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A New Reclosing and Re-breaking DC Thyristor Circuit Breaker for DC Distribution Applications

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Abstract

The DC circuit breaker is essential for supplying stable DC power with the advent of DC transmission/distribution and sensitive loads. Compared with mechanical circuit breakers, which must interrupt a very large fault current due to their slow breaking capability, a solid-state circuit breaker (SSCB) can quickly break a fault current almost within 1 [ms]. Thus, it can reduce the damage of an accident a lot more than mechanical circuit breakers. However, previous DC SSCBs cannot perform the operating duty, and are not economical because many SCR are required. Therefore, this paper proposes a new DC SSCB suitable for DC grids. It has a low semiconductor conduction loss, quick reclosing and rebreaking capabilities. As a result, it can perform the operating duties of reclosing and rebreaking. The proposed DC SSCB is designed and implemented so that it is suitable for home dc distribution at a rated power of 5 [kW] and a voltage of 380 [V]. The operating characteristics are confirmed by simulation and experimental results. In addition, this paper suggests design guidelines so that it can be applied to other DC grids. It is anticipated that the proposed DC SSCB may be utilized to design and realize many DC grid systems.

Key words: DC circuit breaker, DC SSCB, Operating duty, Solid state circuit breaker (SSCB), Thyristor circuit breaker

I. INTRODUCTION

Recently, DC transmission/distribution has become a major concern because it can increase overall system power efficiency compared to existing AC transmission/distribution. Furthermore, since a lot of loads that are sensitive to short faults or voltage sags/swells are being widely utilized with the development of the IT industry, more reliable and stable power supply technologies are required [1], [2].

However, techniques regarding the stability of DC power grids are lacking compared to existing AC power grids. In addition, there is no zero crossing of the current in DC power grids while there is zero crossing of the current in AC power grids. Thus, in DC power grids there are some difficulties in breaking over-currents and short-circuit currents. In addition, unless short-circuit current is quickly cut off, more subsequent damage can occur due to electrical fires caused by electric arcs or sparks [3].

Fig. 1 shows the maximum currents and breaking times of mechanical circuit breakers and SSCBs when short faults occur in a DC Grid. The mechanical circuit breakers are capable of breaking faults in about several tens of [ms] due to their physical structure, Thus, it is difficult for mechanical circuit breakers to prevent a lot of the damage caused by short-circuit faults because of their slow break capability [4].

In contrast, the SSCB can break faults within 1 [ms] at a much lower current level than the maximum fault current level, which reduces a lot of the damage to grid devices.

Fig. 2 shows the operation of a circuit breaker. In the normal state to transmit energy, it performs the closing operation as shown in Fig. 2-(a). If a short fault occurs, it performs the breaking operation as shown in Fig. 2-(b). However, as shown Fig. 2-(c), if the power line is held in the open state for a long time without supplying electric power after a power line is restored to normal operation, the power customers may receive a lot of consequent damages due to the electric power outage. For this reason, IEC-62271-100 prescribes the circuit breaker`s operating duty that the reclosing and rebreaking operations of a circuit breaker should be able to be performed repeatedly. Therefore, a SSCB should break the fault quickly, and perform the operating duty.

There are several types of semiconductor switching

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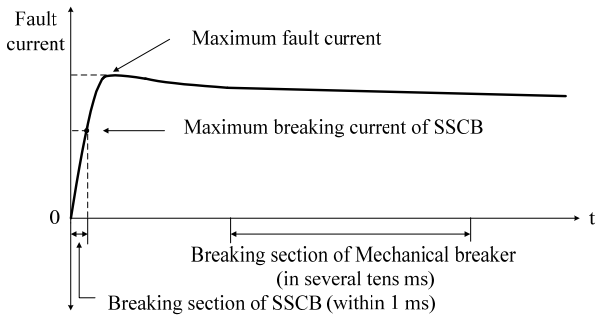

Fig. 1. Breaking section of mechanical circuit breaker and SSCB.

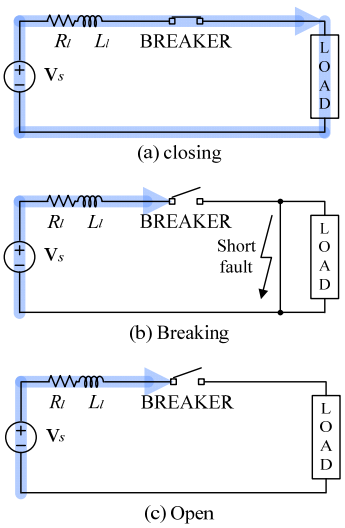

Fig. 2. Closing and breaking operation of DC circuit breaker.

elements such as the IGBT, GTO, GCT and SCR used to implement a SSCB. Among them the SCR is the most suitable for use in SSCBs because it is economical and its on-state loss is relatively small [5], [6]. However, since an AC SSCB using a SCR is based on AC grid characteristics that line commutation is possible, directly applying an AC SSCB to a DC grid can cause a lot of difficulties in terms of interrupting the fault current. Therefore, it is necessary to suggest a DC SSCB that is suitable for DC power grids [7]-[11].

Fig. 3 shows a previously presented DC SSCB [10]. This SSCB supplies power through the main SCR S_1, and the capacitor C is charged when turning on the SCR S_1 and S_2. If a fault occurs, the fault current is broken through the L_1-C resonance current (S_3-C-L_1) by turning on SCR S_3.

A large inductor L_2 is used in this SSCB in order to limit the fault current when a short fault occurs. Therefore, a malfunction of the load may occur because the power source works as a kind of current source. In addition, this SSCB cannot perform the operating duty because it cannot recharge the commutation capacitor C under short circuits on the load side.

