Letters

A Novel High-Power Hybrid DC Breaker Based on Compound Power Electronic Switch With Integrated Commutation Ability

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***Abstract*—Medium voltage dc power system has the characteristics of low line impedance, resulting in high peak and fast rise rate of the fault current. For example, the current in an onboard 10 kV dc grid can rise to more than 40 kA in 3 ms after the failure. Therefore, it is necessary to configure dc circuit breaker with high current breaking capacity. In this letter, a novel high-power hybrid dc breaker based on integrated commutation compound power electronic switch is proposed. By giving full play to the complementary advantages of insulated gate bipolar transistor (IGBT) and integrated gate-commutated thyristor (IGCT), and skillfully integrating the commutation function into the power electronic switch, the proposed dc breaker has the characteristics of low cost, compact, high performance, and can also play a role in current limiting. The working principle of the proposed scheme is described in detail, and a 10-kV prototype with 40 kA current breaking ability is built to verify its feasibility.**

***Index Terms*—Compound power electronics switch, high current breaking, hybrid circuit breaker (HCB).**

I. Introduction

MEDIUM voltage dc (MVDC) power system has the characteristics of low line impedance, small time constant, fast rise rate of short-circuit current, and high short-circuit current peak. DC circuit breaker (DCCB) with fast breaking speed and current limiting function has become the key equipment for the safe operation of MVDC system, which plays a vital role in the engineering realization of dc power system [1], [2].

In the early development of DCCB, mechanical circuit breakers (MCBs) based on arc voltage establishment are used in the dc system. MCB has mature technology and rich application experience. But there are some shortcomings, such as long breaking time, poor current limiting effect, low life, and high maintenance cost [3], [4]. On the other hand, due to the low rated voltage, under the condition of high current, the MCB is difficult to extinguish arc, and it is difficult to meet the requirements of fast current limiting protection of MVDC shipboard power system.

With the development of power electronic switches, the solid-state circuit breaker (SCB) with fast switching, strong current limiting ability, and long life is formed. However, due to the limited voltage and current withstand ability of semiconductor devices, a large number of power electronic switches are needed for series and parallel connection in large capacity applications of power system. The high ON-state loss and high cost limit its application in dc power system [5].

The hybrid circuit breaker (HCB) is proposed to solve the high on-state loss problem of SCB. HCB combines the advantages of mechanical switch and power electronic switch, with fast breaking speed, high reliability, and long life [6]. However, HCB needs to connect auxiliary commutation device in series with mechanical switch to realize the commutation process from mechanical switch to power electronic switch [7], [8], which require additional volume and cost. In addition, HCB still require a large number of power electronic switches in series and parallel, so the cost of HCB is still high [9].

In this letter, a novel integrated commutation compound power electronic based hybrid dc breaker (IC-HCB) with high power ability is proposed to overcome the defects of existing HCBs. By giving full play to the complementary advantages of insulated gate bipolar transistor (IGBT) and integrated gate-commutated thyristor (IGCT), the IC-HCB can realize high current breaking capacity with quite low cost and volume. In addition, the current commutation function is integrated to the compound power electronic switch by using an H-bridge-like structure of IGBT. Thus, the additional auxiliary commutation device with its water cooling system in original HCB scheme can be eliminated, which also saves volume and cost. This letter first introduces the topology and working principle of the IC-HCB. Then, the operation process and parameter analysis of the IC-HCB are analyzed in detail. Finally, a 10-kV prototype is built to verify the feasibility of the proposed topology. The

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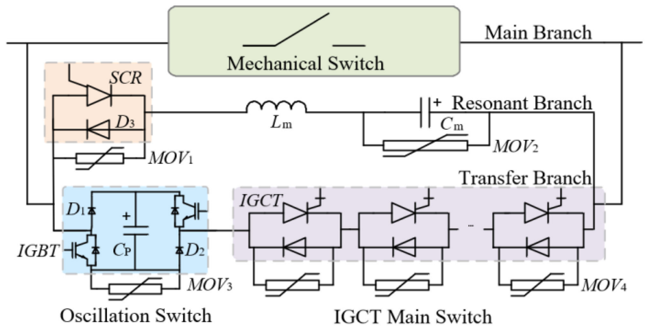


Fig. 1. Topology of the IC-HCB.

experimental results show that the IC-HCB can successfully break current of 40 kA.

