# Letters

# A Novel Solid-State Switch Scheme With High Voltage Utilization Efficiency by Using Modular Gapped MOV for DC Breakers

Kexin Liu, Xiangyu Zhang, Lei Qi, Xinyuan Qu, and Guangfu Tang

***Abstract*—Metal oxide varistors (MOV) is often used to limit the overvoltage generated by the current breaking of dc breaker to protect power electronic device from breakdown. However, while suppressing overvoltage, the MOV also causes the degradation of continuous operating voltage capability. This letter proposes a novel solid-state switch scheme with high voltage utilization efficiency by using modular gapped-MOV (MG-MOV) for dc breakers. The breakable gap is first applied to the protection of power electronic devices. By using the gap to share the voltage in the static-state and be broken down in the dynamic state, the overvoltage and continuous operating voltage of the solid-state switch can be decoupled. Moreover, based on the modular scheme, the instability of the gap discharges and the voltage imbalance of the series devices can be solved well. The working mechanism, voltage-balance and stability issue of the MG-MOV are discussed in detail in this letter, and a 15-kA prototype is developed to verify the feasibility of the novel solid-state switch scheme. The experiment under results show that voltage utilization efficiency can be increased from 44.4% to 72.0% by using MG-MOV.**

***Index Terms*—DCCB, gap, high-voltage solid-state switches, metal oxide varistors (MOV), voltage utilization efficiency.**

## I. Introduction

THE VSC-HVdc technology has been rapidly developed to meet the demand for large-scale grid connection of new energy in recent years. The dc breakers can quickly clear the fault current in the dc grid and are the key equipment to maintain the reliable operation of VSC-HVdc system [1], [2]. Due to the lack of zero-crossing point in the dc system, a large number of semiconductor devices are required to form a solid-state switch in a dc breaker to realize the function of current breaking. Since the devices are easily broken by the overvoltage when they are turned OFF, metal oxide varistors (MOV) is often connected in parallel with the solid-state switch as voltage-limiting circuit. At present, the voltage-limiting circuits are generally composed of MOV [3], [4], as shown in Fig. 1.

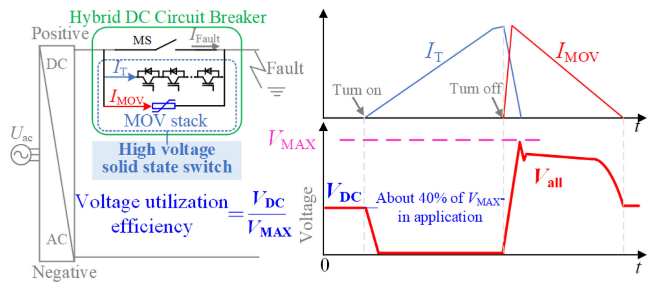


Fig. 1. Voltage utilization efficiency of the solid-state switch scheme in hybrid dc breakers.

Although MOV has the ability of voltage-limiting; however, it also causes the degradation of continuous operating voltage capability of the solid-state switch. In Fig. 1, the definition of voltage utilization efficiency $V_{dc}/V_{MAX}$ is given. $V_{MAX}$ is the maximum withstand-voltage of the solid-state switch. Under this voltage, the MOV needs to show a low resistance characteristic to clamp the overvoltage. And the $V_{dc}$ refers the continuous operating voltage, at which voltage level the solid-state switch with its MOV needs to have a very high resistance. Due to the limited nonlinearity of MOV, a solid-state switch's $V_{dc}$ is often far lower than its $V_{MAX}$, resulting in a waste of the semiconductor devices' voltage capacity.

The nonlinearity of an MOV is generally expressed by the ratio of its residual voltage ($V_{RES}$) for a certain impulse current to its 1 mA reference voltage ($V_{REF}$), as shown in Fig. 2(b). The $V_{RES}/V_{REF}$ of a MOV is usually between 1.4 and 2.5 [5], which means the voltage utilization efficiency of the solid-state switch with parallel MOV is destined to be lower than 70%. Moreover, in actual engineering, MOVs' $V_{RES}$ is generally designed to be lower than the $V_{MAX}$ of the semiconductor devices for the safety margin. Also, MOVs' $V_{REF}$ needs to be higher than the $V_{dc}$ of solid-state switches; otherwise, the MOV will be damaged in the long-term voltage withstanding. Therefore, the voltage utilization efficiency of the solid-state switch in actual projects is often extremely low, which is around 40% in the 200 kV

