Letters

A Novel Oscillating-Commutation Solid-State DC Breaker Based on Compound IGCTs

Xin Yan, Zhanqing Yu, *Member, IEEE*, Lu Qu, *Member, IEEE*, Zhizheng Gan, Rong Zeng, *Fellow, IEEE*, Yulong Huang, *Member, IEEE*, Jian Feng, and Gongyi Zhang

***Abstract*—Medium voltage dc system has fast rise rate in the event of a short-circuit fault. To avoid high-peak fault current, it is necessary to configure dc circuit breaker with fast operation. Solid-state dc circuit breaker has short breaking time and high reliability, which is suitable for Dc system. In this letter, a novel oscillating-commutation solid-state dc circuit breaker based on compound integrated gate-commutated thyristors (IGCTs) is proposed. By combining IGCTs with different advantages, such as high current breaking and high withstand-voltage capability, the proposed dc breaker has the advantages at less breaking time, high performance, low cost, and small volume. The working principle of the proposed scheme is described in detail, and an 8 kV prototype with 7 kA current breaking ability is built to verify its feasibility.**

***Index Terms*—Compound IGCT, high current breaking, oscillating commutation, solid-state circuit breaker.**

I. Introduction

MEDIUM voltage dc (MVdc) power system has the higher rate of current rise in the event of a short-circuit fault, because of its low impedance and small time constant, which will develop extremely high current peaks in a short period of time. To solve the short-circuit problem, dc circuit breaker with fast breaking ability and current limitation function is an indispensable equipment for MVdc power system, which greatly improve the security of systems.[1], [2], [3]

Manuscript received 27 July 2022; revised 29 August 2022; accepted 26 September 2022. Date of publication 4 October 2022; date of current version 18 November 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 51922062, in part by the National Key Research and Development Program of China under Grant 2021YFB2401604, in part by the Integration projects of National Natural Science Foundation of China-State Grid Joint Fund for Smart Grid U2166602, and in part by the Key Projects of the National Natural Science Foundation of China 51837006.
(Corresponding author: Zhanqing Yu.)

Xin Yan, Zhanqing Yu, Lu Qu, Zhizheng Gan, Rong Zeng, and Yulong Huang are with the State Key Laboratory of Safety Control and Simulation of Power System and Large Power Generation Equipment, Tsinghua University, Beijing 100084, China (e-mail: yan-x19@mails.tsinghua.edu.cn; yzq@tsinghua.edu.cn; qulu@mail.tsinghua.edu.cn; ganzz20@mails.tsinghua.edu.cn; zengrong@tsinghua.edu.cn; yulonghuang@tsinghua.edu.cn).

Jian Feng is with the Direct Current Research Center, Sichuan Energy Internet Institute, Tsinghua University, Chengdu 610042, China (e-mail: fengjian@tsinghua-eiri.org).

Gongyi Zhang is with the Energy Internet Research Institute, Tsinghua University, Beijing 100084, China (e-mail: gongyizhang@tsinghua.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2022.3211856.

Digital Object Identifier 10.1109/TPEL.2022.3211856

Mechanical circuit breakers (MCBs), which developed earlier and maturely have low conduction loss. But the disadvantages of MCBs are obvious. Long breaking time, low life, and maintenance cost limit the use of them in the present [4], [5]. Hybrid circuit breakers (HCBs) have shorter breaking time than MCBs and their conduction loss is as low as MCBs. But HCBs still have mechanical switches and arc ablation, which reduce their life. The reliability of the auxiliary device is also the serious problem of HCBs [6], [7]. Solid-state dc breakers (SSCBs) have the advantages of short breaking time, good current suppression capability, and long life. The structure of SSCBs usually is simpler than that of MCBs and HCBs, which reduces the volume of dc breakers. However, due to the limited power capability of semiconductor devices, a high-capacity SSCB needs many power-electronic switches for series and parallel connection, which increases the ON-state loss and cost [8], [9], [10].

