Series LC DC circuit breaker

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Abstract: The article proposes a mechanical DC circuit breaker (CB) based on a series LC circuit. It requires two switches (a fast disconnector and an AC circuit breaker), an inductor and a capacitor, and therefore the cost is expected to be low. A series LC circuit is analysed and it is concluded that fault current will always have natural zero-current crossings which enable use of simple AC CBs. The current commutation into a capacitor is investigated since this is important for successful operation. A number of analytical conditions are derived for the voltage stress across disconnector contacts which enable arc-less contact opening. Experimental results on a 900 V laboratory prototype LC DC CB illustrate successful DC fault clearing, with commutation of 130 A and peak DC current of 190 A. A detailed PSCAD model for 320 kV LC DC CB is developed and DC fault clearing is evaluated in order to understand the possible benefit for high-voltage direct current applications. Further comparisons with the commercialised hybrid DC CB and mechanical DC CB on 320 kV system illustrate some benefits in terms of performance and simplicity. The mechanical LC DC CB operates very fast because of early capacitor insertion, and this results in low peak current and energy dissipation.

1 Introduction

There is significant interest to advance high-voltage direct current (HVDC) transmission technology into multi-terminal DC and DC grids worldwide [1]. There are multiple technical, operational and cost-related difficulties to achieve this goal, but the lack of DC circuit breaker (CB) with acceptable performance and affordable costs is the most prominent technical challenge. Additionally, cost-effective DC CB would bring significant benefits in many other DC systems in industry at medium DC voltage level.

Some of the main challenges with DC faults are [2, 3]:

i. DC fault current has no zero crossings which imply that conventional AC CBs cannot be used. More complex devices are required.

ii. DC fault current will rise to very high values in short time. Fast operating speed (i.e. few milliseconds) is an essential requirement for DC CBs.

iii. DC CBs will require large energy absorbers, which add to DC CB size, weight and cost.

Different DC CB technologies (i.e. solid state, mechanical, and hybrid) have been developed and high-voltage prototypes demonstrated [4–8]. The first generation of DC CBs employed conventional AC interrupters with a passive resonant circuit which generally required quite long arcing of 10–50 ms before interruption [4]. A faster mechanical DC CB with opening time of around 8 ms has also been developed recently and demonstrated as high-voltage prototype [5]. It requires two vacuum AC CBs with fast driving mechanism, and employs pre-charged capacitor. These mechanical topologies generally lead to dissipation of large amount of DC fault current energy, which may reach 30–70 MJ.

The hybrid IGBT-based DC CB [7], is the fastest operating technology, where opening time is specified as 2 ms (time for DC voltage to recover and time to peak current). It also provides low-loss operation in closed state. However, high voltage and current rating for semiconductor valves is the main disadvantage of this DC CB. A unidirectional version requires a semiconductor valve rated for full DC voltage, while bidirectional version will require two such valves which are like valves used in HVDC converters.

The energy dissipation will amount to 10–30 MJ for a typical 320 kV device, which implies large energy absorbers.

The hybrid thyristor-based DC CB [8] is also developed to high-voltage prototype and uses similar topology as IGBT-based hybrid DC CB. It has some advantages of higher current capability and perhaps lower costs, but essentially suffers all shortcomings mentioned with IGBT topology.

The fastest hybrid DC CBs may not be sufficiently fast to avoid converter blocking in case of DC faults. Assuming 2.5 ms total time between fault initiation and peak fault current, the peak current will reach at least 6 kA before the fault is isolated, and this will cause (temporary) blocking of modular multilevel converter HVDC converters. This may become important drawback in DC grid development, since system reliability aspects will be crucial as DC grid grows into very large size.

The cost of DC CB is not known. However, the cost of conventional AC vacuum switches is understood to be much lower than a comparable HV valve used in HVDC [9]. This gives incentive for researching further fully mechanical DC CB topologies.

