SPETO: A Superior Power Switch for High Power, High Frequency, Low Cost Converters

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***Abstract*— This paper presents the design and experimental demonstration of a superior high power device, self-powered emitter turn-off thyristor (SPETO). Different from the conventional high power devices which require the external power input for their gate drivers, SPETO achieves optically controlled turn-on and turn-off, and all the internal power required is self-generated. Low loss gate drive circuit is implemented which allows the simple power-up operation. During normal switching operation, SPETO obtains power for the gate drive during its turn-on operation. SPETO also maintains the reported advantages of ETO such as the high switching frequency capability (over 2kHz), large snubberless turn-off capability (5000A/2800V), low conduction and switching losses, and easy for series and parallel operation. SPETO greatly reduces the cost and increase the reliability of the power converters since no external power supply for device gate drive is required. SPETO is therefore suitable for the high power high frequency voltage source converter applications. Novel switching strategy is also introduced to minimize the gate drive power requirement.**

Keywords-emitter turn-off thyristor; gate turn-off thyristor; gase/gate drive suppression; self-powered ETO

I. INTRODUCTION

Conventional high power semiconductor devices require external power inputs for their gate drivers. In the voltage source converter applications, the external power supplies for the device gate drivers need to be individually designed. The power for each device gate driver is normally provided from low voltage potential (normally ground potential). The insulation transformer is hence required to deliver the power to the device gate driver that is at the high voltage potential. In a high voltage converter, the insulation transformer usually has a large size and it is often difficult to implement the reliable insulation design. These external power supplies for the gate drivers increase the cost and may reduce the reliability of the whole system.

Several gate drive power supply methods [1,2,3] by which the gate drive power is not provided from the low voltage potential through insulation transformer are proposed. However, each of these methods obtains the gate drive power through the dv/dt snubber circuit, and has low efficiency. The power supply for the gate drive needs to be individually designed according to the operation voltage and switching frequency of the device. For the high power converters using snubberless turn-off devices such as IGCTs [4] and ETOs [5,6], the dv/dt snubbers are not required and these methods are difficult to apply.

In this paper, we propose a novel high power device, self-powered emitter turn-off thyristor (SPETO). Different from the conventional high power devices which require the external power input for their gate drivers, SPETO achieves optical turn-on and turn-off, and the internal gate drive power required is self-generated. SPETO obtains power for gate drive through its turn-on operation. This paper presents the design and experimental demonstration of SPETO. Novel switching strategy to minimize the gate drive power requirement for SPETO is also discussed.

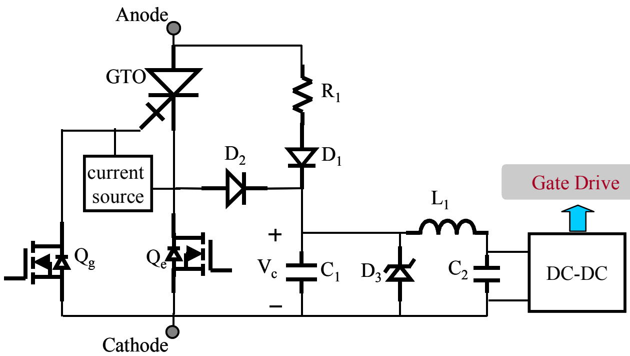
II. DESIGN AND OPERATION MODES OF SPETO

A. Design and Package

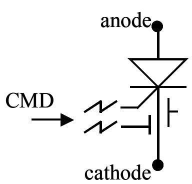
Fig. 1 shows the circuit diagram and circuit symbol of the SPETO. SPETO is a GTO, MOSFETs, and gate drive circuit integrated high power device. In SPETO, an emitter switch Q_e is in series with the GTO, and a gate switch Q_g is connected to the GTO's gate. Q_e, Q_g, and a controllable current source are used for turn-on and turn-off of the GTO [6]. R_1, L_1, $C_{1\text{-}2}$, and $D_{1\text{-}3}$ are used to obtain power and store the energy into cap bank C_1. Then the power from C_1 is supplied to the input of a DC-DC converter. The DC-DC converter generates the power for the internal control and gate drive of SPETO. SPETO does not require the external power input for gate drive. Turn-on and turn-off command to SPETO is transferred through an optical fiber. SPETO can be seen as a two electrical terminal device with an optical command input (CMD) as shown in Fig. 1 (b).