In this letter, a novel oscillating-commutation solid-state dc breaker (OC-SSCB) based on compound integrated gate-commutated thyristors (IGCTs) is proposed. With different characteristic of IGCTs, OC-SSCB can break large current and withstand high voltage, using less power electronic switches. Besides, A switch is series with MOV for decreasing the over voltage during the breaking process, which can reduce the number of switches ON the main branch and save volume and cost. This letter first introduces the topology and working principle of the OC-SSCB. Then, the operation process is explained. Importantly, the key parameters are analyzed and the different types of IGCTs are introduced. Finally, an 8 kV prototype of OC-SSCB is built and the feasibility of this novel topology is verified. The prototype breaks 7 kA current successfully and there is no delay between receiving the command and breaking the current. This novel topology has obvious advantages in cost comparison.

II. Topology and Working Principle

A. Topology of the OC-SSCB

Fig. 1 shows the topology of this novel OC-SSCB. Main branch, oscillated branch and energy absorption branch make up the OC-SSCB. The main branch is composed of two types of IGCTs: v-IGCT and i-IGCT. The characteristic of v-IGCT is high voltage-withstand ability but weak current-breaking ability

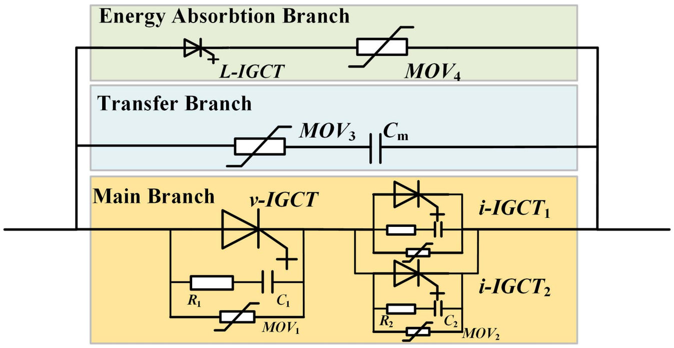

Fig. 1. Topology of the OC-SSCB.

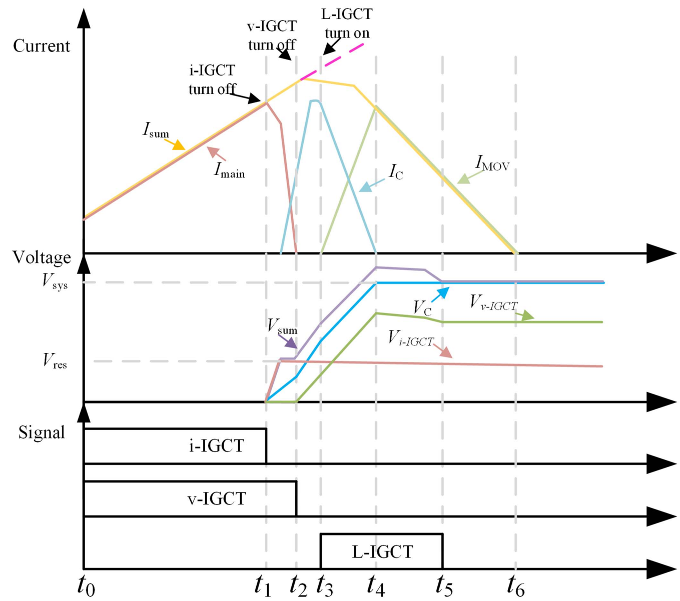

Fig. 2. Operation process of the OC-SSCB.

while i-IGCT has strong turn-OFF capability and weak withstanding voltage. These two types of IGCT are series to make up for their shortcomings. Oscillated branch includes Metal Oxide Varistor (MOV) with low voltage and capacitor C_{m}. When i-IGCT in the main branch is turned OFF, the fault current will be commutated to this branch by a way of capacitor oscillation. A low-level IGCT and MOV_4 is composed of energy absorption branch. The use of L-IGCT can make the rated voltage of MOV_4 lower than the bus voltage, thereby reducing the overvoltage during the breaking process.