The high-speed mechanical switches have been known for many years [10–12]. They normally employ Thomson coils which provide very high initial force to enable contact acceleration. Similar high-speed technology has been used for disconnectors and for circuit breakers. Circuit breakers have arc-sustaining contacts which are heavy and require high driving force, thus lowering operating speed.

High-speed disconnectors have the best prospects of achieving required opening speeds at low costs. Nevertheless, the current breaking capability of disconnectors is minimal, and, as an example, it is listed as 1 A in [13, 14]. A very similar device is also employed by another manufacturer [15].

This research proposes to improve speed of DC fault isolation, by exploiting voltage withstand of fast disconnectors while their contacts are on the move. This new method postulates that a disconnector can insert a series capacitor to convert DC to AC, while another conventional AC CB can interrupt the AC current. The goal is to develop a mechanical DC CB topology with high performance and acceptable costs. Theoretical and simulation methods will be used to develop the design method, while low-voltage experimental approach will verify the concept.
Fig. 1 Schematic of series LC DC CB

Fig. 2 Series LC circuit and response when S1 opens
(a) Circuit diagram, (b) Load current, (c) Capacitor voltage, (d) Voltage derivative

2 Series LC DC CB

Fig. 1 shows schematic of proposed LC DC CB. It includes:

- Fast mechanical switch S1, which can be high-speed disconnector. Fast operating speed brings benefits in terms of size, weight and costs of other components.
- Mechanical switch S2, which is a standard AC CB. Enhanced operating speed brings some benefits.
- Inductor Ldc for limiting initial current rise and for creating LC resonance with Cs capacitor.
- Capacitor Cs for limiting voltage gradient while S1 contacts are separating, and for creating zero-crossings by series LC network with inductor Ldc.

The proposed DC CB consists solely of mechanical components which brings cost advantages. Furthermore energy absorber may not be essential, or if used a modest capacity is needed. Capacitor is the most expensive component, but examples further below indicate that the practical value of capacitance is acceptable.

The CB opening process (DC current interruption) is summarised as follows:

i. S1 and S2 are closed and the ON state losses are negligible. Capacitor Cs is discharged since S1 is closed. On receiving DC CB trip signal the S1 switch is commanded to open immediately. In a short time S1 contacts begin to separate.

ii. While S1 contacts gap increases, the load current charges capacitor Cs. Due to relatively large Ldc and Cs, the capacitor voltage will be stable and can be readily estimated using LC circuit theory. At any instant while contacts are moving, the capacitor voltage should be below the voltage withstand capability of S1. It will be shown that this can be achieved with common disconnector designs. In fully open state S1 is stressed to the peak capacitor voltage.

iii. Once S1 is open the series LC circuit converts DC current into AC current. After Cs is inserted in series, S2 experiences only AC current which has natural zero-crossings and can be easily interrupted. S2 open signal is timed considering switch speed, and to reduce arcing. S2 contacts separate, temporary arc is formed as in all AC CBs, and current is interrupted at the next zero crossing.

iv. At this stage the fault current is interrupted, but capacitor Cs is charged. The next closing process can begin with a charged capacitor, as an example if closing of S1 is timed with zero voltage on Cs on the oscillating voltage waveform. Alternatively, Cs can be simply discharged with an external resistor.

The closing process is not analysed in depth, but it is normally not a big challenge even for high voltage DC circuits. If S1 is closed, S2 can readily close even under load current. Alternatively, S2 is firstly closed and then S1 is closed on the exact point of AC voltage Vdc to avoid arcing.

