Modified Bi-directional Z-Source Breaker with Reclosing and Rebreaking Capabilities

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***Abstract*—A modified topology of a bi-directional z-source circuit breaker with coupled inductor (Bi-CZSB) with reclosing and re-breaking capabilities is introduced in this paper. The proposed breaker can operate with a single coupled inductor for bi-directional power flow. Therefore, the size of the inductor is optimized to 50%, thus the total cost of the breaker is minimized. A brief overview of reclosing and re-breaking requirement is discussed in this paper. The breaker is intended to perform operating duty of reclosing and re-breaking based on the field conditions. Most of the times, faults in the overhead system are due to the temporary transient conditions. Such faults get cleared after the breaker opens and disconnects the circuit. Very few faults lead to permanent damage to the system where they are required to be isolated. Operation of previously proposed Bi-CZSB is discussed under reclosing and re-breaking conditions. Necessary modifications are introduced to perform the reclosing and re-breaking operation in modified Bi-CZSB. Simulation results are presented verifying the desired performance.**

I. INTRODUCTION

Microgrid with DC transmission or distribution has gained more attention due to the reduction in power conversion stages and losses, ease of operation and control, high efficiency and stability. However, DC transmission or distribution brings a lot of challenges in designing a protection for the reliability of power supply. DC distribution is not an established technology as AC because of unavailability of the standards and operating duties in various applications. Furthermore, breaking the DC current is more challenging due to the absence of natural current zero. In a microgrid, power flow is intended to have in both directions. For low voltage DC microgrid system a major challenge is in designing a device which is able to provide the protection in both the directions of power flow. Circuit breakers should be able to function as intended when power flow direction changes. Previously proposed bi-directional z-source breaker (Bi-ZSB) and bi-directional z-source breaker with coupled inductor (Bi-CZSB) utilize an SCR as the main switch which naturally commutates and isolates the fault from the source within a few microseconds [1]. Several other bidirectional topologies are discussed in [2-3]. In this paper, a bi-directional z-source breaker with a coupled inductor(Bi-CZSB) is optimized. It uses the same inductor in forward and reverse power flow.

In the overhead transmission lines, most of the faults are transient in nature and exist for the very small duration of time. These faults occur through ionized current paths created due to lightning, momentary tree or bird contact, or conductor galloping. They do not damage the system if protection device operates and isolates the fault from the system. These faults are cleared once the system is disconnected. In the electromechanical breaker, after the arc path becomes de-ionized, the system can be restored to normal operation by turning on the breaker. In case of solid-state breaker, after a small delay, a breaker should be switched ON to restore the normal operation. This delay must be sufficient enough to ensure that the breaker operating mechanism or configuration stores the necessary energy for a subsequent tripping. If the fault persists even after first reclosing operation then double or triple reclosing attempts are made before isolating the line for maintenance [4,7]. The proposed breaker is also made capable to function under the operating duty of re-breaking and reclosing required in the field.

In this paper, previously proposed Bi-CZSB [1] is optimized by using single coupled inductor for both directions of power flow. Performance of the breaker is verified under various fault conditions and simulation results are presented. For reclosing the breaker, capacitor pre-charging is needed which is addressed by means of a recharging circuit. A simulation study is carried out to verify the breaker reclosing on temporary fault and permanent fault. The paper is organized as follows: Section II discusses the review of solid state breakers with bidirectional power flow capabilities and, under reclosing and re-breaking operating duty as discussed in the literature. Section III shows modified Bi-CZSB, its operation and simulation results. Section IV describes the detailed analysis and design criteria of z-source components. Proposed modifications for recharging the capacitor are discussed in section IV with its working operation and simulation results.

II. GENERAL OVERVIEW OF SOLID STATE CIRCUIT BREAKER

A. *Bidirectional Z-Source Breaker*

Two topologies of bi-directional z-source breaker as shown in Fig. 1 and Fig. 2 were proposed in [1]. These are the

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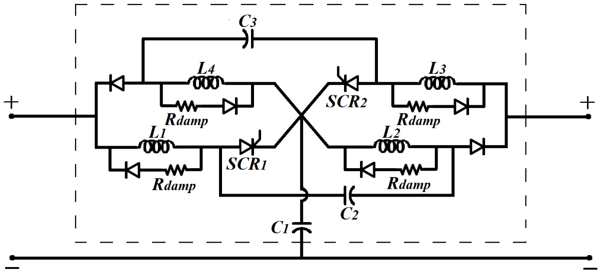


Fig. 1: Bi-directional z-source breaker(Bi-ZSB).

