Letters

Active Optical Modulation for Series-Connected Emitter Turn-OFF Thyristors

Alireza Mojab and Sudip K. Mazumder

***Abstract*—Series connection of high-power thyristors is proposed in the literature for high-voltage applications. Due to the high d*v*/d*t* across series-connected thyristors during turn-OFF, charge equalization techniques have been pursued that increase the fall time to avoid overshoot voltage and device breakdown. Longer fall time for thyristors yields reduced switching frequency and increased losses. As such, a new method to control turn-OFF transition for the series connection of recently developed optical emitter turn-OFF (o-ETO) thyristor is outlined in this letter. The turn-OFF speed of series-connected o-ETOs and their voltage balance are controlled by modulating the optical intensity of the triggering (instead of the high-power) device of the o-ETO.**

***Index Terms*—Optical control, optical emitter turn-OFF (o-ETO) thyristor.**

I. Introduction

Recently, an optical emitter turn-OFF (o-ETO) thyristor introduced in [1] using the light-triggered thyristor (LTT) as its main blocking device and another optically triggered power transistor (OTPT) as the series low-power switch. It is unlike the MOS turn-OFF (MTO) thyristor, gate turn-OFF (GTO) thyristor, and electrical ETO (e-ETO) thyristor that are slower in switching speed and/or require multiple electrical biases [2].

An illustration for the operation of a single-stage o-ETO thyristor during turn-ON and turn-OFF phases is captured in Fig. 1(a). During the o-ETO on-state phase, both IR and UV lasers are illuminated and the o-ETO current flows through the OTPT and the LTT. During the turn-OFF phase, the lasers are turned-OFF and the voltage across the OTPT rises more than the threshold voltage of the self-biased N-channel MOS (NMOS) transistor (connected as a high-threshold voltage diode). Consequently, the NMOS transistor is turned-ON, commuting the main current from anode path to gate path of the thyristor.

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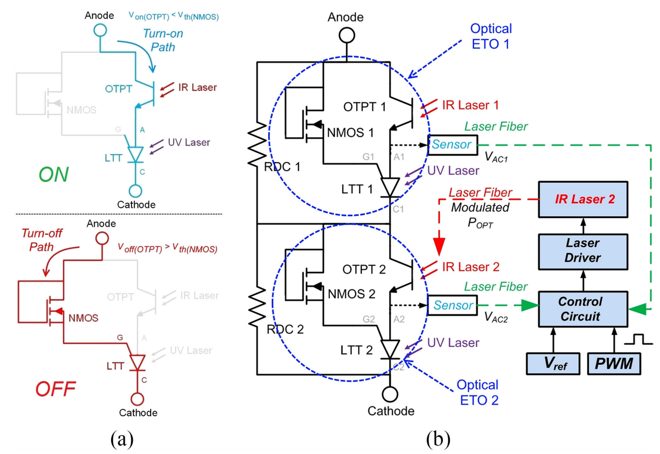

Fig. 1. (a) Operational illustration of an o-ETO thyristor during ON/OFF states. (b) Schematic circuit for the series-connected o-ETO thyristors.

The details for the principle of operation of this o-ETO thyristor structure are provided in [1]. This o-ETO thyristor benefits from being single-bias structure in which there is no low-power electrical driver. One can control and shift the delay in turn-OFF for the o-ETO thyristor by only modulating and tuning the optical intensity of the long-wavelength, lower cost, and readily available IR laser for the low-power OTPT. This feature enables the series of plurality of such o-ETO thyristor to potentially yield high-voltage (HV) operation.

II. Series Connection of o-ETO Thyristors

The fluctuation in voltage across the HV devices is more crucial during turn-OFF switching transition which requires active gate control [3], [4]. Therefore, complex circuit configurations as static/dynamic (active) solutions have been proposed for series-connected devices to achieve the required voltage balance [5]–[7]. In most of them, charge-equalizing protection circuit is used which includes bulky and expensive voltage-balancing capacitors for HV applications on the order of several kVs. Consequently, turn-OFF time is increased and switching frequency is reduced.