II. Proposed IC-HCB

A. Topology of the Proposed IC-HCB

Fig. 1 shows the proposed IC-HCB topology. It includes three current branches: main branch, resonant branch, and transfer branch. The main branch is composed of mechanical switch for normal current flow. The transfer branch consists of oscillation switch and IGCT main switch, which is designed based on the idea of IGCT-IGBT compound power electronic switch proposed in our previous paper [10]. The compound power electronic switch is mainly composed of IGCTs (the IGCT main switch), so as to obtain strong surge capability and voltage withstand capability. And in order to make up for the poor turn-OFF capability of IGCT, a small number of IGBTs are also added to it as the oscillation switch, so as to use its high-current turn-OFF capability to create a turn-OFF opportunity for IGCTs. In this way, the complementary advantages of IGBT and IGCT can be fully utilized, thereby makes the IC-HCB have high performance and strong economy.

However, in the HCB, since the voltage drop of power electronic switches is generally higher than that of mechanical switches, traditional HCBs require an additional auxiliary power electronic switch in the main branch to force the current commutate from the mechanical switch to the power electronic switch, which usually causes additional cost and volume. Therefore, in this letter, when the IGCT-IGBT compound power electronic switch is applied to the HCB, the original IGBT parallel module of the oscillation switch is replaced by an asymmetric H-type half bridge, and the precharged energy storage capacitor C_P is also added. C_p promotes the commutation process of the current from the main branch to the transfer branch through discharge. Therefore, the commutation function can be integrated into the oscillation switch to make the IC-HCB more compact and economical. It should be noted that, in the process of IC-HCB operation, system energy can be charged to C_P, thus the IC-HCB can operate continuously without recharging C_P.

The resonant branch is used to cooperate with the IGBTs to generate an oscillating current superimposed on the transfer branch, which can create the condition for IGCTs to turn OFF at small current. It original composed of resonant capacitor C_m and inductor L_m. In this letter, the thyristor (SCR) and diode D_3 is also added. D_3 provides current flow path in the discharge stage of C_P. Therefore, when the C_P is discharged to promote the current commutation, part of the energy can also be restored to the C_m in resonant branch. And after the commutation process, SCR can play a blocking role to prevent the discharge process of C_m even the IGBTs is already turn-OFF. So the C_m can get an additional precharged voltage before SCR starts the final oscillation, which means the current ability can be improved.