Fig. 4 shows another DC SSCB [11]. This SSCB supplies power through the main SCR T_{11}. If a fault occurs, the fault

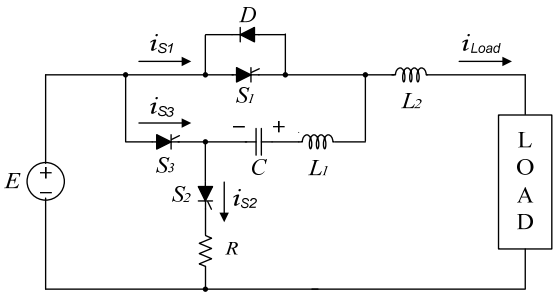

Fig. 3. Previous DC SSCB of Ref [10].

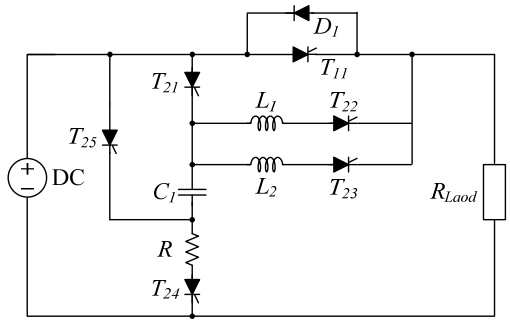

Fig. 4. Previous DC SSCB of Ref [11].

current is broken through the L_1-C_1 resonance current (T_{25}-C_1-L_1-T_{22}) by turning on the SCR T_{25} and T_{22}. This SSCB can perform the operating duty because it can recharge the capacitor. However, since many SCRs are used for the charging and recharging loop of the capacitor and the breaking loop in this SSCB, its economic feasibility is low. In addition, a complex control is required because it has many SCRs.

To overcome such shortcomings, this paper proposes a new DC SSCB that has a low semiconductor conduction loss, and quick reclosing and rebreaking capabilities. As a result, it can perform the operating duties of reclosing and rebreaking [12].

The proposed DC SSCB is designed and implemented at a rated power of 5 [kW] and a voltage of 380 [V] that is suitable for home dc distribution. The operating characteristics are confirmed by simulation and experimental results.

II. Proposed DC Solid-State Circuit Breaker

A. Proposed DC SSCB

Fig. 5 shows the proposed DC SSCB circuit. In the normal mode of the SSCB, the energy is supplied to the load through S_1, and if a short-circuit fault occurs, the fault current is quickly broken by using the L_1-C resonance current i_{S3} through the resonant path of S_3-C-L_1-S_1. Since the number of the auxiliary switches is only two, one (S_2) for charging the commutation capacitor C and the other (S_3) for breaking the

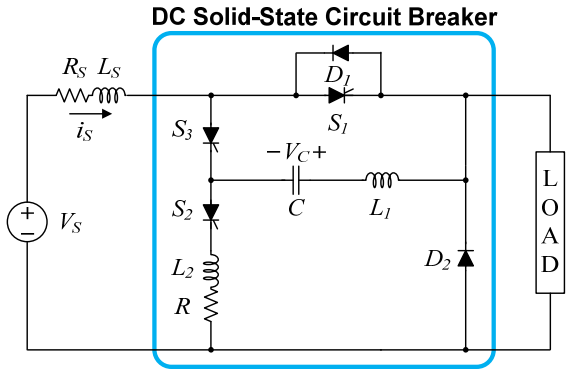

Fig. 5. Proposed DC Solid-State Circuit Breaker.

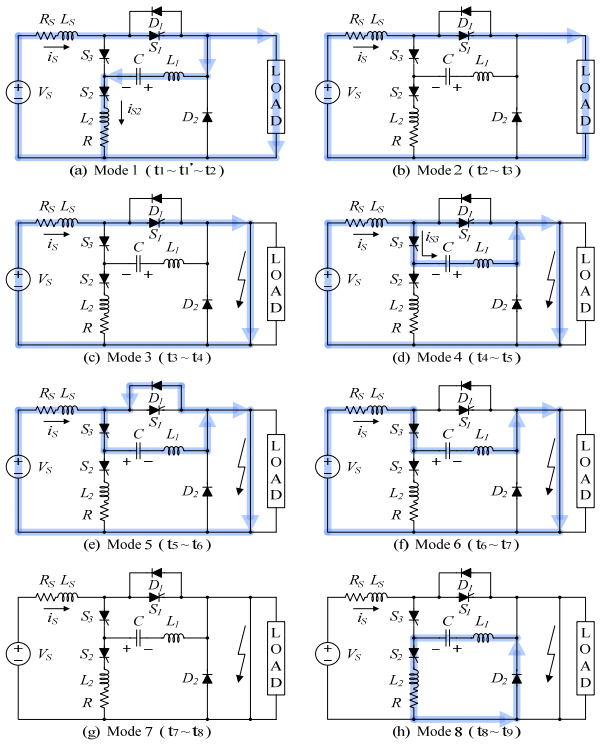

Fig. 6. Operating modes of the proposed DC SSCB.

fault current, the structure of the DC SSCB is simple and economical. Furthermore, the proposed DC SSCB can perform the reclosing and rebreaking operations according to the operation duty because the recharging operation of the commutation capacitor C is possible even when a short-circuit fault lasts on the load side.

Fig. 6 shows the circuit operation modes of the proposed DC SSCB, and Fig. 7 shows the operation waveforms corresponding to each mode. As shown in Fig. 7, the operation of the proposed DC SSCB may be divided into four operation modes. The four operation modes are the charging mode (t_1~t_2) to charge the commutation capacitor C, the normal mode (t_2~t_4) to supply electric power to the load, the breaking mode (t_4~t_8) to break the fault current, and the recharging mode (t_8~t_9) to recharge the commutation capacitor.