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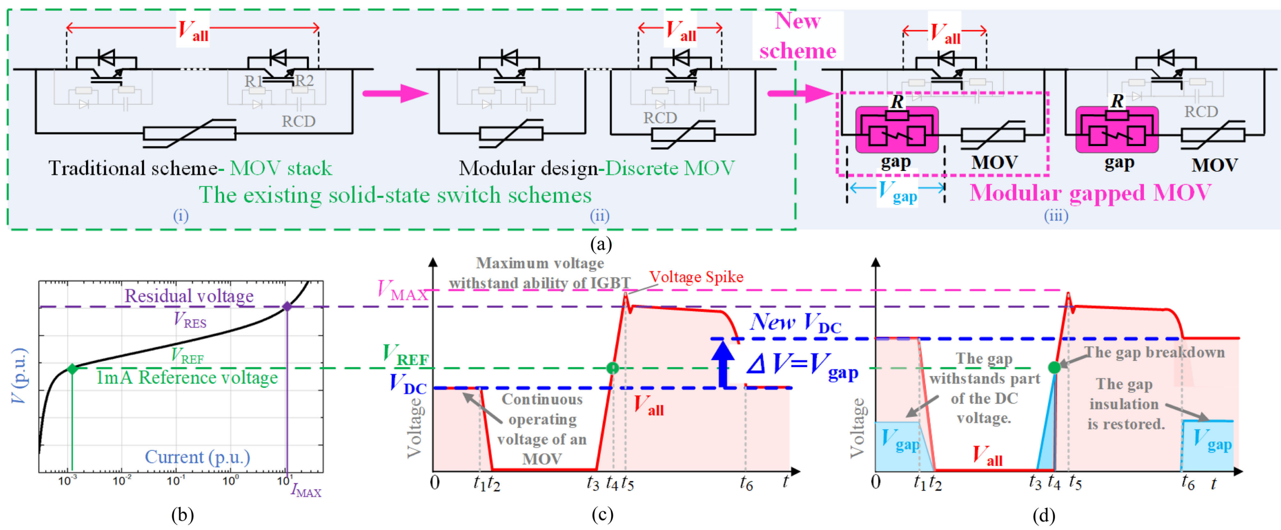


Fig. 2. Working mechanism of the solid-state switch with MG-MOV. (a) Development of the solid-state switch with MOV. (i) and (ii) are the existing schemes, (iii) is the novel solid-state switch scheme proposed in this letter. (b) MOV *V–I* curve. (c) Turn-ON and turn-OFF process of the first two existing schemes in dc breakers. (d) Turn-ON and turn-OFF process of the solid-state switch with MG-MOV.

dc breakers of Zhoushan flexible dc technology demonstration project [6] and the 500 kV dc breakers of Zhangbei flexible dc grid project [3], resulting in the excessive series number and high cost of semiconductor devices.

Although the problem of solid-state switches' voltage utilization efficiency is serious, there is no effective solution at present. As the material performance is difficult to greatly improve, the nonlinearity of MOV can only be improved through a large number of parallel-connection, which is costly and has limited effects.

In this letter, a novel solid-state switch scheme with high voltage utilization efficiency by using modular gapped-MOV to the voltage-limiting circuit of solid-state switch to improve its nonlinear performance. Based on the modular configuration scheme, the problems of series submodules voltage balance and long gap discharge voltage instability are solved well. Thus, the voltage utilization efficiency of the solid-state switches can be effectively improved. Section II proposes a new solid-state switch scheme with MG-MOV, introduces its working mechanism, and discusses the voltage-balance and gap discharge voltage stability issues in detail. On this basis, Section III provides the experimental verification, including a 15 kA experiment for dc breakers are proposed. The breakable gap is first applied. Finally, Section IV concludes this letter.

## II. Proposed Solid-State Switch With Modular Gapped-MOV and Its Characteristic Analysis

### A. Proposed Solid-State Switch With MG-MOV

Inspired by the gapped-MOV for lightning protection [7], the nonlinearity of the MOV can be greatly improved by using a gap. DC breakers are system protection equipment for breaking pulse fault current; they do not operate frequently, which provides the premise for the application of gap in dc breakers.

