**1 Introduction**

High-voltage direct current (HVDC) transmission grids have been extensively studied as the means of integrating large renewable energy sources and strengthening network interconnection [1]. DC circuit breakers (DC CBs) play a critical role in DC grids, controlling the closing and opening of the circuits and isolating the faulted DC lines [2, 3]. The fast-rising, high-level short circuit currents in DC grids require high-speed protection devices, and the hybrid IGBT-based DC CBs have been developed for this application [4–6].

The ultra-fast disconnector (UFD) is a crucial component of hybrid DC CBs which determines their opening speed [4, 6]. The UFD should carry high load current with negligible loss and provide full voltage isolation in a very short time, i.e. 2 ms [4, 6]. The UFD can open only under very small current, i.e. 1 A [6], and this is ensured by the proper operation of other components in a hybrid DC CB [4]. The detailed study in [7] has demonstrated that the UFD current during opening will not be zero due to internal parasitics of the DC CB and the leakage through the commutation switch arrester.

The UFD can also be employed as a switching element on its own. In [8, 9], the UFD is used for fast isolation of faulted DC lines in meshed DC grids based on full-bridge modular-multilevel converters. The benefits are significant since the UFD is much lighter, faster and less expensive than a DC CB. UFDs are further used in many advanced DC CB topologies: four UFDs are employed to remove a semiconductor valve in a bidirectional DC CB in [10], a new method for controlling the voltage between UFD’s contacts is shown to reduce fault current in the DC CB by 30% in [11], while in [12], a novel LC DC CB topology based on the fast commutation and controlled UFD voltage is proposed. In traditional bus-transfer switch applications a similar SF₆ disconnector is utilised [13–15].

Considering growing applications, an accurate electromechanical model of UFD is required for the system-level studies (transient stability, protection). An ideal switch model employed in [16] is only applicable if the UFD operates within its safe operating area (SOA) which assumes very low current and no overvoltage. An accurate UFD model is essential for new DC CB designs since the UFD is dynamically stressed very close to its dielectric breakdown voltage and the commutating current approaches limits.

Failure mode study of DC CB is provided in [17]. The scenarios for UFD failure are numerous and include spurious tripping, the failure of the current sensor in the auxiliary branch or the UFD driver failure [17]. A comprehensive UFD model is required to support such studies and estimate the stresses on the UFD and the rest of the components in the breaker.

For DC grid studies such as those in [7, 9], a detailed UFD model is required to verify that the voltage and current stresses on the UFDs during and after fault isolation do not violate the SOA and cause a restrike, with stability impact.

Some studies on UFD contact dynamics have been reported in [18] where the UFD is modelled as an electro-mechanical system with the driver, magnetically-coupled circuit and the dynamic mechanical system. Ritter et al. [13, 14] investigated SF₆ bus transfer switch under arcing but this is a very low voltage disconnector application.

This paper presents a comprehensive UFD model which links the dynamics of the electromechanical UFD model with the UFD failure mode model for accurately representing the UFD operation outside of the SOA. The aim is to develop a UFD model suitable for component and grid-level studies, which describes in adequate detail the UFD under arcing and the conditions for entering/exiting arcing mode for a practical 320 kV unit. The methodology adopted in the study is to:

(i) Develop an analytical model using MATLAB, COMSOL and PSCAD, for both normal and failure modes.
(ii) Verify the model on 5 kV UFD hardware prototype.
(iii) Extrapolate the model to represent a commercial 320 kV UFD, like those reported in [6, 19].

**2 Electro-dynamic UFD model**

**2.1 Electrical circuit modelling: Thomson coil and driver**

The structure of a prototype 5 kV UFD is shown in Fig. 1, which also represents the topology of commercial UFD although the number of breaking points will be higher [19]. TC (Thomson Coil) actuator provides the required energy for trip/close operation of the UFD and it is comprised of a primary stationary coil and a mobile conductive armature (disk plate) connected to the rod with contacts. Fig. 2 illustrates the equivalent electrical circuit of the TC and the driver as implemented in our 5 kV prototype. When the...
The mutual inductance, which gives rise to the motion of the armature, is dependent on the distance between coil and armature, and therefore it is time/position dependent. The variation of mutual inductance is expressed as a linear function:

\[ M = M_0 - \frac{\mathrm{d}M}{\mathrm{d}z}z = M_0 - M'z \]  \hspace{1cm} (2)

where \( M_0 \) (\( \mu \text{H} \)) is the initial value (\( z = 0 \)), \( M' \) (\( \mu \text{H/m} \)) is the rate of change of the mutual inductance, and \( z \) (m) is the position of the armature. Therefore, (1) is simplified as:

\[ R_{sl} + L_{dc} \frac{\mathrm{d}i_d}{\mathrm{d}t} - M_{dc} \frac{\mathrm{d}z}{\mathrm{d}t} = V_{lc} \]  \hspace{1cm} (3)

\[ R_{sc} + L_{dc} \frac{\mathrm{d}i_d}{\mathrm{d}t} - M_{dc} \frac{\mathrm{d}z}{\mathrm{d}t} = 0 \]  \hspace{1cm} (4)

