A Modular Novel Bidirectional Hybrid DC Circuit Breaker Topology for More Electric Avionics

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A Modular Novel Bidirectional Hybrid DC Circuit Breaker Topology for More Electric Avionics

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Abstract
A DC-based power distribution system is adopted in the architecture for more electric aircraft (MEA) and all electric aircraft (AEA). The paper proposes a bidirectional Direct Current circuit breaker (DCCB) based on coupled inductor capable of interrupting a short circuit current in few tens of microseconds. The proposed topology is a hybrid circuit breaker that provides arc-less current disruption in the primary circuit. The breaking operation is based on the current reflected in the primary winding from the auxiliary resonant circuit (commutation module). In the proposed converter, the time for circuit breaking is significantly reduced using a current-fed high gain converter, which acts as a boost converter to charge the pre-charging capacitor. The same switches employed in the current fed converters are used in commutation; hence, fewer components are needed. The switches are operated so that the pre-charging capacitor voltage profile is unipolar. A modular approach for DCCB is presented that uses the commutation circuit as a module. With the modular approach of breaking the current in the primary circuit, the voltage and current rating of the DCCB can be enhanced. The presented DCCB with modular commutation circuits can interrupt the current flow in the opposite direction, which makes it a bidirectional DCCB. A detailed simulation study is conducted in Matlab Simulink environment, further experimentally the hardware results are validated for breaking the current in 270V/10A and 540V/5A DC systems.

Keywords: modular hybrid DC circuit breaker, zero current switching (ZCS), coupled inductor, bidirectional interrupter
1 Introduction

Recent literature survey indicates, in the transportation sector [1] - [2], the share of electric vehicles (EV) sales is near to 10% to the global total car sales in the year 2021, which is approximately four times of the market share of EV in the year 2019. The expected share of battery-powered EVs globally sold is approximately 30%. By 2050, this is expected to be around 90% across all the segments including two-wheeler, four-wheeler, and multi-axle vehicles. The revolution of battery-powered automotive systems is not just limited to vehicles that run on roads [3], [4] but is also popular among passenger aircraft and fighter jets. There has been tremendous progress in moving towards More electric aircraft (MEA) and all electric aircraft (AEA) [5], [6], [7]. Conventional aircraft use the main voltage level of 115V AC with frequencies ranging from 360Hz to 800Hz. One of the advantages of using DC power over AC power is the current density through a wire is higher in the case of DC [8]. Hence, as the DC voltage increases, the cable size and weight reduce for the same power transfer. Modern standard short- and midrange aircraft tend to use a +/− 270V DC main bus bar [9] - [10], which can reduce the total weight of the power system substantially due to the higher density of the DC system.

Due to the apparent advantages, penetration in distributed generation, and of storage systems, hybrid AC/DC microgrids are gaining importance [11]. The addition of DC or AC equipment/load leads to an increase in the system’s short-circuit capability and poses additional challenges [12]. The DC fault current interruption differs from the AC fault because of the zero-crossing absence. The DC circuit breaker [13] classification is done in three broad categories: solid-state DCCB, Mechanical DCCB, and hybrid DCCB [14]. At a high current level, the mechanical DCCB is a more efficient solution than solid-state DCCB; however, a hybrid DCCB comprises the advantages of both mechanical and solid-state types of DCCBs [15]. A DCCB should have the following characteristics:

• The conduction losses should be minimum.
• The breaking time should be as short as possible without high voltage and high current stress on the switches and other circuit components.
• Feature of current interruption in both directions, in DC system, the source and load terminal can be interchanged depending on the requirement. [16]

