SUMMARY

DC circuit breakers (DCCBs) are one of the key components to facilitate large meshed HVDC grids. Driven by the needs for achieving high speed, low loss and low cost, various DCCB technologies have been proposed for HVDC applications. Unlike AC circuit breakers (AC-CBs), some DCCBs provide a variety of functions, such as proactive opening or fault current limiting (FCL), mainly attributed to the high controllability of the power electronic switches used in such DCCBs. To enable these functions, the intelligent electronic devices (IEDs) are expected to provide signals steering these functions in addition to a trip command. Interoperability between IEDs and DCCBs from different vendors is considered feasible, but expected to be more complex than their AC counterparts, due to the different functions provided by various DCCB technologies. It is therefore crucial to understand which of the functions are essential to fulfil the requirements imposed in HVDC grid protection, and to standardise the interfaces between the IEDs and DCCBs to achieve multivendor interoperability between IEDs and DCCBs provided by different vendors.

This paper first classifies the DCCB functions into minimally required and auxiliary ones based on reviewing the existing literature. Then, standardised interfaces between the IEDs and DCCBs are proposed to enable both types of DCCB functions. An example of such IED is implemented in PSCAD/EMTDC to demonstrate that the proposed interfaces are adequate to enable both minimally required and auxiliary functions using a four-terminal test system. Auxiliary functions of hybrid DCCBs, such as proactive opening, fault current limiting, fast reclosing and reopening, breaker failure internal detection and repeated O-C-O operation are demonstrated by simulations.

KEYWORDS

HVDC grid protection, DC circuit breaker, intelligent electronic device, standardised interfaces, multivendor interoperability
1 INTRODUCTION

Protection against DC faults in meshed high voltage direct current (HVDC) grids is essential to meet the requirement on security of supply in the future hybrid AC/DC power systems [1]. Fully selective HVDC grid protection strategies, utilising DCCBs to protect each component individually, are one of the most promising options for large meshed HVDC grids as the alternatives like de-energisation a whole HVDC grid imply severe impacts on the connected AC grids [2].

In recent years, great effort has been put into developing high speed, low loss and low cost DC-CBs, as interrupting a DC current is both necessary and challenging [3, 4]. Depending on the fault current interruption technology used, DCCBs are typically classified as mechanical, hybrid and power electronic (PE) types [5]. Unlike ACCBs, some DCCBs provide a large variety of functions driven by the needs for high speed and low cost, and enabled by the high controllability of power electronics used in such DCCBs. Common functions of different DCCB technologies have been studied in [6], where the essential functions are modelled and demonstrated on a common test system. However, the analysis did not include the study of standardised interfaces between the IEDs and DCCBs, which would enable a wide range of auxiliary functions such as proactive opening and FCL operation [3, 7]. To enable different DCCB technologies to achieve not only essential but also auxiliary functions, and ensure the interoperability of the HVDC grid protection system and components, it is necessary to define the required interfaces between the IED and DCCB.

This paper proposes standard interfaces for the main functions of the DCCBs which are proposed in the literature. The main functions are, based on a literature review, classified as minimally required and auxiliary. The principles used for proposing the interfaces are: (1) the interfaces should provide control of all minimally required functions for any DCCB technology, (2) the optional interfaces should provide control of all auxiliary functions considering different DCCB technologies, (3) the interfaces are optional if certain DCCB technology does not provide the auxiliary function, and (4) the interface should contain a minimum number of signals required for the control of all functions. An example of an IED implementation using the proposed interfaces is demonstrated to achieve both minimally required and auxiliary functions using a four-terminal test system in PSCAD/EMTDC. Particularly, this paper demonstrates the following cases: proactive opening and FCL operation of a hybrid DCCB using a current reference signal, fast reclosing during backup operation, fast backup operation using coordination with breaker internal failure detection, and repeated O-C-O operation on a overhead line section.

2 HVDC GRID PROTECTION

In a fully selective protection strategy, a decentralised design of HVDC grid protection systems is most likely the preferred option compared to a centralised design, as the decentralised design provides higher reliability and the possibility of employing equipment from multiple vendors thus encouraging cost reduction through vendor competition [8].