Fig. 2 shows the picture of the developed 4.5 kV/4kA SPETO.

Fig. 3 is the cross section drawing of SPETO, showing the various components of the integrated device. SPETO utilizes double side press-pack cooling package and achieves small thermal resistance. The power resistor R_1 is placed on a copper layer, so that the heat of the R_1 is easily transferred to the heat sink.



(a)



(b)

Figure 1. The circuit of SPETO: (a) the circuit diagram and (b) the circuit symbol

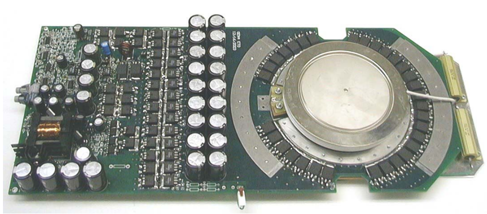


Figure 2. The picture of SPETO.

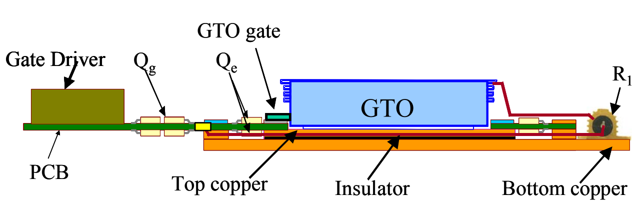


Figure 3. The cross section of SPETO.

B. Three operation modes of SPETO

When SPETO works in a PWM voltage source converter, it has three operation modes: start-up mode, active switching mode, and inactive switching mode. Fig. 4 shows a two level voltage source converter phase leg. $SPETO_p$ and $SPETO_n$ are the upper switch and the lower switch respectively of the phase leg. Fig. 4 shows the SPETOs working at start-up mode. SPETO works at start-up mode when the converter first powered on. In this mode, both $SPETO_p$ and $SPETO_n$ are in off state. The DC-link voltage rises gradually from zero to the final voltage.

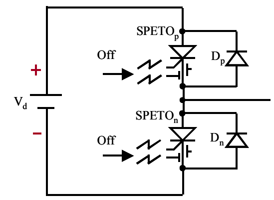
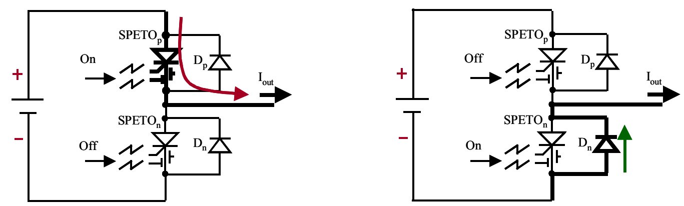


Figure 4. The SPETOs working at start-up mode

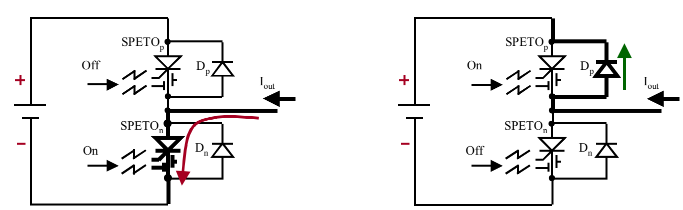
Assuming the output current I_{out} of the phase leg is positive when it flows out of the phase leg. When I_{out} is positive, the upper switch $SPETO_p$ works in the active switching mode as shown in Fig. 5. From Fig. 5, it can be seen that, I_{out} will flow through $SPETO_p$ if $SPETO_p$ is on and $SPETO_n$ is off; I_{out} will flow through D_n if $SPETO_p$ is off and $SPETO_n$ is on.



(a) (b)

Figure 5. $SPETO_p$ working in active switching mode: (a) $SPETO_p$ is on; $SPETO_n$ is off and (b) $SPETO_p$ is off; $SPETO_n$ is on

When I_{out} is negative, the upper switch $SPETO_p$ works in the inactive switching mode as shown in Fig. 6. From Fig. 6, it can be seen that, I_{out} will flow through $SPETO_n$ if $SPETO_p$ is off and $SPETO_n$ is on; I_{out} will flow through D_p if $SPETO_p$ is on and $SPETO_n$ is off. We can know that in the inactive mode, I_{out} will never flow through $SPETO_p$, no matter $SPETO_p$ is on or off.



