The Built-in Current Sensor and Over-Current Protection of the Emitter Turn-off (ETO) Thyristor

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***Abstract*—ETO is an advanced high-power semiconductor device based on hybrid integration of traditional GTO and MOSFET. The ETO has high switching speed, snubberless turn-off capability and low conduction loss. When ETO is conducting current, the total current will go through the integrated MOSFET. In this situation, the MOSFET acts as a small linear resistor whose voltage drop reflects the current through it. This paper discusses a method to measure the current and transfer the current information to a PWM signal whose duty cycle is proportional to the current value. The frequency of the PWM signal is also changed according to the MOSFET's junction temperature. In this way the temperature effect on the MOSFET's on-resistance is eliminated. The sensed current information is sent out through an optical fiber. So it is very easy to be received and used for control purpose. The sensed current information is also used for the built-in over-current protection purpose. The ETO's built-in current sensor, fast turn-off speed, and high current turn-off capability enable the ETO to shut down the fault current very fast in the over-current fault situation. The experimental results show that the error of ETO built-in current sensor is less than 1%. And the over-current protection function effectively stops the rising of the fault current in about 2us after the over-current triggering, and shut down the fault current in about 4us.**

Keywords- current sensor; over-current protection; ETO, GTO

I. INTRODUCTION

The current sensor is an important element in the power electronics systems for the measurement, protection, and control purposes. In the high power application, current transformers, hall effect devices, and current shunts are widely used. The current transformer and hall effect device are convenient to use. But they require expensive and bulky magnetic cores. The shunts are cost effective, but they usually need the complicated signal isolation and amplifier, and also suffer from the noise problems.

The emitter turn-off (ETO) thyristor is a MOS-GTO hybrid [1-6] high power device. Inside the ETO, the GTO is connected in series with the MOSFET. When ETO is conducting current, the total current will go through both the GTO and the MOSFET. In this situation, the MOSFET acts as a small linear resistor whose voltage drop is proportional to the current through it. This paper introduces an ETO built-in current sensor, which 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. But the latching devices such as GTO cannot enter such active region to limit the current. In 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. To protect the GTO, an additional thyristor, so-called crowbar, is often connected in parallel with the GTO. In the over-current situation, the crowbar will be trigged on to divert the current from the GTO. Obviously, those approaches are expensive and not reliable.

The ETO dramatically reduces its storage time to about 1us through the unity gain turn-off [1,2]. Thus 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. This paper demonstrates that the ETO can stop the current rising in about 2us after the over-current triggering.

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II. THE ETO BUILT-IN CURRENT SENSOR

A. The Design of the ETO Built-in Current Sensor

Fig. 1 shows the ETO equivalent circuit and the circuit symbol. Fig. 2 shows the picture of the ETO. Fig. 3 shows the cross section of the ETO. The ETO includes a commercial GTO, a gate switch which is connected to the GTO gate and an emitter switch which is connected in series with the GTO. The emitter switch consists of many MOSFETs in parallel. These MOSFETs have very good current sharing capability due to their strong positive temperature coefficiency. As shown in fig. 1, the parasitic resistance and inductance R_1, C_1, R_2, C_2, etc, which caused by the layout of the MOSFETs and the circuit routing, may affect the current sharing of the MOSFETs and increase the ETO current conduction loss. To reduce these parasitic effects, the circuits are put in a multi-layer PCB, and these MOSFETs are arranged in a ring shape and put very close around the GTO, as can be seen in fig. 2 and fig. 3. 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 fig. 4. During the on state, the gate switch is off and the emitter switch is on. The ETO current will go through both the GTO and the emitter switch MOSFETs. These MOSFETs can be used for the current sensing purpose since voltage drop across the MOSFETs reflect the current through them. In the off state, the emitter switch is off and the gate switch is on, the voltage across the emitter switch MOSFETs does not reflect the current (zero current) through them.