In this letter, active optical modulation control of series-connected o-ETO thyristors is outlined and investigated to optimize the thyristor's turn-OFF time, enabling high-frequency operation. In Fig. 1(b), the series-connected o-ETO thyristors

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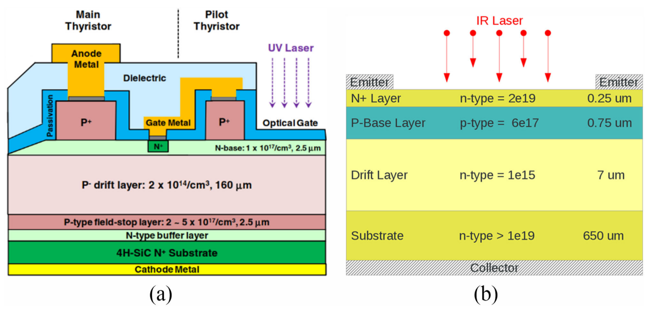

Fig. 2. Device structures for (a) SiC-based LTT [6] and (b) silicon-based OTPT.

with a simple control block diagram of the optical active modulation technique for the o-ETO thyristor is shown.

During o-ETO turn-ON, both IR and UV lasers are triggered, making the current flowing through anode path of the LTTs. After the LTTs are latched, the UV lasers can be turned-OFF to reduce optical power loss; however, the IR lasers should be kept ON to maintain current through the anode of the LTTs. Hence, UV lasers have no effect on the o-ETO turn-OFF. The o-ETO turn-OFF is only initiated when the OTPTs are turned-OFF by deactivating the IR lasers illuminating them.

One can simply control the onset of o-ETO turn-OFF by sending the IR lasers turn-OFF pulse accordingly. Furthermore, the delay in o-ETO turn-OFF is controlled by modulating the optical power of the IR lasers. This is a key advantage of the optical modulation since IR lasers are more reliable and controllable than UV lasers. Long-wavelength IR lasers are also cheaper than short-wavelength UV lasers and deliver higher optical power with better controllability and optical modulation compared to UV lasers.

The primary goal is to optimize the overshoot voltage difference between the two LTTs and prevent high-voltage stress exceeding the breakdown voltage. The on-state voltages of LTT and OTPT devices, which are optimized *a priori* through device fabrication and proper design of epitaxial layers, are sensed to provide the control circuit required information of the turn-OFF times.

III. Results and Discussion

All the models and analysis used in the Silvaco TCAD simulations are based on already available fabricated devices. The SiC LTT and OTPT structures (see Fig. 2) for the o-ETO follow the fabricated devices reported in [8] and [9]. LTT's breakdown and forward-drop voltages are 18 kV and 6.2 V (at 100 A), turn-OFF time is $\approx 1.2\ \mu s$, leakage current is $\approx 1\ \mu A$, and holding current is 560 mA. OTPT's breakdown and on-state voltages are 70 and 1.3 V (at 100 A and 5 W optical power), and leakage current is ≈ 1 mA. First, the device structures for the LTT and OTPT are generated in the Athena module of Silvaco TCAD. Then, the generated devices and structures are imported in the mixed-mode module of the software along with the Spice model for the NMOS transistor, additional parasitic inductances of 3 nH between o-ETO connections, and external inductance of 100 nH. The proposed approach in this paper builds on an all-experimental approach outlined in [10].

