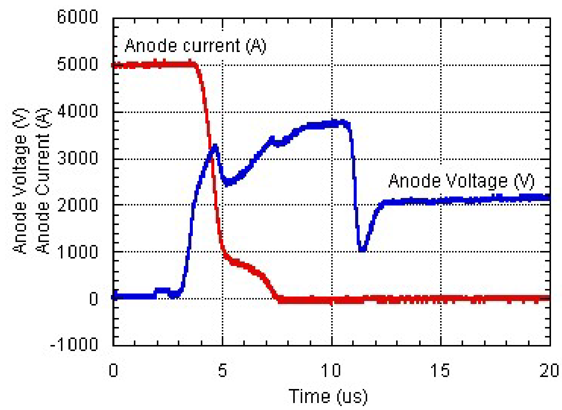


Fig. 1. The picture of the ETO. **Fig. 2. The snubberless turn-off waveform of the ETO at Tj=25 $^\circ C$.**

To demonstrate ETO's transient thermal handling capability, a 10 kHz 12-pulse sequence snubberless switching test was conducted. Fig.3 shows the anode voltage, anode current, and the ETO loss waveforms of the test results. The DC link voltage is 2500V, and the switching current rises from 1000A to 4000A. The duty cycle of the pulse sequence is 50% (50 μs on and 50 μs off). The power loss, mainly caused by the snubberless turn-off, reaches 130J at the end of the last pulse.

For the traditional GTO, its minimum on-time and off-time is long due to its non-uniform current distribution during switching. The non-uniform current distribution can cause non-uniform temperature distribution, leading to hot spots and thermal runaway. The ETO achieves the uniform current distribution during switching through its unity gain turn-off. The heat generated during the switching is evenly distributed across the ETO. In addition, the transient thermal impedance of the ETO is very low in short time pulses, therefore, the ETO can endure very high power in a short time period without causing its junction temperature to exceed the safe operation area. In the test shown in fig. 3, 130J was generated within 1ms but this did not destroy the ETO due to the ETO's even thermal distribution and low transient thermal impedance. This capability sets a large safety margin during ETO's normal operation condition, and is very important for ETO when working at over-load and fault condition. This test shows that the ETO's switching frequency is limited by the thermal handling capability of the package, rather than by the electrical capability. The ETO can operate at extremely high power and in high frequency condition as long as the heat can be removed.

During the ETO's turn-on transient and the on-state, the ETO's gate drive turns the emitter switch on, the gate switch off, and delivers the required GTO gate current. During turn-off transient, the ETO's gate drive only need to turn the emitter switch off, the gate switch on, and does not need to provide the turn off current like the IGCT. Therefore, the ETO needs much smaller gate drive power than that of the IGCT, and the ETO's gate drive power also does not increase much with the increase of the switching frequency, which is favorable for the high switching frequency operation. Fig.4 shows the measurement of the gate drive power consumption of the ETO at 500Hz and 1000Hz respectively. These data are obtained through the test results of an ETO high power boost converter. It can be seen that the ETO gate drive power consumption remains almost constant when the switching current and the switching frequency increase. On the contrary, the IGCT gate drive power consumption increases linearly with the increasing of the switching current and of the switching frequency [4]. Since the ETO gate drive does not need to provide the large turn-off energy during high current turn off, it does not need huge energy storage capacitors, and this is favorable from the reliability point of view. On the other hand, the IGCT need large amount of low lifetime liquid aluminum electrolytic caps to reduce the gate loop inductance and deliver the huge turn-off current.