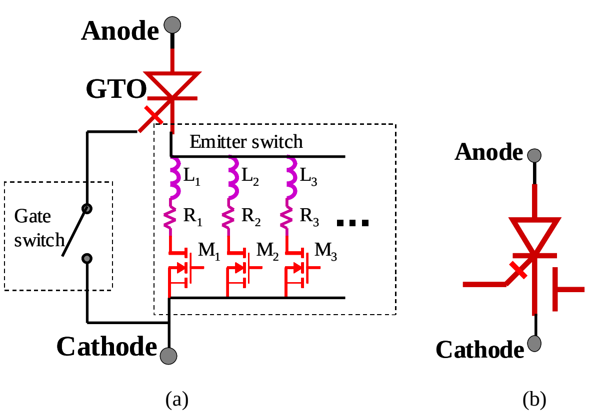

Figure 1. (a) Equivalent circuit and (b) circuit symbol of the ETO.

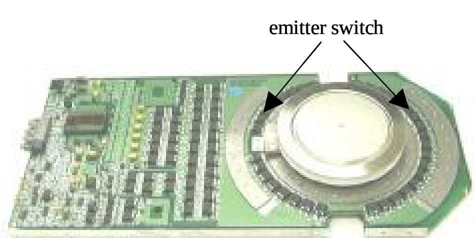

Figure 2. The picture of the ETO.

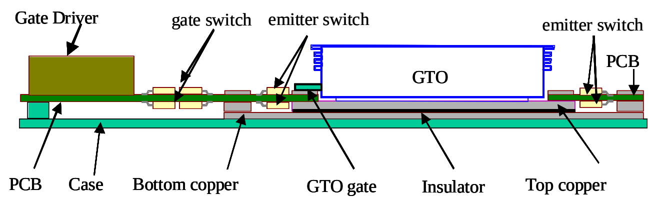

Figure 3. The cross section of the ETO.

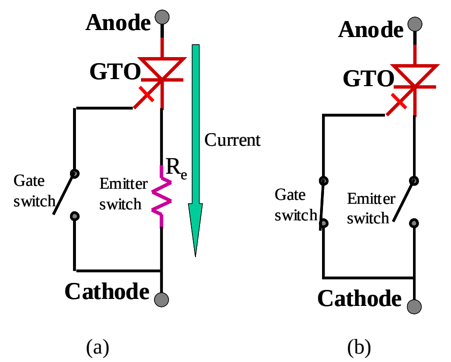

Figure 4. The simplified equivalent circuit of the ETO:

(a) On-state. (b) Off-state.

Fig.5 shows the block diagram of the ETO built-in current sensor and over-current protection. The voltage across the emitter switch V_e is sensed, and sent across a resistor R_1 to the PWM generator (PG) and the comparator and latch (CL). There is a switch S_1 connecting R_1 and electrical ground. In addition, the temperature of the ETO emitter switch is also sensed and transferred to a voltage signal V_t. V_t is also sent to the PG and the CL. In the ETO on state, S_1 is opened and the V_e, which is proportional to the current through the emitter switch, equals to V_i. In the ETO off state, S_1 is closed and the zero voltage, which means that the current through the emitter switch is zero, equals to V_i. V_i is received by PG and CL. The PG generates a PWM signal whose duty-cycle is proportional to V_i. Then the PWM signal is transformed to the optical signal and sent out through the optical fiber.

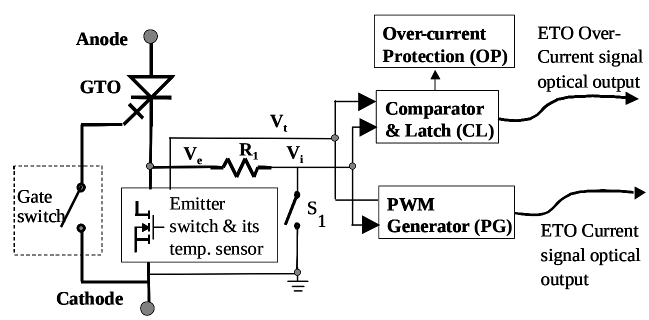

Figure 5. The block diagram of the ETO built-in current Sensor and over-current protection.