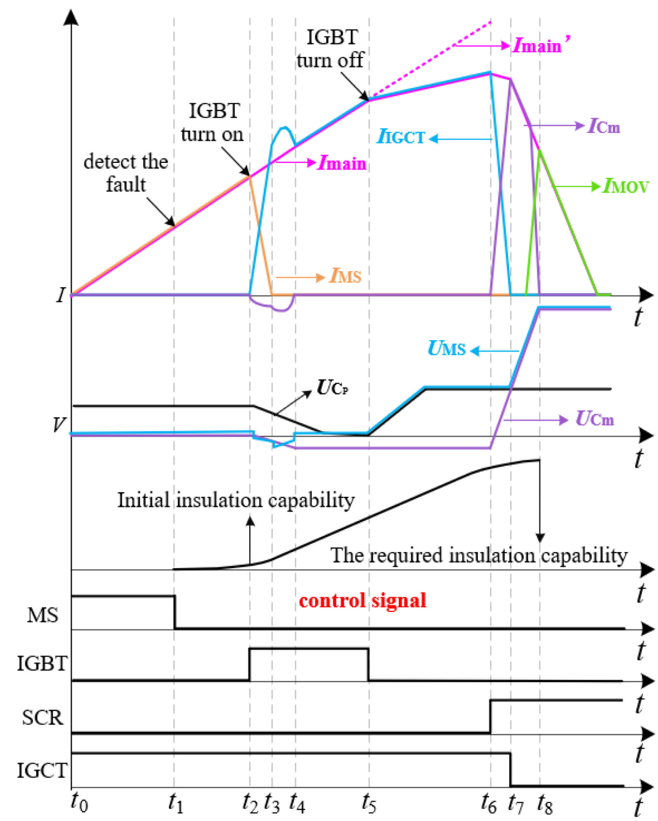


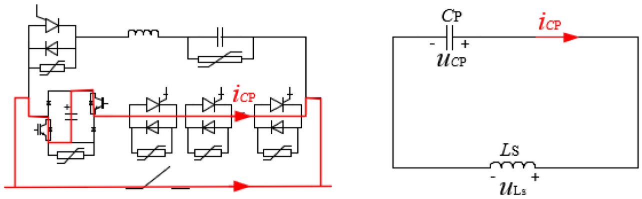
Fig. 2. Operation process of the IC-HCB.

Besides, the introduction of SCR in resonant branch, the oscillation current in resonant branch can be individually controlled by SCR instead of being restricted by the IGBTs and IGCTs, which means the IGBTs, can be turned OFF in milliseconds in advance. Before the mechanical switch has the complete insulation ability, a certain voltage can be established by the IGBTs to limit the rise rate of the fault current. In other words, the controllability of the oscillation switch makes IC-HCB has a certain current limiting ability, which not only reduces the harm of the current shock to the equipment, but also reduces the current breaking requirement for the dc breaker.

B. Operation Process of the Proposed IC-HCB

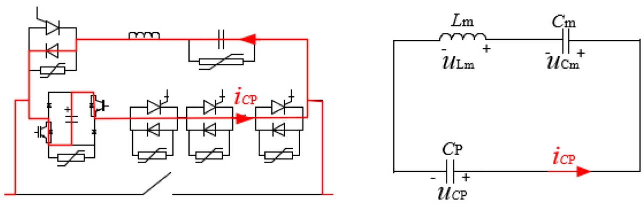
The operation process of IC-HCB is explained according to Fig. 2.

t_0-t_1: Under normal circumstances, all current flows through the main branch. SCR and IGBT are in the state of turn OFF. C_P has a precharge voltage U_{CP0}, and the voltage polarity is shown



(a) (b)

Fig. 3. Commutation process. (a) Current flow path. (b) Equivalent circuit of the IC-HCB.



(a) (b)

Fig. 4. Charging process. (a) Current flow path. (b) Equivalent circuit of the IC-HCB.

in Fig. 1. When $t = t_0$, the short circuit fault occurs, and the fault current begins to rise.

t_1-t_2: At $t = t_1$, the fault current is detected, and the turn OFF command is issued to generate arc between the two contacts of the mechanical switch.

t_2-t_4: At $t = t_2$, mechanical switch has initial insulation capability. IGBT is turned ON, and U_{CP0} is applied reversely on the mechanical switch. The mechanical switch current I_{MS} commutate to the transfer branch. At the same time, C_{P} is discharged to charge C_{m}. At $t = t_3$, the current is completely transferred from the mechanical switch to the transfer branch, the arc is extinguished, and $I_{\mathrm{MS}} = 0$. At this time, the voltage U_{CP} continues to decrease and C_{m} continues to charge. At $t = t_4$, C_{m} voltage reaches to U_{Cm0}, and the voltage polarity is shown in Fig. 1.

Assuming that the stray inductance of the main branch is much smaller than that of the resonant branch. It can be approximately considered that t_2-t_3 only carries on the commutation process, and t_3-t_4 carries on the charging process.