3 Background on series LC circuit

Fig. 2a shows a simple series LC circuit assuming that switch S1 is initially closed. The waveforms are shown for the experimental tests system data used later in the paper, and all parameters are given in the appendix. The initial current is Idc0 = 100 A. Assuming that initially closed S1 opens at t = tsep, the line current and capacitor voltage are shown in Figs. 2b and c. Also, the voltage derivative is of importance and it is illustrated in Fig. 2d. These variables are analytically described by the following formulae:

\[ I_{dc} = I_{dc0}(t - t_{sep}) + \frac{V_{dc0}}{Z_{sep}} \sin(\omega_0(t - t_{sep})) \]  

\[ V_{dc} = V_{dc0} - V_{dc0}(t - t_{sep}) + Z_{dc0}A_0 \sin(\omega_0(t - t_{sep})) \]

where \( A_0 = 2\pi f_0 = 1/\sqrt{L_{dc}C_s}, Z_{sep} = \sqrt{L_{dc}/C_s}, \) and Idc0 is the initial value of Idc at t = tsep. The first and second derivatives of the voltage in (2) are

\[ \frac{dV_{dc}}{dt} = \omega_0 V_{dc0} \sin(\omega_0(t - t_{sep})) + \omega Z_{dc0} \cos(\omega_0(t - t_{sep})) \]

\[ \frac{d^2V_{dc}}{dt^2} = \omega_0^2 V_{dc0} \sin(\omega_0(t - t_{sep})) - \omega Z_{dc0} \sin(\omega_0(t - t_{sep})) \]

The key values of importance are:

- Peak current Idc0 and instant of occurrence tsep:

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$I_{dcp} = \sqrt{V^2_d + V^2_c/Z_0}, \quad \tan(\omega(t_{dcp} - t_{sep})) = \frac{V_d}{I_{dcp}Z_0}$

(5)

Peak voltage $V_{Csp}$ and instant of occurrence $t_{VCsp}$:

$V_{Csp} = V_d + \sqrt{V^2_d + I^2_{dcp}Z_0}, \quad \tan(\omega(t_{VCsp} - t_{sep})) = \frac{I_{dcp}}{V_d}$

(6)

Peak voltage derivative $DV_{Csp}$ and instant of occurrence $t_{DV_{Csp}}$:

$DV_{Csp} = \omega\sqrt{V^2_d + I^2_{dcp}Z_0}, \quad \tan(\omega(t_{DV_{Csp}} - t_{sep})) = \frac{V_d}{I_{dcp}Z_0}$

(7)

There are several properties of this circuit which are of importance for DC CB application:

i. Opening $S_1$ DC circuit converts into AC circuit. A common mechanical AC CB could be used as $S_2$.

ii. As seen in (1), average value of line current is zero, implying that current zero crossings are certain, and energy dissipation at interruption might be low.

iii. Series capacitor is very effective in reducing the peak current magnitude. Peak current and peak voltage remain constant in the oscillating cycles, and can be managed with selection of $I_{dcp}$ and $C_s$.

iv. Low current can also be interrupted. As seen in (1) oscillating current is created even for $I_{dcb} = 0$.

v. The operating speed is high since the current limiting process starts as soon as capacitor voltage begins to rise.

The peak voltage is of the most significance for the switch $S_1$ design, while the peak current has most significant impact on the DC grid. Fig. 3 shows the peak voltage $V_{cp}$ and peak current $I_{dcp}/I_{dcb}$, depending on $Z_0$, where $Z_0 = 1$ corresponds to the base case in Fig. 2.

4 Current commutation from switch to a capacitor

4.1 Essential design condition

An important aspect of the DC CB design is the capability to commutate current from the switch $S_1$ to the capacitor $C_s$.

The withstand (or breakdown) voltage across contacts $V_{br}$ is assumed linearly proportional to the contact separation $z$, at any instant while contacts are moving $0 < z < z_{max}$:

$V_{br} = zd, \quad 0 < z < z_{max}$

(8)

where $d$ is the dielectric strength of gap medium, which for air is $d_{air} = 3 \text{ kV/mm}$, while for SF6 it is $d_{SF6} = 7.5 \text{ kV/mm}$ [16]. $z_{max}$ is the maximum contact distance achieved at time $t_{max}$. In order to avoid strike at any point while contacts are moving, the following essential condition should be satisfied:

$zd > V_{br}, \quad 0 < z < z_{max}$

(9)

where capacitor voltage $V_{Cs}$ is assumed identical to the gap voltage. The actual voltage waveform $VCsp$ is the complex expression in (2). The contact distance $z$ will be another complex trajectory which depends on the chosen switch $S_1$. Some simplifications will be assumed in order to derive practical design conditions. There is no need to consider thermal aspects since no notable arcing is occurring.