B. The Static Performance of the ETO Built-in Current Sensor

Fig. 6 shows the V_e vs. the ETO current in the ETO on state, and demonstrates their linear relationship in 20^oC as shown in (1).

$$V_e = I \bullet 0.000083 \qquad (1)$$

Based on this relationship, the PG is designed. Assuming the ETO switch frequency is 1kHz, and the duty-cycle is between and 5% and 95%, then the minimum on time is about 50us. To make sure that the current sensor can catch at least one point during the ETO minimum on time situation, the period of PG is chosen as 25us. So the switching frequency of PG is set to 40kHz. Although the ETO is capable of turning off 4000A without any snubber [2], its operating current, which is rather limited by ETO's thermal resistance, is usually below 3000A. So we set the PG duty cycle from 50% to 90% according to the 0A and 3000A ETO current. So we can get that the voltage-duty cycle relationship of PG is

$$Dutycycle = \frac{I}{7500} + 0.5 \cdot \qquad (2)$$

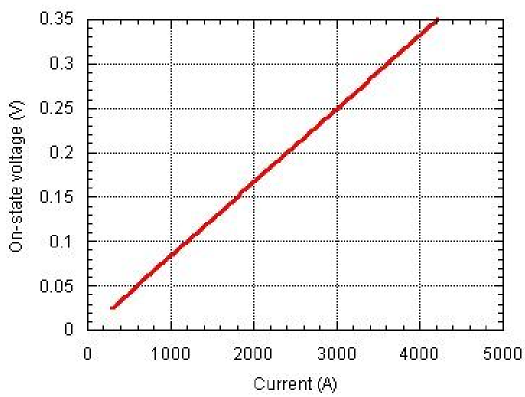

Figure 6. The on-state characteristic of the emitter switch.

Fig. 7 shows the experiment results of the built-in current sensor output PWM duty cycle vs. the current. As can be seen, the test results meet the design requirement very well. The measurement error of ETO built-in current sensor is less than 1%.

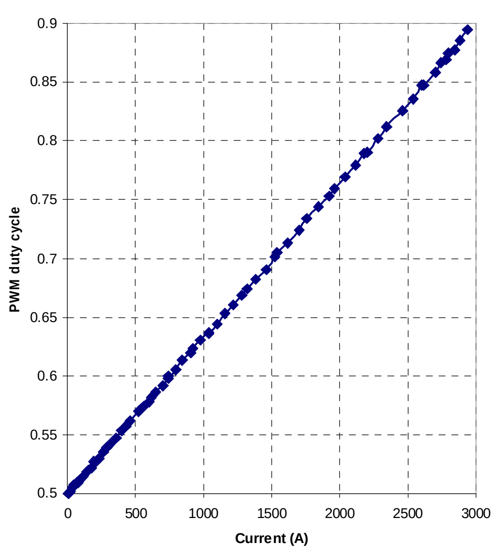

Figure 7. Measured current sensor output PWM signal duty cycle vs. the ETO current.

C. The Dynamic Performance of the ETO Built-in Current Sensor

The ETO with the built-in current was tested in a boost type PWM converter. In this converter, the ETO built-in current sensor measured the ETO current on-line during the ETO switching. The output PWM optical signal of the ETO built-in current sensor was received by another circuit board and transformed back to the electrical PWM signal for measurement. Fig. 8 shows the experimental test result of the current sensor output (bottom curve) vs. the ETO current measured by the rogowski coil (top curve) during one PWM pulse. The accuracy of the ETO built-in current sensor can be seen more clearly in fig. 9. Fig. 9 shows a reconstructed current whose value is proportional to the built-in current sensor output duty cycle. As can be seen from fig. 9, that the built-in current sensor output meets very well with the current measured by the rogowski coil. And the measurement delay is less than 25us (the period of the PWM signal).

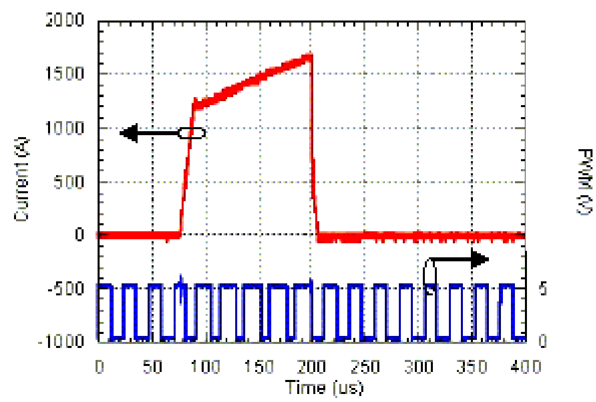

Figure 8. Measured current and current sensor output PWM signal during a PWM pulse.

