Power Semiconductor Devices for High Power Current Source Converters

-Overview of a symmetrical emitter turn-off (ETO) thyristor-

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Abstract

This paper presents the development of an power semiconductor device for the high power current source converter (CSC). The CSC is very attractive in high power applications due to its lower output dv/dt, easy regeneration capability and implicit short-circuit protection. Traditionally, either a symmetrical gate turn-off (GTO) thyristor or an asymmetrical GTO in series with a diode is used as the power switch in the CSC. Since the GTO has a lower switching speed and requires a complicated gate driver, the symmetrical GTO based CSC usually has low dynamic response speed and low efficiency. To achieve high power rating, fast dynamic response speed and low harmonics, an advanced semiconductor device are needed for the CSC. Based on symmetrical GTO and power MOSFET technologies, a symmetrical emitter turn-off (ETO) thyristor is developed that shows superior switching performance, high power rating and reverse voltage blocking capability. Based on a six-switch CSC cell, the multilevel CSC has the advantages of high power rating, low harmonics, fast dynamic response and modularity. Therefore, it is very suitable for high power applications.

Keywords : Power Semiconductor Device, Emitter Turn-off Thyristor, Current Source Converter, FACTS, STATCOM

1. Introduction

A power semiconductor switch (power semiconductor device) is a component that is controlled to either conduct a current when it is commanded ON or block a voltage when it is commanded OFF. This change of conductivity is made possible in a semiconductor by specially arranged device structures that control the carrier transportation. The time that it takes to change the conductivity is also reduced to the microsecond level as compared to the millisecond level of a mechanical switch. By employing this kind of switch, a properly designed electrical system can control the flow of electric energy, shaping the electricity into desired forms [1]. If a power semiconductor device

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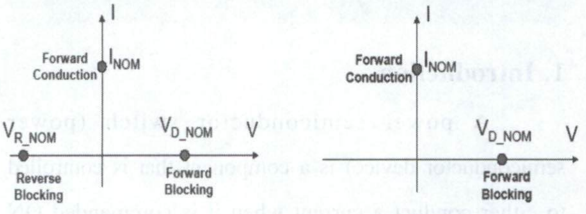
can block forward voltage as well as the reverse voltage during the OFF state, it is defined as a symmetrical device. On the other hand, a power semiconductor device that can only block the forward voltage during the OFF state is defined as an asymmetrical device. Most of the semiconductor devices can only conduct forward current during the ON state [2-3].

Therefore, the symmetrical device has three operation states: forward conduction mode, forward blocking mode and reverse blocking mode, as shown in Fig. 1(a). For an asymmetrical device, only two operation modes exist: forward conduction mode and forward blocking mode, as shown in Fig. 1(b).



(a) (b)

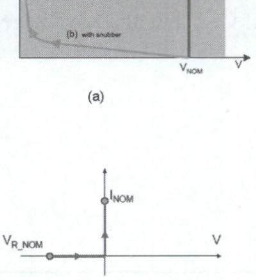
Fig. 1. Device operation states for (a) symmetrical device and (b) asymmetrical device.

Turn-on Operation

A typical turn-on operation of a power semiconductor switch changes its operation state from its forward or reverse blocking mode to its forward conduction mode. Changing a device's operation state from forward blocking mode to forward conduction mode is defined as a forced turn-on, while changing a device's operation state from reverse blocking mode to forward conduction mode is defined as a load-commutated turn-on. The turn-on trajectory is determined by circuits rather than by the device itself. During the forced turn-on transition, the switch may simultaneously undergo both high voltage and high current, as represented by curve (a) in Fig. 2(a), where the device's voltage stays constant while its current increases until it hits the device's nominal current level. This kind of turn-on, also called a snubberless turn-on, happens in most power converters. So the device stress is high in this case. The current overshoot occurs due to the reverse-recovery of an associated diode (or a switch). With a snubber circuit, the voltage-current trajectory can be shaped as curve (b) shown in Fig. 2(a), where the device voltage collapses before the current increases to the normal value, resulting in dramatically reduced device stress [2]. During the load-commutated turn-on transition, the device begins to conduct current only after the device voltage becomes positive, as shown in Fig. (b). Therefore, the device stress is usually low in this case.