Because of the power limitation of power electronics devices, the traditional SSCBs usually use devices in series and parallel to form the main branch, which increases the size and cost of the circuit breakers. To solve this problem, the OC-SSCB combines the advantages of different IGCTs to cope with the increase in voltage and current levels. The i-IGCT is used to cut OFF high fault current and the voltage is built to commutate current, which plays an important role like the load commutation switch (LCS) switch in HCBs. When the current in the main branch decreases a very low level, v-IGCT can turn OFF safely and then withstand high voltage. The RC and MOV paralleled with IGCTs can adjust static voltage distribution and dynamic voltage distribution. In this way, the power capability can rise with low cost and volume.

The capacitor C_{m} in the oscillated branch can generate oscillating current with the i-IGCT, which helps the commutation of fault current and creates safe turn-OFF moment for v-IGCT. The resonant frequency depends on the capacitor C_{m} and the loop stray inductance L_{m}. MOV_3 with low rated voltage can prevent the fault current from charging C_{m} in advance to ensure the current commutation successfully. Moreover, this MOV can suppress overvoltage spikes caused by overcharge of C_{m} and a certain amplitude of ac harmonics. Besides, L-IGCT in the energy absorption branch is used to reduce the voltage of series MOV. When the short circuit happens, L-IGCT is turned ON and MOV_4 limits the overvoltage at the residual voltage. When the process is finished, L-IGCT is turn OFF and withstands bus voltage with MOV_4, which reduces the overall voltage level of the MOV, making the overvoltage in the breaking process is lower. So fewer IGCTs are required in the main branch. The voltage that L-IGCT withstands is low and the turn-OFF current is small, so the requirements of the device for voltage and current are pretty low.

B. Operation Process of the Proposed Topology

The operation process of the OC-SSCB is shown in Fig. 2.

t_0-t_1: Supposing a short circuit fault occurs at t_0, the current starts to increase on the main branch at a high rising rate. The protection system detects and judges the fault current, then issues a breaking instruction to the OC-SSCB at t_1. During this time, the fault current develops on the main branch and the di/dt is limited by a suitable reactor to make sure the current is below the maximum turn-OFF capability of i-IGCT at t_1.

t_1-t_2: When receiving the breaking signal, the i-IGCT turns OFF first and the current flows the RC path, which is paralleled with i-IGCT. The voltage across the snubber capacitor increases rapidly as the current surges. However, because of the MOV_1 parallel to i-IGCT, the voltage will be clamped at $V_{\mathrm{res},}$ and the fault current will be commutated to the oscillate branch by this voltage. By adjusting the capacitance of the capacitor, an oscillating current with a higher amplitude can be obtained, so that the current on the main circuit can be reduced a very low level at t_2.

t_2-t_3: At t_2, the v-IGCT can turn OFF naturally as the current on the main branch reduces a very low level. By oscillating commutation, the fault current flows through C_{m}. When the current on the main branch is low, the v-IGCT can be turned OFF safely since the fault current has been commutated to the transfer branch. Even if the fault current is very high, the v-IGCT does not have the requirement of high turn-OFF current capability. So, the withstand voltage capability of it can be improved. As the current flows through C_{m}, the voltage of SSCB increases quickly. At t_3, the L-IGCT is turned ON before the voltage of C_{m} exceed the rated voltage of MOV_4.

t_3-t_4: As current is commutated, the voltage across C_{m} increases. When the voltage reaches the rated voltage of MOV_4, the resistance of MOV_4 will decrease and the current will be commutated from the oscillating branch to the energy absorption

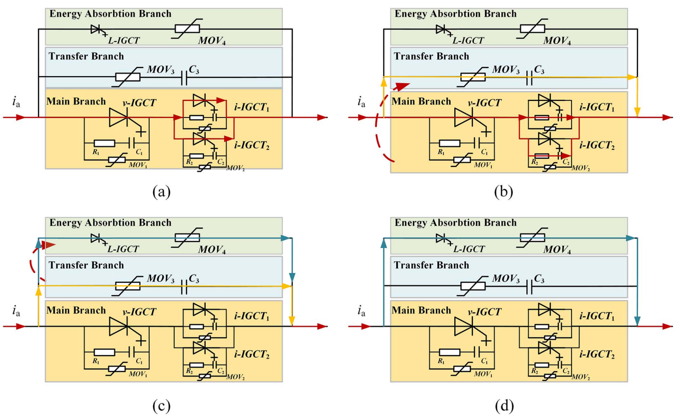

Fig. 3. Working principle of the OC-SSCB.