Although there are many challenges in DCCB designing because of the absence of zero current or voltage crossing, various methods, and topologies exist in literature to create forced zero crossings. Zyborski et al. presented a hybrid arc-less DCCB capable of low losses in the conduction state [17]. It is a bidirectional CB; nevertheless, the commutation circuit’s current flow needs to be double the fault current. The switch rating has to be more than the fault current of the circuit. Hybrid DCCB topology is proposed for low voltage applications like aircraft power distribution [18]. In the conduction stage, the voltage drop across the semiconductor device leads to a less efficient circuit breaker. Meyer et al. [19] used Integrated Gate Commutated Thyristor (IGCT) in parallel with a mechanical switch. The semiconductor switching path will be enabled when arc impedance is more than the semiconductor switch’s on-state resistance. DCCB is required in applications like particle accelerators and plasma.
confinement devices [20]. Due to the parallel arrangement of the mechanical switch and semiconductor paths, the circuit is prone to arcing while opening a mechanical switch in case of fault occurrence. ABB’s HVDC breaker [21], which can be contained in a box, uses a mechanical switch in series with a semiconductor switch of small current and voltage capability. This circuitry parallels the series connection of several highly-rated semiconductor switches. The drawback of such arrangement [22] is that the hybrid DCCB is lossy because a semiconductor switch is constantly in a conduction state along with the mechanical switch. A slight enhancement in the parallel combination of mechanical switch and semiconductor is done by adding a freewheeling diode parallel to the supply [23]; however, it is prone to arc in switching action. In Z source-based DCCB [24], [25], current commutation is done using the impedance network; however, it has the drawback of automatic actuation if there is even a slight load variation. The issues of high starting current and unwanted power flow are rectified using a parallel snubber branch which dissipates the trapped energy in the inductor [26]; nevertheless, in the Z source, load current flows through the semiconductor device, so conduction losses are significant [27]. Lazzari et al. [28] implemented a Low Voltage hybrid DCCB, which addresses the problem of twice the fault current in the circuit elements. Its limitations are the usage of a high number of components used in the resonant circuit. During regular operation, one semiconductor switch always conducts; hence the losses are more extensive than other hybrid DCCB topologies.

Ray et al. [29] used a thyristor-based commutation circuit using a unipolar capacitor, in which the commutation circuit and primary circuit are coupled through a coupled inductor. The advantages of this topology are higher because of the turn ratio in the coupled inductor gives a degree of freedom in selecting appropriate circuit elements of lower ratings. One more degree of freedom can be added if the resonating capacitor’s voltage is increased. Four switches are used for a current-fed converter to charge the capacitor more than the input voltage supply [30]. A conventional boost converter is deterred because unipolar capacitor charging operation is required, which is possible by the bridge topology of switches. Using lower rating devices, a DCCB circuit breaker with enhanced voltage and current rating is desirable. Modularity and scalability are feasible with a DCCB if several modules can be connected in series and parallel according to the requirement [31] -[32].

The organization of the paper is as follows: In section 2, the salient features of the proposed topology is listed. Section 3 explains the proposed topology in various modes and working principles. The functionality of DCCB in reverse fault current is described in section 4. The modular approach for current and voltage rating enhancement is elaborated in section 5. Designing of circuit parameters is done in section 6. The simulation results are presented in section 7, along with necessary waveforms. Section 8 shows significant experimental results for DCCB and its modular approach with relevant descriptions. Some important conclusions are presented in section 9, along with discussions.
2 Salient features of the proposed topology

- The presented topology [33] uses the same switches for charging the commutation capacitor and fault current interruption.
- A coupled inductor used gives an additional degree of freedom in designing circuit elements.
- It is a bidirectional DCCB, which can interrupt fault current in either direction.
- A unipolar capacitor is used, which has more energy density than bipolar capacitors.
- The current and voltage rating of the circuit breaker is enhanced by using a modular approach.
- In the individual modules, lower-rating generic semiconductor switches, and passive components are used.