Forward Biased Safe Operation Area

The forward biased safe operation area (FBSOA) defines a maximum forward voltage current region in which the device can be commanded to operate with simultaneous high voltage and current, as shown by the shaded area in Fig. 3. The device current can be controlled through its gate (or base), and the length of the operation is only restricted by its thermal limitation [A4]. Devices with FBSOA normally have an active region in which the device current is determined by the control signal level, as shown in Fig. 3.



(a)

(b)

Fig. 2. I-V trajectories of a device for (a) forced turn-on with or without a snubber circuit and (b) load-commutated turn-on.

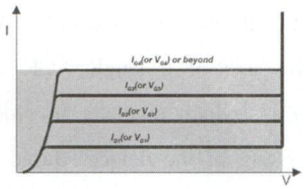


Fig. 3. Forward I-V characteristics of a device and its FBSOA definition.

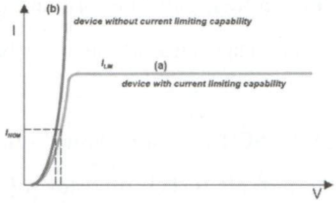


Fig. 4. Forward I-V characteristics of two type of devices with/without self-current limiting capability.

A device with FBSOA (such as a MOSFET) normally has the self-current-limiting capability, the ability for a switch to limit its maximum current regardless of the voltage applied, and its typical I-V curve is shown as curve (a) in Fig. 4. In contrast, a device without FBSOA (such as a GTO) cannot self-limit its current, and its typical I-V curve is shown as curve (b) in Fig. 4. For a device with good FBSOA, hence the self-current limiting capability, the turn-on di/dt can be controlled through the gate, and most importantly no current crowding occurs during the turn-on transient. Therefore, snubberless turn-on can be applied to these devices. On the other hand, for a device without FBSOA, the turn-on di/dt is uncontrollable, and current crowding may happen in a localized area. This is particularly true for large area devices; therefore, a snubberless turn-on is not possible in these devices, and an external snubber circuit needs to be used to avoid current-crowding problems [2]. The snubber circuit will increase a system's component count, size and cost. Therefore, a device with good FBSOA is preferred in a power conversion system.

Turn-off Operation

A typical turn-off operation of a power semiconductor switch changes its operation state from forward conduction mode to forward or reverse blocking mode. Changing a device's operation state from forward conduction mode to forward blocking mode is defined as a forced turn-off, while changing a device's operation state from forward conduction mode to reverse blocking mode is defined as a load-commutated turn-off. During the forced turn-off transition, the switch may simultaneously undergo both high voltage and high current, as represented by curve (a) in Fig. 5(a), where the device's current stays constant while its voltage increases. Once the device voltage reaches its nominal value, the device current begins to decrease. So the device stress is high in this case. The voltage overshoot occurs due to the di/dt applied to the stray inductance in the current-commutation loop. With a snubber circuit, the voltage-current trajectory can be shaped as shown by curve (b) in Fig. 5(a), where the device current decreases before the device voltage increases to the normal value, resulting in dramatically reduced device stress.

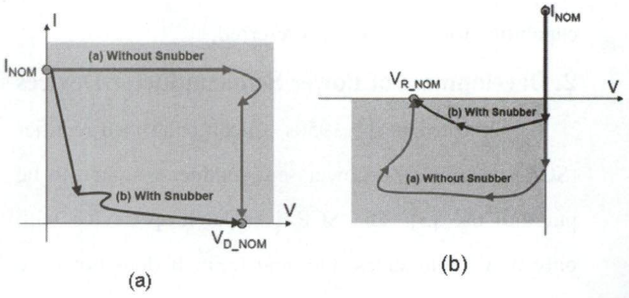


Fig. 5. I-V trajectories of a device for (a) forced turn-off with or without snubber circuit and (b) load-commutated turn-off with or without snubber.