In a decentralised design, each terminal of a DC line is protected by one or more dedicated IEDs, such as separate IEDs for primary and backup protection. Fig. 1 gives an example of such decentralised design, only showing the fault clearing unit (FCU), the IED for primary protection, and essential signals for DC line and busbar protection. A FCU consists of a residual circuit breaker (RCB) for isolation, a DCCB for fault interruption and a line inductor for limiting the rate-of-rise of the fault current. Depending on the protection algorithms used, a line
protection IED may use local and/or remote measurements, telecommunication signals from remote IEDs, and coordination signals with local IEDs in the same substation for fault identification and protection coordination. The interfaces between a DCCB and its associated IED include tripping or closing commands from the IED and breaker status monitoring to the IED.

3 HIGH VOLTAGE DC CIRCUIT BREAKER TECHNOLOGY

Although various DCCB technologies have been proposed in the literature, the most promising ones are mechanical, hybrid and power electronic DCCBs. A 200 kV hybrid DCCB has already been put into operation in the Zhoushan 5-terminal HVDC system and 500 kV ones are under construction in the Zhangbei 4-terminal HVDC grid [9, 10]. Third party independent test of mechanical DCCB prototypes rated at 80 kV has been tested in the PROMOTioN project [11]. Although at the moment, power electronic DCCBs are limited to low voltage DC implementations, they may become economically viable at high voltages as the losses of power electronic devices decrease in the future [12]. In recent years, innovative breaker topologies or control methods have been proposed focusing on capability enhancement, cost reduction or added current flow control capability, e.g., unidirectional or multi-port circuit breakers [13–16].

3.1 Mechanical DCCB

Mechanical DCCBs typically superpose an AC current provided by a resonant circuit on the DC fault current to create zero-crossings, and consequently use an AC breaker for current interruption [4, 17–19]. Different implementations focus on circuit design to either speed up the resonance injection process or reduce component requirements and costs.

Two examples of mechanical DCCBs are given in Fig. 2. To interrupt and isolate the faulted line, both the main vacuum interrupter (S₁) and the RCB (S₂) are required to open. Repeated O-C-O operation with acceptable speed is desirable to provide auto-reclosure functions on overhead line sections. This requirement imposes a time constraint on the recharging of the capacitor banks in the resonant branch (Fig. 2 (a)) and the DC link of the VSC (Fig. 2 (b)). To deal with this requirement, the examples in [20] make use of a second current injection branch, which avoids the need to recharge the capacitor of the first branch, and a large DC link capacitor which has sufficient stored energy for two consecutive opening operations.
3.2 Hybrid circuit breaker

Hybrid circuit breakers combine the benefit of a low-loss mechanical switch and fast controllable power electronics, such as examples given in Fig. 3, thus achieving fast operation and low on-state losses [3, 21]. Alternative circuit topologies using full-bridge or H-bridge submodules have been proposed to achieve similar functions as the IGBT-based breaker [22, 23].

3.3 Power electronics circuit breaker

Power electronics based circuit breakers are capable of interrupting a DC fault current in the microseconds range, however, at a cost of high on-state losses. An example of such circuit is similar to the IGBT-based hybrid breaker but without the load current branch [24].

4 DC CIRCUIT BREAKER FUNCTIONS

In the literature, various breaker functions have been proposed additional to the basic function of fault current interruption. To ensure interoperability between different breaker technologies, it is beneficial to categorize them into minimally required and auxiliary functions. The minimally required functions are referred to those that any DCCB is required to fulfil for HVDC grid protection applications regardless of the employed technologies. By contrast, the auxiliary functions are optional by definition and not required for all types of DCCB technologies. These functions can be used in HVDC grids to improve the performance of the protection system.

4.1 Minimally required functions

The following functions are proposed to be included as minimally required functions.

- Current interruption: interrupt a DC fault current upon receiving a trip order.
• **Close operation**: close upon receiving a closing order.