4.2 Final voltage condition

The first design condition is obtained assuming that capacitor voltage at maximum separation distance is adequate:

$dz > V_{Cs}, \quad z = z_{max}, \quad t = t_{max}$

(10)

For a given $S_1$, $z_{max}$ and $t_{max}$ will be known and (10) can be used to obtain initial values for $I_{dcb}$ and $C_s$. However (10) would assume an average voltage gradient, and therefore it is not sufficient condition to satisfy (9) for any $z$.

4.3 Topology for considered switch $S_1$

From this point it will be assumed that $S_1$ is a disconnector of a common design topology which is shown in simplified diagram in Fig. 4. Some conventional disconnectors, SF6 switches and oil switches have such design [13, 17–20], which is characterised by lateral contact overlap in closed state. The lateral overlap, denoted as OL, implies that contacts will accelerate to a non-zero velocity at the separation instant. Considering topology in Fig. 4 the contact separation distance $z$ is determined using the absolute contact position $x$:

$z = 2x - OL$

(11)

A high-speed switch will be commonly driven by a pair of Thomson coils, as shown in Fig. 4, which provide fast acceleration, but only an initial pulse of driving force. Therefore, and considering studies in [13, 17], the following two assumptions can be accepted:

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• maximum contact velocity is achieved before contacts separate,  
• contact velocity remains constant after separation \( v = \text{const} \).

For a given \( S_1 \) the contact velocity \( v \) will be known.

### 4.4 Condition at contact separation

At \( z = 0 \), (9) is difficult to analyse because of singularity. To facilitate design around singularity point, (9) is expressed using contact velocity \( v \), and voltage derivative from (3):

\[
d \int_{t_{sep}}^{t} v \, dt > \int_{t_{sep}}^{t_{sep}} \left( \frac{dV_{cs}}{d\tau} \right) \, d\tau, \quad t_{sep} < t < t_{\text{max}}
\]

(12)

The above equation is valid for any final time \( t \) including instant of contact separation \( t = t_{sep} \). Replacing \( t = t_{sep} \) in (12):

\[
v d > \frac{dV_{cs}}{d\tau}, \quad z = 0, \quad t = t_{sep}
\]

(13)

An observation is made firstly that the capacitor voltage derivative may not be zero at the instant of contact separation, as seen in (3) and in Fig. 2d. Replacing (3) in (13) for \( t = t_{sep} \), the second necessary condition for arc-less commutaton is

\[
v d > I_{dc0}C_s, \quad z = 0, \quad t = t_{sep}
\]

(14)

In practical terms, the contact velocity at separation determines current \( I_{dc0} \) that can initiate commutation to \( C_s \).

### 4.5 Average voltage gradient condition

The above two conditions: (10) and (14) are not sufficient to satisfy (9). This is concluded considering that capacitor voltage derivative \( dV_{cs}/d\tau \) has a peak value in interval \( t_{sep} < t < t_{\text{max}} \), and it initially increases as seen from the sign of the second derivative in (4) and from Fig. 2d. A sufficient but conservative condition to satisfy (9) is to assume that voltage has constant gradient equal to peak voltage derivative obtained in (7). This leads to a simple conservative condition:

\[
v d > \sqrt{V_{dc} + I_{dc0}C_{s}}, \quad 0 < z < z_{\text{max}}, \quad 0 < t < t_{\text{max}}
\]

(15)

A more accurate condition for (constant) voltage gradient can be obtained by averaging (12) in the interval between separation and the peak of the first derivative: \( t_{sep} < t < t_{DVdcp} \). This condition can be obtained using (2), (7) and (12):

\[
v d > \frac{V_{cs}}{I_{DVdcp}}, \quad t = t_{DVdcp}
\]

(16)

### 5 900 V LC DC CB experimental verification

#### 5.1 Experimental circuit

The DC CB testing circuit at Aberdeen laboratory has been used previously for testing hybrid and mechanical DC CBs and is described in [17, 21]. It controls DC voltage to 900–1000 V, and supplies fault current of over 500 A.