(a) (b)

Figure 6. $SPETO_p$ working in inactive switching mode: (a) $SPETO_p$ is off; $SPETO_n$ is on and (b) $SPETO_p$ is on; $SPETO_n$ is off.

The lower switch $SPETO_n$ follows the same working principle as that of $SPETO_p$. When I_{out} is negative, $SPETO_n$ works in the active switching mode. When I_{out} is positive, $SPETO_n$ works in the inactive switching mode.

C. *The power consumption of SPETO in off state and during switching*

The gate drive power consumptions of the SPETO in off state and during switching are quite different. During off state (no switching), The gate drive power consumption of SPETO is only the control IC's quiescent power consumption.

When SPETO is commanded to turn on, the emitter switch MOSFETs are turned on and the gate switch Q_g is turned off. At the same time, a firing current pulse is injected into the GTO's gate by a current source to turn on the GTO. While SPETO is on, a DC current is provided for the GTO's gate in order to ensure that the GTO remains in a low conduction loss state. When SPETO is commanded to turn off, the emitter switch MOSFETs are turned off and the gate switch MOSFETs are turned on. So during switching, current pulse injection, MOSFETs gate drive, and DC current injection will consume power. The power consumptions of current pulse injection and MOSFETs gate drive are proportional to the switching frequency.

Fig. 7 shows the power consumptions of SPETO in off state and during switching at different frequencies. In Fig. 7, P_GTO_DC denotes SPETO's DC current injection power consumption. P_GTO_pulse denotes SPETO's pulse current injection power consumption. P_MOSFET denotes SPETO's MOSFETs gate drive power consumption. It can bee seen that SPETO's gate drive power consumption in off state is very small (below 0.5W). SPETO's gate drive power consumption increases dramatically from off state to switching state and also increases with the switching frequency.

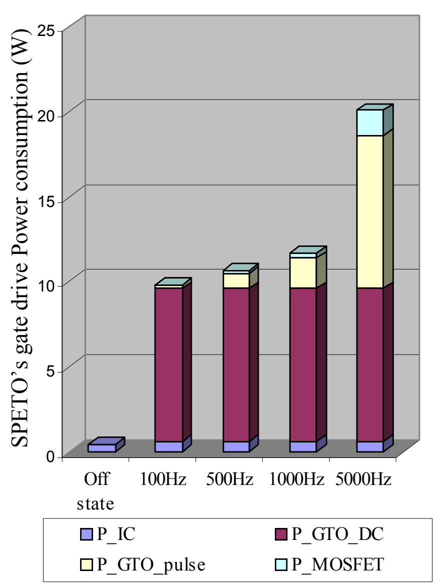


Figure 7. SPETO's gate drive power consumptions in off state and during switching at different frequencies

In the following sections, we will describe SPETO's operation principle and experimental results in the three working modes.

III. The Operation Principle and Implementation of SPETO in Start-Up Mode

At power-up of SPETO, the power for gate drive is received through R_1 by SPETO's anode voltage V_{anode}, as shown in Fig. 8. The charge current I_{c1} charges capacitor bank C_1 and then provides the power input to the DC-DC converter through filter L_1 and C_2. The power that is delivered to DC-DC by R_1 is expressed by (1).

$$P_1 = V_c \cdot \frac{(V_{anode} - V_c)}{R_1} \tag{1}$$

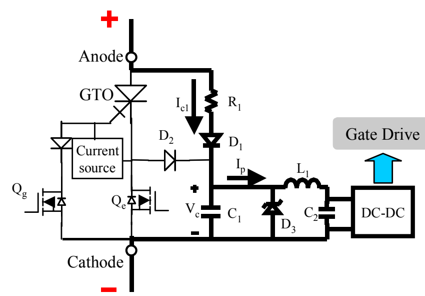


Figure 8. The start-up operation of SPETO

From (1), it is clear that the higher the V_{anode}, the more power can be obtained by the DC-DC, and at a given V_{anode}, the maximum power can be obtained by DC-DC when

$$V_c = \frac{V_{anode}}{2} \tag{2}$$

During start-up, SPETO works at off state. From Fig. 7 it can be known that SPETO's gate drive power consumption P_1 is less than 0.5W. The minimum V_{anode} for SPETO to get enough power for start-up is set at 500V. A DC-DC converter with line under-voltage detection function (UV) is designed for the DC-DC. At power-up, UV keeps DC-DC off until V_c reaches the under-voltage threshold, which is set at 250V according to (2). Then from (1), the value of R_1 is designed to be 125 kohm.