Compared with the MOV stack scheme and discrete MOV scheme, as shown in Fig. 2(a-i) and (a-ii) [2]–[4], [6]. On the basis of the discrete MOV scheme, the breakable gap is applied to the voltage-limiting circuit of solid-state switch, as shown in Fig. 2(a-iii). The gap can easily improve the continuous operating voltage $V_{\mathrm{dc}}$ in static-state. When the gap is broken down and maintained at a low resistance, it does not affect the overvoltage suppression, and decoupling the continuous operating voltage and overvoltage.

The breakable gap is paralleled with resistor $R$, in static-state, the resistor $R$ matched with the leakage resistance of MOV to keep the gap from discharges, and the voltage across the MOV is the continuous operating voltage to ensure that MOV will not be damaged in the long-term voltage withstanding.

As shown in Fig. 2(c) and (d), the new continuous operating voltage of the novel solid-state switch is equal to the sum of the gap voltage and the continuous operating voltage $V_{\mathrm{dc}}$ of the MOV. This novel scheme greatly increases the long-term rated voltage that a single semiconductor device can play.

More importantly, this modular scheme can convert the high voltage problem in the MOV stack scheme to the low voltage problem in a single module. Compared with the long gap, the discharge voltage of the short gap is more stable [8]. Of course, the performance of the gap and stability of the gap discharge voltage has yet to be tested by multiple tests.

In addition, for series solid-state switches, MG-MOV does not have the same voltage self-balancing ability as discrete MOV in static-state; the voltage balancing circuit is needed. These two issues will be discussed in detail as follows.

### B. Working Mechanism of the Solid-State Switch With MG-MOV

The equivalent model of the circuit is shown in Fig. 3, where $R_0$ is the equivalent resistance of MOV, which is related to its voltage. $C_{\mathrm{gap}}$ is the partial capacitance of the gap, $C_{\mathrm{MOV}}$ is the junction capacitance of a MOV. The model does not consider

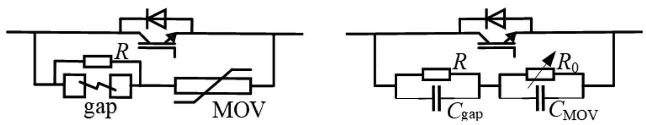


Fig. 3. Equivalent model of the circuit.

parasitic parameters. The working process of the solid-state switch with MG-MOV is as follows:

*0-t₁(static-state):* The gap does not discharge and shares part of the dc voltage in the static-state, and the voltage across the MOV is its continuous operating voltage. The limitations of the circuit at this stage are

$$\begin{cases} V_{\rm all} = V_{\rm dc-NEW} = V_{\rm gap} + V_{\rm dc} \leq kV_{\rm MAX} \\ V_{\rm dc} = 0.85V_{\rm REF}, V_{\rm gap}/V_{\rm dc} = R/R_0 \end{cases} \tag{1}$$

where $V_{\rm all}$ is the voltage across the solid-state switch, $V_{\rm dc\text{-}NEW}$ is the improved operating voltage of the solid-state switch, $k$ is the safety factor of the device, generally 0.8–0.9.

*$t_1$-$t_3$:* The semiconductor device is turned ON at $t_1$, $I_{\rm T}$ increases gradually, and the voltage $V_{\rm all}$ drops to the forward voltage of semiconductor device.

*$t_3$-$t_4$:* At $t_3$, the semiconductor device is turned OFF, and the current is transferred to snubber circuit. $V_{\rm all}$ is gradually increases. In $t_3$–$t_4$ stage, $C_{\rm gap}$ is generally a few pF, $C_{\rm MOV}$ is a few to tens of nF, before the gap discharges, $V_{\rm all} \approx V_{\rm gap}$, the gap withstands most of the voltage. At $t_4$, $V_{\rm gap} \geq V_{\rm gpb}$, the gap discharges first, where $V_{\rm gpb}$ is the pulse discharge voltage.

*$t_4$-$t_5$:* Ignore arc voltage, $V_{\rm all} = V_{\rm MOV}$. Since the voltage exceeds the $V_{\rm REF}$ of the MOV, MOV starts to work, the current transfers from snubber circuit to MOV branch, and the MOV limits the overvoltage and absorbs the system energy.