Fig. 5 shows the experimental LC DC CB. The high-speed disconnector operates in around 2 ms with 3 mm separation in air, and it is described in [17, 22]. Copper contacts of 20 mm width are used, while the closed-state overlap is \( OL = 1.5 \) mm. Thomson coils are described in [17], and they provide maximum contact velocity of 2 m/s achieved just before the contacts separate, around 400 \( \mu \)s after the trip signal. This disconnector is capable of interrupting only around 0.5 A DC current at voltages over 100 V.

The switch \( S_2 \) is a commercial 900 V Kilovac AC contactor, which has opening time of around 3.2 ms. All the parameters for the experimental DC CB are presented in Table 1. The measuring equipment is:

- *The contact position \( z \) is measured using a hall-effect sensor. Contact separation \( z \) is estimated using (11). Separation velocity is estimated by differentiating \( z \).*
- *Currents are measured using Agilent, 2 MHz, 500 A DC probes, and Voltages are measured using TESTEC, 100 MHz, differential probes.*

Data is captured over 8 ms on Agilent 200 MHz oscilloscope. The time is synchronised with \( S_1 \) trigger.

#### 5.2 Testing current commutation into capacitor

In order to confirm the commutation principle from a switch into a capacitor a simple experimental circuit is created as shown in Fig. 6a. A 10 A current source is shorted with \( S_1 \) switch from the experimental set-up in Fig. 5 which receives trip at \( t = 0 \). The capacitor voltage is a straight line in this case and therefore the conditions (10), (14) and (16) give the same result: \( C_s > 1.8 \) \( \mu \)F. To ensure adequate safety margin, \( C_s = 10 \) \( \mu \)F is selected.

The circuit currents are shown in Fig. 6b, and the conclusion is that the switch current \( I_{dc} \) rapidly reduces to zero, while the main current is commutated to capacitor.

Fig. 6c shows that the capacitor voltage rises fast and no arcing is present. Fig. 6d illustrates that the measured contact velocity is around 2 m/s at separation, which remains constant. After commutation, it is seen that the power supply reduces current because of overvoltage protection, but this does not negate validity of conclusions.

#### 5.3 Testing DC fault current interruption

The value for inductance \( L_{dc} = 6.8 \) mH is determined firstly considering that trip signal is sent at \( I_{dc} = 40 \) A and desired initial
current is $I_{dc} = 130$ A. The condition (14) gives $C_s > 22$ μF, while (15) gives $C_s > 24$ μF. To account for parasitic impedances and to provide consistent safety margin (at $z_{max} = 3$ mm, $V_{max} = 1.3$ kV) $C_s = 160$ μF is selected.

Fig. 7 shows the experimental results for clearing a DC fault. The initial load current is around 5 A, and fault is detected when $I_{dc} > 40$ A. It is seen in Fig. 7c that it takes around 150 μs for contacts to start moving, while separation occurs at $t = 400$ μs. Also, the velocity at separation is $v = 2$ m/s ($t = t_{sep}$) which then remains constant. The speed increase at the very end of travel is a consequence of bi-stable springs.

Fig. 7b shows the $S_1$ switch current, capacitor current and DC line current. It is observed that 130 A is commutated from $S_1$ to $C_s$ instantaneously and without arcing. Many further tests have been performed and no arcing or contact deformation is observed. However no tests are done to optimise capacitance to a smaller value. The DC current is interrupted at first zero crossing (at 4.5 ms) by contactor $S_2$.