During the load-commutated turn-off transition, the device current begins to decrease first while the voltage does not change much until the device current becomes negative. When the negative device current increases, the negative device voltage also increases. The negative device current begins to decrease once it reaches its peak value, resulting in a negative over-voltage as well as high stress on the device, as shown by curve (a) in Fig. 5(b). Similarly, with a snubber circuit, the voltage-current trajectory can be shaped as shown by curve (b) in Fig. 5(b) with much lower device stress.

Reverse Biased Safe Operation Area

The reverse biased safe operation area (RBSOA) is defined as the maximum voltage and current boundary within which the device can turn off without destructive failure [4]. Obviously, a device's RBSOA should be larger than all its possible turn-off I-V trajectories. A device without sufficiently large RBSOA needs an external circuit (snubber) to reduce the size of its turn-off I-V trajectory in order to ensure safe turn-off operation. The switching operation conducted without the help of a snubber is called snubberless switching, while the process utilizing a snubber is called snubbered switching. Since a snubber increases the system's component count, hence its size and cost, the snubberless switching capability for a device is preferred.

2. Development of Power Semiconductor Devices

Invented in the 1950s, silicon controlled rectifier (SCR) was the first power semiconductor switch to be put into use [5]. The SCR is a latch-up device with only two stable states: ON and OFF. It does not have FBSOA. The SCR has a good trade-off between its forward voltage drop and blocking voltage due to the strong conductivity modulation provided by the injections of both electrons and holes. With a simple structure, the size of a single SCR can be easily increased to a six-inch diameter in order to increase the current rating of the device. Based on a six-inch silicon wafer, 8.0-kA/10.0-kV SCRs are commercially available. The SCR can also block reverse voltage due to its symmetrical structure. However, SCRs cannot be turned off through their gate controls, and instead must use a load-commutated turn-off, such as that shown in Fig. 5(b).

Since the SCR cannot be turned off through the gate, the gate turn-off (GTO) thyristor [6] with forced turn-off controllability was subsequently developed. The basic structure of a GTO is similar to that of an SCR, except that many gate fingers are placed around the cathode of the GTO. Because of the gate control, the latch-up mechanism can be broken during the turn-off transition, resulting in full gate-control capability. For a fully controllable device, the GTO has the highest power rating and the best trade-off between the blocking voltage and the conduction loss. However, GTOs' dynamic performance is poor. Since the GTO lacks FBSOA and has poor RBSOA, a dv/dt snubber is required during turn-off, and a di/dt snubber is required during turn-on. As a current- driven device, it also requires a complicated gate driver, resulting in high gate-driver loss. GTOs can be made to be either symmetrical or asymmetrical.

The bipolar junction transistor (BJT) [7] is the earliest controllable device, and served as the workhorse device for power-conversion applications up until two decades ago. With fairly good FBSOA and RBSOA, its dynamic performance and switching speed are better than those of the GTO. However, the trade-off between its blocking voltage and its forward voltage drop is poor, and so no power BJT with a good forward voltage drop is designed beyond 1.5 kV. The control circuit is usually complicated and lossy since the BJT is a current-driven device. The RBSOA and FBSOA are also significantly limited by the second breakdown of a power BJT [8]. BJTs are asymmetrical devices.

The power MOSFET [9] is a voltage-controlled device with excellent dynamic performance due to its majority-carrier current-conduction mechanism. Except that its power rating is limited by the resistive conduction loss, the power MOSFET has become a nearly perfect power switch for applications below 600 V due to its fast switching speed, voltage control and excellent FBSOA and RBSOA. Snubberless turn-on and turn-offcan be achieved in MOSFETs. The MOSFET is also an asymmetrical device.