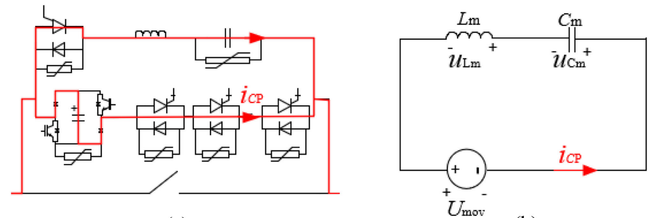
Fig. 3(a) is the ideal current flow path during t_2-t_3. The main branch is equivalent to stray inductance L_{S}, ignoring the circuit resistance, IC-HCB can be equivalent to the circuit shown in Fig. 3(b).

It is easy to know that under the condition of breaking fault current I, the residual voltage U_{CPr} on C_{P} after the mechanical switch is switched OFF is (at $t = t_3$)

$$U_{\mathrm{CPr}} = \sqrt{\frac{C_{\mathrm{P}} {U_{\mathrm{CP0}}}^2 - L_{\mathrm{S}} I^2}{C_{\mathrm{P}}}}. \tag{1}$$

During t_3-t_4, the current flow path is shown in Fig. 4(a). Fig. 4(b) is the equivalent circuit. According to Kirchhoff ' s law, the expression of current i_{CP} can be given as

$$i_{\mathrm{CP}} = \frac{U_{\mathrm{CPr}}}{L_{\mathrm{m}}\omega} \sin \omega t. \tag{2}$$



(a) (b)

Fig. 5. Oscillation process. (a) Current flow path. (b) Equivalent circuit of the IC-HCB.

The angular frequency is

$$\omega = \sqrt{\frac{C_{\mathrm{m}} + C_{\mathrm{P}}}{C_{\mathrm{m}} C_{\mathrm{P}} L_{\mathrm{m}}}}. \tag{3}$$

The resonant capacitor voltage u_{Cm} can be expressed as

$$u_{\mathrm{Cm}} = \frac{U_{\mathrm{CPr}}}{C_{\mathrm{m}} L_{\mathrm{m}} \omega^2} \times (1 - \cos \omega t). \tag{4}$$

At $t = t_4$, the voltage on capacitor C_{m} is

$$U_{\mathrm{Cm0}} = \frac{2U_{\mathrm{CPr}}}{C_{\mathrm{m}} L_{\mathrm{m}} \omega^2}. \tag{5}$$

t_5-t_6: At $t = t_5$, IGBT is turned OFF. The transfer branch current I_{IGCT} flows through D_1 and D_2 in the oscillation switch. In this process, the system energy fills C_{P} with voltage U_{CP}'. And the establishment of voltage U_{MS} greatly slows down the rising rate of I_{main}. It should be noted that C_{p} will not be overcharged because its voltage is limited by MOV_3.

t_6-t_8: At $t = t_6$, SCR is turned ON. Under the action of the resonant capacitor voltage U_{Cm0} and the protection voltage U_{MOV} of the arrester in the oscillation switch, C_{m} produces an oscillating current from right to left superimposed on the IGCT, and the IGCT current decreases. At $t = t_7$, the current I_{IGCT} decreases to zero, so turn OFF IGCT. After IGCT is turned OFF, instantaneous overvoltage U_{Cm} is established. When $t = t_8$, the overvoltage of C_{m} exceeds the reference voltage of the paralleled arrester, then the current is commutated to the arrester for energy dissipation. When the line current drops to 0, the whole operation process is completed.

During t_6–t_7, the current flow path and equivalent circuit are shown in Fig. 5.