Once DC-DC powers up, UV is disabled to extend the input voltage operation range: DC-DC can still work even when V_c drops to 20V. A zener diode D_3 is used to limit the V_c within 300V.

Suppose SPETO's maximum anode voltage during operation is 2800V. The maximum power consumption of R_1 is about 24W. R_1 is mounted at the heat sink of SPETO as shown in Fig. 3. The capability of the water-cooling system for each SPETO is normally designed around several kilowatts. So R_1 adds only a very small burden to SPETO's cooling system.

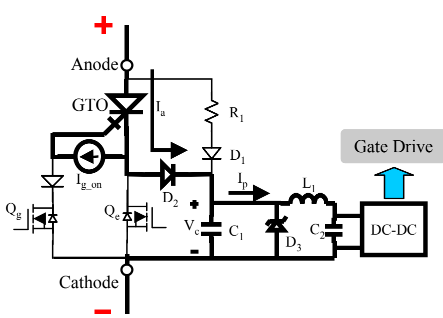
IV. The Operation Principle and Experimental Demonstration of SPETO in Active Switching Mode

A. The Operation Principle

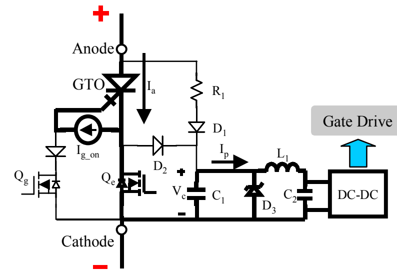
The power consumption of the gate driver of SPETO is much bigger during switching operation as shown in Fig. 7. Apparently, the power delivered through R_1 is not enough in these situations, and V_c, the voltage of the capacitor bank C_1, will gradually decrease during SPETO's switching. The following method is proposed to maintain V_c within a certain range. The objective of the method is to control V_c to be between V_{ref1} and V_{ref2}:

$$V_{ref1} < V_c < V_{ref2} \tag{3}$$

V_c is constantly monitored by the control circuit. Referring to Fig. 9, when SPETO is commanded to turn-on, the gate switch Q_g is turned on, and a firing pulse I_{g_on} is injected into the GTO's gate by a current source to turn on the GTO. At the same time, the control circuit will check V_c. If V_c is lower than V_{ref1}, the SPETO will enter into the charging turn-on mode, and the turn-on of Q_e will be delayed. Since GTO is turned on and Q_e is still off, the GTO current I_a will be forced to charge capacitor bank C_1 through D_2, as shown in Fig. 9 (a). As a result, V_c will increase. The increasing rate of V_c depends on both I_a and the capacitance of C_1. When V_c increases to V_{ref2}, Q_e is turned on, D_2 is reverse biased and I_a will be diverted to Q_e from D_2, as shown in Fig. 9 (b). Then V_c stops increasing, and the input power of DC-DC is provided by the energy stored in C_1. If V_c is higher than V_{ref1} when SPETO is commanded to turn on, Q_e will be turned on immediately, and the operation shown in Fig. 9 (a) will be bypassed. C_1 is designed to be a large capacitor bank and can store a large amount of energy. Once it is charged to or above V_{ref2}, the energy stored in C_1 is large enough to maintain the gate drive power of SPETO for a fairly long time before V_c is discharged to V_{ref1}. Normally, the operation shown in Fig. 9 (a) happens once in several thousand switching cycles.



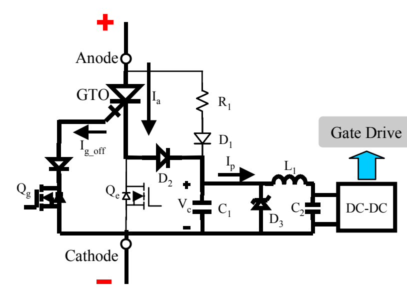
(a)



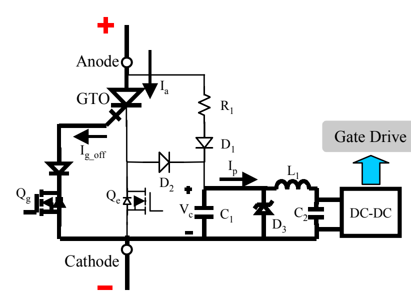
(b)

Figure 9. The turn-on operation of SPETO: (a) the charging turn-on mode of SPETO and (b) the normal turn-on mode of SPETO.