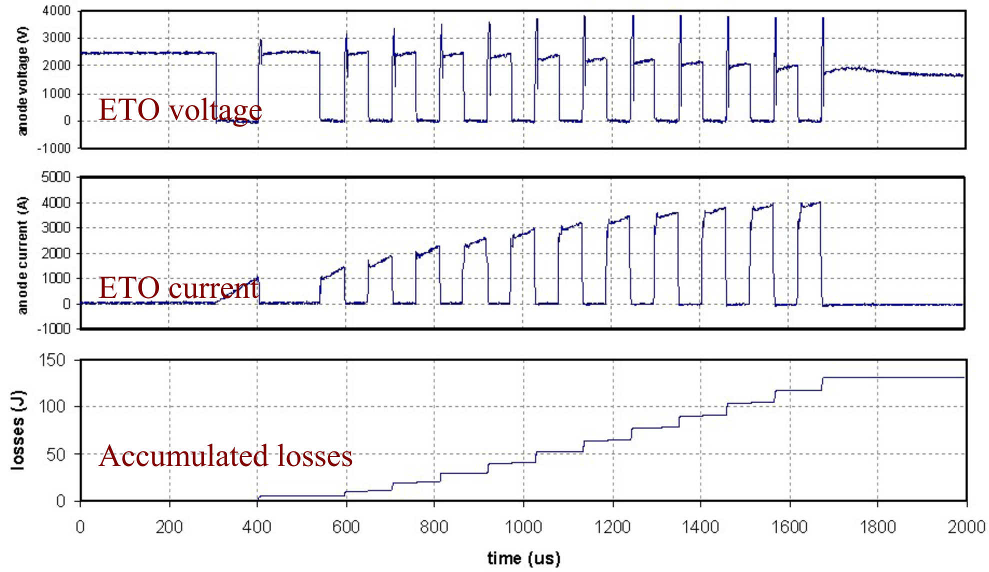


Fig.3 ETO switching waveforms when switching at 10kHz for 12 pulses with a starting Tj=25 $^{\circ}C$.

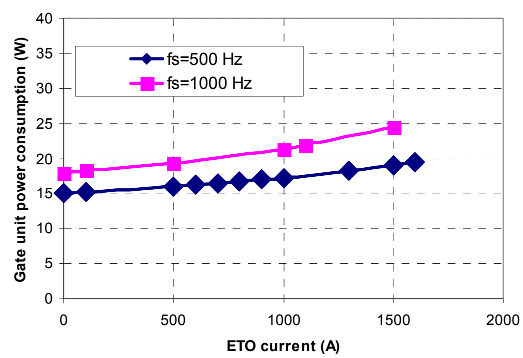


Fig. 4. The gate drive power consumption of the ETO at different swithing frequency and 50% duty cycle.

To evaluate the reliability of the ETO, the ETO power cycling test was conducted at the NSWCCD. A 900A DC input boost converter was built as shown in fig. 5. The output voltage of the converter is 2000V. In one test, the ETO converter worked for 4 hours at 500Hz switching frequency and 2000A peak turn-off current. In another test, the ETO converter worked for 4 hours at 1000Hz switching frequency and 1300A peak turn-off current. In both tests the ETO junction temperature reaches 113 ^{o}C. A one hour power cycle was then conducted. In this test, the input voltage was cycled between 200V and 500V for an hour at a rate of 1 cycle every 6 minutes. The test results are shown in fig. 6. These tests demonstrated that the ETO has high reliability.

Although water cooling has been widely used for the thermal management of thyristor based devices, the heat pipe solution is atracting more and more attention. The heat pipe has the advantage as high reliability and low cost. The ETO maximum power vs. heat sink thermal resistance is shown in fig. 7. The two different heat pipes (1001 and 1084), together with the water cooling are shown in fig. 7 for comparision.

III. Energy Storage System Demonstration

To show the superior performance of the ETO in an energy storage system, an ETO-based STATCOM with real power injection capability utilizing the Transmission Ultra-CAPacitor (TUCAP) concept as shown in fig. 8 has been initiated. The STATCOM-TUCAP system will be coupled to 13.8kV distribution power network via a three-phase transformer and has a continuous power capability of 4.5 MVA or 3 MW for 2 second to alleviate flicker mitigation caused by arc furnace at a TVA powered facility. The TUCAP module is being developed at EPRI-PEAC by series connecting a number of low voltage UCAP (42 V) to reach 2 kV voltage required to interface with the ETO converter. The development of TUCAP will be discussed in another paper in this conference by EPRI-PEAC.