• **O-C-O operation**: a DCCB is required to have a repeated O-C-O capability upon receiving trip-closing-trip order from the IED, in case of backup protection or overhead line applications.

• **Monitoring and communication**: a DCCB is required to monitor and communicate breaker status (such as, open/close and ready-to-operate) to the IED for protection coordination.

### 4.2 Auxiliary functions

The following functions are identified as auxiliary, therefore, optional in HVDC grid protection.

• **Proactive opening**: refers to the capability of a DCCB to proactively open the load current branch and commutate the current to the main branch upon receiving an initiating signal from the IED, prior to the fault being identified on the line [3]. The DCCB is also required to abort the proactive opening and revert to normal operation, preferably without causing voltage and current transients if the fault is not identified on the line.

• **Fast reclosing/reopening**: refers to the capability of a DCCB to keep certain component(s) in close/open position to perform fast reclosing/reopening. For instance, the DCCB can keep the RCB in closed position during an O-C cycle in case of breaker failure backup operation to eliminate the opening and reclosing delay of the RCB, or keep the load current branch in open position to achieve fast second opening during an O-C-O cycle [20].

• **Fault current limiting (FCL) mode**: refers to the capability of a DCCB to control the DC current to desired values during a fault or DC voltage restoration [7, 25–28].

• **Breaker failure internal detection**: refers to the capability of a DCCB to internally monitor and detect a breaker failure during current interruption [29].

• **Self-protection**: this function entails two sub-functions: (1) opening without a trip order from the IED. In case of abnormal operating conditions, such as thermal overloading of power electronics or surge arresters, the DCCB may be required to trip without the receipt of an external trip order [20]. (2) maintaining closed state. Although the DCCB is ordered to open by an external trip order, the DCCB closes itself again during the opening process if its internal monitoring predicts the DCCB is not able to interrupt the fault current [6,29].

Other functions such as integrated current flow control and DCCBs with unidirectional fault current interruption have also been proposed in the literature [15, 16]. However, they are not considered in this paper as the focus is on the functions related to fault clearing with the highest selectivity.

### 5 IED INTERFACES

To achieve the minimally required functions and allow for auxiliary functions, the interfaces between an IED and DCCB are proposed as shown in Fig. 4. The principles used for proposing the interfaces are: (1) the interfaces should provide control of all minimally required functions for any DCCB technology, (2) the optional interfaces should provide control of all auxiliary functions considering different DCCB technologies, (3) the interfaces are optional if certain
DCCB technology does not provide the auxiliary function, and (4) the interface should contain a minimum number of signals required for the control of all functions.

The inputs and outputs of a IED are divided into (1) local and remote measurements from measurement devices, (2) interfaces between the IED and DCCB, (3) interfaces between the local and remote IEDs for fault identification, and (4) breaker failure detection inputs and outputs between the IED and the adjacent IEDs in the same substation.

**Figure 4: Proposed interfaces between the IED and DCCB (blue: minimally required, magenta: auxiliary, \(N_p, N_l\): the number of poles and lines).**

### 5.1 Local and remote measurements

Depending on the fault detection and identification algorithms, local and/or remote measurements may be used. Local voltage and/or current measurements (\(V_{\text{LCL}}, I_{\text{LCL}}\)) are typically used for non-unit protection algorithms, such as voltage/current derivative and travelling wave extraction [30]. For current differential algorithms, both local and remote currents (\(I_{\text{REM}}\)) are required [31].

### 5.2 Interfaces with the remote IED

The interfaces between the local and remote IEDs are required when communication-based protection algorithms are used. Examples are travelling wave differential, travelling wave tripping and blocking scheme, and current directional comparison [32, 33]. For a travelling wave differential algorithm, locally calculated travelling wave signals (\(TW_{\text{REM_OUT}}\)) are sent through the communication channel to the remote IED to compare the travelling waves. Similarly, blocking, tripping and current directional signals (\(BLK_{\text{REM_OUT}}, TRIP_{\text{REM_OUT}}, ISIGN_{\text{REM_OUT}}\)) are communicated between the local and remote IEDs to assist fault identification.