3 Working Principle of the Proposed Topology

The proposed bidirectional DCCB, shown in Fig. 1, consists of six MOSFETs $S_1$ - $S_6$, a pre-charging capacitor $C$, a coupled inductor $L$ with primary winding $1 - 1'$ and secondary $2 - 2'$, a line inductor $L_L$, and a mechanical switch $MS$. MOSFETs $S_1$ - $S_4$ enable the functionality of the unipolar capacitor. To charge the capacitor more than the input voltage, a conventional bidirectional boost converter cannot be used because the unipolar capacitor needs to discharge such that the inductor current may flow in any direction depending on the fault current direction. $1 - 1'$ of the coupled inductor is connected with the primary circuit, whereas winding $2 - 2'$ is associated with the capacitor charging circuit. The capacitor charging circuit also works as a commutation unit, enabling the current in the primary circuit to be opposite of the load current. An active current limiting circuit consisting of a resistor $R_S$ and a MOSFET $S_6$ is used in the circuitry to reduce the capacitor charging current. With the assistance of timing diagrams, as shown in Fig. 2, the operating modes of the DCCB are as follows:

![Proposed DC circuit breaker](image_url)
Mode-I \([t_0 \text{ to } t_1]\): during this mode, as shown in Fig. 3(a) and 3(b), switches \(S_1\) to \(S_5\) are operated to charge the capacitor from the source \(V_g\). As indicated in Fig. 3(a), the switches \(S_1, S_2\) are turned ON, and current flows in \(2 - 2'\) winding of the coupled inductor. In Fig. 3(b), the switches \(S_1, S_2\) are turned OFF, and switch \(S_5\) is turned ON; hence, due to the inductor current direction, the anti-parallel diode of switches \(S_3, S_4\) freewheels. In the absence of the switch \(S_5\), when current flows in the primary circuit in regular operation, the mutual current will flow in commutation winding \(2 - 2'\) through freewheeling diodes and varies the capacitor voltage. A current-limiting resistor \(R_S\) is used to limit the excessive current in the current-fed converter. When the capacitor voltage \(v_C\) reaches a particular voltage level \(v_{C_{init}}\), which is fixed by the input voltage \(V_g\) and duty ratio \(D\), the switching of \(S_1-S_5\) is cut off; thus, the capacitor isolates itself from the circuit and maintains its charge.

Mode-II \([t_1 \text{ to } t_2]\): After assigning an appropriate duty ratio for the switches \(S_1\) to \(S_5\) between time instants \(t_0\) and \(t_1\), the capacitor charging is stopped at time instant \(t_1\). There is current flow in the \(2 - 2'\) winding of the coupled inductor, this cannot be reduced to zero instantly. To make the inductor current zero, the switches \(S_3\) and \(S_4\) are turned ON, as shown in Fig. 3(c). The capacitor \(C\), which is charged more than the input voltage \(V_g\), starts discharging through the switches \(S_3-S_4\), the freewheeling diode of switch \(S_6\) and the \(2 - 2'\) winding of the coupled inductor. The circuit is such that it opposes the inductor current. When the current in the \(2 - 2'\)
winding is zero, the switches $S_3$ and $S_4$ will be turned OFF. At this instant, $t_2$, the capacitor is charged, and the inductor current is zero.

**Mode-III** [$t_3$ to $t_4$]: The period between time instants $t_2$ and $t_3$ is kept as buffer time. The circuit corresponding to the buffer period is shown in Fig. 3(d). At time instant $t_3$, as shown in Fig. 3(e), the mechanical switch $MS$ is turned ON, and current $i_m$ starts to flow in the primary circuit. The load is purely resistive, so due to $1-1'$ winding’s self-inductor and an additional line inductor $L_L$, the primary circuit’s current $i_m$ increases slowly. After a particular time, both inductors saturate, and a steady-state current $I_{mp}$ flows in the primary circuit.

**Mode-IV** [$t_4$ to $t_5$]: At time instant $t_4$, fault occurs, and short circuits the load. The current $i_m$ increases as there are only $1-1'$ winding’s self-inductor and an additional inductor $L_L$ in parallel to the voltage source $V_g$ as shown in Fig. 3(f). There is no action by the resonant circuit until the current $i_m$ reaches some preset value $I_{mf}$.