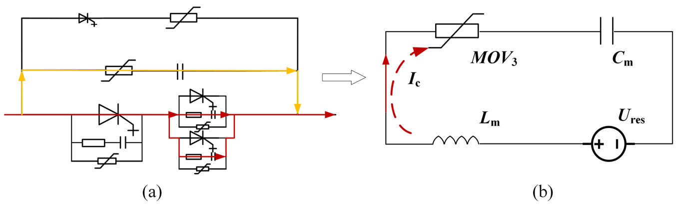

Fig. 4. Oscillation process. (a) Current flow path. (b) Equivalent circuit of the OC-SSCB.

branch. Finally, the current will all flow into this branch and the voltage will be clamped at $V_{\rm sys}$.

t_4-t_5: During this time, the energy in the system is absorbed by $\rm MOV_4$. The voltage and current will gradually decrease as the energy reduce. At t_5, the voltage decreases to the bus voltage. *L*-IGCT can turn OFF at this time because the current is pretty low. The performance of existing IGCT can easily meet this demand.

t_5-t_6: After the *L*-IGCT turning OFF, the voltage in the $\rm MOV_4$ decreases so that the current can drop to 0A. At t_6, the breaking process completes.

The working principle is shown in Fig. 3.

C. Analysis of the Commutation Process

Whether the breaking process can realize successfully depends on the commutation from t_2 to t_3. On the one hand, this commutation must ensure that all the current is commutated to the oscillating branch. On the other hand, the oscillation period affects the time when the *v*-IGCT turns OFF. Therefore, it is necessary to analyze the commutation process.

At t_2, the *i*-IGCT turns OFF. The current charges the snubber capacitor and the paralleled MOV clamps the voltage at its residual voltage, as shown in Fig. 4(a). During the commutation process, the voltage across the *i*-IGCT can be regarded as a constant voltage source. The analytical model can be simplified as Fig. 4(b). The fault current is driven by the voltage source from the main branch to the oscillating branch. $L_{\rm m}$ represents the stray inductance of the commutation loop.

TABLE I
PARAMETER OF THE PROTOTYPE

		Parameter
Main branch	*v*-IGCT	$U_{\max} = 8$kV; $I_{\max} = 3$ kA
	i-IGCT	$U_{\max} = 4.5$kV; $I_{\max} = 8$ kA
	MOV_1	5 kV at 1 mA; 8 kV at 10 kA
	MOV_2	3 kV at 1 mA; 4.2 kV at 10 kA
Oscillation branch	$C_{\rm m}$	100 μF
	MOV_3	0.8 kV at 1 mA; 1.2 kV at 10 kA
Energy branch	*L*-IGCT	$U_{\max} = 4.5$ kV; $I_{\max} = 5$ kA
	MOV_4	8 kV at 1 mA; 11 kV at 10 kA

The oscillation frequency can be expressed as

$$\omega = \sqrt{\frac{1}{C_{\rm m} L_{\rm m}}}. \tag{1}$$

The equation in the oscillation process can be expressed as

$$\left\{ \begin{array}{l} L_{\rm m}\frac{di}{dt} + U_{\rm m} + U_{\rm mov} = U_{\rm res} \\ i = C_{\rm m}\frac{du_m}{dt} \end{array} \right\}. \tag{2}$$

By calculating (2), the expression for the commutated current and the voltage of $C_{\rm m}$ is obtained as

$$i_o(t) = \sqrt{\frac{C_{\rm m}}{L_{\rm m}}} \sin\left(\sqrt{\frac{1}{L_{\rm m}C_{\rm m}}}t\right) \cdot (U_{\rm res} - U_{\rm mov}) \tag{3}$$

$$u_c(t) = \left[1 - \cos\left(\sqrt{\frac{1}{L_{\rm m}C_{\rm m}}}t\right)\right](U_{\rm res} - U_{\rm mov}). \tag{4}$$

The maximum commutable current can be expressed as

$$I_{c\max} = \sqrt{\frac{C_{\rm m}}{L_{\rm m}}}(U_{\rm res} - U_{\rm mov}). \tag{5}$$

By properly selecting parameters, the fault current can be lower than the maximum commutable current, ensuring the safety of *v*-IGCT turn OFF.