### 5.3 Interfaces between the IED and DCCB

Similar to the DCCB functions, the interfaces between the IED and DCCB are divided into minimally required and auxiliary.

**Minimally required interfaces**

These interfaces (highlighted in blue in Fig. 4) are required for all DCCB technologies to enable the minimally required DCCB functions.
• **TRIP_BRK**: open (1) and close (0) order to the DCCB. A change from low to high initiates breaker opening and high to low initiates breaker closing. TRIP_BRK becomes 1, if a DC fault is identified on the line or one of the adjacent DCCB has failed, which requires backup protection.

• **ST_BRK**: open (1) and closed (0) status of the DCCB.

• **BRK_RDY**: indicates ready-to-operate (1) and not-ready-to-operate (0) status. For instance, the DCCB may required certain time between a consecutive opening and closing cycle due to thermal limits. The BRK_RDY signal monitors such thermal status of the DCCB and will change from 0 to 1 once it is ready for the next operation.

**Auxiliary interfaces**

These interfaces (highlighted in magenta in Fig. 4) are optional for all DCCB technologies. Any DCCB technology can make use of these interfaces to enable its auxiliary functions or otherwise disregard them.

• **BRK_I_REF**: used for initiating a proactive opening (BRK_I_REF = 0) and FCL mode when a DC fault is detected but not identified on the line. The reference current level during FCL operation is typically in the range of 1 – 2 pu. A high value (e.g. 5 pu) can be used to indicate a no-operation status. In the literature, an additional fault detection signal is typically used in combination with the current reference to initiate proactive opening or FCL mode [25, 26]; however, this paper uses only the current reference to minimize the number of interfaces.

• **TRIP_RCB**: open (1) and close (0) order to the RCB of a DCCB for fast reclosing or reopening. This external RCB control offers the flexibility to eliminate the time delay introduced by the RCB operation during reclosing or reopening.

• **ST_RCB**: open (1) and closed (0) status of the RCB of a DCCB.

• **BRK_HLH**: remains high (1) is the DCCB is healthy, and changes to low (0) if a breaker failure is detected internally.

### 5.4 Coordination signals with adjacent IEDs

Local breaker failure backup detection is performed at the IED and a breaker failure detection (BRK_FAIL_OUT) is sent to the adjacent IEDs to trip the adjacent DCCBs. In the meantime, breaker failure inputs (BRK_FAIL_IN) from the adjacent IEDs are used to trip the DCCB when any of the adjacent DCCBs fails during a DC fault.

### 5.5 Example implementations of the IED

An example of the IED implementation in PSCAD/EMTDC for a mechanical and hybrid DCCB is shown in Fig. 5. The IED is composed of four function blocks: breaker monitoring, fault detection and identification, coordination with local IEDs and breaker failure detection. Breaker failure internal protection is assumed for both examples to enable fast breaker failure backup protection.

The main differences of the implementations between mechanical and hybrid DCCBs are the control of the RCB, proactive opening and FCL mode. For mechanical DCCBs, as opening the RCB is required as part of the fault current interruption process [20], one trip command TRIP_BRK is sufficient to open or close the DCCB; whereas a separate signal TRIP_RCB is
used to operate the RCB for hybrid DCCBs to facilitate fast reclosing or reopening. Correspondingly, the status of all components are monitored by ST_BRK for mechanical DCCBs; while for hybrid DCCBs, ST_BRK only monitors the load commutation switch (LCS), the ultra fast disconnector (UFD), and the main breaker (MB) and ST_RCB monitors the status of the RCB.

Figure 5: An example of IED implementations. (a) For mechanical DCCB (b) For hybrid DCCB (breaker status: 1 open, 0 closed; trip signals: 1 trip, 0 close, unused interfacing signals are marked with gray).

6 TEST SYSTEM

A four-terminal test system is developed to demonstrate the minimally required and auxiliary functions using the proposed interfaces, based on the test system used in [25]. The converters are modelled with a Type 4 detailed equivalent circuit model as specified in [34], where individual submodule switching states and capacitor voltages are represented. All converters have the same power rating of 1265 MVar. During normal operation, MMC2 and MMC4 are operating in active power control mode, exporting 600 MW and 1000 MW, respectively. MMC1 and MMC3 are operating in voltage power droop control mode, importing 1200 MW and 400 MW, respectively. The main parameters of the converter station are listed in Table 1.