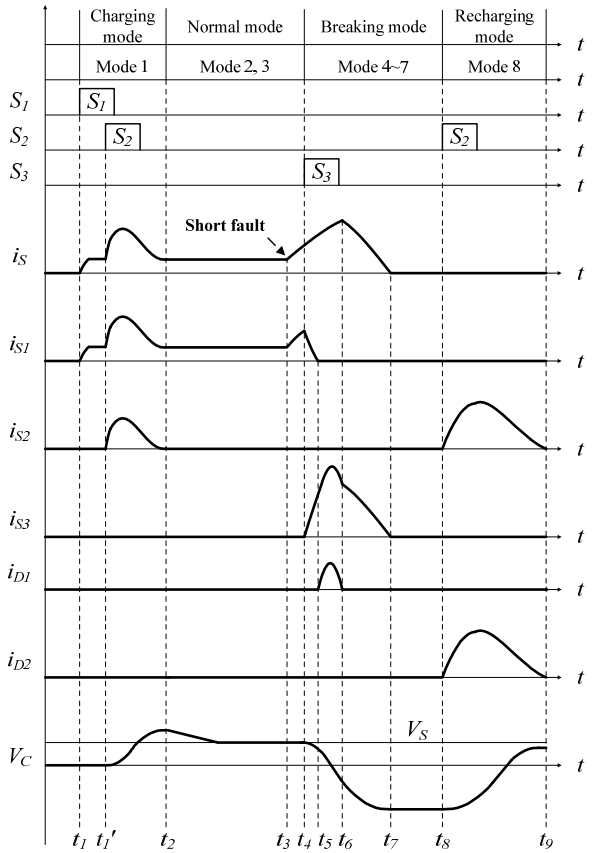

Fig. 7. Operating waveforms of the proposed DC SSCB.

TABLE I
THE COMPARISON BETWEEN PREVIOUS DC SSCBS AND PROPOSED DC SSCB

Necessary Functions and components	previous DC SSCB 1 (Fig 3)	previous DC SSCB 2 (Fig 4)	Proposed DC SSCB
SCR	3	6	3
Diode	1	1	2
Inductor L	2	2	2
Capacitor C	1	1	1
Operating Duty	X	O	O

At t_3 in Fig. 7, when a short-circuit fault occurs, the fault current i_{S3} rapidly increases. At t_4, when the fault current is three or four times higher than the full load current, the short-circuit fault is detected and the breaking mode begins. When the breaking mode is completed, the recharging mode to recharge the commutation capacitor begins in order to perform reclosing of the DC SSCB.

The operating characteristics at each mode are as follows.

B. Operation Modes

(a) Mode 1 (Charging mode: t_1 ~ t_1' ~ t_2)

Charging the capacitor C must be preceded because the proposed DC SSCB breaks the fault current by using the L_1-C resonance current. Thus, at mode 1, the capacitor is charged

to a certain voltage required for breaking the fault current by turning on the SCR S_1 and S_2.

At t_2, the charging of the commutation capacitor is already completed, the SCR S_2 is naturally turned off, and the normal mode of the DC SSCB begins.

At t_2, the voltage of the commutation capacitor is higher than the source voltage E [V]. However, the charged voltage decreases due to natural discharge because the leakage resistance of the AC capacitor used in the DC SSCB is small. Thus, the voltage of the capacitor V_C decreases to the source voltage E [V].

(b) Mode 2 (Normal mode: t_2~t_3)

Since mode 2 is the normal operating mode of the DC SSCB, electric energy is supplied to the load through SCR S_1. In addition, the DC SSCB monitors faults such as voltage sag/swell and short circuit current.

(c) Mode 3 (Normal mode: t_3~t_4)

Mode 3 is the section where the fault current increases after a short circuit fault occurs on the load side. Although the short circuit current increases from t_3, the SSCB operates in the normal mode because the magnitude of the fault current is still smaller than a preset reference value to determine the presence of a short circuit fault.

(d) Mode 4 (Breaking mode: t_4～t_5)

Mode 4 is the section where the SCR S_1 is turned off. At t_4, when the SCR S_3 is turned on, the L_1-C resonance current i_{S3} begins to flow. Thus, the L_1-C resonance current i_{S3} gradually increases. When the L_1-C resonance current i_{S3} becomes equal to the short circuit current i_S at t_5, S_1 is naturally turned off because the current i_{S1} becomes 0 [A].

(e) Mode 5 (Breaking mode: t_5~t_6)

At t_5, the L_1-C resonant current i_{S3} becomes larger than the short circuit current i_S. Thus, at t_5~t_6, the current i_{D1} flows as much as the difference between the L_1-C resonance current i_{S3} and the short circuit current i_S.

At t_6, the L_1-C resonant current i_{S3} is the same as the short circuit current i_S, and the diode D_1 is turned off.

(f) Mode 6 (Breaking mode: t_6～t_7)

At mode 6, since the SCR S_1 and the diode D_1 are turned off, the current i_{S3} is the same as the short circuit current i_S. Therefore, the L-C resonant current flows depending on the combined inductance of the inductors L_S and L_1.

When the L-C resonance current i_{S3} gradually decreases to zero, the SCR S_3 is naturally turned off at t_7 and the capacitor C is reversely charged to the maximum voltage value.

(g) Mode 7 (Breaking mode: t_7～t_8)

Mode 7 is the section where no current flows in the DC SSCB because all of the short-circuit current flowing through each device is interrupted.

(h) Mode 8 (Recharging mode: t_8～t_9)

Mode 8 is the section where the commutation capacitor is recharged before being discharged again in the next breaking mode. In the DC SSCB, the commutation capacitor should be recharged to a certain voltage required for the re-break before performing the next reclosing operation. If SCR S_2 is turned on, the capacitor is recharged through the path S_2-L_2-D_2-L_1-C as shown in Fig. 6-(h). Thus, the proposed SSCB can recharge the commutation capacitors even under a short circuit fault on the load side.

When the recharging of the capacitor is complete, the SSCB should again perform the reclosing operation by turning on SCR S_1 regardless of the state of the load side in order to carry out the operation duty of the reclosing and rebreaking operations. When turning on SCR S_1, if the short fault is already removed, the SSCB works in (b) mode 2 of Fig. 6. However, if the short-circuit fault still lasts, as shown in (c) mode 3 of Fig. 6, the SSCB rebreaks the fault current in Mode 4~7 and performs the recharging of the capacitor in Mode 8.