III. Prototype and Experiment of the OC-SSCB

To verify the feasibility of this novel topology of SSCB, a 8 kV/7 kA OC-SSCB prototype is developed. The value of capacitor $C_{\rm m}$ is chosen based on the breaking current and estimated stray inductance $L_{\rm m}$. Besides, the value of MOVs is determined by the characteristic of IGCTs and the fault current. The key parameters of the prototype are shown in Table I. The experimental platform setup is shown in Fig. 5. An *LC* test platform is built to simulate the fault current. Fig. 6 shows the waveforms of 7 kA interruption experiment results with 10 kV overvoltage.

When t = 4.8 ms, IGCTs on the main branch is turned ON and the current increases. When t = 7.2 ms, the current on the main branch reaches at 7 kA. The *i*-IGCT is turned OFF and the voltage of it reaches the residual voltage of $\rm MOV_1$ rapidly. At the same time, *L*-IGCT is turned ON. Then, the current is

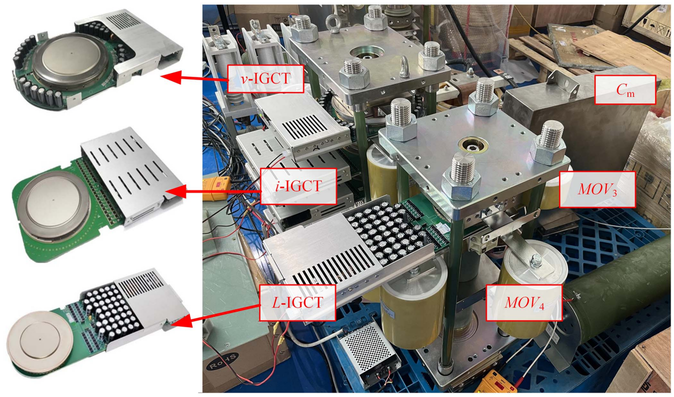

Fig. 5. Prototype of OC-SSCB.

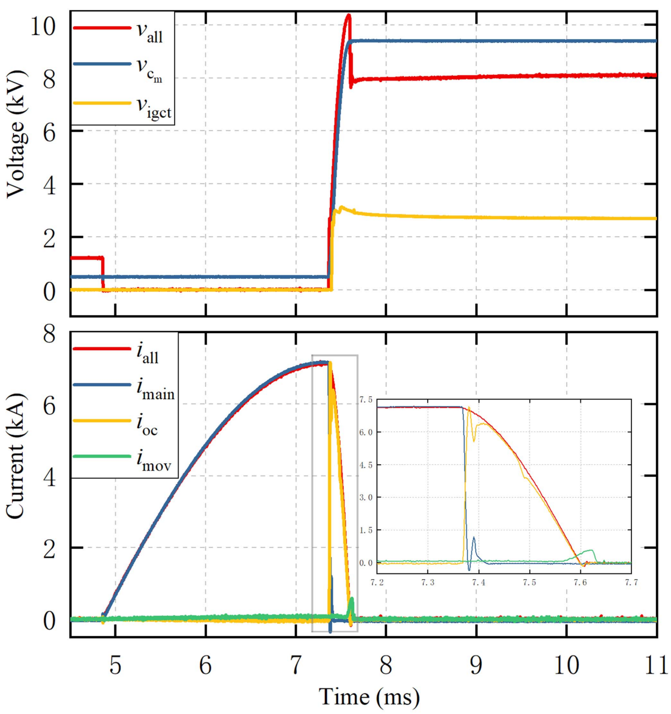

Fig. 6. Overall waveforms of interruption experiment.