Based on the idea of a MOS-controlled BJT, the insulated gate bipolar transistor (IGBT) [10] was developed. The IGBT fundamentally changes the BJT's current control into voltage control while maintaining the BJT's advantages. IGBTs have excellent RBSOA and FBSOA. In addition, the use of a wide-base PNP transistor in the IGBT structure results in a much better conductivity modulation effect than is achieved with a conventional BJT; thus, the voltage rating of the IGBT can be pushed toward that of the GTO. To date, IGBTs have become the best device for applications in the range of 600 V to 3000 V. Most commercial IGBTs are asymmetrical device although theoretically a symmetrical device can also be developed.

For high power applications, traditionally, a high power SCR is used as the symmetrical power semiconductor device for a CSC [11]. Since the SCR does not have the forced turn-off capability, the operation of the thyristor in a CSC is totally load commutated at the line frequency. Due to its low switching frequency, its dynamic response speed is low and a large filter is needed to attenuate the harmonics. The symmetrical GTO with capabilities of both forced turn-off and reverse voltage blocking, was then introduced to the market [12-15]. Using a symmetrical GTO device, the Sinusoidal Pulse Width Modulation (SPWM) scheme [16] can be used to modulate device switching. Compared to the SCR, the switching frequency for a symmetrical GTO is higher. Therefore, the dynamic response speed and output current harmonics are greatly improved for a symmetrical GTO based CSC. However, the GTO has several disadvantages [17]. During the turn-off transient, the P-N-P-N four-layer structure causes inhomogeneous transient current distribution that results in a small RBSOA. A dv/dt snubber is needed to ensure that the GTO operates within the RBSOA during the turn-off process. During the turn-on transient, the P-N-P-N four-layer structure latches quickly and causes a current-crowding problem. Therefore, a turn-on di/dt limiting snubber is demanded. Furthermore, since the GTO is a current-controlled device, its gate driver is bulky and dissipates hundreds of watts in a typical application. The large parasitic inductance in GTO gate drivers usually result in a very long storage time and a turn-off gain of 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 being challenged by high power IGBTs that offer higher speed, a larger SOA and easier controls. However, the conduction loss of the high power IGBTs is still much higher than that of the GTO. The IGBT's high conduction loss results in lower system efficiency. Furthermore, since no symmetrical IGBTs are commercially available now, the IGBT based

CSC is not feasible. This situation will continue into the near future.

On the other hand, a lot of efforts have recently gone into improving the switching performance of the GTO-oriented devices. One type of GTO-based semiconductor device with a wider RBSOA is the Integrated Gate Commutated Thyristor (IGCT). With dramatically improved turn-off performance, the IGCT will help to maintain the domination of GTO technology in high power areas. Symmetrical GCTs have also been introduced to the market for industrial drive applications. In an IGCT based CSC, the dv/dt snubber is dramatically reduced due to the improved turn-off performance of the IGCT. However, the IGCT does not have an FBSOA, so a di/dt snubber is still needed. The fairly high gate drive power is one of the limitations for high-frequency switching. Besides, the cost of the symmetrical IGCT is high due to its specially designed device structure.

The Emitter Turn-off (ETO) Thyristor is another type of GTO based superior high power semiconductor device. Based on the mature technology of the GTO and power MOSFET, the ETO provides a low-cost and advantageous 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 and 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.

3. Operation Principle of the Symmetrical ETO

According to GTO theory, the 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 thyristor 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. During this transition, the device I-V curve changes from curve (a) to curve (b), as shown in Fig. 6, resulting in a dynamic current limiting capability for the GTO cell, and hence a uniform current distribution and wide RBSOA.