TABLE II
ELECTRICAL CHARACTERISTIC FOR DESIGN

Mode	Element	electrical characteristic
Charging mode	L_1	Inductance [uH], Peak current [A]
	C	Capacitance [uF], Max voltage [V]
	SCR S_1	Max voltage [V], Average current [A], t_q [us]
	SCR S_3	Peak current [A]
	Diode D_1	Max voltage [V], Peak current [A]
Breaking mode	L_2	Inductance [uH], Peak current [A]
	R	Resistance [Ω]
	SCR S_2	Max voltage [V], Peak current [A]
	SCR S_3	Max voltage [V],
	Diode D_2	Max voltage [V], Peak current [A]

III. DESIGN OF THE PROPOSED DC SSCB

In order to design the proposed DC SSCB, a characteristic derivation of the voltage and current in each mode is required. Each component of the proposed DC SSCB has the maximum current and voltage in the breaking mode and recharging mode. Therefore, the capacity of the device should be determined considering the breaking mode and recharging mode. The electrical characteristic of the circuit components are considered according to each mode as shown in Table II.

A. Characteristic Derivation in the Charging Mode

Fig. 8 shows an equivalent circuit of the charging mode, and Fig. 9 shows the waveforms of i_{S1} and i_{S2} in the charging mode. In section t_1', if the SCR S_2 is turned on, the underdamped current i_{S2} flows through the capacitor.

If the charging current i_{S2} is controlled as overdamped, quick break is impossible because the charging time becomes longer and too much time is spent until the SCR S_2 is turned off. Therefore, the condition of the underdamped circuit is expressed as Equation (1), and the charging current i_{S2} is derived as Equation (2).

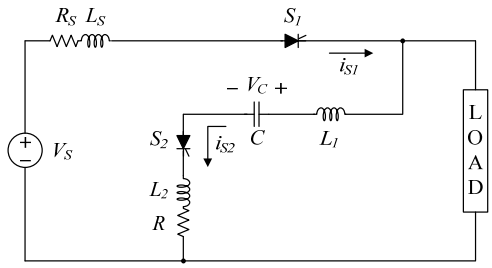

Fig. 8. Equivalent circuit of charging mode.

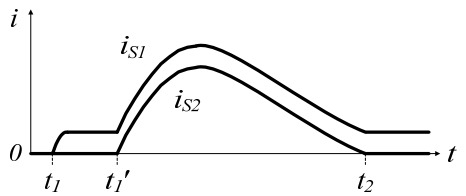

Fig. 9. i_{S1} and i_{S2} waveforms in charging mode.

$$R < 2\sqrt{\frac{L_{Th}}{C}} \qquad (L_{Th} = L_S + L_1 + L_2) \tag{1}$$

$$i_{S2}(t) = \frac{V_S}{L_{Th} \cdot \omega_d} e^{-\frac{R}{2L_{Th}}t} \cdot \sin(\omega_d \cdot t)$$

$$(\omega_d = \sqrt{\frac{1}{L_{Th}C} - \frac{R^2}{4L_{Th}^2}}) \tag{2}$$

The maximum current of the charging mode does not have to be considered because it is less than the short circuit fault current.

B. Characteristic Derivation in the Breaking Mode

Fig. 10 shows an equivalent circuit in the breaking mode (Mode 4~7: t_4~t_8) of the DC SSCB and Fig. 11 shows the current waveform of the devices in the breaking mode (t_4~t_8).

At t_3~t_6, the short-circuit current i_S is as follows:

$$i_S = i_{S1} = \frac{E}{L_S}(t - t_3) + i_{LOAD} \tag{3}$$

In Fig. 6-(d), the voltage equation is the same as Equation (4) because the SCR S_1 is turned on and the resistance of the loop is almost 0 [Ω]. The L_1-C resonant current i_{S3} is expressed as Equation (5).

Thus, the maximum current flowing through the proposed DC SSCB is equal to equation (6) when a short fault occurs.

$$V_{S1} = -(V_C + V_{L1}) = 0 \tag{4}$$

$$i_{S3} = \frac{E}{\sqrt{\frac{L_1}{C}}} \sin\left(\frac{t - t_4}{\sqrt{L_1 C}}\right) \qquad (t_4 \le t \le t_6) \tag{5}$$

$$i_{S3\_max} = \frac{E}{\sqrt{\frac{L_1}{C}}} \text{ [A]} \tag{6}$$

As Equation (6) implies, if the capacitance C becomes larger or the inductance of L_1 becomes smaller, the peak value of the L_1-C resonance current i_{S3} becomes larger. If the peak value of the L_1-C resonant current i_{S3} becomes excessively larger, it is not economical because a large capacity of the SCR and diode are required. Therefore, the inductance L_1 and the capacitance C should be properly selected considering the necessary ratings of SCR S_3 and the diode.

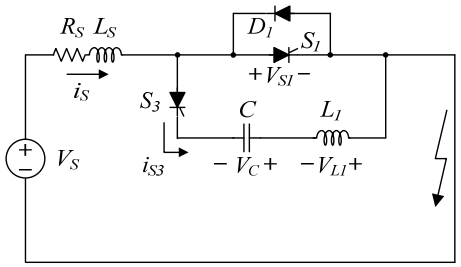

Fig. 10. Equivalent circuit of breaking mode (Mode 4～7:t_4~t_8).

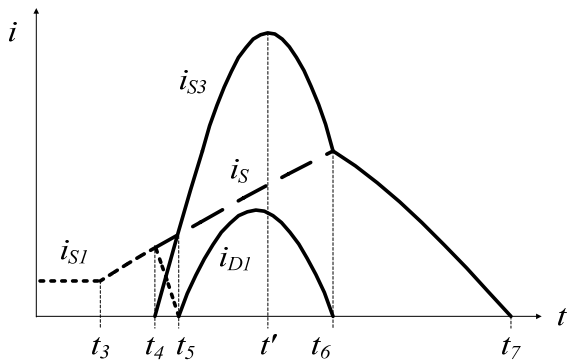

Fig. 11. i_{S1}, i_{S3}, i_S and i_{D1} waveforms of breaking mode. (Mode 4～7 : t_4~t_8).