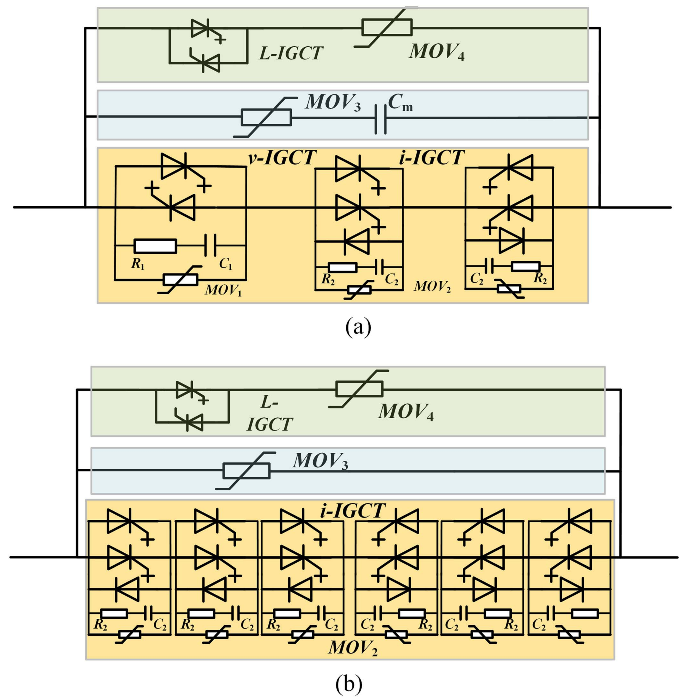

Fig. 7. Comparison of OC-SSCB and traditional SSCB. (a) The novel topology in this paper. (b) The traditional topology.

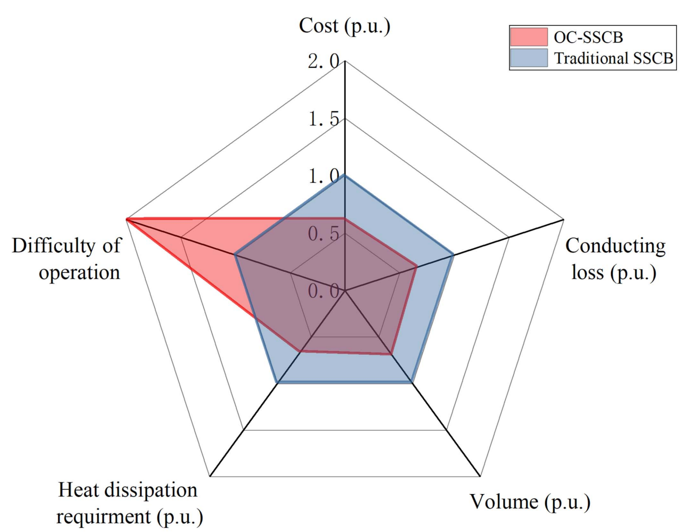

Fig. 8. Comparison of five important indicators between OC-SSCB and traditional SSCB.

commutated to the oscillating branch within 20 μs. As the current is totally commutated, the current through the *v*-IGCT decreases to 0 A, and this IGCT is turned OFF. After that, *L*-IGCT is turned ON. The voltage of $C_{\rm m}$ increases as the current charges it. When the voltage reaches 8 kV, MOV_4 starts to work and the current is commutated to energy absorption branch. As the voltage increases further, the current flows through the MOV_4, and the energy in the system is absorbed by the MOV_4. When the voltage drops to the bus voltage, *L*-IGCT is turned OFF and the breaking process is completed. Because MOV_3 absorbs much energy, the current commutated to the energy absorption branch is very low.

When the *i*-IGCT is ordered to turn OFF, the fault current cannot rise and starts to drop after 20 μs. So, the breaking time of the OC-SSCB is much shorter than 3 ms. According to the definition of the breaking time of the hybrid circuit breaker, the breaking time of the OC-SSCB is 20 μs.

IV. Discussion

The OC-SSCB topology makes full use of the advantages of different types of IGCTs to achieve high capacity with fewer components, saving costs, and optimizing volume. Fig. 7 shows the topology in this paper and traditional topology, respectively, and Fig. 8 compares the OC-SSCB and the traditional series-parallel topology in five perspectives, which the voltage level is 10 kV and the current level is 10 kA.