Fig. 5. The picture of the ETO booster converter.

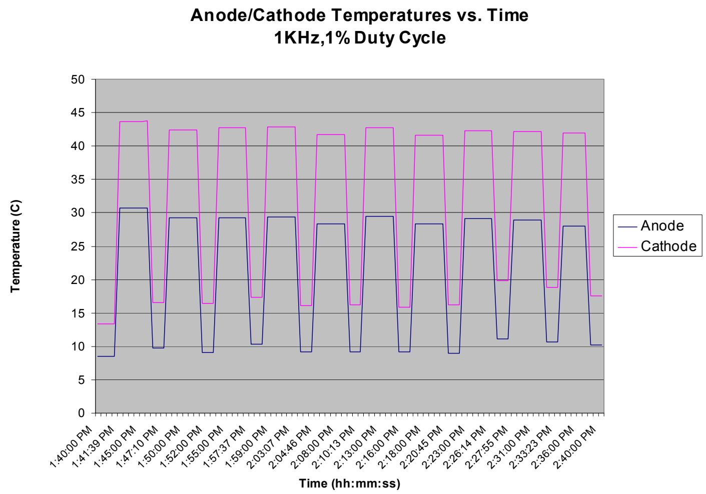


Fig. 6. the test results of the one hour power cycle test.

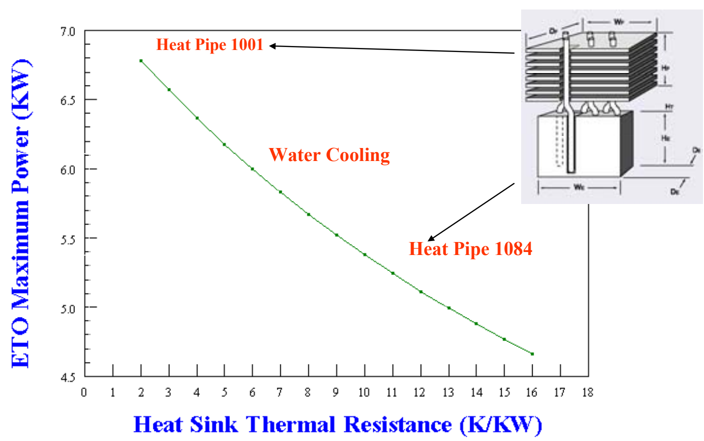


Fig. 7. ETO maximum power vs. heat sink thermal resistance

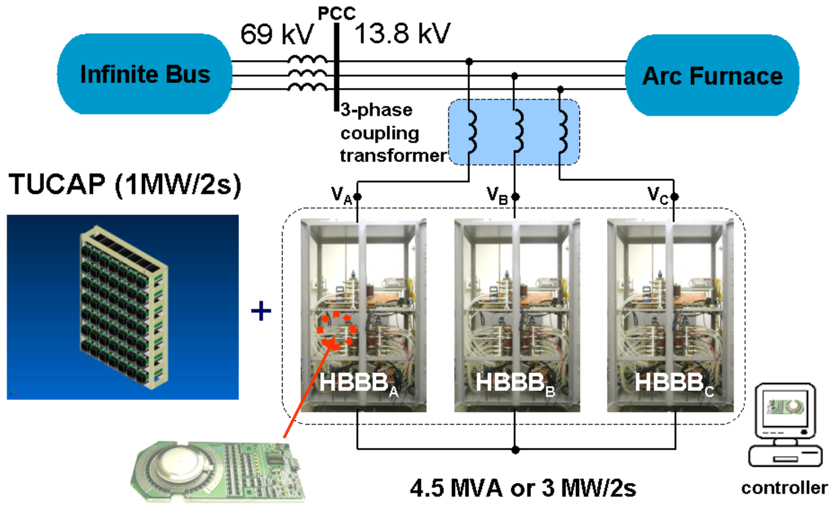
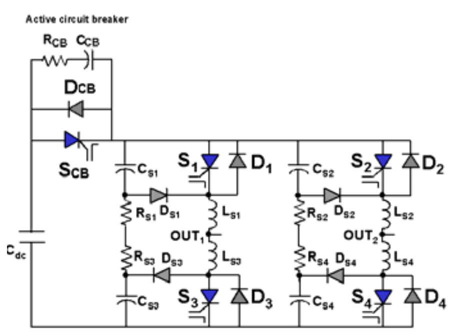