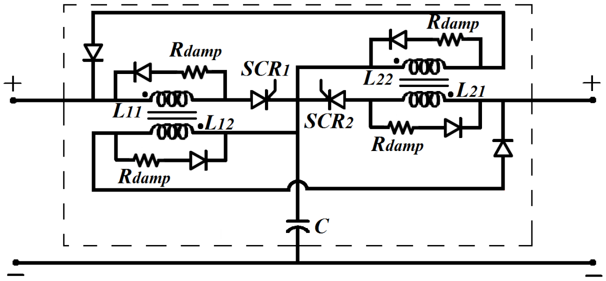


Fig. 2: Bi-directional z-source breaker with coupled inductor(Bi-CZSB).

type of purely solid state breakers. They use L-C network to naturally commutate the SCR under fault conditions. Bi-directional circuit breaker (Bi-ZSB) shown in Fig. 1 uses L_1, SCR_1, L_2, C_1 and C_2 for the forward power flow and L_3, SCR_2, L_4, C_1 and C_3 for the reverse power flow. When the fault occurs on the load side of the breaker, capacitor C_1 discharges through SCR_1 and C_2, and instantly starts feeding the fault. However, the current through the inductor remains nearly constant as it opposes the sudden change in the current. When the discharging current through C_1 becomes equal to the load current, SCR commutates naturally. Once the capacitor C_2 is fully charged, the fault gets isolated from the source.

The operating principle of the bi-directional z-source breaker with coupled inductor shown in Fig. 2, remains in-line with Bi-ZSB. Here, instead of two separate inductors, one coupled inductor is used as a current flowing through both the inductors remain identical in all the modes of operation. During the fault, C discharges through L_{12}. The current through L_{12} increases rapidly which induces the voltage across L_{11} according to Lenz's low. As a result, a reverse current flows in L_{11} opposing the main SCR current. Hence, the current through SCR becomes zero and it gets turned-off.

The fault current limiter and interrupter (FCLI) proposed in [2] is another bidirectional circuit breaker working on a basic z-source concept. It is able to limit and break the current in both the directions. The z-source components are configured as shown in Fig. 3. For the SCR commutation, several auxiliary capacitors are used. As per z-source breaker operating principle, the current through the inductors can not change instantly under fault, and the current is diverted to SCR and z-source capacitors. Therefore, the SCR turns-off naturally.

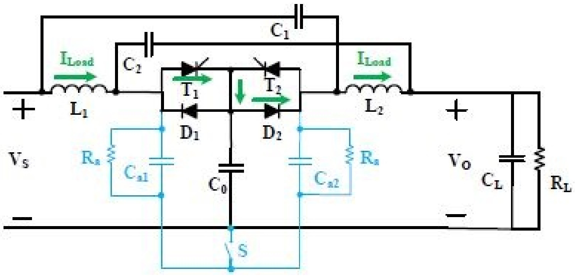


Fig. 3: Fault current limiter and interrupter (FCLI).

B. Solid State Breakers under Reclosing and Re-breaking Operation

DC Solid State Circuit Breaker (SSCB) discussed in [5] is as shown in Fig. 3. The main SCR T_{11} is turned on to supply power to load. When the fault occurs, T_{25} and T_{22} are turned on to break the fault current by creating a resonance current through $T_{25} - C_1 - L_1 - T_{22}$ loop. Switches T_{11}, T_{25} and T_{22} are naturally commutated due to the resonance. After the commutation of T_{11}, T_{25} and T_{22}, T_{21} and T_{24} are turned-on to charge the capacitor C_1 before the next turn off operation.

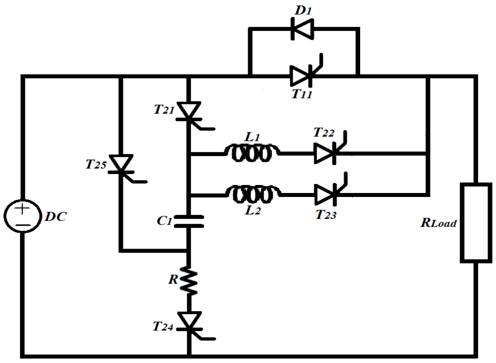


Fig. 4: Structure of DC solid state circuit breaker (SSCB)[5].