### 2.2 Dynamic mechanical model

The force on armature \( (F_a) \) is expressed as follows:

\[ F_a = F_e - F_f - F_b = m \frac{\mathrm{d}v}{\mathrm{d}t} = m \frac{\mathrm{d}^2z}{\mathrm{d}t^2} \]  \hspace{1cm} (5)

where \( F_e, F_f, F_b \) are the electromagnetic, friction and bistable forces respectively, \( v \) (m/s) is the operation speed of UFD, and \( m \) (kg) is the total mass of armature and the push/pull rod.

The electromagnetic energy in this system \( (w_e) \) is comprised of the stored energy in the coil, the armature and the mutual inductance, which is expressed as:

\[ w_e = \frac{1}{2} L_0 i_a^2 + \frac{1}{2} L_i i_a^2 - M i_a i_c \]  \hspace{1cm} (6)

The electromagnetic force is obtained by differentiating (6):

\[ F_e = - \frac{\mathrm{d}w_e}{\mathrm{d}z} = \frac{\mathrm{d}M}{\mathrm{d}z} i_a \]  \hspace{1cm} (7)

The bi-stable spring provides a force depending on the length, the position of the armature, and the stiffness of the springs as shown in Fig. 3 and can be modelled as [18]:

\[ F_b = 2k(x_0 + |z - L_0| - z_0)^3 - \frac{k}{|z|} \]  \hspace{1cm} (8)

where \( x_0 \) is the pre-compression constant, \( z_0 \) and \( L_0 \) are the initial lengths as shown in Fig. 3; and \( k \) is the stiffness constant.

The friction force comprising of Columb and static friction has been modelled as a function of relative velocity [20]:

\[ F_f = F_C + (F_s - F_C)e^{\frac{(z-z_0)^2}{2\sigma^2}} \]  \hspace{1cm} (9)

where \( F_C \) and \( F_s \) are the Columb and the static frictions, respectively, and \( v_s \) is the Stribeck velocity (at peak value for Stribeck friction).

### 3 UFD model structure

Fig. 4 shows the proposed UFD model structure, consisting of an ideal switch \( S_1 \) (0-open, 1-closed) variable resistor \( R_{arc} \) and an analytical part. \( S_{UFD} \) (0/1) is the control signal received form the DC grid protection, \( F_s \) is the force on armature, \( z_0 \) is the electrode gap analysed in Section 2, while \( R_{arc} \) is the arc model resistance studied in Section 4.
in normal operation, thermal phenomena are neglected in dielectric conditions and is represented as:

$$ V = z_g E_d n_{hop} $$

where $z_g$ is the arc current while $A$ and $B$ are empirically determined constants for a particular air gap distance and current range. Separate Paukert's coefficients at high and low currents are needed because the arc voltage increases with current in the high current range but decreases with the current in the low current range (negative resistance) [23]. The transition current at which this occurs in the Paukert's model is assumed as $I_t = 100$ A [22].

In its original form, Paukert's arc model is not suitable for this application since both the gap distance and current magnitude change dynamically with the operating conditions the UFID is subject to. It is, therefore, necessary for $A$ and $B$ to change as well. To ensure a smooth transition between various Paukert's coefficients, an interpolated Paukert's model is proposed.

The Paukert's coefficients $A_i$, $B_i$, $A_k$, and $B_k$, defined at air gap distances of $z_{g1}$ and $z_{g2}$, respectively and belonging to the same current range, are used to determine the interpolated Paukert's coefficients are obtained as follows:

$$ A_{12} = A_i + \frac{A_k - A_i}{z_{g2} - z_{g1}}(z_g - z_{g1}) $$

$$ B_{12} = B_i + \frac{B_k - B_i}{z_{g2} - z_{g1}}(z_g - z_{g1}) $$

This interpolation makes $A_{12}$ and $B_{12}$ continuous smooth functions of $z_g$ so that (12) covers a wide range of UFID air gap distances. The coefficients $A_i$, $B_i$, $A_k$, and $B_k$ are defined separately for currents above and below the transition current $I_t$. To combine two operating ranges into one smooth function, transition function $O(I_{arc})$ is defined as