Fig. 7a shows that capacitor voltage rises to 1150 V in 1.5 ms, and it is limited by the arresters. The switch $S_2$ is timed in order that the contacts separate when the DC current reduces to a low value, just before the first zero-crossing. It is seen that $S_2$ produces some arcing on voltage $V_{S2}$ which lasts between 4 and 4.5 ms, at low voltage and low (20 A) current. The final voltage increase across $S_2$ (to around 150 V which is difference between arrester and DC supply voltage.) indicates successful interruption.

Fig. 7c shows the full switch contact position trajectory, and it also shows that the contact separation velocity is around 2 m/s.

The experimental LC DC CB is using the same test system, same disconnector and control as the reported hybrid DC CB [22], to enable comparison. However in [22] the current peaks at much higher levels.
higher value of 500 A which is the consequence of 2 ms waiting time for disconnecter to fully open.

6 Evaluation of 320 kV series LC DC CB

6.1 320 kV series LC DC CB design

The LC DC CB concept has not been proven on high voltage hardware. This section gives only estimate of parameters and performance for a 320 kV LC DC CB in order to evaluate if there would be a possible benefit of scaling this topology to 320 kV. The design will be based on the principles in previous sections, and on the available 320 kV components. A complete model is developed in PSCAD, and the main parameters are given in Table 2. The condition (10) results in

\[ C_s \geq 7.8 \mu F, \]

condition (14) gives \( C_s \geq 8 \mu F \), while the condition (15) gives \( C_s = 8 \mu F \). To provide 60% safety margin, \( C_s = 13 \mu F \) is selected. This would be initial capacitor of \( 320 \text{ kV} \), which is four times higher than the capacitor of \( 2 \text{ kA} \) IGBTs (around 2.5 pu). Table 3 shows comparisons according to expected performance of LC and mechanical DC CB components. Energy dissipation reduces as voltage increases, and may not be acceptable for other HVDC components. Energy dissipation reduces as voltage increases, and further optimisation will be required.

6.2 PSCAD model

A detailed dynamic model for contact trajectory of the switch S1 is developed (Thomson coils, driving circuit, mechanical system) as described in [13]. The arcing is not occurring in \( S_1 \) in normal operation and therefore are model is not essential. To simulate a possible dielectric breakdown, which would imply permanent failure of this DC CB, \( S_1 \) contact resistance \( R_{S1} \) is made:

\[ R_{S1} = \begin{cases} 0.002 \Omega, & v_{CS} \geq V_s \\ 10^2 \Omega, & v_{CS} < V_s \end{cases} \]  

(17)

The modelling of DC circuit breaker follows methods described in [24]. A fixed 320 kV DC source is used and DC fault is represented with a 0.1 \( \Omega \) resistance.

6.3 Simulation results

Fig. 8 shows the DC fault clearing simulation results, where the time instants are noted as in previous sections:

- \( t_f = 0.35 \text{ ms} \) – DC fault,
- \( t_0 = 0.0 \text{ ms} \) – fault detected, \( S_1 \)-trip signal, \( I_{dc0} = 2.6 \text{ kA} \),
- \( t_{sep} = 0.55 \text{ ms} \) – contact separation, \( x = 15 \text{ mm}, z = 0 \text{ mm} \), \( I_{dc0} = 3.4 \text{ kA} \),
- \( t_{dc} = 1.65 \text{ ms} \) – peak current, \( V_{CS} = 320 \text{ kV}, I_{dc0} = 4.4 \text{ kA} \),
- \( t_{sep} = 2.2 \text{ ms} \) – maximum gap, \( V_{CS} = 480 \text{ kV}, x = 96 \text{ mm} \),
- \( t_{S2} = 7.5 \text{ ms} – S_2 \) opens, \( I_0 = 0, V_{CS} = 430 \text{ kV} \)

In Fig. 8a it is seen that \( V_{CS} > V_{lim} \), which ensures current commutation to \( C_s \) without arcing. The voltage rises while contacts are moving, and it is limited to 480 kV by the arresters. In Fig. 8b, the peak fault current rises to 4.4 kA, which is just below typical blocking threshold for 2 kA converter IGBTs (around 2.5 pu). Fig. 8c illustrates that \( S_1 \) current commutates fully to capacitor at \( t_{sep} = 0.55 \text{ ms} \). Fig. 8d shows contact position \( x \), separation distance \( z \) and velocity \( v \).