The state equation in the oscillation process can be obtained

$$L_{\mathrm{m}} C_{\mathrm{m}} \frac{d^2 u_{\mathrm{Cm}}}{dt^2} + u_{\mathrm{Cm}} + U_{\mathrm{mov}} = 0. \tag{6}$$

According to (6), the expression of i_{CP} can be expressed as

$$i_{\mathrm{CP}} = -C_{\mathrm{m}} \sqrt{\frac{1}{C_{\mathrm{m}} L_{\mathrm{m}}}} \left(U_{\mathrm{Cm0}} + U_{\mathrm{mov}}\right) \sin \sqrt{\frac{1}{C_{\mathrm{m}} L_{\mathrm{m}}}} t. \tag{7}$$

In a quarter period of LC oscillation, the amplitude of i_{CP} is equal to fault current I, the following equation can be obtained

$$I = \sqrt{\frac{C_{\mathrm{m}}}{L_{\mathrm{m}}}} \left(U_{\mathrm{Cm0}} + U_{\mathrm{mov}}\right). \tag{8}$$

In the design process of resonant branch parameters, (1), (3), (5), and (8) need to be satisfied.

TABLE I
PROTOTYPE PARAMETER

capacity		10kV/40kA
Resonant branch	MOV_1	3.9 kV at 1 mA; 6.0 kV at 40 kA
	L_m	stray inductance (about 4 μH)
	C_m	300 μF
	MOV_2	7 kV at 1 mA; 15.5 kV at 40 kA
Oscillation switch	IGBT	ST3000GXH24A (IEGT)
	C_P	1 mF
	MOV_3	2.4 kV at 1 mA; 3.8 kV at 40 kA
IGCT main switch	IGCT	5SHY 42L6500
	MOV_4	3.9 kV at 1 mA; 6.0 kV at 40 kA

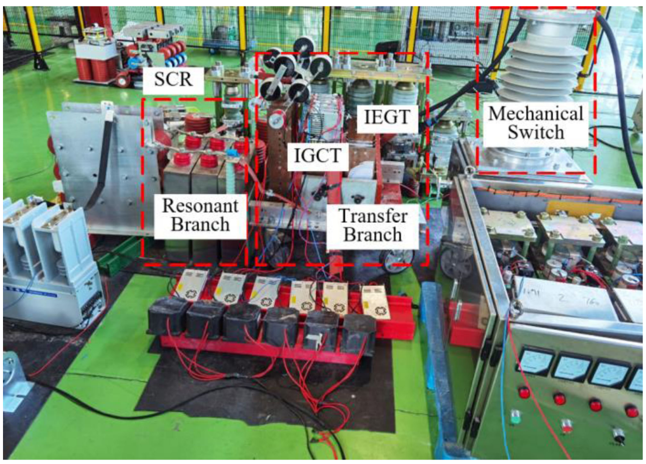


Fig. 6. 10-kV/40-kA prototype of IC-HCB.

In fact, the commutation process from mechanical switch to transfer branch and the precharge process of resonant capacitor occur simultaneously. Therefore, a certain margin should be considered when designing C_{m}.

III. EXPERIMENTS OF THE IC-MCB

In order to verify the feasibility and effectiveness of the proposed topology, an *LC* discharge test circuit is built and a 10 kV/40 kA IC-MCB prototype is developed. First, the number of IGBT and IGCT is determined according to the current and voltage level, and the relevant arrester parameters are determined according to the withstand voltage ability of IGBT and IGCT. The values of stray inductance L_{S} and L_{m} are estimated after determining the main circuit topology. Finally, considering the commutation ability and the residual voltage of C_{P}, the values of C_{P} and C_{m} are determined according to (1), (5), and (8). The key parameters of the prototype are shown in Table I. The experimental setup is shown in Fig. 6.

Before the experiment of the prototype, the functions of each module are detected, including IEGT (Injection Enhanced Gate Transistor, one kind of IGBT), IGCT current evenness, *di*/*dt* capability of SCR, etc. Then verify the turn-OFF ability of compound power electronic switch. The verification results show that each module works well.