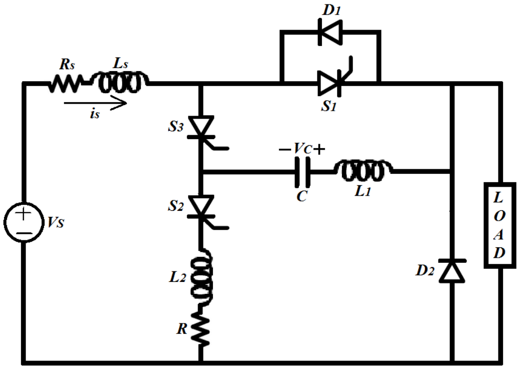


Fig. 5: DC solid state circuit breaker (SSCB) [6].

Another topology of DC solid state circuit breaker is shown in Fig. 4 as discussed in [6]. Switch S_1 is turned on to supply the load and simultaneously, S_2 is turned-on to charge the capacitor C. Once the capacitor is charged, S_2 is turned-off.

When the fault occurs, S_3 is turned-on to create the resonance. Resonance current increases and becomes equal to the fault current, thus S_1 gets commutated. When the resonance current reduces to zero, S_3 naturally commutates. Then S_2 is turned on where the commutation capacitor is recharged through the $S_2 - L_2 - D_2 - L_1 - C$ loop. Thus, this SSCB can recharge the commutation capacitors even under a short circuit fault on the load side [6]. Once the capacitor is recharged, the breaker should be turned on again by turning on S_1. Both these topologies can perform the operating duty of reclosing and re-breaking because it can recharge the capacitor. However, due to the higher number of SCRs, overall cost and control complexities are high.

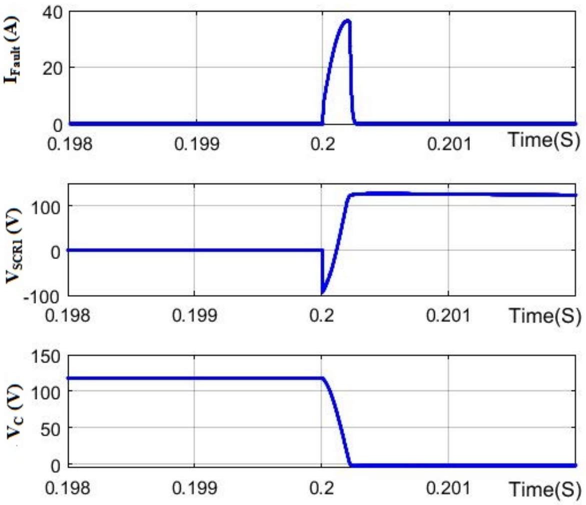


Fig. 6: Simulation results of Bi-CZSB.

As mentioned in [1] during the fault, capacitor C gets discharged and creates natural commutation condition across SCR_1 to isolate the fault from the source for both Bi-ZSB and Bi-CZSB. Simulation results of Bi-CZSB are shown in Fig. 6 for the reference. As can be seen from the graph, the capacitor is completely discharged at the end of the first cycle. If an attempt is made to reclose the breaker on a permanent fault, a breaker should isolate the fault again. So, the capacitor C should be pre-charged to handle the fault while reclosing. Proposed Bi-ZSB and Bi-CZSB in [7] are suitable for re-closing and re-breaking operation. The capacitor re-charing is achieved by the delayed switching of SCRs.

III. MODIFIED BI-DIRECTIONAL COUPLED Z-SOURCE BREAKER

The proposed modified DC circuit breaker topology of a bi-directional z-source breaker with a coupled inductor (Bi-CZSB) is shown in Fig. 7. Here a single coupled inductor is used to achieve bi-direction performance instead of two coupled inductors in [1]. The operating principle is in line with Bi-CZSB.

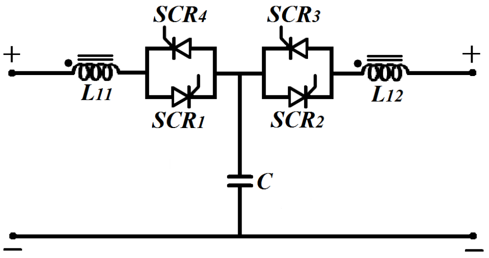


Fig. 7: Proposed modified bi-directional ZSB with coupled inductor (Bi-CZSB)

In the modified Bi-CZSB, a conduction path is shown in Fig. 8(a). Current flows from source to load via coupled inductors L_{11} and L_{12}, and thyristors SCR_1 and SCR_2. Both the switches SCR_1 and SCR_2 are turned-on by giving gate signal for a short period. Once the conduction starts, capacitor C is charged to source voltage. When the short-circuit fault occurs, capacitor C starts discharging through inductor L_{12} and SCR_2 as highlighted in Fig. 8(b). As inductors L_{11} and L_{12} are wound on the same core, a sudden rise in L_{12} current induces a negative voltage across L_{11}. This, in turn, causes a reverse current to flow in inductor L_{11}; thus the resultant current through L_{11} and SCR_1 goes to zero. As the gate pulse of SCR_1 is removed, it naturally commutates and isolates the source from the fault as shown in Fig. 8(c).