When SPETO is commanded to turn off, Q_e is turned off and Q_g is turned on. The voltage between Q_e's drain and source (V_{Qe}) begins to increase, forcing cathode current commutate to Q_g via the GTO's gate. If I_a is high, V_{Qe} will reach V_c and forward bias D_2, as shown in Fig. 10 (a). Then V_{Qe} will be clamped to V_c, and so it will stop increasing. V_c is designed to be lower than the break down voltage of the MOSFETs. So the drain voltage of the MOSFETs will never reach break down voltage, and this is favorable for the MOSFET's long-term reliability. After the total GTO cathode current is diverted to GTO's gate, there will be no current go through Q_e as shown in fig. 10 (b), and V_{ds} will drop. The total anode current I_a will continue flowing through the GTO's gate. When the storage time of the GTO ends, the GTO's anode voltage will start to increase. When the GTO's anode voltage increases to above the DC-link voltage, I_a will fall to zero, entering the off state, and the GTO supports the whole voltage applied on SPETO. In off state, the operation of SPETO is the same as the drawing shown in Fig. 8. C_1 obtains energy from R1 in off state.



(a)



(b)

Figure 10. The turn-off operation of SPETO: (a) before unity turn-off gain achieved and (b) after unity turn-off gain achieved.

The gate loop inductance of SPETO is minimized to ensure that the time required to divert the current from the GTO's cathode to gate is smaller than the GTO's storage time, to achieve the unity turn-off gain. In this situation, SPETO can be safely turned off without dv/dt snubber.

B. The Experimental demonstration of SPETO in active switching mode

The characteristics and performance of SPETO are measured in a boost converter shown in Fig. 11. In this circuit, SPETO is turned off without dv/dt snubber. The DC-link voltage is 2000V. The experimental results are shown in Fig. 12. V_{ref1} and V_{ref2} are set to be 100V and 150V. V_c is 95V when SPETO is commanded to turn on. At time t_1, SPETO is commanded to turn on. Since V_c is lower than V_{ref1}, the turn-on of Q_e is delayed. After GTO is turned on, SPETO's anode voltage drops to V_c (the operation is shown in Fig. 10 (a)). Since Q_e is still off, V_{Qe} begins to rise very fast and eventually is clamped to V_c. Then I_a starts to charge C_1. And V_c starts to rise. At time t_2, V_c reaches V_{ref2}. Then Q_e is turned on. V_{Qe} drops to nearly zero, and I_a is diverted to Q_e immediately. D_2 is reverse biased and V_c stops increasing. At time t_3, SPETO is commanded to turn off. Q_e is turned off first. Then V_{Qe} starts to rise rapidly and clamped to V_c (the operation is shown in Fig. 10 (b)). V_{Qe} drops down when the unity turn-off gain is achieved. Eventually V_a rises to above DC-link voltage and I_a decreases to zero. SPETO turns off 2000A to the 2000V DC bus without snubber. During this switching cycle, V_c is charged from 95V to about 135V. SPETO successfully obtains about 10.1J energy in this switching cycle. This energy can maintain SPETO's gate drive for about 1s switching at 1000 Hz.