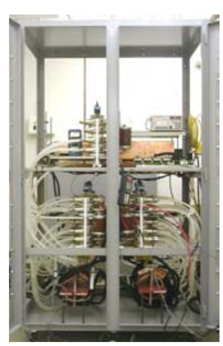
Fig. 8. ETO-based STATCOM associated with TUCAP.

IV. ETO-Based H-Bridge Building Block (HBBB) for High Power Application

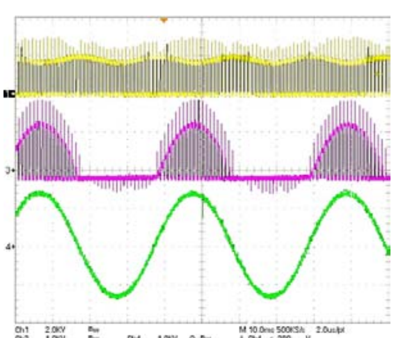
As a basic unit of the power converter in the proposed system, ETO-based H-bridge inverter prototypes have been developed. Although the ETO has the snubberless turn-off capability, a small dv/dt snubber circuit is required to reduce the switching loss and to increase the long-term switch reliability. Because the high-power diode's reverse recovery increases the stress on the ETO, the di/dt is needed to reduce such switch stress. The schematic of the proposed H-bridge converter with dissipative snubber discharge and a dc capacitor is shown in fig. 9 (a). S_1 to S_4 are the main switches that represent the ETOs and D_1 to D_4 are the main anti-parallel diodes. The McMurray snubber circuit comprises dv/dt capacitors C_{SN}, di/dt inductors L_{SN}, auxiliary diodes D_{SN}, and discharge resistor R_{SN}, where N ranges from 1 to 4. Three possible output voltage levels at the Out_1 node, with respect to the Out_2 node can be synthesized; i.e., $+V_{dc}$, 0, and $–V_{dc}$. Fig. 9 (b) shows a hardware prototype of the ETO-based HBBB. To verify the performance of the HBBB prototype, experiment has been conducted, and the results are shown in fig. 9 (c). The test condition is as follows: line frequency of 25 Hz, switching frequency of 1 kHz, modulation index of 0.9, DC bus voltage of 2 kV, and output RMS current of 1.0kA. The results indicate superior operating of the HBBB in all aspects.



(a)



(b)



(c)

Fig. 9. (a) Schmatic of ETO-based HBBB (b) HBBB hardware prototype (c) Experimental results from the top: S_1 switch voltage (2 kV/div), S_1 switch current(1 kA/div), and Load current (1 kA/div).

V. Digital Controller Development

Digital system controller is another important part of the system. To verify control strategy and stability, DSP-based controller and a real-time testbed have been designed and implemented as shown in fig. 10. The testbed is configured as a scaled down version of the STATCOM-TUCAP system using three 42 V UCAPs as energy storages. The control technique is designed to independently control reactive and reactive power.

Two key experiments have been conducted to show the performance of the control system. Fig. 11 and fig. 12 show the experimental results of the STATCOM-TUCAP system operating in reactive power compensation mode. The system is commanded to exchange reactive power with the power network. Fig. 11 shows that the STATCOM generates capacitive current and is then commanded to instantaneously generate inductive current, while fig. 11 shows the STATCOM operates in the other direction. The results indicate the sub-cycle responses of the STATCOM to the commands.