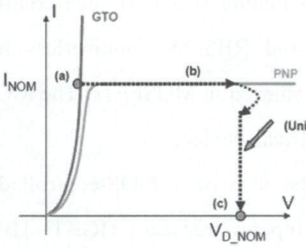
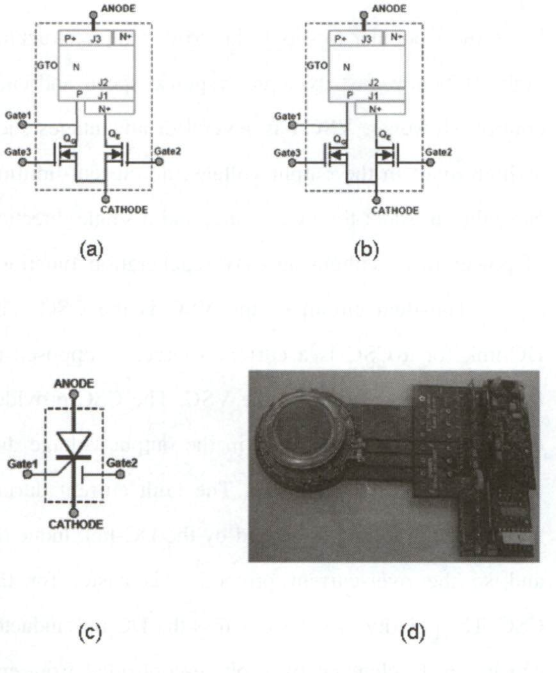


Fig. 6. Forward I-V characteristics of the ETO during a forced turn-off transition.

The ETO is an MOS-GTO hybrid device that makes the GTO operate under the hard-driven condition. 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. The equivalent circuit of the asymmetrical ETO is shown in Fig. 7(a). An asymmetrical ETO is realized by using an asymmetrical GTO in series with an emitter switch QE and by connecting gate switch QG to the GTO’s gate. During the forced turn-off transient, QE is turned off and QG is turned on. The GTO’s cathode current is totally bypassed via switch QG before the anode voltage begins to rise. In this way, the thyristor latch-up is broken, and the ETO is turned off under a unity turn-off gain condition, resulting in snubberless turn-off capability. It should be stressed that the turn-off is a voltage-controlled process. So the gate driver of the ETO is very compact and dissipates much less power. During the turn-on transient, QE is turned on and QG is turned off. Thanks to the tightly integrated gate driver, a high current pulse plus a DC current are injected into the GTO gate to reduce the turn-on delay time and improve the turn-on di/dt rating.

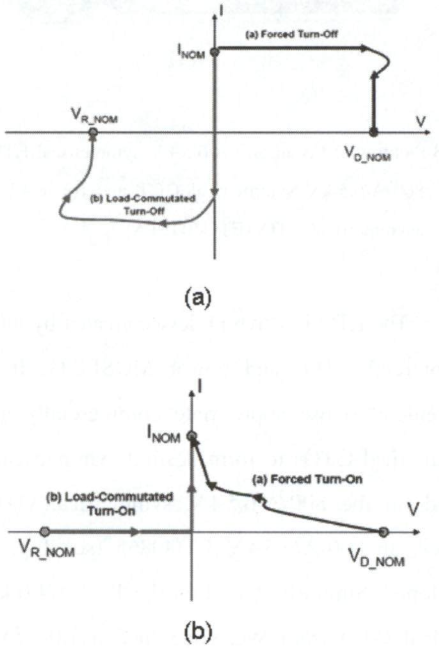


(a) (b)

(c) (d)

Fig. 6. (a) Asymmetrical ETO equivalent circuit, (b) symmetrical ETO equivalent circuit, (c) circuit symbol and (d) a picture of 1-kA/4.5-kV symmetrical ETO with its gate driver.