If the inductance L_1 is larger than the line inductance L_S, the SSCB cannot break the fault current. In order to break the fault current, the current i_{S3} should be higher than the short circuit current at t_5~t_6 in Fig. 11. Thus, if the inductance L_1 is larger than the inductance L_S, the current is increases faster than i_{S3}. Thus, the current i_{S3} cannot be higher than the current i_S.

The line inductance L_S varies depending on the installation environment of the SSCB and the point where the short circuit occurs. The line inductance L_S can be measured when the shortest short circuit fault point is determined. Since the line inductance L_S measured in experimental setup of this paper is 64 [uH], the inductance L_1 should less than about 60 [uH]. The inductor L_1 in this paper is designed to be 25 [uH].

The capacitance C should be selected in order to secure the t_q (turn-off time) of the SCR S_1. Fig. 12 shows the circuit turn-off time t_q guaranteed by the circuit topology, and the device turn-off time t_q of the SCR S_1 provided by the datasheets.

In order for SCR S_1 to be turned off completely, the applied anode-to-cathode voltage V_{S1} should maintain a negative value for a longer duration than the device t_q. In

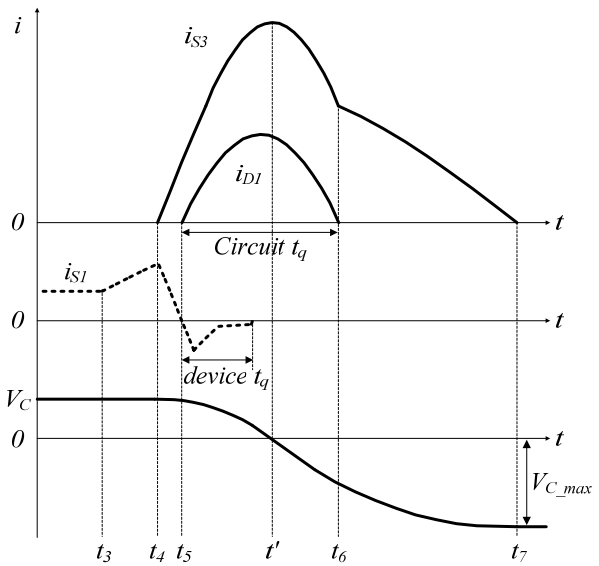

Fig. 12. Turn-off times of SCR S_1 and capacitor voltage V_C.

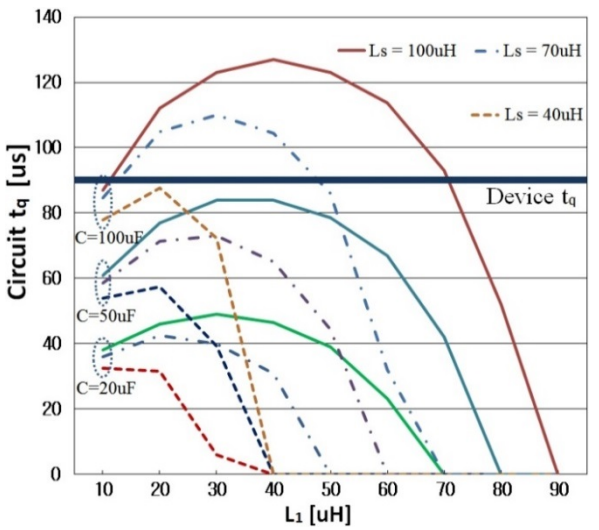

Fig. 13. Circuit turn-off time t_q with the variations of L_S, L_1 and C.

other words, the circuit turn-off time t_q should be longer than the device turn-off time t_q of the SCR S_1 as expressed in equation (7).

$$device\ t_q < circuit\ t_q \tag{7}$$

Since the SCR S_1 and the diode D_1 are connected in parallel, as shown in Fig. 10, the reverse voltage of the SCR S_1 is equal to the on-drop voltage of the diode. Therefore, if the conduction time of the diode corresponding to the circuit t_q satisfies equation (7), the SCR S_1 can be turned off completely.

Fig. 13 shows the circuit turn-off time t_q for the main SCR S_1 when the line inductance L_S, the inductor L_1, and the capacitor C vary. When the commutation capacitor C becomes larger, the circuit turn-off time t_q becomes longer. Therefore, if a sufficiently large capacitance is chosen, the SCR S_1 can be turned off stably. However, since too large a capacitor may be expensive, the capacitance C should be selected properly large, while ensuring that the circuit t_q is longer than the device t_q.

The device t_q shown in the data sheet of the SCR S_1 is about 50[us] under a test condition voltage of 50[V]. In the proposed DC SSCB, since the reverse voltage of the SCR S_1 is kept as low as the on-drop voltage, about 1.2[V], of the diode D1, the actual device t_q increases to approximately 1.8 times longer than the datasheet device t_q. Thus, considering the actual device t_q of 90(=50[us]x1.8) [us], shown in Fig. 13, the capacitance C should be selected, as shown in Fig. 13, so that the circuit t_q may be longer than the actual device t_q of 90 [us]. In this paper, when selecting a capacitance of 100 [uF], the device t_q of 110 [us] is secured.

The rated voltage of the commutation capacitor C should be determined by section t'~t_7 in Fig. 12. The capacitor C begins charging in the reverse direction, and has a maximum charging voltage V_{C_max} at t_7. Therefore, the maximum voltage V_{C_max} of the commutation capacitor C can be obtained by equation (8)~(11).

$$V_C(t_6) = E \cdot \cos\left(\frac{t_6 - t'}{\sqrt{L_1 C}}\right) \tag{8}$$

$$i_{S3}(t_6) = i_S(t_6) = \frac{E}{L_S}(t_6 - t_3) + i_{LOAD} \tag{9}$$

$$i_{S3}(t) = i_{S3}(t_6) \cdot \cos\left(\frac{t - t_6}{\sqrt{L_S + L_1}}\right) + \frac{E - V_C(t_6)}{\sqrt{\frac{L_S + L_1}{C}}} \cdot \sin\left(\frac{t - t_6}{\sqrt{(L_S + L_1)C}}\right) \quad (t_6 \le t \le t_7) \tag{10}$$

$$V_{C\_max} = -\frac{1}{C}\int_{t_6}^{t_7} i_{S3}(t) \cdot dt + V_C(t_6) \tag{11}$$

Fig. 14 shows the maximum voltage V_{C_max} of the capacitor C when the inductance L_1 and the capacitance C vary.