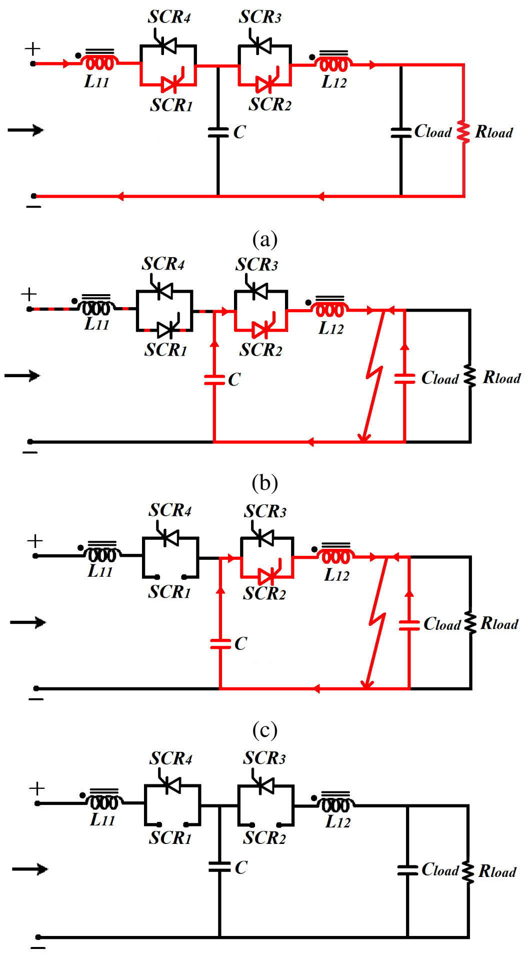
Capacitor C and inductor L_{12} form a parallel $L_{12}-C$ circuit and continue feeding the fault as shown in Fig. 8(c). Parallel inductor and capacitor loop results in voltage oscillations across the capacitor C. While the capacitor voltage becomes negative, the voltage across SCR_2 becomes negative. As the gate pulse of SCR_2 is removed, it naturally turned-off. By end of this stage, capacitor C is charged to a negative voltage.

TABLE I: Simulation Parameters

	Bi-CZSB
Source Voltage (Vs)	120 V
Z-Source Inductor (L_{11}, L_{12})	410 μH
Z-Source Capacitor (C)	50 μF
Load Resistance	40 Ω
Damping Resistance	0.3Ω

A simulation study is carried out with the parameters listed in Table-I. Simulation results are shown in Fig. 9 to verify the breaker operation in the fault condition. When a fault occurs, a negative voltage appears across SCR_1 and current through it becomes zero, thus SCR turned OFF naturally as can be seen from Fig. 9(a) and Fig. 9(b). It immediately disconnects the source from the fault as can be understood from SCR current. Therefore, the fault current is not reflected back to the source. By the end of the fault isolation process, capacitor C is charged to negative voltage as seen from Fig. 9(a). Current though both inductors L_{11} and L_{12} are shown in Fig. 9(c). The capacitor current and fault current are as shown in Fig. 9(d) and Fig. 9(e).

During the reverse power flow, same inductors L_{11} and L_{12} are used along with the switches SCR_3 and SCR_4. Similarly, breaker performance can be explained for the reverse power flow as well. In the proposed modified topology, features of Bi-CZSB are achieved with reduced number of components.



(a)

(b)

(c)

(d)

Fig. 8: Different modes of operations of modified Bi-CZSB (a) normal conduction mode, (b) fault instant, (c) post SCR_1 commutation and (d) post SCR_2 commutation.

IV. ANALYSIS AND DESIGN

In this section, the operation and parameter design of the proposed topology are explained in detail. The breaker is turned-on by applying the small duration gate pulses to SCR_1 and SCR_2 simultaneously. Under normal steady-state condition, breaker establishes the load current I_{load} with voltage drop across inductors (L_{11} and L_{12}) and SCRs (SCR_1 and SCR_2 or SCR_3 and SCR_4). So, during normal operation load current can be written as;

$$I_{load} = \frac{V_s - V_{SCR_1} - V_{SCR_2}}{R_{L_{11}} + R_{L_{12}} + R_{load}} \tag{1}$$

For the breaker design, the major considerations should be the ramp rate of fault current and the detectable current magnitude which determines the commutation of the SCR. As the fault occurs, the current rises abruptly. The current through inductors can not change instantly, a major part of the fault current is supplied by the z-source capacitor and load capacitor. The minimum fault current required by the capacitors to naturally commutate the SCR, is a function of amplitude and ramp rate of the fault current. So, L and C components of the z-source network should be designed in such a way that it can turn-off the SCR in different fault conditions.