*$t_5$-$t_6$:* The current in MOV branch decreases gradually, and the current drops to 0 at time $t_6$. The gap is insulated, and the MG-MOV circuit withstands the system dc voltage again.

### C. Voltage Balancing Issue of the Solid-State Switch With the MG-MOV

For series power electronic devices, voltage balancing is designed to protect each device from exceeding withstand voltage. For passive static voltage balancing of series-connected devices, generally, a suitable resistor is connected in parallel with the devices.

When series devices are turned OFF, with the MOV stack in the traditional design, the voltage is extremely disequilibrium, as shown in Fig. 4(a), the slowest device is just beginning to turn OFF when the fastest device's voltage has exceeded the rated value. For the MG-MOV scheme, although the turn-OFF processes still have a large difference between each other, as shown in Fig. 4(b). When the gap is broken down and maintained at a low resistance, each device's voltage is limited by the MOV when it rises to $V_{\rm RES}$, like the dynamic threshold effect of the discrete MOV scheme [9]. Thus, the devices' inconsistency only affects their voltage establishment sequence, and the maximum voltage on each device is balanced. More importantly, the consistency requirements for devices are low.

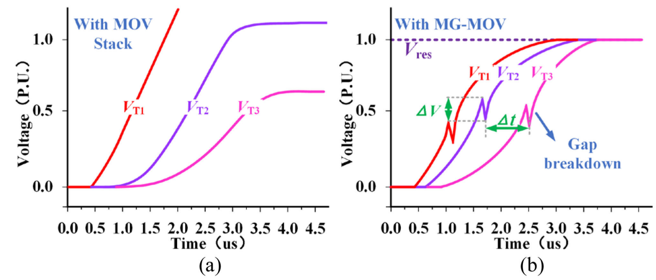


Fig. 4. Voltage-balancing characterization of the solid-state switch with the MG-MOV. (a) Voltage balancing issue is the traditional design. (b) Dynamic threshold effect of the solid-state switch.

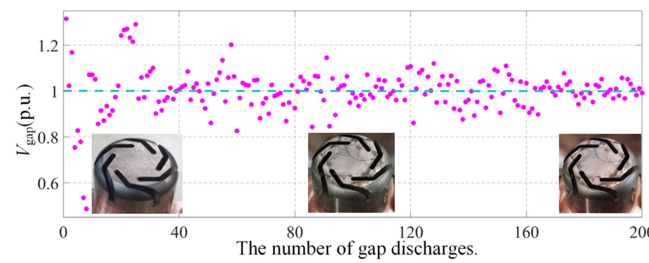


Fig. 5. Stability of the MG-MOV discharge voltage.

### D. Stability and Lifetime Issues of the Modular Gapped-MOV

The performance of gap determines whether MG-MOV scheme can be applied. In this letter, transverse magnetic contact is applied to the MG-MOV circuit. When the transverse magnetic contact is breaking current, the arc rotates and burns between the gap, which delays the generation of anode spots and improves the breaking ability of the gap. The material of the contact is tungsten copper. After multiple discharges, the contact surface is basically unchanged, and there is no obvious peak. Fig. 5 shows the contact surface condition after 100 and 200 discharges.

Taking the average gap discharge voltage as a benchmark, the distribution of 200 times pulse discharge voltage of the gap is shown in Fig. 5. The discharge voltage of the gap decreases first, and then increases with fluctuation. Finally, it maintained relatively stable. The gap discharge voltage fluctuation range does not exceed 10%.

As for the lifetime of gapped-MOV, refer to MOVs maximum surge current derating curve, under dc circuit breaker working conditions, its lifetime is about hundreds to thousands of times. So, the lifetime expectance of the gap should be the same. As for the lifetime of the gap used in this article, we are still exploring. The main reason is that the laboratory does not have the test conditions for long-term large-current breaking of solid-state switches.