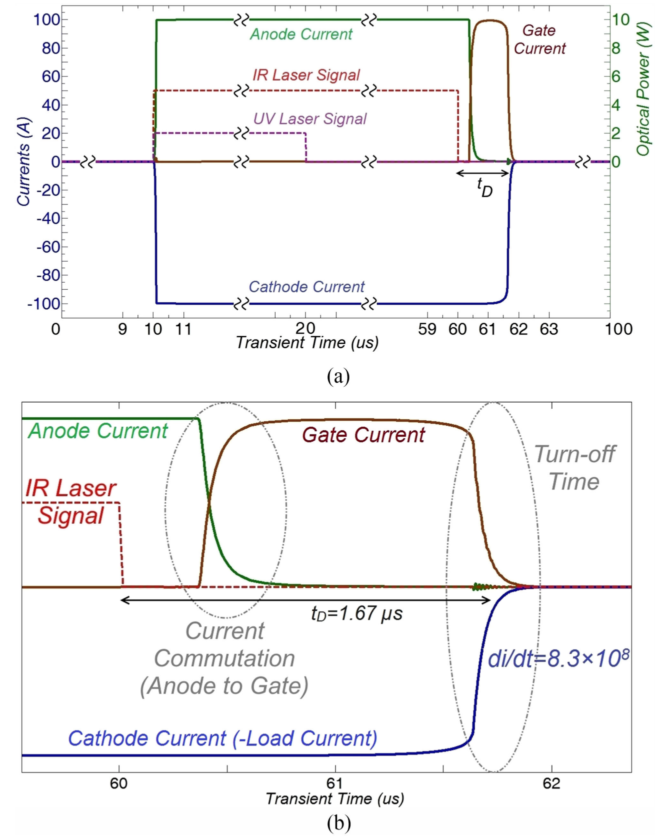

Fig. 3. Currents through the LTT (a) for one switching cycle and (b) enlarged view during turn-OFF.

A. Single-Stage o-ETO Thyristor

During o-ETO turn-OFF, the current through LTT device, operating with a 15-kV bias, transfers from anode path to the gate path, as illustrated in Fig. 3. This huge amount of current, pushed into the gate terminal of the LTT, forces it to turn-OFF rapidly. Power of OTPT's triggering IR laser affects the speed of transferring the current from o-ETO anode path to gate path. Therefore, one can control the turn-OFF speed for the o-ETO thyristor by only adjusting the power of the IR laser.

In Fig. 4(a), load current (– cathode current) of the o-ETO thyristor for different optical powers of the IR laser is shown during turn-OFF. By increasing the optical power from 0.5 to 8 W, one can delay the o-ETO turn-OFF by about 700 ns. Variations in delay are notable since the difference in turn-OFF speeds between two similar o-ETO thyristors is expected to be less than 200 ns [11].

Fig. 4(b) captures the OTPT on-state voltage and the delay in o-ETO turn-OFF time (t_D) with varying OTPT optical power. Lower power for the IR laser yields a shorter delay in o-ETO turn-OFF time, but leads to higher OTPT on-state voltage. Following Fig. 4(b), IR-laser power greater than 1 W is required to achieve acceptable low OTPT on-state voltage.

B. Series-Connected o-ETO Thyristors

For series connection of two LTTs, the bias voltage and load current are considered to be 30 kV and 100 A, respectively. The values for DC grading Resistor (RDC) resistors (see Fig. 1) are