A. Minimum Detectable Fault Magnitude

As discussed, the fault current is predominantly supplied by the z-source capacitor and the load capacitor. The amount of z-source capacitor current (i_C) supplied during the fault can be calculated as,

$$i_C = \frac{C}{C + C_{load}} \times i_{fault} \tag{2}$$

and, the current supplied through load capacitor C_{load} can be expressed as

$$i_{C_{load}} = \frac{C_{load}}{C + C_{load}} \times i_{fault} \tag{3}$$

The SCR commutates when the current through L_{11} because of the current flowing through L_{12} becomes equal to the load current I_{load}. Considering ideal coupled inductor, the current induced in L_{11} can be considered same as i_C but it will be in the reverse direction. When fault occurs, initially i_{fault} will be,

$$i_{fault} = G_{fault} \times V_s \tag{4}$$

And, the fault conductance is given by,

$$G_{fault} = \frac{C + C_{load}}{C} \times \frac{1}{R_{load}} \tag{5}$$

Where, I_{load} is the load current, G_{fault} is the fault conductance which must be higher than load conductance, and R_{load} is the load resistance.

B. Minimum Detectable Fault Ramp Rate

A fault conductance is assumed to increase linearly with slope K from zero to G. Thus, the ramp rate can be expressed as

$$K = \frac{G_{fault}}{\Delta t} \tag{6}$$

And, the fault current in terms of K can be expressed as

$$i_{fault} = V_{out} \times K \times t \tag{7}$$

Substituting i_{fault} in equation (3)

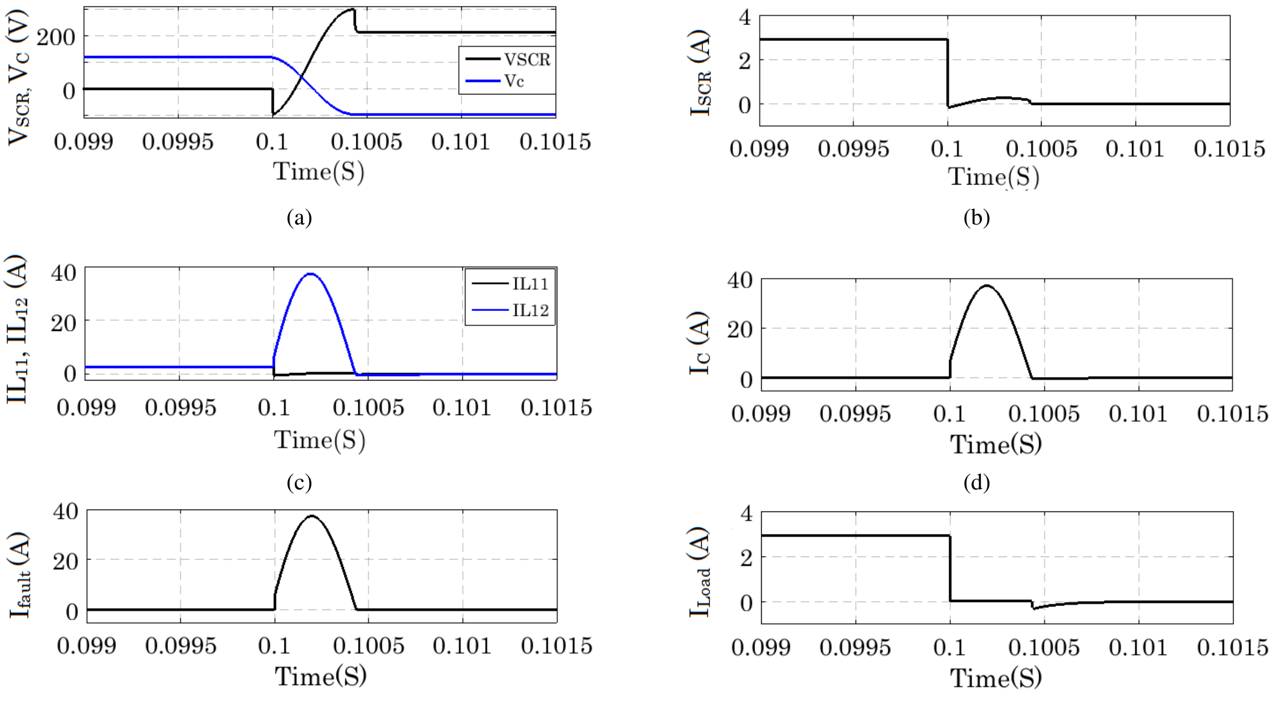
$$i_{C_{load}} = \frac{C_{load}}{C + C_{load}} \times V_{out} \times K \times t \tag{8}$$