**Mode-V** [$t_5$ to $t_6$]: At time instant $t_5$, the current $i_m$ reaches preset value $I_{mf}$. At this instant, the switches $S_3$-$S_4$ are turned ON. As shown in Fig. 3(g), the current $i_C$ starts from the capacitor, flows through switches $S_3$, $S_4$, freewheeling diode of switch $S_6$, the inductor’s $2-2'$ winding, voltage source $V_g$ and freewheels through the switch $S_5$ diode; hence, the current $i_{LL}$ direction reverses. Due to mutual inductance, mutual current flows through winding $1-1'$, opposite to the current $i_m$. The current $i_{LL}$ increases in the reverse direction due to the resonant circuit; hence, current $i_m$ decreases further. At instant $t_6$, the current in the primary circuit becomes zero. The mechanical switch will be opened at this instant, as shown in Fig. 3(h), which is a zero current switching (ZCS).

**Mode-VI** [$t_6$ to $t_7$]: In the previous mode, the current in the primary circuit becomes zero; however, the current in $2-2'$ winding of the coupled inductor is not zero. If the circuitry remains the same as in the previous mode, a considerable current will flow in the secondary circuit due to resonance. This large current may damage the switches, and the capacitor will be charged to the opposite polarity, which is undesirable. Switching is done as mentioned in Fig. 3(h) so that the energy stored in the coupled inductor is again transferred to the source itself. This makes the overall circuitry efficient as no energy loss exists in any operation mode except mode-I and mode-II, where the current limiting resistor is used to limit the capacitor charging current. Switch $S_5$ is turned ON, due to which input voltage source $V_g$ comes in series with the $2-2'$ winding of the coupled inductor. It will oppose the current in the $2-2'$ winding of the coupled inductor. When the current in the circuit becomes zero, the switch $S_5$ is turned OFF.

4 Bidirectional Operation of DCCB

In a DC-based distribution system, the boundary between source and load definition becomes opaque. The bidirectional operation of the proposed DCCB is of importance, where the source acts as a load, and the load acts as a source. The proposed DCCB has an in-built bidirectional current breaking capability without adding additional components to the existing circuitry. However, in the switching control, there is a slight modification.
In the above-explained mode-I, the switch set of $S_3, S_4$ are turned ON for $DT_S$ time duration, whereas for rest of switching cycle, the reverse conducting diode of the switch $S_1, S_2$ along with switch $S_5$ conducts. For the residual current neutralization in the inductor, switches $S_3, S_4$ are turned ON in mode-II. The switching scheme for mode-III and mode-IV remains the same. In mode-V, to clear the fault that occurred at the load side, switches $S_1, S_2$ are turned ON along with the switch $S_6$, which bypasses the current limiting resistor. In mode-VI, switch $S_1, S_6$ is turned ON to neutralize the secondary winding inductor current.

5 Modular Approach of DCCB

The voltage rating of the proposed DCCB can be augmented if the rating of all the components increases. However, there is a limitation in the rating of each component; hence, a modular approach of DCCB is a better idea. In the modular approach, the commutation circuit is connected so that the overall current and voltage rating of the DCCB is extended. Fig. 4 shows the two modules connected in series in the proposed DCCB.

During capacitor charging mode, both the capacitors $C_1$ and $C_2$ will come in series, and the overall charge will be shared amongst these capacitors. The gain formula for output voltage will not be applicable as no load is connected at the output terminals.
Hence, both capacitors will charge until the capacitors achieve a preset voltage. The current limiting resistors further reduce the charging current, and capacitors will take longer to charge. As explained earlier, the same switching action will happen in both modules during fault occurrence and inductor current neutralization. The connection of two modules in series will increase the reserve current $i_{LL}$ in the commutation circuit, which further reflects into the primary circuit and break the primary circuit current with high source voltage.