The number of power devices in the novel is much less than that in the traditional topology. Because the cost of capacitor is low, which is under 2000 RMB, the cost of the two topologies can be equal to the number of full-controlled power devices. So, the cost of the new topology is about 60% of the traditional topology. Besides, because using more devices, the conducting loss of traditional topology is higher than that of the novel topology. As shown in Fig. 7, the ON-state voltage drop of the traditional topology consists of the voltage drops of three level IGCTs in series and three diodes in series. In comparison, the voltage drops of the topology proposed in this article only consists of the voltages of a *v*-IGCT, two parallel *i*-IGCT, and a diode. The conducting loss of the novel topology is about 60% of that of the traditional topology. Therefore, the requirements for heat dissipation of traditional topology are also higher. Despite the increased capacitance, the novel topology is still smaller because there are fewer power devices. The volume of OC-SSCB is 70% of that of traditional SSCB. The operation of OC-SSCB is more difficult due to the current commutation. However, IGCTs have a current zero-crossing detection function, so the turn-OFF time of the *v*-IGCT can be judged by the IGCT itself. This simplifies the control difficulty to a certain extent.

V. Conclusion

This letter proposes an OC-SSCB that combines different types of IGCTs and realizes high power breaking with low cost. As the voltage and current levels increase, this novel topology has more obvious advantages at cost. With fewer IGCTs on the main branch, the structure can be simplified and the ON-state loss is less than the traditional SSCBs. Besides, the breaking time of the OC-SSCB is still very short, which can effectively suppress the development of fault current. The 8 kV prototype can successfully turn off 7 kA current, which verifies the feasibility of the OC-SSCB topology. The proposed topology provides an effective design scheme for the dc breaking demand on MVdc.

References

[1] W. Chen et al., “Development and prospect of direct-current circuit breaker in China,” *High Voltage*, vol. 6, pp. 1–15, 2021.

[2] C. Meyer, M. Kowal, and R. W. De Doncker, “Circuit breaker concepts for future high-power DC-applications,” in *Proc. 40th IAS Annu. Meeting Conf. Rec. Ind. Appl. Conf.*, Oct. 2005, vol. 2, pp. 860–866.

[3] C. M. Franck, “HVDC circuit breakers: A review identifying future research needs,” *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 998–1007, Apr. 2011.

[4] H. Sun, H.-W. Joo, Y. Wu, M. Rong, C.-Y. Bae, and Y.-G. Kim, “Calculation of the switch arc in low voltage circuit breaker considering the interaction between the contact movement and the arc force,” in *Proc. 5th Int. Conf. Electric Power Equip. Switching Technol.*, 2019, pp. 235–238.

[5] F. Yang et al., “Low-voltage circuit breaker arcs—Simulation and measurements,” *J. Phys. D, Appl. Phys.*, vol. 46, 2013, Art. no. 273001.

[6] A. Hassanpoor, J. Häfner, and B. Jacobson, “Technical assessment of load commutation switch in hybrid HVDC breaker,” in *Proc. Int. Power Electron. Conf.*, Hiroshima, Japan, 2014, pp. 3667–3673.

[7] W. Wen, Y. Huang, Y. Sun, J. Wu, M. Al-Dweikat, and W. Liu, “Research on current commutation measures for hybrid DC circuit breakers,” *IEEE Trans. Power Del.*, vol. 31, no. 4, pp. 1456–1463, Aug. 2016.

[8] R. Schmerda, R. Cuzner, R. Clark, D. Nowak, and S. Bunzel, “Shipboard solid-state protection: Overview and applications,” *IEEE Electrific. Mag.*, vol. 1, no. 1, pp. 32–39, Sep. 2013.

[9] S. Wang et al., “A 15-kA solid-state circuit breaker research and development for the switch network unit of the EAST Tokamak,” *IEEE Trans. Plasma Sci.*, vol. 49, no. 9, pp. 2979–2986, Sep. 2021.

[10] F. Agostini et al., “1MW bi-directional DC solid state circuit breaker based on air cooled reverse blocking-IGCT,” in *Proc. IEEE Electric Ship Technol. Symp.*, 2015, pp. 287–292.