Solving the above equation (8)

$$V_{out} = V_s \times \exp\left(-\frac{K.t^2}{2(C + C_{load})}\right) \tag{9}$$

Hence, the fault current and the z-source capacitor current can be re-written as;

$$i_{fault} = V_s \times K \times t \times \exp\left(-\frac{K.t^2}{2(C + C_{load})}\right) \tag{10}$$



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 9: Simulation results of modified Bi-CZSB

$$i_C = V_s \times K \times t \times (\frac{C}{C + C_{load}}) \times \exp{(-\frac{K.t^2}{2(C + C_{load})})} \quad (11)$$

By solving the above equation, the time at which capacitor current becomes maximum can be derived as

$$t_{max} = \sqrt{(\frac{C + C_{load}}{K})} \quad (12)$$

After substituting t_{max} from (12) in (11), maximum capacitor current i_{Cmax} can be obtained as

$$i_{Cmax} = \sqrt{(\frac{K}{e.(C + C_{load})})} \times V_S \times C \quad (13)$$

In order to have a perfect commutation, the reflected current in L_{11} due to the current flowing through L_{12} should be equal or more than the load current I_{load}. Considering both inductors identical, the same current as i_C would flow in L_{11}. Therefore, the minimum detectable fault ramp rate can be written as,

$$K_{min} = e \times \frac{1}{R_{load}.C} \times \frac{C + C_{load}}{C} \times \frac{1}{R_{load}} \quad (14)$$

While sizing the z-source parameters, appropriate ratio C_{load} / C can be chosen based on minimum detectable fault current requirement. By maintaining the ratio C_{load}/C, size of the capacitor can be changed in order to set the minimum detectable ramp rate. While selecting SCR, one should also take into account the reverse recovery time and short time withstand current ratings.

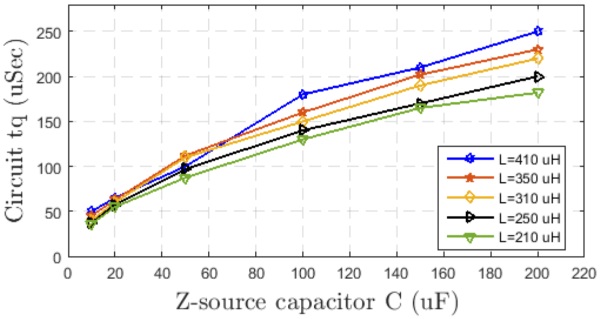


Fig. 10: Circuit tq vs z-source capacitor.

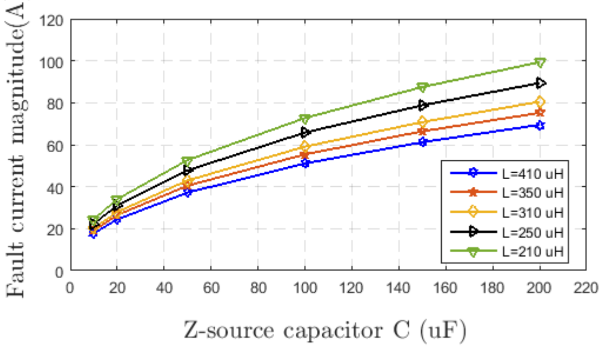


Fig. 11: Fault current magnitude vs z-source capacitor.

Fig. 10 shows the variation in circuit tq (time for which commutation condition occurs across SCR naturally) with different values of z-source components C and L (L_{11} and L_{12}). While selecting the SCR, its reverse recovery time should be less than circuit tq to have a complete commutation of the SCR. Fig.11 shows the maximum fault current magnitude with respect to the variation in z-source capacitor C and inductor L (L_{11} and L_{12}). As can be inferred from the graph, device short time withstand current rating should be more than maximum fault current magnitude.