Figure 6: A four-terminal symmetrical monopolar test system.
Table 1: Converter and grid parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated apparent/active power $S/P_{DC}$</td>
<td>1265/1200</td>
<td>[MV A/MW]</td>
</tr>
<tr>
<td>Rated DC voltage $U_{DCp},U_{DCn}$</td>
<td>±320</td>
<td>[kV]</td>
</tr>
<tr>
<td>Rated transformer voltages</td>
<td>400/333</td>
<td>[kV]</td>
</tr>
<tr>
<td>Transformer leakage impedance</td>
<td>0.18</td>
<td>pu</td>
</tr>
<tr>
<td>Arm capacitance $C_{arm}$</td>
<td>22</td>
<td>[$\mu F$]</td>
</tr>
<tr>
<td>Arm inductance $L_{arm}$</td>
<td>42</td>
<td>[mH]</td>
</tr>
<tr>
<td>Arm resistance $R_{arm}$</td>
<td>0.6244</td>
<td>[$\Omega$]</td>
</tr>
<tr>
<td>Converter DC smoothing reactor $L_{DC}$</td>
<td>10</td>
<td>[mH]</td>
</tr>
</tbody>
</table>

Table 2: Main parameters of the hybrid and mechanical DCCB.

<table>
<thead>
<tr>
<th>DCCB</th>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td>LCS commutation time</td>
<td>$T_{LCS}^0$</td>
<td>250 $\mu$s</td>
</tr>
<tr>
<td></td>
<td>UFD opening/closing time</td>
<td>$T_{UFD}^0/T_{UFD}^c$</td>
<td>2/2 ms</td>
</tr>
<tr>
<td></td>
<td>RCB opening/closing time</td>
<td>$T_{RCB}^0/T_{RCB}^c$</td>
<td>30/30 ms</td>
</tr>
<tr>
<td></td>
<td>UFD/RCB residual current</td>
<td>$I_{chUFD}/I_{chRCB}$</td>
<td>0.01/0.01 kA</td>
</tr>
<tr>
<td></td>
<td>Line inductor</td>
<td>$L_{line}$</td>
<td>50 mH</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Main vacuum interrupter opening/closing time</td>
<td>$T_{V I}^0/T_{V I}^c$</td>
<td>8/50 ms</td>
</tr>
<tr>
<td></td>
<td>RCB opening/closing time</td>
<td>$T_{RCB}^0/T_{RCB}^c$</td>
<td>30/8 ms</td>
</tr>
<tr>
<td></td>
<td>Making switch opening/closing time</td>
<td>$T_{MS}/T_{MS}$</td>
<td>30/8 ms</td>
</tr>
<tr>
<td></td>
<td>Main VI/RCB residual current</td>
<td>$I_{chVI}/I_{chRCB}$</td>
<td>0.01/0.01 kA</td>
</tr>
<tr>
<td></td>
<td>Line inductor</td>
<td>$L_{line}$</td>
<td>100 mH</td>
</tr>
</tbody>
</table>

6.1 DCCB model

An active resonance injection based mechanical DCCB (Fig. 2 (a)) and an IGBT-based hybrid DCCB (Fig. 3 (a)) are modelled as examples for validation, based on models developed in [20, 25]. Other types of mechanical and hybrid DCCBs, such as the VSC assisted and H-bridge ones are expected to have comparable performance as the examples. The parameters of the DCCBs are taken from [20], and the most important ones are shown in Table 2.

For the mechanical DCCB, two parallel interruption branches, including mechanical switches $S_{3,a}, S_{3,b}$ and capacitors $C_{p,a}, C_{p,b}$ are modelled for repeated O-C-O operation. One trip signal TRIP_BRK and three breaker monitoring signals ST_BRK, BRK_HLH, and BRK_RDY are used for the mechanical DCCB.