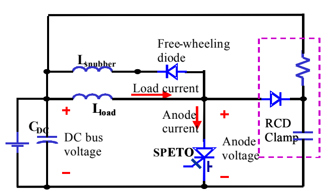


Figure 11. The test circuit for SPETO in active switching mode

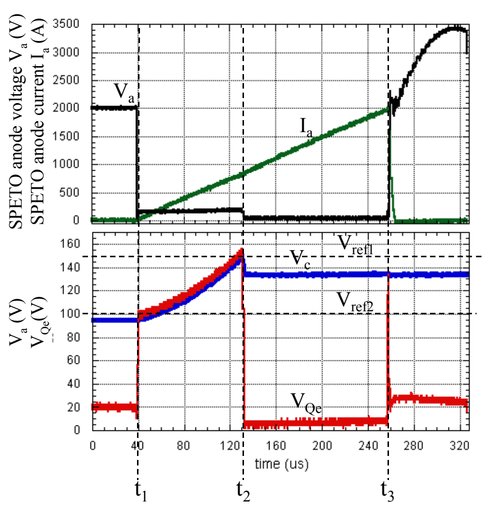


Figure 12. The experimental results of SPETO in active switching mode

V. The Operation Principle and Experimental Demonstration of SPETO in Inactive Switching Mode

A. The operation principle

In designing a voltage source PWM converter, the gate drivers of the upper switch and the lower switch of a phase leg are usually fed with complimentary (with dead-time) on/off commands, no matter they are working in active switching mode or inactive switching mode. In section II, we know that when SPETO works in the inactive mode, I_{out} will never flow through SPETO (I_{out} flows through the other SPETO or the anti-parallel diode), no matter SPETO is on or off. So in inactive switching mode, SPETO is not able to obtain power through charging turn-on operation as shown in Fig. 9 (a). From Fig. 7 we know that the gate drive power consumption of SPETO is much bigger in switching modes than that in off state. So in inactive switching mode, the SPETO gate driver consumes power but cannot obtain power through charging turn-on operation. As a result, V_c will decrease in the inactive switching mode. In order to keep SPETO working well, the output line frequency has to be high enough to guarantee that SPETO can obtain power through charging turn-on before V_c decreases too low and DC-DC converter runs out of regulation.

When a device works at inactive switching mode, it does not conduct current. So the turn-on of the device is unnecessary. In this situation, the turn-on operation of the device can be suppressed to save the gate drive power [7]. Conventionally this method is implemented within the PWM controller and need the output current direction detection. For SPETO, we propose a novel SPETO gate drive suppression function that is implemented within the SPETO gate driver. The SPETO gate driver monitors the on/off state of the SPETO's anti-parallel diode and keeps SPETO off if its anti-parallel diode is conducting current.

To reduce the turn-off switching loss of SPETO, the anode short type or transparent emitter GTO [8,9,10] is used to build SPETO. Inside the anode short GTO, there is a parasitic diode D_p from GTO's gate to anode, as shown in Fig. 13. In our design, D_p is utilized to implement this novel SPETO gate drive suppression function.

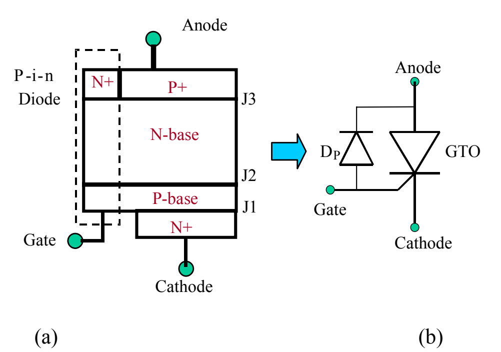
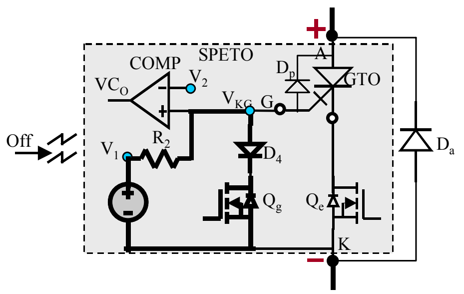


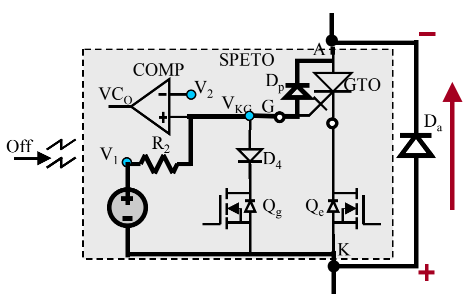
Figure 13. Anode short GTO: (a) device model and (b) circuit model

Fig. 14 shows the circuit diagram of SPETO's gate drive suppression function. D_a is SPETO's anti-parallel diode. The gate drive suppression circuit includes reference voltage V_1, V_2, and a resistor R_2. When SPETO is commanded to be off and D_a is not conducting current, there will be a small current flowing through R_2, D_4, and Q_g, as shown in Fig. 14 (a). V_2 is set to be smaller than V_{KG}. Then VC_0, the output of COMP, will be high. When D_a starts to conduct current, the current flowing through D_4 and Q_g will be diverted to D_p, making V_{KG} lower than V_2, as shown in Fig. 14 (b). Then VC_0 will be low, and the low output is used to suppress any SPETO's turn-on command. By this approach, SPETO will not be turned on when its anti-parallel diode is conducting current.