TABLE II: Comparison of Breaker Component Count

	Bi-ZSB	Bi-CZSB	Proposed Bi-CZSB	FCLI[2]
SCR	2	2	4	2
Diode	2	2	-	2
Inductor	4	2	1	2
Capacitor	3	1	1	3

Table-II shows the comparison of breaker components for previously proposed Bi-ZSB, Bi-CZSB and FCLI[2]. The performance of the circuit breaker is achieved with less number of components in the proposed topology. With the coupled inductor, overall inductance remains same but it is achieved with the lesser number of turns than using two separate inductors. Hence steady state losses are reduced. However, the voltage across SCR is higher due to the absence of freewheeling diodes across both the inductors. Thus, the voltage rating of the devices should be selected accordingly.

V. Reclosing and Re-breaking Operation

As explained previously, capacitor C is charged to a negative voltage during the fault isolation process. For the breaker to perform re-breaking operation while reclosing, the capacitor should be pre-charged. The topology discussed in the above section is integrated with the capacitor recharging circuit as highlighted in Fig. 12 to pre-charge the capacitor during the fault isolation process itself. The recharging circuit consists of inductor L_R, diode D and resistor R.

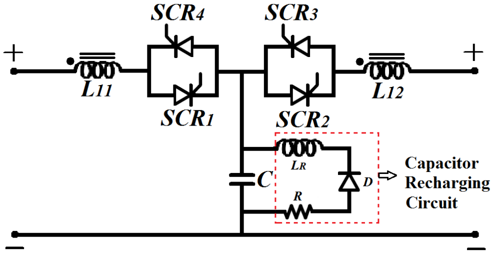
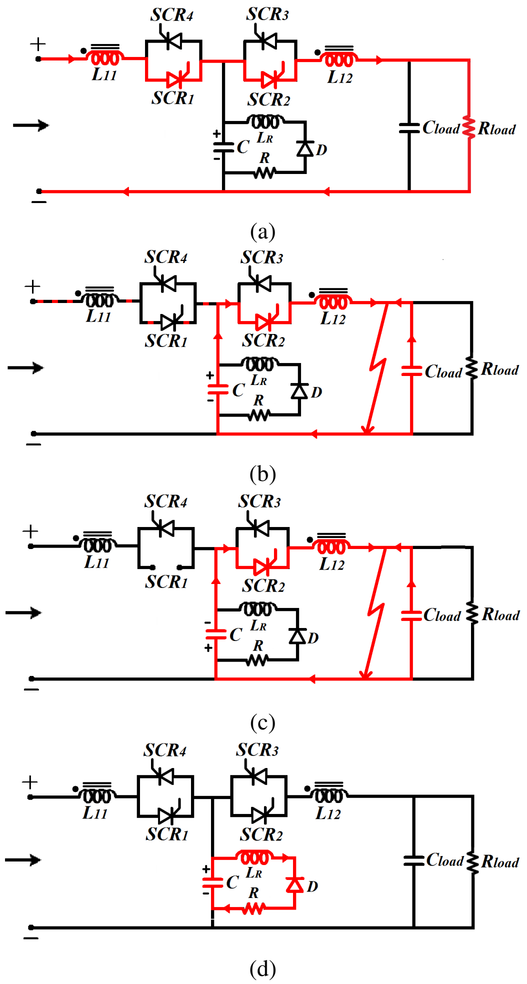


Fig. 12: Modified Bi-CZSB with capacitor recharging circuit

A. *Operation of capacitor re-charging circuit*

The operation of the circuit can be explained by different modes of fault isolation as shown in Fig. 13. Normal operation of the breaker shown in Fig. 13(a) which remains identical as explained earlier in Fig. 8(a). Initial two modes of fault isolation process shown in Fig. 13(b) and Fig. 13(c) are same as explained earlier. As mentioned in the previous section, capacitor C is charged to a negative voltage post commutation of SCR_2 as shown in Fig. 13(c). A negative voltage across capacitor forward biases the diode D of the recharging circuit as highlighted in Fig. 13(d). Hence, a conduction path is between the capacitor C, inductor L_R, resistor R and diode D. The voltage across capacitor oscillates and charge the capacitor to a positive voltage. Thus, the diode D gets reverse biased and recharging circuit is opened. Now, capacitor C is charged to a positive voltage, ready for handling the next reclosing and re-breaking operation.