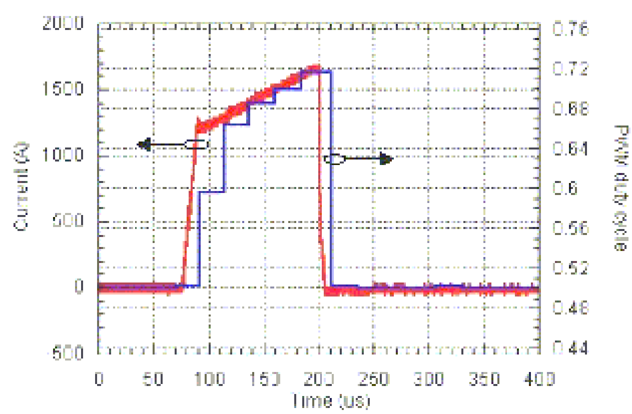

Figure 9. Measured current and reconstructed current.

D. The Temperature Compensation of the ETO Built-in Current Sensor

The on-resistance of the MOSFET increases with the increasing temperature. Fig. 10 shows the emitter switch on-resistance vs. the temperature. The on-resistance of the MOSFET at 100°C is about 50% bigger than that at 20°C. So if the temperature effect is not compensated, built-in current sensor will have big measurement error during temperature changing. We linearized the data in fig. 10 and get the following relationship between the emitter switch on resistance R_{on} and its junction temperature T_j.

$$R_{on} = T_j \bullet 0.00052 + 0.07118 \quad (3)$$

As shown in fig. 5, the case temperature of the MOSFETs is measured by a linear current sensing IC. Since many MOSFETs connected in parallel to form the emitter switch, each MOSFETs consumes small amount of power even in the ETO heave load. The temperature difference between the MOSFET's case and junction is small (less than 3^oC). So the case temperature, T_c, can be measured and used for the temperature compensation purpose.

From (3) one can get the ETO current

$$I_{on} = \frac{V_i}{T_j \bullet 0.00052 + 0.07118}. \quad (4)$$

From (4) it can be seen that the proportion, addition, and division are needed to eliminate the temperature effect. We think this approach is too complicated for the analog circuit to realize within the ETO driver. And the calculation error can also be a problem.

Another approach is to send out the temperature information and calculate (4) by the controller outside the ETO. And (4) is very easy to calculate by the microprocessor controller. In this paper, the MOSFET temperature information is carried by the PWM switching frequency of the built-in current sensor. So the duty cycle of the PWM output of PG is proportional to Vi, and the frequency is proportional to T_c. With this approach, both the voltage and temperature of the MOSFETs are sent out by one PWM signal.

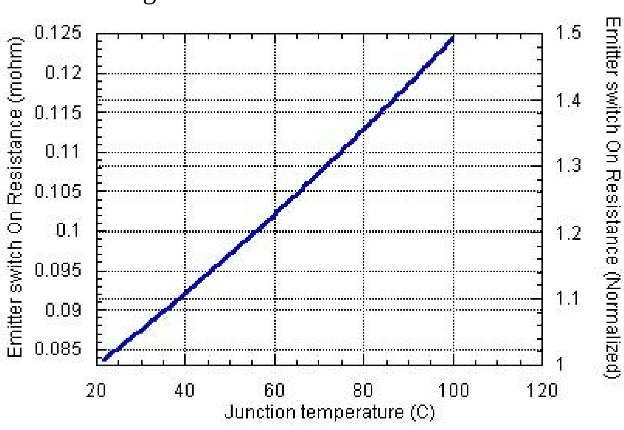

Figure 10. Emitter switch on-resistance vs. temperature.

E. Calculating the Converter Load Current from the Output of the ETO Built-in Current Sensor

The output of the ETO built-in current sensor can be used for the current control purpose. Fig. 11 shows a simplified circuit of an ETO phase leg for voltage source converter. Usually the load current sensing is needed for the current control of the converter. The ETO current I_{ETOP} and I_{ETON} can be measured by the ETO built-in current sensor. Fig. 12 shows a small period of the typical ETO current and diode current when the load current direction is positive (current going out of the phase leg). In this situation, the load current goes through the top ETO S_p and the bottom diode D_n alternatively. I_{ETOP} is the load current when it goes through the ETO. And the I_{DP} is the load current when it goes through the diode. I_{ETOP} can be measured by the ETO. I_{DP} can not be measured. However, because of the di/dt snubber, inductor filter, and the load inductance, the load current changing rate dI_{load}/dt is limited. As can be seen in fig. 12, one can assume that I_{DP} is equal to I_{ETOP} in the same switching cycle. There will be error caused by this assumption. If the load and the inductors in the circuit are taken into account, the changing rate of the I_{DP} can be calculated. And the more accurate I_{DP} can be obtained. These methods will not be discussed in this paper. When the load current is negative, the load current goes through the bottom ETO S_n and the top diode D_p alternatively. The situation is similar to that of the positive load current.