**Fig. 5**: Parallel connection of two commutation modules

Fig. 5 shows the two modules connected in parallel in the proposed DCCB. Similar to the above case, the overall rating of individual modules is the same. During capacitor charging mode, the capacitors $C_1$ and $C_2$ are connected in parallel. Individual modules will contribute to the current through the secondary winding $2 - 2'$ of the mutual inductor $L$ in fault clearance. The connection of two parallel modules in the commutation circuit enables the usage of a high current load in the primary circuit. Both series and parallel connections of modules are required when both the load current and source voltage ratings are high.

## 6 Designing of Circuit Parameters

The following parameters need to be designed/selected in the circuit mentioned in Fig. 1.
$L_1$: Self-inductance of primary of the coupled inductor.
$L_2$: Self-inductance of secondary of the coupled inductor.
$M$: Mutual inductance of the coupled inductor.
$L_L$: Line inductance present in the primary circuit.
$N_1$: Number of turns in the primary winding of the coupled inductor.
$N_2$: Number of turns in the secondary winding of the coupled inductor.
$S_1 - S_6$: Switches in commutation circuit.
$MS$: Mechanical switch in the primary circuit.
$R_S$: Current limiting resistor.
$C$: Capacitor in commutation circuit.

Mutual inductance is dependent on the self-inductance of the individual windings.

$$M = k\sqrt{L_1 L_2}$$

(1)

$K$ is the coupling constant, which can be taken as 0.9.

Self-inductances $L_1$ and $L_2$ are dependent on the number of turns $N_1$ and $N_2$ respectively.

$$L_1 \alpha N_1^2$$

(2)

$$L_2 \alpha N_2^2$$

(3)

Using equations (2) and (3), the ratio of $N_1$ and $N_2$ can be obtained.

$$\frac{L_1}{L_2} = \frac{N_1^2}{N_2^2} = n^2$$

(4)

Using equations (1) and (4),

$$M = nkL_2$$

(5)

Neglecting the non-idealities, the following equations correspond to the circuit when we turn ON the switches $S_3$ and $S_4$ for the breaking operation as described in Mode-V.

$$\left( L_1 + L_L \right) \frac{di_m}{dt} - M \frac{d}{dt} i_{LL} = V_g$$

(6)

$$M \frac{d}{dt} i_m - L_2 \frac{d}{dt} i_{LL} = v_c - V_g$$

(7)

$$i_{LL} = C \frac{d}{dt} v_C$$

(8)

The solutions of these equations will provide the variation of the current $i_m$, $i_{LL}$, and voltage $v_c$ with time. Various circuit parameters like capacitor $C$, capacitor’s initial voltage $V_{C_{init}}$, different inductors $L_1$, $L_2$, $M$, $L_L$, preset fault current in the primary circuit $I_{m_{init}}$ and initial current in the resonant circuit $I_{LL_{init}}$ will impact on the solution of the equations (6)-(8). The simulation study and experimental validation of the circuit are conducted on a circuit of 270V DC source and 5A load; hence, the
circuit parameters are designed accordingly. If the current in the primary circuit \( i_{m} \) is 40% higher than the steady-state current, the circuit is understood to be under short-circuit fault. For the design of the circuit parameters, \( I_{m,\text{init}} \) is taken as 7\( \text{A} \), \( V_{C,\text{init}} \) is taken as 1000\( \text{V} \), and \( I_{L1,\text{init}} \) is taken as 0\( \text{V} \) because there is no current flow in the commutation circuit when the fault occurs. Assigning the initial values in the equations (6)-(8), the approximate calculated values of inductance \( L_1 \) and \( L_1 \) are 20\( \text{mH} \) and value of capacitor \( C \) is 20\( \text{mF} \). The value of mutual inductor \( M \) is 18\( \text{mH} \), calculated using equation (5) and other calculated values of inductances. Designing the inductor for the peak current of 20\( \text{A} \), the number of turns \( N_1 \) and \( N_2 \) comes out to be 63, and appropriate enameled wire is used for the required current rating. A 100/60/28 ferrite core is used for mutual inductor winding. A suitable gadget for the core is 3D printed using a 3D printer (creality sermon V1 pro), for which the design was made using OpenSCAD software. A resistance of 35\( \Omega \) is considered for the current limiting resistor \( R_S \) so that the charging current of the capacitor remains under 5\( \text{A} \).