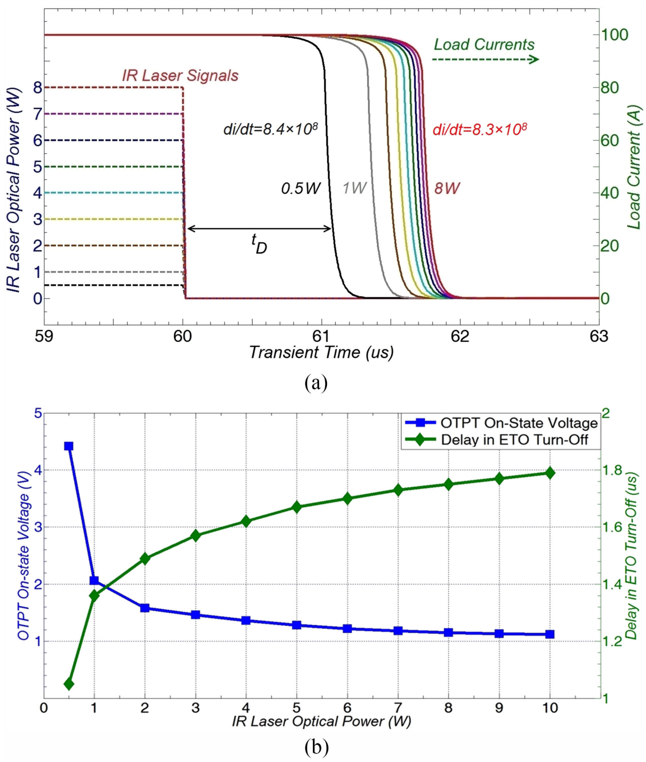

Fig. 4. (a) Load current during turn-OFF for an o-ETO thyristor with different optical powers on the OTPT. (b) OTPT on-state voltage and delay in o-ETO thyristor turn-OFF with different IR laser optical powers.

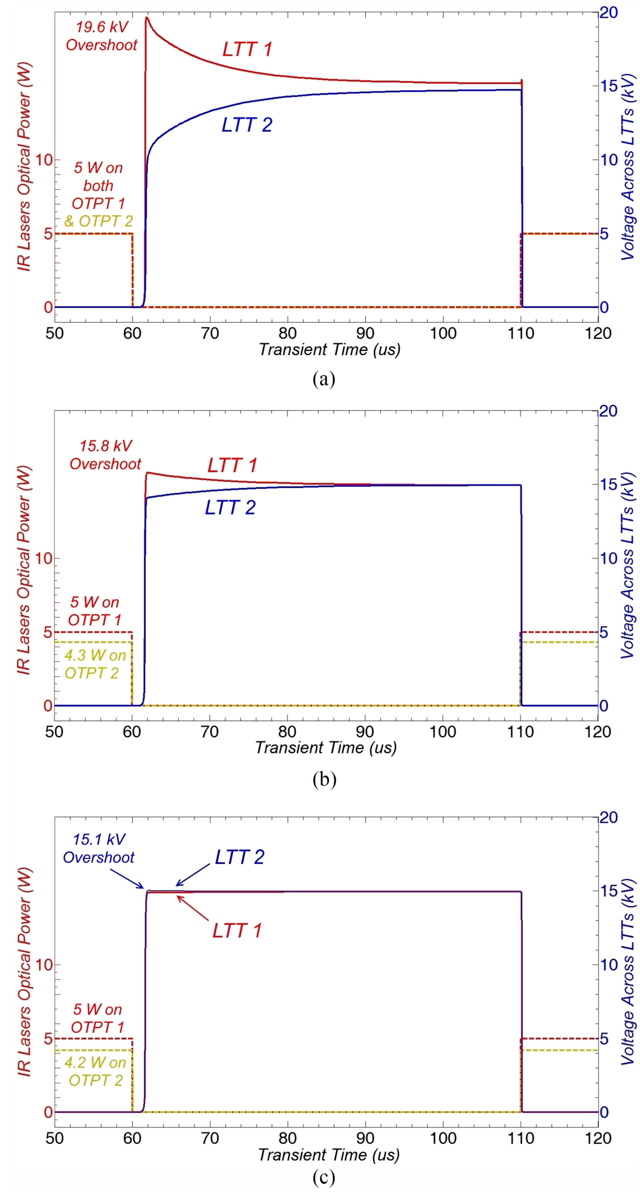

Fig. 5. Voltage across the LTTs of the two series-connected o-ETO thyristors for one switching cycle (a) without any optical power modulation of OTPT 2, (b) and (c) with reduced optical powers of 4.3 and 4.2 W for OTPT 2, respectively. LTT 2 lags LTT 1 by 25 ns in turn-OFF time.

chosen to be 500 kΩ to pass a current of 30 mA during o-ETO off state. Therefore, the power loss on each of these RDC resistors is 450 W. These two RDC resistors are used to establish equal voltage drop across the two LTTs during o-ETO off-state phase.