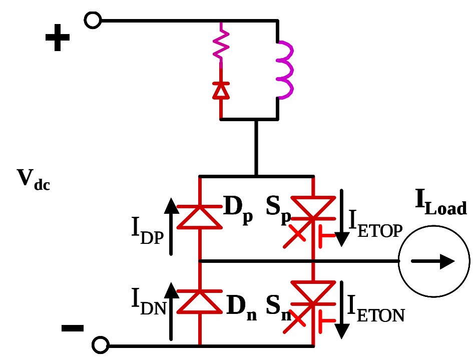

Figure 11. Simplified circuit of an ETO phase leg.

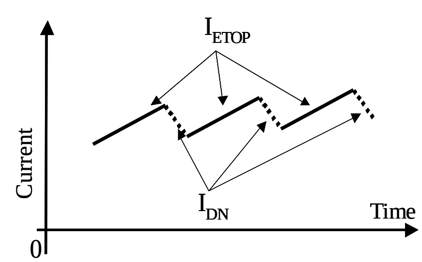

Figure 12. The ETO current and the diode current.

Fig. 13 shows the flowchart of the load current calculation for one ETO phase leg. The ETO has an on/off status output though optical fiber, indicating the on and off status of the ETO. It is assumed that both the built-in current sensor outputs and the on/off status output of the top and bottom ETO are received by the microprocessor through the optical fibers.

The first step is to find which ETO is in the on-state from the on/off status output. Then calculates output PWM signal's duty cycle and the frequency of the ETO which is in on-state. If the duty cycle is equal to 50%, it can be known that the ETO is not conducting current- either the antiparallel diode is conducting current or the load current is zero. The current can be supposed to remain unchanged in this situation. Otherwise, the ETO is conducting current. At the same time the load current direction can be known. The next step is the load current calculation base on the current-duty relationship shown in fig. 7, and temperature compensation shown in (4). At last, the load current is updated.

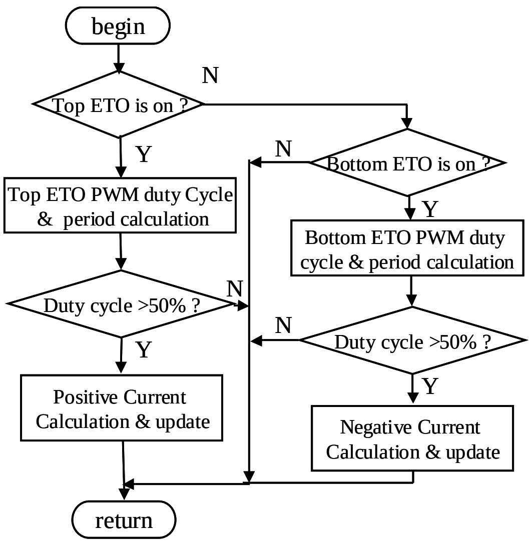

Figure 13. The flowchart of the current calculation.

F. The Built-in Current Sensor of the Reverse Conducting ETO.

If the reverse conducting GTO [7] is used, a reverse conducting ETO, RCETO, can be built. The RCETO equivalent circuit and circuit symbol are shown in fig. 14. The reverse conducting ETO can conduct both the positive current whose direction is from anode to cathode, and the negative current whose direction is from the cathode to anode. During each situation, the emitter will be turned on and conduct current. Obviously, the voltage across the emitter switch will be positive when it is conducting positive current, and negative when it is conducting negative current. With the same built-in current sensor, the output PWM duty cycle will cover from 0% to 100%. A duty cycle bigger than 50% indicates a positive current and lower than 50% indicates a negative current.