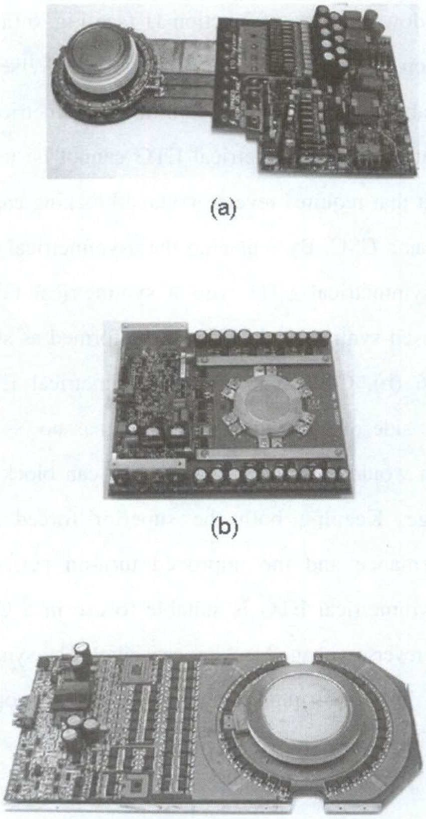
With superior forced turn-off capability as well as improved turn-on performance, the asymmetrical ETO is a good candidate for use in a VSC where the device always has a positive voltage stress. However, the asymmetrical ETO usually has a low reverse voltage blocking rating (about 20 V) that is dictated by the breakdown voltage of junction J1 (see Fig. 6 (a)), since junction J3 (see Fig. 6 (a)) cannot block reverse voltage with anode-shorting structure in the asymmetrical ETO. Therefore, the asymmetrical ETO cannot be used in a circuit that requires reverse voltage-blocking capability, such as a CSC. By replacing the asymmetrical GTO in an asymmetrical ETO with a symmetrical GTO, the proposed symmetrical ETO can be formed as shown in Fig. 6 (b). Compared to the asymmetrical ETO, the anode side of the symmetrical ETO has no N+ region, which would short junction J3, so it can block reverse voltage. Keeping both the superior forced turn-off performance and the improved turn-on performance, the symmetrical ETO is suitable to use in a CSC due to its reverse voltage-blocking capability. The symmetrical ETO is a two-quadrant device, and its operation trajectories are shown in Fig. 7.



(a)

(b)

Fig. 7. I-V trajectories of the symmetrical ETO during (a) turn-off transition and (b) turn-on transition.



(a)

(b)

(c)

Fig. 8 Pictures of (a) an 800-A/6.5-kV symmetrical ETO, (b) an 800-A/6.5-kV symmetrical GCT and (c) a 4-kA/4.5-kV asymmetrical ETO (ETO4045TA).

The ETO is a hybrid device created by integrating commercial GTOs and power MOSFETs. It is very convenient to use appropriate commercially available symmetrical GTOs to form desired symmetrical ETOs. Based on the 800-A/6.5-kV symmetrical GTO from Dynex, an 800-A/6.5-kV ETO0865 (see Fig. 8(a)) is developed. Similarly, based on the 1.0-kA/4.0-kV symmetrical GTO from Westcode Inc., a 1.0- kA/4.0-kV symmetrical ETO (the ETO1040W, seel Fig. 6(d)) is developed. The symmetrical ETO can also be formed by using a commercial power diode in series with an asymmetrical ETO. Fig. 8(c) shows the picture of a 4-kA/4.5-kV asymmetrical ETO (the ETO4045TA) developed at Virginia Tech's CPES [K9]. For comparison purposes, the 800-A/6.5-kV symmetrical gate-commutated thyristor (SGCT GCU08AA130, see Fig. 8(b)) from Mitsubishi Inc. has also been characterized.

4. High Power Current Source Converter

With the advance of power semiconductor devices, more and more power electronics systems are used in high power utility and industry applications. The VSC is the most popular topology due to its simple structure, high efficiency, fast dynamic response speed and easy control. However, VSC has several disadvantages such as high dv/dt in the output voltage, no current-limiting capability in shoot-through failure, and a single direction of power flow without an easy regeneration function.

The dual circuit of the VSC is the CSC. The DC-link for a CSC is a current source, as opposed to the voltage source used in the VSC. The CSC provides the advantages of low dv/dt in the output voltage due to the output filter capacitor. The fault current during shoot-through failure is limited by the DC-link inductor, and so the over-current protection is easier for the CSC. The polarity of voltage across the DC-link inductor can be easily changed by a phase-controlled front-end rectifier, implementing the regeneration capability with less effort. Especially for high power applications, these advantages overcome the disadvantages of higher conduction loss and more complicated control and the CSC topology becomes a competitive candidate.