7 Simulation Results

The simulation study of the circuit is conducted on a circuit of 270\( \text{V} \) DC source and 5\( \text{A} \) load. Table 1 shows the circuit parameters which are considered for the simulation studies.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ( V_g )</td>
<td>270( \text{V} )</td>
</tr>
<tr>
<td>Primary winding self-inductance ( L_1 )</td>
<td>20( \text{mH} ), 20( \text{A} )</td>
</tr>
<tr>
<td>Primary winding self-inductance ( L_2 )</td>
<td>20( \text{mH} ), 20( \text{A} )</td>
</tr>
<tr>
<td>Mutual inductance ( M )</td>
<td>18( \text{mH} )</td>
</tr>
<tr>
<td>Capacitance ( C )</td>
<td>20( \text{mF} ), 2( \text{kV} )</td>
</tr>
<tr>
<td>Load ( R )</td>
<td>1( \text{kV} ), 5( \text{A} )</td>
</tr>
<tr>
<td>Current limiting resistor ( R_S )</td>
<td>35( \Omega )</td>
</tr>
<tr>
<td>Preset fault current ( I_{m,\text{init}} )</td>
<td>7( \text{A} )</td>
</tr>
<tr>
<td>Capacitor initial voltage ( V_{C,\text{init}} )</td>
<td>1( \text{kV} )</td>
</tr>
<tr>
<td>Initial current in the resonant circuit ( I_{L2,\text{init}} )</td>
<td>0( \text{A} )</td>
</tr>
</tbody>
</table>

Fig. 6 shows the waveforms obtained from simulation study for the 270\( \text{V} \), 5\( \text{A} \) circuit. The charging of the capacitor starts at a time instance of 1 second. The charging current is kept under limit using an active current limiting circuit. At a time of 1.7 second, the capacitor charges up to its predefined voltage level of 1\( \text{kV} \). The capacitor voltage is downscaled by 1/100 per unit in all the simulation results. During this time, the current through the inductor is unidirectional; however, the current through the capacitor is bidirectional. At a time of 3 second, the mechanical switch is turned \( ON \), so the current \( i_m \) is raised to 5\( \text{A} \) as a load of 54\( \Omega \) is connected. The transition of \( i_m \) is not instantaneous because of the presence of a line inductor \( L_L \) and self-inductor \( L_1 \) of the mutual inductor \( L \) in the circuit.
The enlarged simulation result is shown in Fig. 7 for the fault occurrence and clearance stages. The fault occurs at 4 second, and the primary branch current $i_m$ increases. The nature of the rise in the $i_m$ current is linear because the inductors come in series with the voltage source $V_g$. The commutation circuit is activated when the current reaches a preset value of 7A (40% higher than steady-state current). The capacitor discharges; hence the $i_c$ current is negative in Fig. 7. The current through the secondary of the mutual inductor $i_{LL}$ also follows the $i_C$ current. The reflected current in the primary circuit opposes the rise in the short circuit current, and the current $i_m$ reduces. Eventually, the $i_m$ current and capacitor current $i_c$ come to a standstill together, but current $i_{LL}$ is not zero at that instant. At this instant, the mechanical switch is opened. After the fault clearance, the inductor secondary comes
in the DC source series, giving back its stored energy to the source. When the current $i_{LL}$ becomes zero, the commutation circuit is isolated from the DC source and the rest of the circuitry through proper switching. There is a slight notch in all the simulation results because of the sampling time (10$\mu$S) used in the simulation studies.