(a)

(b)

(c)

(d)

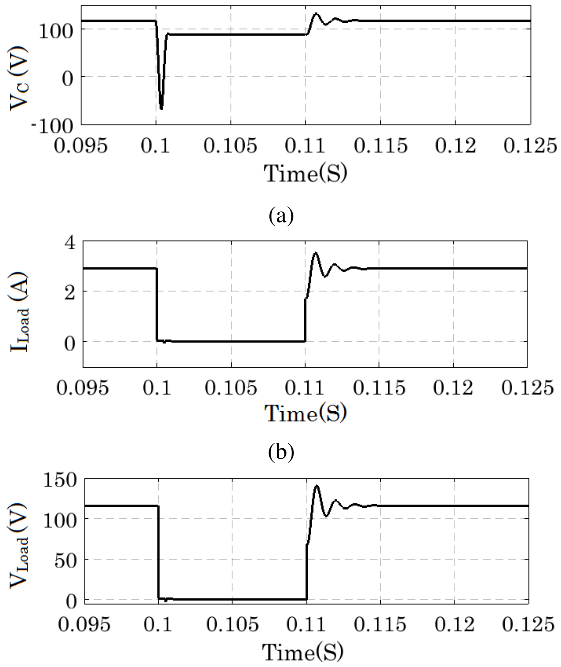
Fig. 13: Different modes of operations of modified Bi-CZSB (a) normal conduction mode, (b) fault instant, (c) post SCR_1 commutation and (d) post SCR_2 commutation when recharging circuit gets activated.

TABLE III: Simulation Parameters

Parameters	Bi-CZSB
Source Voltage (Vs)	120 V
Z-Source Inductor (L_{11})	410 µH
Z-Source Inductor (L_{12})	820 µH
Z-Source Inductor (L_R)	450 µH
Z-Source Capacitor (C)	50 µF
Load Resistance	40 Ω
Damping Resistance	0.3Ω

B. Breaker performance in temporary and permanent fault condition

Simulation study of the breaker is carried out with the parameters shown in Table-III. Components of reclosing loop are selected considering one cycle of reclosing and re-breaking operation. Fig. 14 and Fig. 15 show the simulation results of the breaker under temporary and permanent fault conditions respectively. The first fault has occurred t = 0.1 sec, and the beaker has cleared the fault completely. Fig. 14(a) and Fig. 15(a) shows the voltage across the capacitor C. As can be seen from the graph that post-fault at t = 0.1 sec, the capacitor is again charged during the fault isolation process itself. Now, a breaker is reclosed at t = 0.11 sec after the fault is cleared. As fault is already cleared, the breaker gets reconnected and starts feeding the load normally as can be seen from Fig. 14(b) and Fig. 14(c). Now If a fault is still present in the system and the breaker is tried to reclose at t = 0.11 sec, as can be seen from Fig. 15(b)and Fig. 15(c), the breaker gets disconnected immediately as intended.

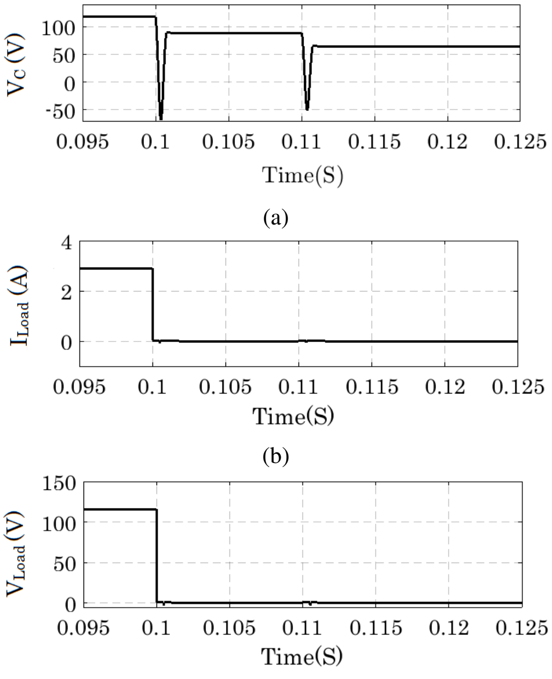


(a)

(b)

(c)

Fig. 14: Simulation results of breaker reclosing under temporary fault condition



(a)

(b)

(c)

Fig. 15: Simulation results of breaker reclosing under permanent fault condition.

VI. CONCLUSION

In this paper, a bi-directional z-source circuit breaker with coupled inductor is modified to reduce a total number of components. Desired performance of the breaker is achieved with a single coupled inductor, hence overall size and the cost of the breaker is significantly reduced. A breaker performance is studied for re-closing and re-breaking operating duty with additional capacitor recharging circuit. A capacitor recharging circuit is introduced to automatically pre-charge the capacitor, making it ready for the next re-closing and re-breaking operation. Like Bi-CZSB, this topology does not require an SCR control unit to clear the fault or to change its power flow direction. Additionally, capacitor C is automatically pre-charged during the fault isolation process itself. The proposed modified topology of Bi-CZSB is simulated in MATLAB to verify the performance and results are found satisfactory.

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