When D_p is conducting current, the magnitude of the current is limited to a small value by R_2. So the current flowing through D_p will not cause any abnormal failure problems [11].



(a)



(b)

Figure 14. The circuit diagram of SPETO's gate drive suppression function: (a) SPETO is commanded to be off and D_n is not conducting current and (b) SPETO is commanded to be off and D_n is conducting current

B. *The Experimental demonstration of SPETO's gate drive suppression function*

SPETO's gate drive suppression function is tested in a SPETO based high power H-bridge converter as shown in Fig. 15. S_1, S_2, S_3, and S_4 are four SPETOs. In this test, the upper and lower SPETOs are fed with complementary PWM signal with dead time. SPETO suppresses the turn-on command when its anti-parallel diode is conducting current. SPETOs also send out their on/off status feedback signal through optical fibers.

The SPETO S_2's input switching command, on/off status feedback signal, S_2's current plus D_2's current, and the load current I_{load} are measured and shown in Fig. 16. From Fig. 16 it can be seen that although S_2 is fed with continuous PWM command signal, it suppresses the turn-on command when its anti-parallel diode D_2 is conducting current (when I_{S2} plus I_{D2} is negative). SPETO's gate drive suppression function is successfully demonstrated.

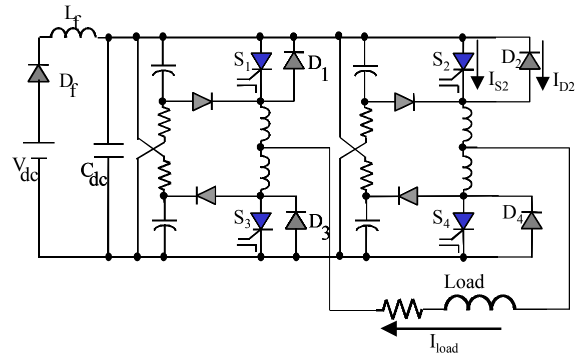


Figure 15. SPETO based high power H-bridge converter

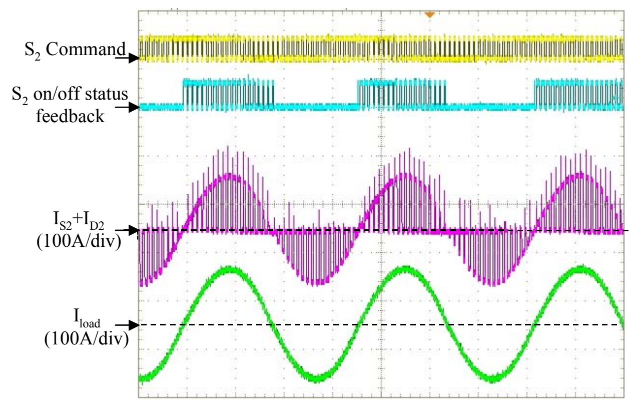


Figure 16. The experimental results of SPETO based high power H-bridge converter

VI. CONCLUSIONS

This paper presents the design and experimental demonstration of SPETO. SPETO achieves optically controlled turn-on and turn-off, and all the internal power required is self-generated.

SPETO has three working modes: start-up mode, active switching mode, and inactive switching mode. SPETO has a simple and low power loss circuit to obtain power for start-up. In active switching mode, SPETO obtains gate drive power through its charging turn-on operation. In inactive switching mode, to save gate drive power, SPETO suppresses its unnecessary turn-on when its anti-parallel diode is conducting current.

Besides the greatly simplified control interface architecture, SPETO also has such advantages as high switching frequency capability (over 2kHz), large snubberless turn-off capability (5000A/2800V), low conduction and switching losses, and easy for series and parallel operation. The internal power generation and snubberless turn-off functions are demonstrated through the experiment. SPETO can greatly reduce the cost and increase the reliability of the power converters since no external power supply for device gate drive is required. SPETO is hence very suitable for the high voltage converter applications such as devices series-connected and multilevel converters.

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