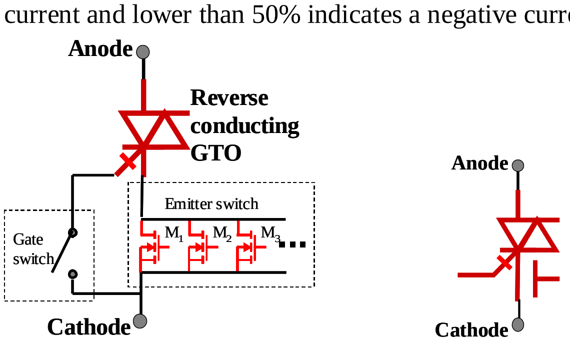

Figure 14. (a) Equivalent circuit and (b) circuit symbol of the RCETO.

Fig. 15 shows a simplified circuit of a RCETO phase leg. Compared to the circuit shown in fig. 11, the RCETO not only simplifies the phase leg circuit, but also simplifies the built-in current sensor. With the RCETO built-in current sensor, the load current can be easily calculated by (5).

$$I_{load} = I_{RCETOP} - I_{RCETON} \quad (5)$$

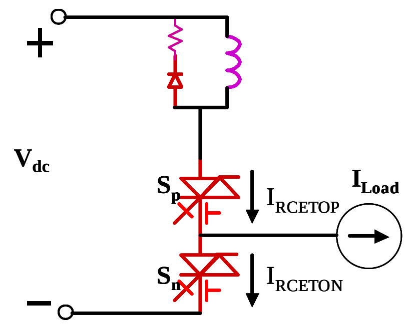

Figure 15. Simplified circuit of a RCETO phase leg.

III. 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. As can be seen in fig. 5, the voltage signal V_i is also sent to a comparator and latch block (CL). In CL, V_i 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 V_t is also sent to CL. The trigger voltage can be adjusted by V_t. 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 ETOs or trigger the circuit breaker to shut down the current.

It takes less than 500ns between the over-current triggering and the ETO emitter switch being turned off. The ETO storage time and the turn-off voltage rising time greatly depend on the main switch, GTO, being used. Normally, the ETO storage time is about 1us, and the turn-off voltage rising time is about 1us. So it takes less than 3us between the over-current triggering and the ETO anode current start to decrease, in another word, the ETO over-current protection delay is less than 3us.

The device over-current is usually caused by the short circuit, the malfunction, or the component failure. When these problems happen, the current will lose control and rise until the over-current protection of the ETO triggers, bringing the ETO anode voltage up to the DC link voltage. In faulty situations, 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.

Fig. 16 shows the over-current protection waveform. In this test, the ETO over-current trigger value was set to 3800A. The current rising rate was limited to 200A/us by the di/dt snubber. It can be seen that when the ETO current rose to the trigger value, the ETO over-current protection was triggered. The ETO started to turn off. After about 200ns, the over-current warning signal was sent out by the optical fiber. Then the optical signal was transferred to electrical signal by another circuit for measurement. The signal is show in fig. 16. After the ETO storage time, the ETO anode voltage started to rise. The ETO current continued rising until its anode voltage reached the DC link voltage. Fig. 15 shows that the ETO current began to decrease at about 4200A, at 2us after the over-current triggering. Then the ETO current decreased to zero in about 4us.

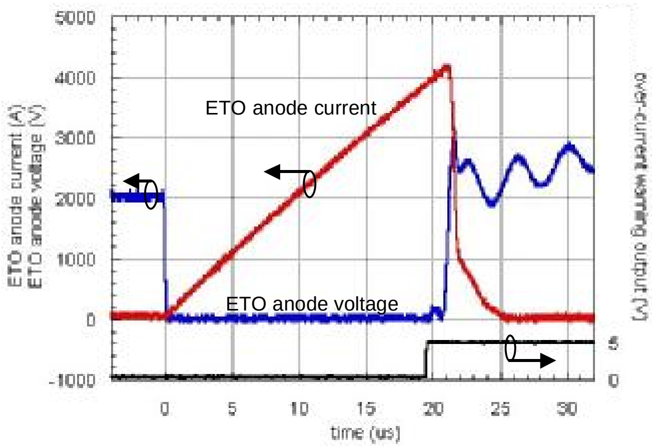

Figure 16. The over-current protection waveform

IV. Conclusion

The ETO built-in current sensor is a low cost, high precision, and convenient to use function. Experimental results show that the measurement error is below 1%. And the measurement delay is less than 25us. 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 in a very short time. Test results show that it takes less than three microseconds between the over-current triggering and the anode current stopping rising. 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.

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