The device structures and semiconductor parameters of the two LTTs have been modified so that a time difference varying between 25 to 300 ns is achieved between the devices. These process variations and parameters include but are not limited to carrier concentration, thickness of layers, carrier lifetime, mobility of carriers, recombination velocity, and energy traps for the Shockley–Read–Hall model.

A single UV laser source with a wavelength of 266 nm and optical power of 20 mW is used for both LTTs. The wavelength of the IR lasers for both OTPT devices is 808 nm; however, the optical power is modulated only for one of the OTPTs to compensate the difference in turn-OFF delay for the two LTTs. This optical modulation is optimized to achieve the best possible voltage sharing between the two LTTs during o-ETO turn-OFF time and to avoid high overshoot voltage.

For a nominal optical intensity and current level, a nominal on-state voltage ($V_{\rm ON}$) is expected for all devices. Therefore, the on-state voltage across the OTPT and LTT devices during on-state phase in each cycle is monitored. The sensed values are compared with nominal values and if a change is observed in the sensed on-state voltages ($V_{\rm ON} \pm \delta$), then the optical power of the IR laser is changed accordingly ($P_{\rm OPT} \pm \delta$) to predict and compensate the delay in o-ETO turn-OFF.

In addition to the to the on-state voltages, the di/dt and dv/dt of the signals are monitored. There are two inputs to the feedback control circuit. Once the control circuit senses the first triggering signal, it can decide which LTT stage is being turned-OFF earlier. A delay compensator circuit (DCC) initiates the onset of transition for the OTPT device to change its optical intensity accordingly. The onset of transition is initiated in the proper time considering the total delay in the feedback loop.

As a case example for this study, the voltage across the two LTTs is shown in Fig. 5 for one switching cycle when LTT 2 lags LTT 1 by 25 ns during turn-OFF. Fig. 5(a) shows the case when there is no optical modulation and the optical powers for both OTPT 1 and OTPT 2 are set at 5 W default. The overshoot voltage across LTT 1 is higher since it turns-OFF faster than

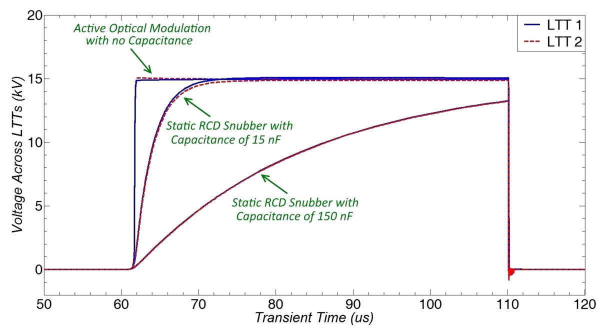

Fig. 6. Comparison of turn-OFF transition between active optical modulation and conventional static RCD snubbers.

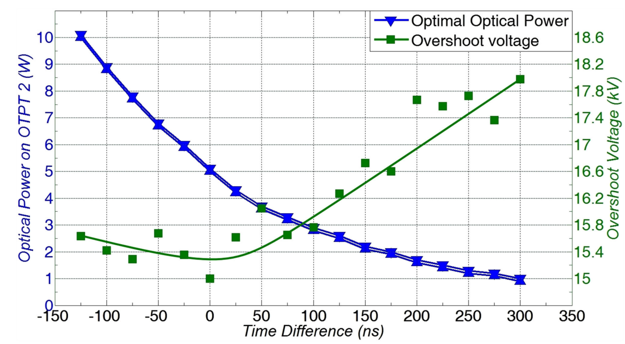

Fig. 7. Optimized optical power of OTPT 2 and maximum overshoot voltage across the LTTs with various turn-OFF time differences.