![Schematic diagram of series and parallel arrangement of commutation modules](image)

**Fig. 8:** Schematic diagram of series and parallel arrangement of commutation modules

![Simulation results (540V, 10A)](image)

**Fig. 9:** Simulation results (540V, 10A)

Pertaining to the DC source of 540V and a load of 10A, four modules of commutation circuits are connected in a 2-by-2 array, as shown in Fig. 8. Both the voltage and current rating of the DCCB is enhanced by using modular commutation circuits in series and parallel. Fig. 9 shows the simulation result for the circuit. The total voltage ($V_{C1} + V_{C2}$) of the series-connected capacitors after capacitors charging equals a preset value of 2kV. The current $i_m$ rises linearly when the fault occurs, and the fault-suppressing action is taken when the current $i_m$ reaches a preset value of 12A.
The total commutating current $i_{LL}$ which is the sum of individual commutation currents ($i_{LL1} + i_{LL2}$), goes up to a peak current of 20A. Hence, the modular approach of connecting the commutation modules in an array assures the capability of breaking higher load current.

Fig. 10 shows the simulation result of the circuit when the polarity of the source is reversed. The capacitor is charged to the same voltage level of 1kV; however, the current $i_m$ is negative. When the fault occurs, the current $i_m$ will be $-7A$. The direction of current $i_{LL}$ is also reversed because the reflected current in the primary circuit has to be in the reverse direction. This action shows the bidirectional fault clearance capability of the proposed DCCB.

![Fig. 10: Simulation results for bidirectional operation (-270V, -5A)](image)

8 Experimental Results

Fig. 11 shows the hardware setup of the proposed system. A DC power source supply gives 270V/540V to the circuit. A mutual inductor of 100/60/28 ferrite core is used with 63 turns for 20mH self-inductance of each winding. Different mutual inductors are used in the experiment for various turns ratio. A line inductor of 0.5mH, and a capacitor bank of 20mF, 1kV are shown in the figure. Each measurement board contains two voltage (LEM LV25P) and two current sensors (LEM LA55). In the circuitry, three current and one voltage sensor are used to measure the appropriate current and voltage at various nodes. The DCCB board has five IGBTs (Mfg no. IXBX25N250) along with gate drivers based on ISO5451 gate driver and SG3525 PWM IC. The switch for the current limiting resistor and mechanical switch, the same IGBTs with gate drivers are used on a separate board. A resistive load bank acts as a current-limiting resistor, whereas a load resistor is shown as a rheostat. A ±15V DC supply is used to power the measurement boards and gate driver boards. The
microcontroller (TMS320F28379D) takes the input from the measurement boards and provides a suitable gate pulse to the gate drivers.

Fig. 11: Experimental setup of proposed DCCB

Fig. 12(a) shows the hardware result for a DCCB of 270V source and 5A load. With a voltage scaling of 500V per division, the capacitor is charged up to 1kV. During the capacitor charging, the current $i_{LL}$ and $i_c$ also vary with the time to charge the capacitor. The current-limiting resistor restricts the charging current and leads to a higher charging time for the capacitor. The main switch is turned ON, and the $i_m$ curve rises to a current of 5A. After one second, an artificial fault is created by shorting the load through a DC contactor (part no. DCNLEV100–BN). The enlarged picture of the encircled portion in Fig. 12 (a) is shown in Fig. 12(b). After creating the fault, the $i_m$ current rises linearly and reaches the preset fault level of the current. The commutation circuit takes preemptive measures to suppress the fault current. It turns ON the switches such that the current $i_{LL}$ (same as the current $i_c$, until the fault vanishes) causes the current flow in the primary circuit in the reverse direction. As soon as the fault is cleared, the mechanical switch is turned OFF; hence, the current $i_m$ is not going in the negative direction. The current flowing through the secondary
Fig. 12: Hardware results (a) (270V, 5A). (b) Enlarged waveforms (270V, 5A).

Fig. 13: Primary circuit current $i_m$ corresponding to (a) different capacitor pre-charging voltage. (b) different capacitor pre-charging voltage

side of the mutual inductor $i_{LL}$ will not be zero instantaneously, and it discharges to the DC source through proper switching action.