A four-submodule hybrid DCCB with proactive opening, fault current limiting, fast reclosing and fast opening functions is implemented in PSCAD. Trip signals, TRIP_BRK, TRIP_RCB, breaker current reference signal, BRK_I_REF, and breaker monitoring signals are used for the hybrid DCCB. The proactive opening is initiated by a falling edge of the breaker current reference, BRK_I_REF (5 to 0 pu) to start the opening process of the load current branch (Fig. 3 (a)). The FCL operation is controlled by BRK_I_REF and breaker internal overcurrent detection, and automatically stopped once the breaker current decreases below a pre-determined threshold. Details on the IGBT-based hybrid DCCB model can be found in [25].

6.2 IED model

Both primary and local breaker failure backup protection are implemented in each IED. At the DCCB side, breaker failure internal detection is implemented and the BRK_HLH signal is used
to communicate the breaker failure status to the associated IED.

**Primary protection**

A two-out-of-three voting scheme with three independent fault detection algorithms is used in this paper for the primary protection. For line protection IEDs, a non-unit algorithm using voltage and current derivative [30], a travelling wave derivative algorithm, and a travelling wave blocking scheme [33] are implemented as examples. For the IEDs associated with the converter DCCBs, a voltage derivative instead of travelling wave blocking scheme is used. The sampling frequency of the primary protection algorithms is 100 kHz. Derivatives are calculated based on 5 samples using the following equation,

$$dX_n = \frac{\sum_{i=0}^{4} X(n-i) - \sum_{i=5}^{9} X(n-i)}{5}$$

(1)

**Local breaker failure backup protection**

Fast breaker failure protection based on local voltage and current measurements are implemented at each line protection IED. The adopted algorithm trains a classifier using linear discriminant analysis based on voltage and current data samples, obtained from simulating cleared and uncleared faults along a cable. The classifier is expressed in equation (2), where $y_{th}$ is the threshold to distinguish cleared and uncleared faults. Detailed description of the algorithms can be found in [35].

$$\begin{cases} 
    y_k = \omega_1 i(k) + \omega_2 u(k) \\
    y_{th} = \frac{y_1^d + y_2^d}{2} 
\end{cases}$$

(2)

where $y_k$: transformed value of the classifier, $i(k), u(k)$: the $k^{th}$ current, voltage sample, $\omega_1, \omega_2$: the voltage and current coefficients, $y_1^d$ and $y_2^d$: two closest transformed samples from uncleared and cleared faults.

**Breaker failure internal protection**

Breaker internal commutation currents and current derivative criteria are used for internal failure detection, based on [29]. The LCS and UFD currents are used for monitoring the internal commutation process for a hybrid DCCB. The breaker failure internal detection functions are given in equation (3).

$$BRK_{HLH} = 0, \quad \begin{cases} 
    |i_{LCS}| > I_{thr}, t > t_{trip} + T_{LCS}^o, \text{ or} \\
    |i_{UFD}| > I_{thr}, t > t_{trip} + T_{UFD}^o, \text{ or} \\
    \frac{di_{CB}}{dt} > -I_0, t_{trip} + T_{UFD}^o < t < t_{trip} + T_2 
\end{cases}$$

(3)

where $t_{trip}$ is the tripping instant. The first two overcurrent criteria operates when the current in the LCS or UFD is larger than the pre-determined threshold after the opening time has elapsed. The third criterion operates when the current decreases slower than the pre-determined threshold, $I_0$. The fault current suppression is expected to happen between $t_{trip} + T_{UFD}^o$ to $t_{trip} + T_2$. Similarly, the current in the main vacuum interrupter $i_{V I}$ is used for internal failure detection in a mechanical DCCB.

**7 CASE STUDIES**

In this section, using the proposed interfaces to enable the aforementioned auxiliary functions and repeated O-C-O operation is demonstrated by simulation studies.
7.1 Proactive opening

A solid pole-to-pole fault at the cable $L_{13}$ terminal near bus 3 ($f_1$) is applied at 0 ms in the simulation. All DCCBs are modelled as hybrid types, while the proactive function of DCCB$_{31}$ is enabled or disabled to demonstrate the impact. The proactive function of all the rest DCCBs are disabled throughout the simulations.