Fig. 15 shows the voltages of a devices that performs the breaking operation at $t \rightarrow t_7^-$ of Fig. 12. As shown in Fig 15, since the SCR S_3 is turned on until just before t_7, the maximum positive voltage of the SCR S_1 satisfies equation (12).

$$V_{C\_max}(t_7^-) = V_{S1\_max}(t_7^-) = V_{D1\_max}(t_7^-) \tag{12}$$

In addition, the reverse voltage of the SCR S_1 is always the same as the on-drop voltage of the diode D_1. Therefore, the rated voltage of the SCR S_1 should be determined considering its forward voltage, that is, the maximum voltage of the commutation capacitor.

The current flowing through the SCR S_1 has a maximum value at t_4 in Fig. 12, and it is three or four times higher than the average current (full-load current). Since the peak non-repetitive surge current of the SCR is approximately ten times higher than the mean on-state current, the SCR S_1 can be selected considering only its average current.

Fig. 16 shows the maximum current of the diode D_1 when L_1 and C vary. Since the maximum voltage of the diode D_1 is

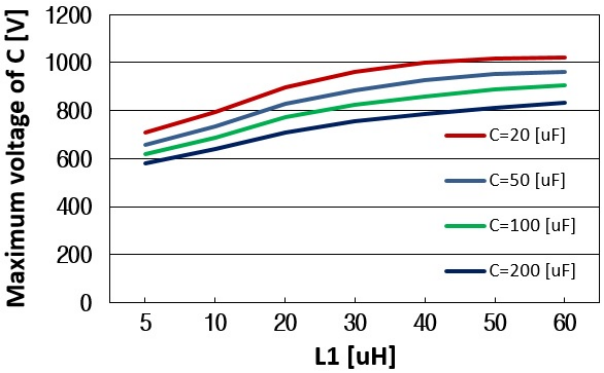

Fig. 14. Maximum voltage V_{C_max} of capacitor when L_1 and C vary.

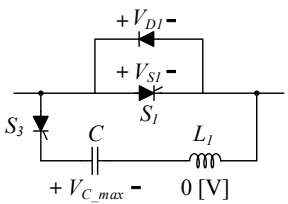

Fig. 15. Voltage of devices at t_7^- in breaking mode.

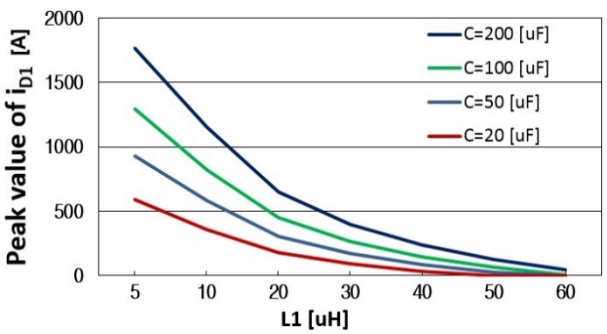

Fig. 16. Maximum current of diode D_1 when L_1 and C vary.

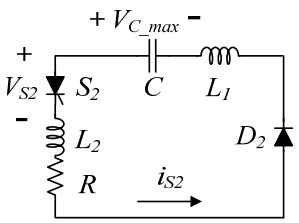

Fig. 17. Equivalent circuit of recharging mode.

the same as the voltage V_{C_max} of the capacitor C, the rated voltage of the diode D_1 should be designed only considering the maximum voltage of the commutation capacitor C.

C. Characteristic Derivation in the Recharging Mode

Fig. 17 shows an equivalent circuit of the recharging mode. Since the SCR S_2 and the diode D_1 are turned on at t_8~t_9, the voltage equation of the recharging mode is equal to equation (13).

The most important role of the recharging mode is to recharge the commutation capacitor to a certain voltage. It should be enough to re-break the SSCB. Therefore, the

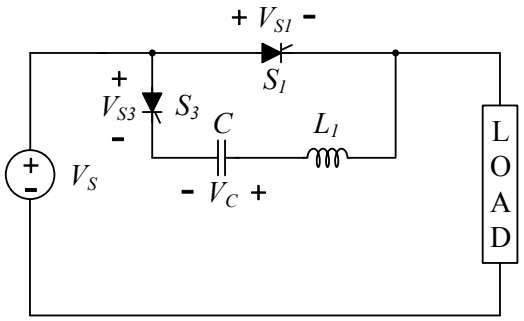

Fig. 18. Equivalent circuit of SSCB at t_9 in Fig 7.

recharging current i_{S2} should be under damped. The condition where the recharging current i_{S2} becomes an underdamped current is equal to equation (14). The resistance R and inductor L_2 can be selected by equation (14).

In the recharging mode, the recharging current equation is expressed as Equation (15), and the recharging voltage equation of the commutation capacitor C is expressed as Equation (16).

$$V_{C\_\max} = (L_1 + L_2)\frac{di_{S2}}{dt} + R \cdot i_{S2} + \frac{1}{C}\int_{t_8}^{t_9} i_{S2} \tag{13}$$

$$R < 2\sqrt{\frac{L_1 + L_2}{C}} \tag{14}$$

$$i_{S2}(t) = \frac{V_{C\max}}{L \cdot \omega_d} e^{-\frac{R}{2L}t} \cdot \sin(\omega_d \cdot t)$$

$$(L = L_1 + L_2,\ \omega_d = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}) \tag{15}$$

$$V_C(t_9) = \int_{t_8}^{t_9} i_{S2}(t) \cdot dt - V_{C\max} \tag{16}$$

Since the capacitor is charged to E [V] in the charging mode, the recharged voltage of the capacitor should be E [V] or secure t_q of the SCR S_1. Therefore, the resistance R and the inductance L_2 should be selected according to equations (14)~(16) so that the recharging voltage of the commutation capacitor $V_C(9)$ is E [V].