### E. Dimensioning, Cost and Power Loss Issues of the Modular Gapped-MOV

Regarding gapped-MOV used in the letter, Fig. 6 shows the gapped-MOV we used. The gap is about 100 mm long, 80 mm high, and 80 mm wide, the gapped-MOV will have a larger

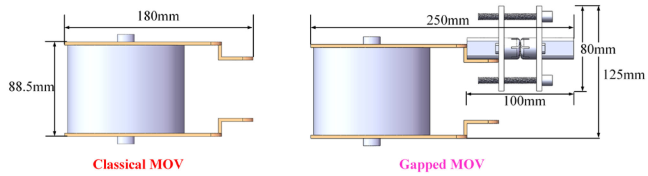


Fig. 6. Layout of the classical MOV and the gapped-MOV.

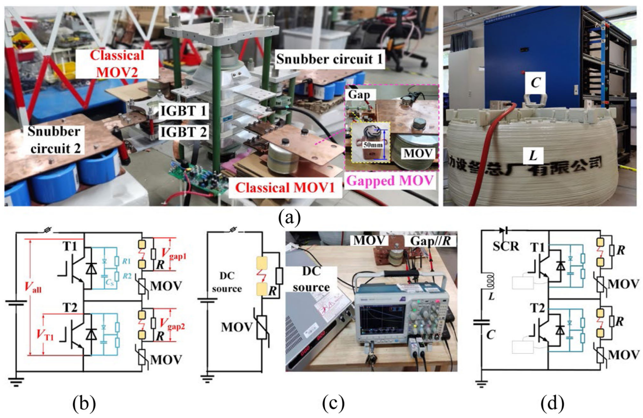


Fig. 7. Comprehensive experimental method of the solid-state switches with MG-MOV. (a) Solid-state switch prototype. (b) Ideal experimental circuit. (c) Static-state operating experiment circuit. (d) Large current breaking experimental circuit.

TABLE I
CIRCUIT PARAMETER DESIGN

| | | | | | |
|---|---|---|---|---|---|
| MOV | $V_{REF}$ | 2.4kV(1mA) | $R$ | 6MΩ/10W | |
| | $V_{DC}/R_0$ | 2.0kV/10MΩ | IGBT | 4.5kV/3kA | |
| | $t_f$, $I_{pulse}$, $V_{RES}$ | 1.5$\mu$s,7kA,3.6kV | RCD | $R_1$, $R_2$ | 100kΩ |
| | $E$ | 50kJ | | $C_S$ | 50$\mu$F |
| Gap | $V_{gsb}$ | ≤2kV | | Diode | 4.5kV/2000A |
| | $V_{gpb}$ | ≤4kV | | | |

[1]RCD snubber circuit is used in the solid-state switch, $R_1$ and $R_2$ are the static voltage-balancing resistors, and $C_S$ is the snubber capacitor.
[2]$R$ is the parallel resistance of the gap; $R_0$ is the leakage resistance of the MOV. [3]$t_f$ is the front time of the impulse current; $E$ is the maximum energy that a single MOV device can absorb.
[4]$V_{gpb}$ is the pulse discharge voltage, $V_{gsb}$ the static-state discharge voltage.

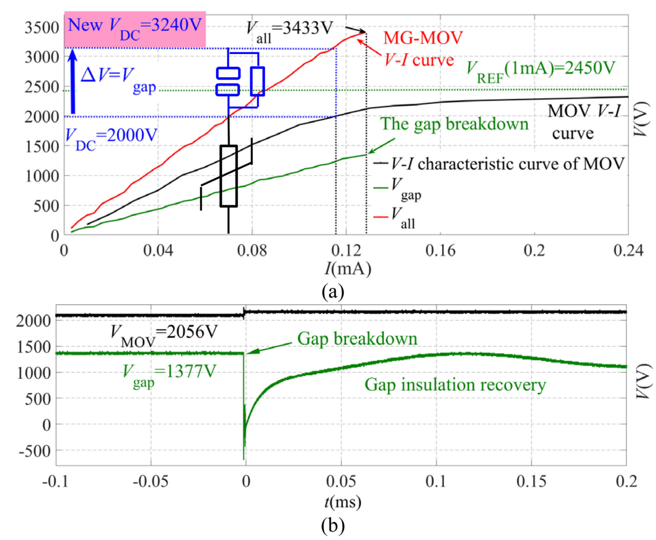


Fig. 8. DC static-state operating experimental result. (a) V–I curve of MG-MOV. (b) Discharge voltage waveform of gap in static-state.

volume than the classical MOV device. Its length will increase from 180 to 250 mm, and its height will increase from 88.5 to 125 mm. However, compared with the volume of high voltage solid-state switches, as shown in Fig. 7(a), the gap has little effect on the layout of the solid-state switch.