In case 1 where the proactive function of DCCB$_{31}$ is disabled, the breaker current reference BRK$_{1}$ I REF remain high (5 pu). On the contrary, in case 2 once the fault is detected, BRK$_{1}$ I REF changes from 5 to 0 pu, which initiates the proactive opening of the load current branch, and the LCS is opened after a presumed commutation delay of 250 $\mu$s. Compared to case 1 where proactive opening is disabled, using proactive opening during primary protection reduces the breaking current and energy of the DCCB, and the fault interruption time. These reductions are more pronounced especially for a slow fault identification.

![Figure 7: Proactive opening of a hybrid DCCB (DCCB$_{31}$). Subscript 1: proactive opening disabled, subscript 2: proactive opening enabled, fault location: $f_1$.](image)

7.2 FCL operation of hybrid DCCBs

FCL operation of hybrid DCCBs are found to be particularly effective when working with slow DCCBs, such as at the same busbar or converter side [25, 26]. Using FCL operation of the adjacent hybrid DCCBs at the same busbar to a mechanical DCCB is demonstrated in this case. The line breaker DCCB$_{31}$ is assumed to be a mechanical DCCB. All other DCCBs are assumed to be hybrid ones.

After the trip order, TRIP BRK31 changes from 0 to 1, the mechanical DCCB starts to open. If the FCL operation is disabled, the current reference BRK$_{1}$ I REF34 and BRK$_{1}$ I REFC3
remains high, FCL operation of DCCB\textsubscript{34} and DCCB\textsubscript{C3} are not activated (Fig. 8 (a)). On the contrary, the current references change from 5 to 2 pu if the FCL operation is enabled, and DCCB\textsubscript{34} and DCCB\textsubscript{C3} start FCL operation and control the breaker current to 2 pu. The FCL operation stops automatically by DCCB internal control once the current reduces below a predetermined threshold after fault clearance by the mechanical DCCB\textsubscript{31} (Fig. 8 (b)). Note that the arcing voltage of the mechanical DCCB is assumed to be high enough to ensure successful opening during the FCL operation.

The advantages of using FCL operation of hybrid DCCBs are a reduced breaking current and energy absorption of the mechanical DCCB, and a decreased fault interruption time. The energy dissipated in the mechanical DCCB is reduced from 22.4 MJ to 5.4 MJ by using FCL operation of the adjacent hybrid DCCBs in this particular example.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{FCL operation of hybrid DCCBs with a mechanical DCCB, fault location: \(f_1\).}
\end{figure}

7.3 Fast reclosing during backup protection

A solid pole-to-pole fault is applied at the middle of cable \(L_{13} (f_2)\) to demonstrate the fast reclosing function of hybrid DCCBs during backup protection. The line breaker DCCB\textsubscript{31} is assumed to have failed during the fault clearing process, and the breaker failure is detected by the local breaker failure detection at the IED. All DCCBs are hybrid type with a breaker opening time of 2 ms and a line inductor of 50 mH.

Once the fault is identified by IED\textsubscript{13} and IED\textsubscript{31}, trip signals of the main breakers and RCBs, TRIP\_BRK\textsubscript{13}, TRIP\_BRK\textsubscript{31}, TRIP\_RCB\textsubscript{13} and TRIP\_RCB\textsubscript{31} change to high (Fig. 9 (a)).
The status of the main breaker and the RCB change to high (open) once they are fully opened (Fig. 9 (b)). The local breaker failure backup protection at IED$_{31}$ detects a breaker failure, consequently, the main breakers of DCCB$_{34}$ and DCCB$_C3$ are ordered to open by TRIP_BRK34 and TRIP_BRKC3, respectively (Fig. 9 (a)). In the meantime, the trip signals of the RCBs (TRIP_RCB34 and TRIP_RCBC3) remain low to enable fast reclosing function. The fault current in RCB$_{31}$ reaches below the residual current level once the fault current is interrupted by the adjacent DCCBs, and the status of RCB$_{31}$, ST_RCB31 changes to high (open). After a predetermined reclosing waiting time of 40 ms, the trip signals, TRIP_BRK34 and TRIP_BRKC3 change to low and reclose the main breakers.