Figs. 7 and 8 are the waveforms of 40 kA interruption experiment results.

First, C_{P} is precharged to 3 kV before the IC-HCB operates. At $t = 0.6$ ms, the turn-OFF command of the mechanical switch

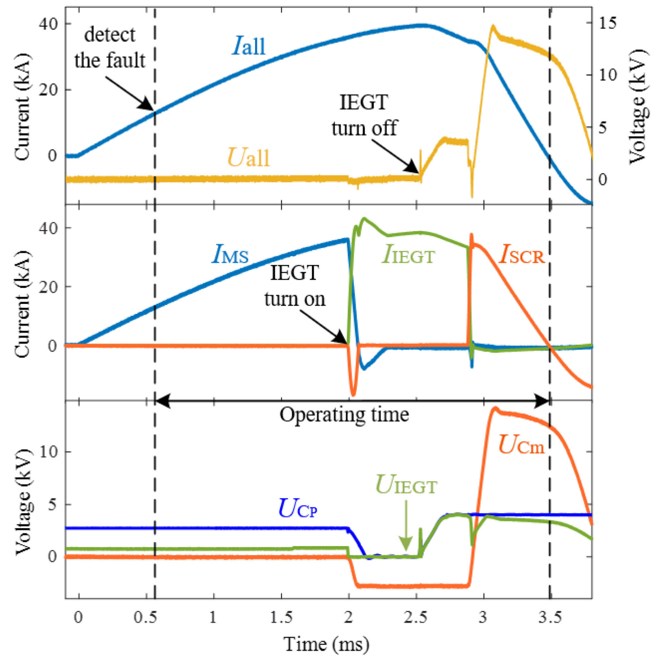


Fig. 7. Waveforms of 40 kA interruption experiment.

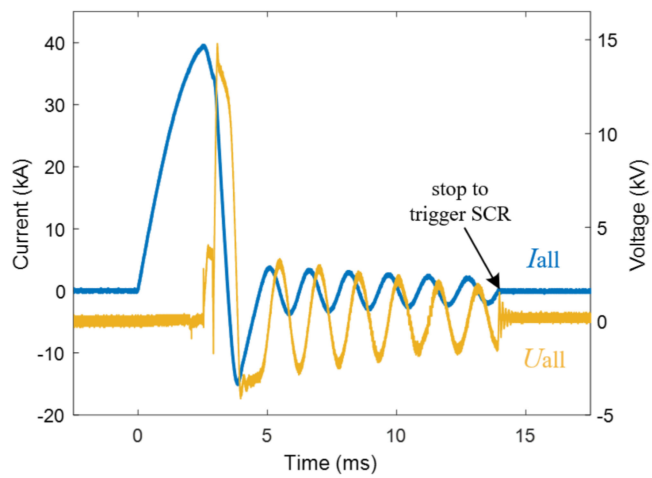


Fig. 8. Overall waveforms of 40 kA interruption experiment.

is issued, and the contact of the mechanical switch begins to separate gradually. At $t = 1.95$ ms, IEGT is turned ON. Since the capacitor voltage U_{CP} is reversely applied to the mechanical switch, the current I_{MS} can be commutated to the transfer branch and the current I_{IEGT} increases rapidly. At the same time, the negative pressure is applied to C_{m}, and the reverse parallel diode D_3 of SCR is used to charge the capacitor C_{m}. At $t = 2.1$ ms, U_{Cm} reaches 2.82 kV. During the charging process, U_{CP} gradually drops to zero. Since the passive high-voltage probe is used to measure the two-terminal voltage of the fast mechanical switch, U_{all} is still zero. It can be seen that after conducting IEGT, I_{SCR} has a reverse current spike, which is because I_{MS} drops to zero. However, due to the existence of U_{CP} and the absence of medium recovery time, I_{SCR} will have a reverse current.