All of the currents flowing through the resistance R, inductance L_2, SCR S_2, and diode D_2 are the same. Therefore, if the resistance R and the inductance L_2 are determined, the peak current of the SCR S_2 and the diode D_2 can be obtained by equation (15).

The SCR S_2 is turned off at t→$t8^-$ in Fig. 17. Therefore, the voltage of the SCR S_2 is the same as the maximum voltage V_{C_max} of the commutation capacitor C.

Fig. 18 shows the equivalent circuit of the SSCB at t_9 of Fig. 7. At t_9, the recharging mode is completed. Since the SCR S_1 is in the off-state, the voltage V_{S1} of the SCR S_1 is equal to V_S. In addition, the recharged voltage V_C of the capacitor is V_S. Therefore, the maximum voltage V_{S3} of the SCR S_3 is $2V_S$.

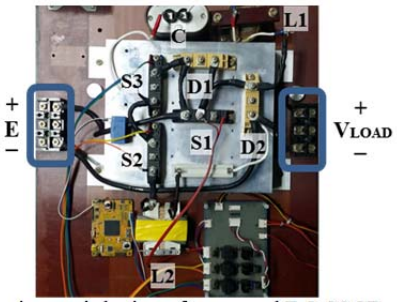

Fig. 19. Experimental device of proposed DC SSCB.

TABLE III
SYSTEM PARAMETERS

Parameters	Specification
Power rating	5 [kW], 380 [Vdc]
Full load current	13.1 [A]
Line impedance R_S, L_S	50 [mΩ], 64 [uH]
Range of trip setting	13.1 [A] → 50 [A]
Short fault switch resistance	100 [mΩ]
L_1	23 [uH], i_{peak}= 1000 [A]
L_2	400 [uH], i_{peak}=500 [A]
C	100 [μF], 1200 [VAC]
R	1 [Ω], 40 [W]
SCR - SKKT 56/16E (semikron, module type)	1600[V], i_{av}=60[A], i_{peak}=1500[A]
Diode - SKKD 81/16E (semikron, module type)	1600[V], i_{av}=80[A], i_{peak}=2000[A]

IV. SIMULATION AND EXPERIMENTAL RESULTS

Fig. 19 shows an experimental prototype of the proposed DC SSCB. The design specifications and system parameters of the proposed DC SSCB are shown in Table 3. The simulation results are obtained through PowerSim (PSIM version 9.1) simulation software.

A. Charging Mode

Fig. 20 shows simulation waveforms of the commutation capacitor voltage and current when the SCR S_1 and S_2 is turned on in the charging mode. Fig. 21 shows the measured waveform of Fig. 20.

B. Breaking Mode

Fig. 22 shows simulation waveforms of i_S, i_{S3}, i_{S1} and i_{D1} in the breaking mode, and Fig. 23 shows measured waveforms of Fig. 22. It can be seen that the SCR S_1 is turned off by the L_1-C resonant current i_{S3}, and that the fault current i_S is broken rapidly within 300 [usec].

C. Recharging Mode

In the recharging mode of the proposed DC SSCB, it should be possible to recharge the capacitor even under a short circuit fault on the load side. Fig. 24 shows simulation waveforms of the capacitor voltage V_C and the current i_C in the recharging mode, and Fig. 25 shows measured waveforms

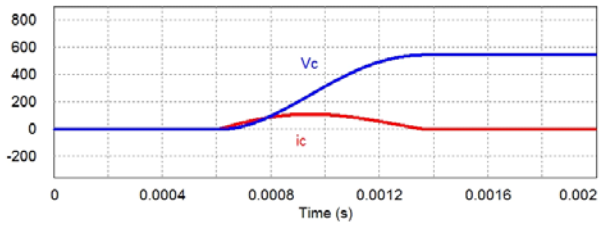

Fig. 20. Simulation waveforms V_C and i_C of charging mode.

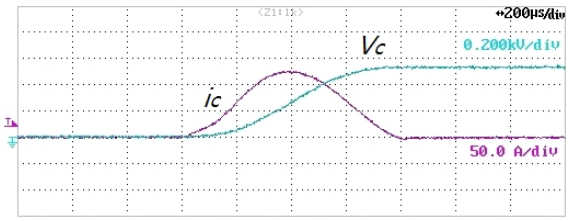

Fig. 21. Measured waveforms V_C and i_C of charging mode.

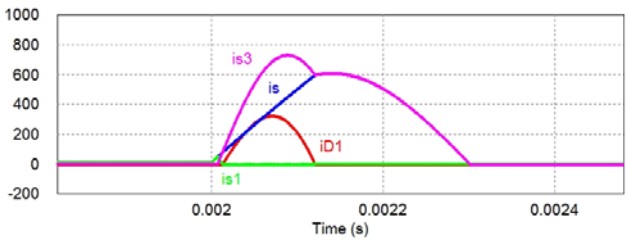

Fig. 22. Simulation waveforms i_S, i_{S1}, i_{S3} and i_{D1} of breaking mode.

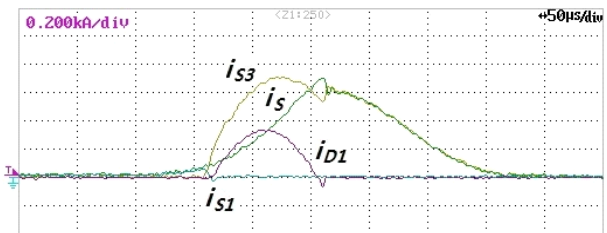

Fig. 23. Measured waveforms i_S, i_{S1}, i_{S3} and i_{D1} of breaking mode.