Fig. 13(a) shows the impact of different turns ratio of the mutual inductor on the fault clearance time. In the case of a short circuit fault, the rising time depends solely on the primary side (main circuit) of the mutual inductor $L$; however, the decaying time depends on both primary and mutual inductance $M$. The explanation of this statement can be given with the help of equations (6)-(8). In the top curve of Fig. 13(a), a mutual inductor of $20mH : 20mH$ is connected to the circuit, which approximately has a mutual inductance of $18mH$. The rise time and decaying time are
Fig. 14: Voltage and current rating enhancement. (a) Connecting two parallel commutation modules. (b) Connecting two series commutation modules.

160µS and 80µS, respectively. The central figure corresponds to the mutual inductor of 20mH : 5mH, in which the mutual inductor is approximately 9mH. Due to the lesser value of the secondary side self-inductor, the rise in commutation current is sharp, and it leads to lesser fault clearance time. The condition is reversed in the last curve, where a mutual inductor L of 5mH : 20mH is used. The rising current is less due to the smaller primary side inductance, and the current decaying time is more extensive due to the lesser current on the secondary side because of the high inductance value.

A family of primary circuit current curves $i_m$ for different capacitor voltages is shown in Fig. 13(b). The rise time is independent of the capacitor voltage because it does not contribute to the fault current increase. However, it affects the decay time as with the high capacitor charge, the current in the commutation increases, which in turn reduces the current in the primary circuit rapidly.

Fig. 14(a) corresponds to the DC source of 270V and the load of 10A. Two commutation circuits are connected in parallel in the hardware setup. In this figure, two currents $i_{LL1}$ and $i_{LL2}$ link to the different commutation currents from each of the modular circuits. In this circuit, the mutual inductor $L$ of 20mH : 20mH is used, and the present fault current level is 12A. So the time taken to rise the current $i_m$ is 160µS, equal to the time taken to reach 7A from 5A (same time as in the first curve of Fig. 13(a)). The decay time is high as compared to the decay time in Fig. 13(a) because of the high preset fault current. Fig. 14(b) corresponds to the DC source of 540V and the load of 5A. Two commutation modules are connected in series; hence, both capacitors charge up to a voltage of 1kV. The time taken for the rise of the current $i_m$ is almost half of Fig. 15(a) because the source voltage is doubled to 540V. The decay time of the fault current $i_m$ is reduced as the two modules, each with capacitor voltage of 1kV, are suppressing the fault current.

Fig. 15 shows the experimental results for the DCCB with a voltage source of reverse polarity. During the fault, the fault current $i_m$ reaches to −7A from −5A. The
direction of commutation current $i_{LL}$ is also reversed as it has to reflect an opposite current in the primary circuit; however, the direction of the capacitor current $i_C$ is the same as the capacitor is discharging during fault clearance.

![Fig. 15: Hardware results for bidirectional operation](image)

9 Summary and Conclusions

The paper demonstrates a novel DCCB with modularity which enhances the voltage and current rating of DCCB. The proposed DC circuit breaker is tested at various source voltages and load currents. The bidirectional property and modularity are also validated through the experimental results. A comparative study with various hybrid DCCBs, available in the literature is conducted. Table II compares four DCCBs with the proposed DCCB on various factors like pre-charging capacitor voltage, bidirectional fault-breaking capability, modularity, and the number of energy storage elements. The capacitor is precharged in the hybrid DCCBs, which is done through either an RLC circuit or a power electronic converter. In the proposed hybrid DCCB, the capacitor pre-charging is done through a current-fed converter; hence a factor of $n$ is shown in the table. The switches of the current-fed converter are also used in providing a commutation current to counter the fault current. A bidirectional fault current breaking capability is a desired feature of any DCCB because the source can act as load and vice-versa. Modularity and scalability are required for applications with high fault current breaking capability and high source voltage. The proposed hybrid DCCB has the feature of voltage and current rating enhancement capability with minimal energy loss.
Table 2: Comparative Studies with Existing Literature

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Declarations
Not applicable

References