In terms of cost, the two longitudinal magnetic contacts total 0.018(p.u.), and the two MOV devices total 0.04(p.u.), the cost of the gap is negligible relative to the cost of the IGBTs [1(p.u.) each]. So, the gapped-MOV has a very high-cost performance.

In terms of power losses, dc circuit breakers are usually equipped with a mechanical switch, and the series modules do not need to withstand long-term dc voltage. The dc circuit breaker only withstand the dc voltage of the system during the reclosing period (a few hundred ms) or when the system has a permanent fault. Thus, the power losses and aging problem of the MOV can be ignored [9].

## III. Experimental Results of the Solid-State Switch With MG-MOV

To verify the correctness and effectiveness of the proposed scheme, we build an experimental platform to carry out static-state operating experiment and large current breaking experiment, as shown in Fig. 7.

Fig. 7(a) is a solid-state switch prototype, two semiconductor devices are connected in series, and each semiconductor device is in paralleled with the MG-MOV and the snubber circuit. Fig. 7(b) is an ideal experimental circuit, but without sufficient dc power supply system or capacitor bank, it is difficult to carry out dc static-state operating experiment and current breaking experiment of the solid-state switches with MG-MOV under actual working conditions in laboratory. We have to carry out the static-state operating experiment and large current breaking experiment step by step.

The static-state operating experiment circuit is proposed, as shown in Fig. 7(c). For the static-state operating experiment, it is mainly to verify the effect of the gapped-MOV on solid-state switch's continuous operating voltage improving, the requirement for the capacity of the power supply is relatively low. During the experiment, a dc voltage was applied to the solid-state switch and gradually increased, and the MOV and the gap each shared part of the voltage. Until the voltage of the MOV is its continuous operating voltage, then increase the voltage by a small amount until the gap breaks down.

Regarding the large current breaking experiment, *LC* oscillating circuit is a commonly used circuit for dc circuit breaker, as shown in Fig. 7(d), the capacitor *C* is precharged, and the circuit is turned ON after triggering the thyristor SCR. Taking the 500 kV circuit breaker in the Zhangbei flexible dc grid project as a

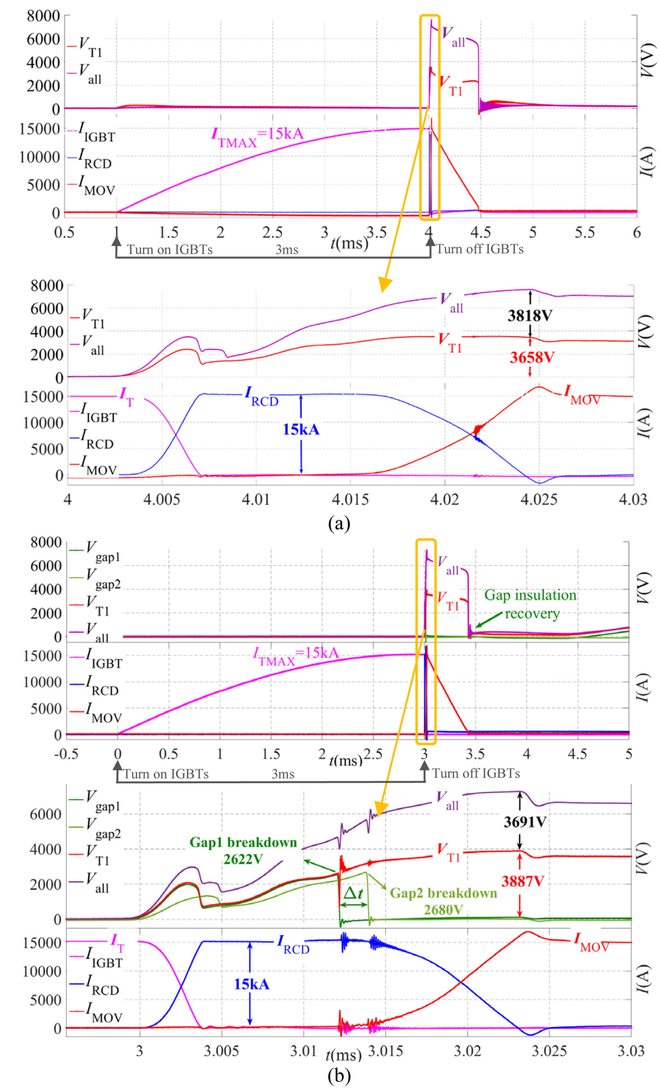


Fig. 9. Solid-state switch large current breaking experimental result. (a) Two series solid-state switches using classical MOV devices. (b) Two series solid-state switches using modular gapped-MOV devices.