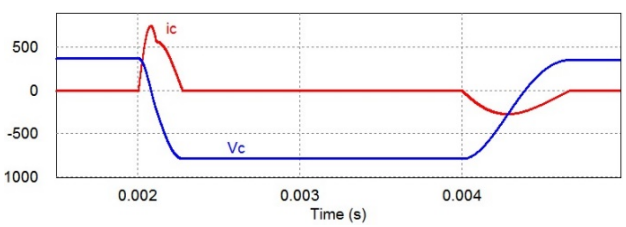

Fig. 24. Simulation waveforms V_C and i_C of recharging mode.

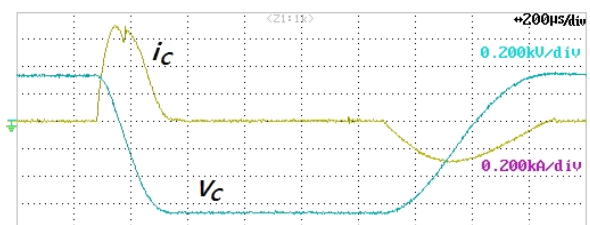

Fig. 25. Measured waveforms V_C and i_C of recharging mode.

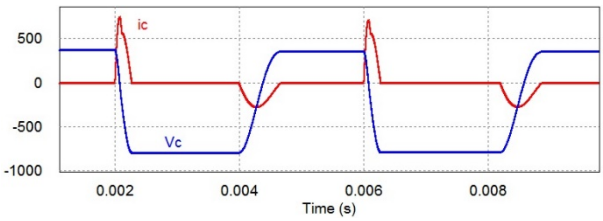

Fig. 26. Simulation waveforms V_C and i_C.

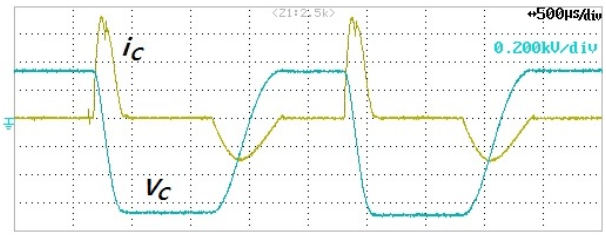

Fig. 27. Measured waveforms V_C and i_C.

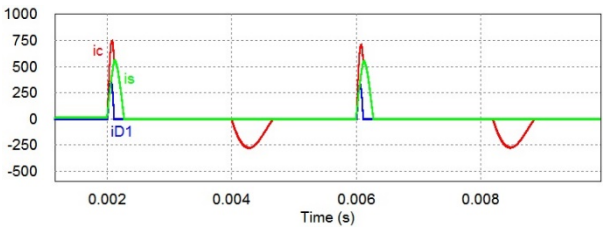

Fig. 28. Simulation waveforms i_S, i_C and i_{D1}.

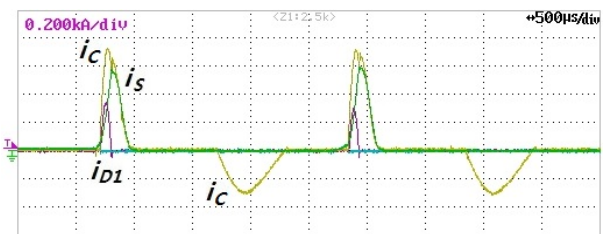

Fig. 29. Measured i_S, i_C and i_{D1} waveforms.

of Fig. 24. It can be seen that the capacitor C is properly recharged by turning on the SCR S_2. Therefore, Fig. 24 and 25 confirm that the proposed DC SSCB can recharge the commutation capacitor even when a short-circuit fault lasts on the load side. Thus, it is able to reclose and rebreak repeatedly in the short-circuit fault on the load side.

Fig. 26 shows the capacitor voltage V_C and the capacitor current i_C when performing the operation duty of reclosing and rebreaking, and Fig. 27 shows measured waveforms. In the case of a short circuit fault that lasts it can be verified that the rebreaking operation is properly performed through the detection of the short-circuit fault as soon as the DC SSCB is reclosed.

Fig. 28 shows simulation waveforms of the current i_S, i_{D1} and i_C in the recharging and rebreaking modes, and Fig. 29 shows the measured waveforms of Fig. 28.

It can be seen that the DC SSCB sequentially performs breaking, recharging, reclosing, rebreaking, and recharging operations very well even when a short circuit fault lasts.

As shown in Fig. 8, 10 and 17, the stray inductance is connected to the inductor L_1 or L_2 in series, and it has a much lower value than the inductance L_1 or L_2. Therefore, they do not affect the charging, breaking and recharging operations of the SSCB. As shown in Fig. 23, the effect of the stray capacitance occurs for a short time 10 [usec] from the time when the diode D_1 is turned off. However, since the resonance current caused by the stray capacitance of the diode D_1 has a very low value and the SCR S_1 is already in the turn-off state, it has little effect on the breaking operation of the SSCB. Therefore, there is no need to consider parasitic components such as stray inductance and stray capacitance.

V. CONCLUSIONS

Since sensitive loads and DC distribution are used widespread, the DC SSCBs are essential to maintain the high power quality of the DC grid. Therefore, this paper proposes a new DC SSCB that has low conduction loss due to its main thyristor, simple structure, and good characteristic of rapid breaking within 300[usec] of short circuit faults. Furthermore, the manufacturing cost of the proposed DC SSCB can be reduced thanks to lower rated devices and a reduced number of auxiliary SCRs. It can also perform the operating duty of reclosing and rebreaking since the recharging operation of the capacitor is possible regardless of the fault state on the load side.

The operating characteristics of the proposed DC SSCB are verified by simulations and experiments under short circuit faults. In addition, this paper suggests design guidelines so that it can be applied to other DC grids. It is anticipated that the proposed DC SSCB may be utilized to design and realize many DC grid systems.

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