For flexible AC transmission systems (FACTS) devices and energy storage systems, power converters with high voltage, high current, low harmonics and fast dynamic response speed are required. With traditional three-level CSC topology, power semiconductor devices in series or parallel connection are needed to achieve high voltage rating. Complicated balancing circuits are required for the proper operation of the series or parallel devices. Device derating is usually needed. The switching frequency for high power semiconductor devices is usually low, since it is limited by the switching loss in high power applications. Therefore, the harmonics in the output voltage and current are high and the dynamic response is slow. To limit the harmonics within a standard, an external filter is usually needed, and this addition will further reduce the dynamic response speed. Therefore, paralleling converters instead of devices is preferred for high power applications [G1-G5]. To further increase the power rating and to reduce harmonics, multilevel converters based on PWM converter cells are developed. The multilevel converter is a trend for high power applications. For multilevel CSC topology, there are two kinds of topologies. In one, the multiple CSC, several CSCs are in parallel connection and thus share the same DC-link current through current-sharing inductors and proper control, as shown in Fig. 9. The capacity of the multiple CSC can be increased, and the harmonics contained in the output voltage and current waveforms can be reduced through phase-shift PWM control among parallel CSCs. However, to ensure DC current sharing and to prevent the circulating current among the parallel CSCs, additional current-sharing components and complicated control must be applied.

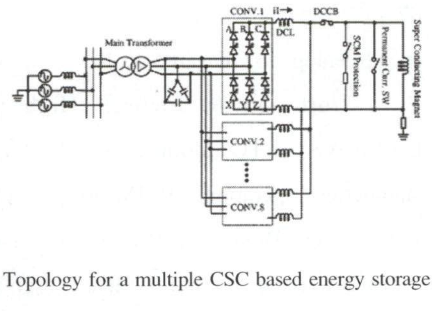


Fig. 9. Topology for a multiple CSC based energy storage system.

Another method for achieving the low switching frequency and low harmonic distortion for high-power applications is to apply a generalized current multilevel cell to form multilevel CSCs. Many smaller current-sharing inductors are employed to ensure current sharing among the different branches. The multilevel output current is achieved through proper control of the active switches. In this version of multilevel CSC, the current sharing between active switches relies on their on-state voltages, and thus complicated control is also needed. In this topology, the modular design is also not used due to its complicated structure and control.

Since the basic structure for the parallel-cell multilevel CSC is six-switch CSC cell, symmetrical power semiconductor devices are needed to block both the reverse voltage and the forward voltage. Traditionally, only the symmetrical GTO has been available for the high power CSC. Recently, two types of high-power fast-switching symmetrical power semiconductor devices have also been available and they are symmetrical ETO and symmetrical IGCT. Symmetrical ETOs with blocking voltage up to 6.5 kV and maximum controllable turn-off current up to 1000 A have been developed Symmetrical IGCTs with the blocking voltage up to 6.5 kV and maximum controllable current up to 1500 A are commercially available. Using these advanced symmetrical power semiconductor devices with superior levels of switching performance, the switching frequency for the multilevel CSC can be improved, resulting in a system with fast dynamic response and lower harmonics.

5. Conclusion

An advanced symmetrical device, the symmetrical ETO, is proposed. Its on-state characteristics, forced turn-on characteristics, forced turn-off characteristics as well as the load-commutated turn-off characteristics for symmetrical ETO are evaluated. The symmetrical ETO has the ability to achieve snubberless forced turn-off due to its unity-gain turn-off. The forced turn-on performance is improved by its tightly-integrated gate driver. However, the symmetrical ETO is still suitable for use in high-power circuits that require reverse voltage-blocking capability, due to its lower conduction loss, fewer components and the simplicity of its circuit without a dv/dt snubber.

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Biography

Paisan Boonchiam works at department of electrical engineering. His research interests are applications of FACTS and custom power devices, power quality, power system dynamic and stability, power system planning and optimization techniques.