When U_{CP} drops to zero, the IEGT module changes from series to parallel. At $t = 2.55$ ms, the fault current reaches 40 kA.

TABLE II
COST AND TURN-OFF TIME COMPARISON

Cost	IC-HCB	Traditional HCB
Capacity	10 kV/40 kA	10 kV/40 kA
Mechanical switch	5 p.u.	5 p.u.
Auxiliary commutation device	-	20 p.u.
Transfer branch	21.8 p.u.	57.6 p.u.
Resonant branch	8.2 p.u.	-
Total cost	35 p.u.	82.6 p.u.
Action time	< 3 ms	< 3 ms

Turn OFF IEGT, the current is charged to $C_{\rm P}$ through the diodes D_1 and D_2, the polarity of $U_{\rm CP}$ is shown in Fig. 1. During $t =$ 2.55 ms $- t =$ 2.87 ms, $U_{\rm CP}$, $U_{\rm IEGT,}$ and the overall voltage $U_{\rm all}$ increase. The residual voltage of the arrester in parallel with the oscillation switch is 3.9 kV, and $U_{\rm all}$ is limited to about 3.9 kV.

At $t = 2.87$ ms, SCR is turned ON, and the voltage $U_{\rm CP}$ reaches to 4 kV. $U_{\rm CP}$ and $U_{C{\rm m}}$ are used to commutate the current from the transfer branch to the resonant branch and arrester. $I_{\rm SCR}$ increased rapidly and $I_{\rm IEGT}$ decreased rapidly to zero. When the current $I_{\rm IEGT}$ drops to zero at $t = 2.9$ ms, turn OFF IGCT and let the IGCT withstand voltage. After the current is commutated to the resonant branch, the capacitor $C_{\rm m}$ is charged. When the voltage $U_{\rm Cm}$ reaches the residual voltage of the arrester, the arrester absorbs energy and completes the current breaking process. It can be seen from Fig. 8 that $I_{\rm all}$ continues to oscillate for a period of time. The reason is that after the IC-HCB clears the fault, the SCR continues to trigger 10.5 ms. Stop triggering SCR in violent oscillation will damage SCR due to the reverse recovery process. When $I_{\rm all}$ decays to low enough, SCR is stopped to trigger. At $t = 14$ ms, the residual oscillation current appears.

IV. COST DISCUSSION

Based on the prototype built in Section III, the cost of key components of IC-HCB is calculated and compared with the traditional HCB. It is assumed that all the IGBTs and mechanical switches used in the traditional HCB and IC-HCB are the same. As shown in Table II, at the capacity of 10 kV/40 kA, IC-HCB saves the cost of auxiliary commutation device. Therefore, the main branch cost of IC-HCB is only 20% of the traditional HCB. In order to ensure sufficient surge and voltage withstand ability, the transfer branch of traditional HCB needs to be series and paralleled by a large number of IGBTs. The transfer branch cost of traditional HCB is 57.6 p.u. (1 p.u. refers to 10 000 RMB). Since IGCT has higher surge ability than IGBT, IGCT does not need parallel connection. The cost of transfer branch of IC-HCB is reduced, which is only 37.8% of that of traditional HCB. Although the resonant branch in IC-HCB requires additional cost, the overall cost of IC-HCB is 35 p.u., which is only 42.4% of the traditional HCB. It can be seen that at the same capacity level, the cost of IC-HCB is much lower than that of traditional HCB.

V. CONCLUSION

This letter proposes an IC-HCB that makes full use of the complementary advantages of IGBT and IGCT. The IC-HCB saves cost and volume by integrating the commutation ability to the oscillation switch. The IC-HCB also has current limiting function, which reduces the harm of the current shock to the equipment and the current breaking requirement for the dc breaker. The 10-kV prototype can successfully turn OFF 40 kA current, which verifies the feasibility of the IC-HCB topology. The proposed IC-HCB provides an effective design scheme for the dc breaking demand on MVDC.

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