The fast reclosing function allows for fast voltage and power restoration without opening and reclosing the RCB. The voltage and power restoration time are at least 60 ms shorter than without fast reclosing in the studied case, as it takes 30 ms to open and another 30 ms to reclose the RCB.

![Figure 9: Fast reclosing during breaker failure backup protection, fault location: $f_2$.](image)

### 7.4 Breaker failure internal detection

The simulation conditions are same as in section 7.3, other than that the breaker failure internal detection function of DCCB$_{31}$ is enabled.
Compared to the local breaker failure detection BF_LCL31, the internal breaker failure detection BF_HLH31 indicates a breaker failure as soon as the commutation time (with a margin of 250 µs) has elapsed after receiving the tripping order (Fig. 10 (a)). This leads to faster opening of the backup DCCBs and reduction on the breaking current and absorbed energy as compared to using local backup detection (Fig. 9 (c)–(d) and Fig. 10 (c)–(d)).

![Figure 10: Breaker failure internal detection, fault location: \( f_2 \).](image)

### 7.5 Repeated O-C-O operation

The cable section \( L_{13} \) is replaced with a 350 km overhead line, and a permanent pole-to-pole fault is applied at the middle of the line \( (f_2) \). The de-ionisation time of the overhead line is assumed to be 200 ms in the simulation [36].

#### 7.5.1 Hybrid DCCB

Both cases with the fast reopening function disabled and enabled are compared in the case of a hybrid DCCB. When the fast reopening function is disabled, the LCS and UFD are closed during the closing operation. Although the fault is identified again as soon as the main breaker is closed, the second opening operation needs to wait until finishing the closing operation (Fig. 11 (a)). On the contrary, the fast reopening function allows the LCS and UFD remain opened during the O-C-O operation, and the main breaker interrupt the fault again with a negligible delay (Fig. 11 (b)) [20]. The breaking current and energy duties during the second opening operation are considerably small compared to the case with the fast reopening disabled.
Fast reopening disabled

Fast reopening enabled

Figure 11: Repeat O-C-O operation of a hybrid DCCB for a pole-to-pole fault on an overhead line section, all DCCBs: hybrid type, fault location: $f_2$.

7.5.2 Mechanical DCCB

During the first opening operation, the first resonance injection branch, $S_{3,a}, C_{p,a}$ is used. The main vacuum interrupter, the RCB and the making switch, $S_{3,a}$, start to operate at the same time after the trip order is sent to the mechanical DCCB. The status of the RCB becomes open after the current in the DCCB reaches to the residual current level. The main vacuum interrupter and the RCB are closed with a closing mechanical delay of 50 ms after the presumed de-ionisation time. The fault is again identified as soon the DCCB is closed and the second resonance injection branch, $S_{3,b}, C_{p,b}$ is used for the opening operation with the same opening sequence. The breaking current and energy duties are of similar degree for both opening operations.

Figure 12: Repeat O-C-O operation of a mechanical DCCB for a pole-to-pole fault on an overhead line section, all DCCBs: mechanical type, fault location: $f_2$. 

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8 CONCLUSION

In this paper, the main functions of the DCCBs are classified into minimally required and auxiliary based on a literature review. To enable both types of functions for various DCCB technologies, standardised interfaces between IEDs and DCCBs were proposed and implemented in a four-terminal test system in PSCAD/EMTDC. The simulation studies demonstrated that the proposed interfaces allow both hybrid and mechanical DCCBs to achieve their designed functions. In particular, it is shown that the auxiliary functions of hybrid DCCBs and breaker failure internal detection have the advantage of reducing breaking current and absorbed energy. In addition, the proposed interfaces were shown capable of enabling various DCCB technologies to achieve multivendor interoperability in a single HVDC grid.

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