reference, two parallel 4.5 kV/3000 A IGBTs turn OFF the 25 kA fault current in 3 ms, in this letter, single 4.5 kV/3 kA IGBT is used is a solid-state switch, the solid-state switches turn OFF the pulse current-$I_{\mathrm{TMAX}} = 15$ kA in 3 ms.

Based on the above-mentioned analysis and [9], and taking the solid-state switch in the 500 kV circuit breaker in the Zhangbei flexible dc grid project as a reference, the appropriate circuit parameters are shown in Table I. The parameters are easy to obtain, so the parameter calculation will not be discussed here. In addition, after multiple tests and adjustments, the appropriate gap spacing is obtained.

### A. Static-State Operating Experimental Result

The static-state operating experiment has low power requirements for dc power supply, and ordinary dc power supply can be used for experiment. As shown in Fig. 8, the *V–I* curve of MG-MOV is shown in the figure (red curve). Compared with the *V–I* curve of MOV (black curve), the continuous operating voltage $V_{\mathrm{dc}}$ increases from 2000 to 3240 V, and the voltage utilization efficiency of solid-state switches increases from 44.4% to 72.0%. The setting of new $V_{\mathrm{dc}}$ should consider the influence of system voltage fluctuation; the static-state discharge voltage should be higher. Here, the gap discharge voltage margin is set to 200 V. The static-state discharge voltage is 1377 V, and the voltage across the MOV is 2056 V, $V_{\mathrm{all}} = 3433$ V. Furthermore, the dynamic characteristics of the MG-MOV remain to be verified.

### B. Large Current Breaking Experimental Result

Based on the large current breaking experiment circuit in Fig. 6, and the test waveform of the solid-state switch breaking 15 kA current is shown in Fig. 9. IGBTs turn ON, and the fault current reaches 15 kA after 3 ms, then IGBTs are turned OFF. Fig. 9(a) shows the experiment result of the two series solid-state switches using classical MOV devices. Fig. 9(b) shows the experiment result of the two series solid-state switches using modular gapped-MOV devices.

The large current breaking process of the two solid-state switch schemes is basically the same. As mentioned earlier, in IGBTs turn-OFF transient, the gap shares almost all the voltage. When the voltage exceeds the pulse discharge voltage of gap, the gap discharges. Then, the MOV absorbs energy and limits overvoltage. $I_{\mathrm{MOV}}$ gradually decreased to 0, the gaps are insulated.

In Fig. 9(b), the two gaps are broken down successively, and the discharge voltages are 2622 and 2680 V. Due to the dynamic threshold effect of the MG-MOV, each device's voltage is limited by the MOVs. The voltage spikes of the two series devices with are 3887 and 3691 V. The voltage spikes of the two series devices with classical MOV devices are 3818 and 3658 V. The voltage spikes are slightly different, which may be related to the parameters of MOVs and the parasitic parameters in circuit.

In summary, the experimental results show that no module is damaged, the performance of the gaps and the proposed novel solid-state switch scheme is good.

## IV. Conclusion

This letter proposes a novel solid-state switch scheme with high voltage utilization efficiency by using modular gapped-MOV for dc breakers. Due to the dual advantages of the MG-MOV scheme, the continuous operating voltage of the 4.5 kV solid-state switches is increased from 2000 to 3240 V, the voltage utilization efficiency is increased from 44.4% to 72.0%. The static voltage-balancing issue and dynamic threshold effect of the MG-MOV are also discussed in detail. Meanwhile, the overvoltage of the solid-state switches meets the design requirements. The solid-state switches have broken large current up to 200 times and the gaps are in good condition, the stability of the gap discharge voltage has also been verified.

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