6.4 Comparisons with hybrid and mechanical DC CB

In order to enable initial evaluation, a model for 320 kV hybrid DC CB [7] and 320 kV current injection mechanical DC CB [5] are also developed. In all 3 models, the same \( V_{dc} \), \( L_s \) and energy absorbers are used. The trip signal is at the same instant and therefore the current magnitude at the trip instant \( (t = 0) \) is identical. The resonant circuit components \( (L_p \) and \( C_p \) for mechanical DC CB are calculated assuming 2.6 kHz resonant frequency [5], and they are shown for completeness. Series connection of multiple units might be required.
7 Conclusion

The article proposes a mechanical DC CB based on a series LC circuit (LC DC CB). It requires one fast disconnector, a fast AC Circuit breaker, an inductor and a capacitor, and therefore the cost is expected to be low and comparable with other mechanical DC CBs. It is illustrated that this DC CB converts DC current into AC, which will always have zero-current crossings and hence simple AC CBs are employed for the final interruption. The current commutation into a capacitor when disconnector opens is analysed and it is derived that analytical conditions exist to enable successful commutation.

Experimental results on a 900 V laboratory prototype DC CB illustrate successful DC fault clearing. A very good commutation of 130 A current is observed and clearing of 190 A peak DC fault current is demonstrated.

A detailed PSCAD model for 320 kV DC CB is developed and DC fault clearing is demonstrated, although no demonstrator is built at this voltage. Further comparisons with the existing 320 kV hybrid DC CB and mechanical DC CB illustrate significant possible benefits in terms of performance and costs. LC DC CB operates fast, and this leads to low peak current and energy

Table 3 Comparison of 320 kV series LC, hybrid and mechanical DC CB for identical initial conditions

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<td>t_{max} (V_{dcmax})</td>
<td>2.0 ms</td>
<td>2.0 ms</td>
<td>8.0 ms</td>
</tr>
<tr>
<td>I_{dc} 4.4 kA</td>
<td>5.8 kA</td>
<td>15.7 kA</td>
<td>—</td>
</tr>
<tr>
<td>t_{DCP} (I_{dcpeak})</td>
<td>1.65 ms</td>
<td>2.0 ms</td>
<td>8.0 ms</td>
</tr>
<tr>
<td>E_{a} 5.7 MJ</td>
<td>9.7 MJ</td>
<td>66 MJ</td>
<td>—</td>
</tr>
<tr>
<td>t_{S2} (I_{dc} = 0)</td>
<td>7.5 ms</td>
<td>9.3 ms</td>
<td>25.5 ms</td>
</tr>
</tbody>
</table>

Table 4 Comparison of capacitors for LC and mechanical DC CB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LC DC CB</th>
<th>Mech. DC CB</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{s}</td>
<td>13 μF</td>
<td>3.3 μF</td>
</tr>
<tr>
<td>V_{c}</td>
<td>489 kV</td>
<td>507 kV</td>
</tr>
<tr>
<td>I_{p}</td>
<td>4.4 kA</td>
<td>15.7 kA</td>
</tr>
<tr>
<td>f_{p}</td>
<td>99 Hz</td>
<td>2.7 kHz</td>
</tr>
<tr>
<td>t_{c}</td>
<td>5.5 ms</td>
<td>0.37 ms</td>
</tr>
</tbody>
</table>

Fig. 8 Simulation responses for 320 kV LC DC CB
(a) Capacitor and contact withstand voltages, (b) Load and arrester currents, (c) Switch S_{1} and capacitor currents, (d) Switch S_{1} contact position and velocity
dissipation. Adequate design could potentially achieve very low peak fault current.

8 Acknowledgments

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9 References


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