LTT 2. As shown, an overshoot voltage of 19.6 kV is observed across the LTT 1.

In the second run, shown in Fig. 5(b), the optical power for OTPT 2 is reduced to 4.3 W while the optical power for OTPT 1 is kept at the default value of 5 W. It is seen that the overshoot voltage of LTT 1 is reduced from 19.6 to 15.8 kV. By further reducing the optical power for OTPT 2 from 4.3 to 4.2 W, the turn-OFF process of LTT 2 becomes faster than LTT 1 with an overshoot voltage of about 15.1 kV for LTT 2, as shown in Fig. 5(c). With this optical modification, the difference in turn-OFF times for the two LTTs is compensated and the voltage is shared closely across the two LTTs.

It should be noted that once the control circuit detects the first triggering signal from one of the LTT stages, it decides whether to increase or decrease the optical intensity of the OTPT device. Therefore, even if some parameters of the devices change with operating temperature and working time, the triggering onset will be changed by the DCC accordingly to ensure a reliable function.

The proposed optical modulation scheme is aimed to reduce the switching loss during turn-OFF phase of the series-connected optical ETO thyristors. To evaluate the reduction in switching loss, a comparison of turn-OFF transition behavior between the proposed active optical method and conventional static voltage-balance method is provided. In conventional methods, an RCD snubber is used to create a voltage balance during turn-OFF. Not only these high-voltage capacitors are bulky, but also they slow down the turn-OFF speed of such series-connected power devices. A larger capacitor in RCD circuit results in better voltage balance, but slower turn-OFF. On the other hand, smaller capacitor in RCD circuit results in faster turn-OFF, but higher ringing in load current and worse voltage balance. In Fig. 6, the turn-OFF transition behavior for the proposed active optical modulation method compared with two static RCD snubbers with small and large capacitors is shown.

The results provided in Fig. 5 are for a sample case, when LTT 1 is faster than LTT 2 by 25 ns. However, if LTT 2 is faster than LTT 1 for another sample case, then the controller needs to provide higher optical intensity on OTPT 2. The same procedure is followed for other difference in delay times between the two LTTs. In Fig. 7, obtained maximum overshoot voltage and optimized optical power on OTPT 2 versus the time difference in turn-OFF (dt) between the two LTTs are shown.

According to Fig. 7, the turn-OFF time of LTT 2 can lag (positive dt) or lead (negative dt) the turn-OFF time of the LTT 1. By increasing the turn-OFF time difference between the two LTTs, the required optical power for the OTPT corresponding to the slower o-ETO thyristor is decreased. In other words, less optical power is required for the slower o-ETO thyristor and higher optical power for the faster ETO stage.

It is also shown in Fig. 7 that for all scenarios, the maximum overshoot voltage is always less than 18 kV (the LTT device breakdown voltage) using this optical modulation scheme. The maximum overshoot voltage is increased for larger time difference between the two LTTs. Therefore, it is desirable to use very similar LTT devices for series connection of these high-power structures.

In this work, optical power of 5 W is considered for both OTPTs as a default operating point since the modulation swing is maximum for this level; however, if the delay variation between the two thyristors is minor, then lower optical powers can be used for the OTPTs.

IV. Conclusion

In this letter, series connection of o-ETO thyristors with active optical driver was outlined and explored. It is shown that the optimal voltage balance between the two high-power LTTs can be achieved during o-ETO thyristor turn-OFF time by means of only optical power modulation for the low-power and low-voltage triggering OTPTs, both of which use low-cost and readily available long-wavelength lasers for control. Using this active control technique, turn-off snubbers are not required to protect the LTTs from high overshoot voltages. This proposed modulation scheme is intended primarily for the o-ETO structure as presented in this paper. However, it can be extended to e-ETO structures as well and may be possible to extend with modification to optical/electrical integrated gate-commutated thyristors (IGCTs) and optical MTO thyristors.

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