With help of the ultra capacitor, the STATCOM can be commanded to supply real power for a given period of time. Fig. 13 shows an experimental result of the STATCOM generating pulsating real power current. This feature is usually utilized to solve flicker mitigation in the bus common with arc furnaces. The results show fast real power compensation. Our next step is to test the controller with the high power ETO converter in the configuration shown in fig.8.

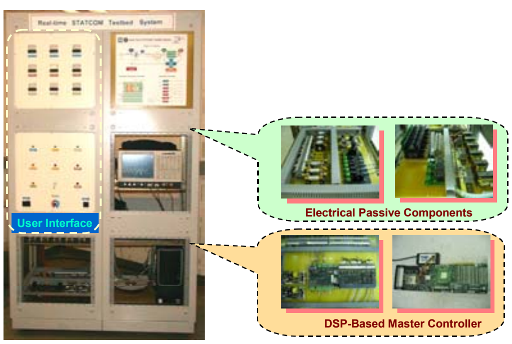


Fig. 10. Real-time STATCOM Testbed system.

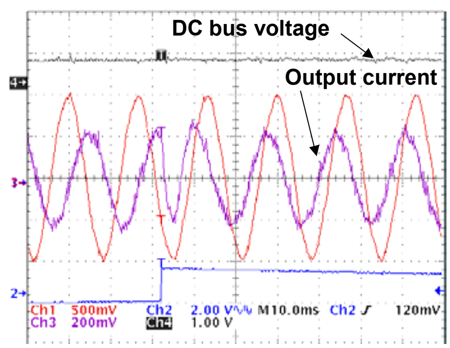


Fig. 11. Reactive var compensation from capacitive mode to inductive mode

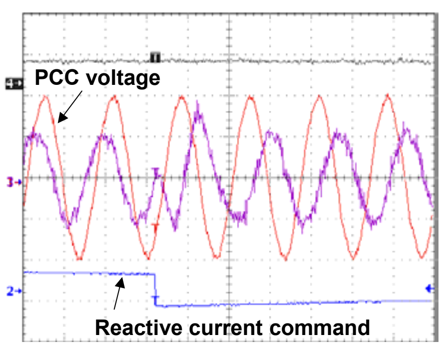


Fig. 12. Reactive var compensation from inductive to capacitive mode mode

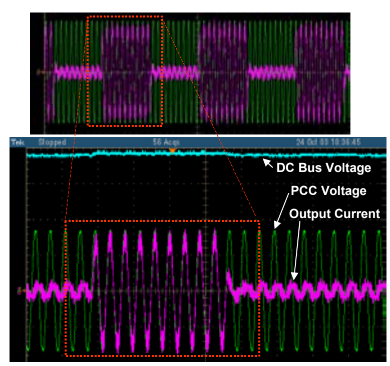


Fig. 13. Experimental results of real power compensation.

IV. Conclusions

The ETO is a high power semiconductor device suitable for high power high frequency operation. The ETO's homogenous switching due to the unity turn-off gain and high turn-off gate current rising rate enlarges the SOA to full dynamic avalanche, and enables the ETO to operate at extremely high power and high frequency conditions as long as its junction temperature is kept at a safe value. The ETO's switching frequency is limited by the thermal dissipation, rather than the electrical capability. ETO's short turn-off storage time, high turn-on di/dt capability, low switching and conduction losses, and the low gate drive unit power consumption allow the ETO converter to operate at much higher power and higher frequency than that of the traditional GTO. 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, the system's cost can be significantly reduced, and the reliability can be greatly improved. ETO's high power high frequency operation is successfully demonstrated in a megawatt H-bridge voltage source converter. The development of TUCAP as an energy storage element and the advancement of the digital controller will enable us to demonstrate an ETO based energy storage system in the near future.

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