$$ O(I_{arc}) = \exp\left(-\frac{I_{arc}^2}{I_t^2}\right) $$

The finalised interpolated Paukert's model is given as

$$ V_{arc} = [1 - O(I_{arc})] A_{12} n_{hop}^h + O(I_{arc}) A_k n_{hop}^h $$

where $A_{12}$, $B_{12}$, for high current ($I_{arc} > I_t$) and $A_k$, $B_k$ for low current ($I_{arc} < I_t$) are interpolated coefficients $A_{12}$ and $B_{12}$. When the current is low, $O(I_{arc}) \approx 1$ so $V_{arc} \approx A_k n_{hop}^h$. Conversely, when current is high, $O(I_{arc}) \approx 0$ so $V_{arc} \approx A_{12} n_{hop}^h$. The pre-calculated arc resistance is obtained by dividing (16) with $I_{arc}$:

$$ R_{arc} = [1 - O(I_{arc})] A_{12} n_{hop}^h I_{arc}^{-1} + O(I_{arc}) A_k n_{hop}^h I_{arc}^{-1} $$

Transferring the arc model from the voltage (16) to the resistance form (17) is advantageous because the resistance, unlike voltage, is independent of the current direction. This simplifies model, since (16) is not real if $I_{arc} < 0$ whereas (17) is evaluated using only the current magnitude.

4.3 Arc resistance calculation in SF$_6$

For high-voltage applications, the UFID is isolated using sulphur-hexafluoride (SF$_6$) rather than air [6]. Owing to its high dielectric strength, SF$_6$-insulated switchgear requires the smaller distance between contacts and has shorter operating time [24]. Despite its widespread use in the electric power industry, the knowledge about SF$_6$ arc modelling is limited, contrary to the arcs in the air where comprehensive experimental data is publicly available [22, 23].

A study on SF$_6$ arcs in DC disconnectors (in the function of a load transfer switch) concluded that the arc resistance at a fixed gap width is generally independent of the current magnitude [13–15]. The same conclusion has also been reached in earlier studies on SF$_6$ arcs [25]. It is assumed that the behaviour of arcs in conventional SF$_6$ disconnectors is similar to the behaviour of arcs in UFIDs, and the arc model from [13–15] is adopted.
Considering the data presented in [14, 15], it is evident that SF$_{arc}$ voltage $V_{arc}$ greatly depends on the gap distance $z_g$, and an analytical expression is derived as:

$$ V_{arc} = 14.3 + 12.33 \cdot z_g^{0.64} \text{ (V)} $$ (18)

where $z_g$ (mm) is gap distance. By dividing (18) with the arc current $I_{arc}$, the expression for SF$_{arc}$ resistance is obtained as

$$ R_{arc} = \left( 14.3 + 12.33 \cdot z_g^{0.64} \right) \cdot I_{arc}^{-1} $$ (19)

5 UFD model verification in normal operation

The UFD model is implemented in PSCAD, considering two test systems: 5 kV laboratory hardware and 320 kV commercial UFD.

5.1 5 kV hardware UFD demonstrator

Fig. 6 shows a photograph of the 5 kV UFD prototype while Table 1 presents the parameter values for TC and driver. This UFD is an upgrade on the UFD prototypes employed in experimental setups in [10–12] The TC and armature used in this UFD is shown in Fig. 7. Two nine-turn TCs are driven from 2700 µF capacitors at a voltage around 300 V to provide double (reciprocal) contact motion for opening/closing operation. The reciprocal motion results in an improvement in the contact separation speed. The mass of each moving assembly (armature, rod and contacts) is about 175 gr. The contacts maximum distance is about 3.5 mm.

Our study not only indicates mutual inductance but also stray inductances and stray parameters which, as shown in (1)–(5), play a significant role in the model. Therefore, COMSOL Multiphysics software has been utilised to numerically evaluate the parameters for electromagnetic interactions.

Fig. 8 shows the current density and the magnetic flux in the holder and coil obtained by COMSOL for 5 kV UFD. As can be seen, the flux is denser in the centre and vertically distributed along the surface which is consistent with results in [18]. The self-inductance and the resistance of the coil ($L_c$, $R_c$) are measured on hardware (an RLC meter LCR-8101G) to confirm COMSOL results. However, it is not feasible to measure inductance and resistance of the disk-shaped armature and discriminate between the self and mutual inductances. These results have been compared with the analytical formula for a single-layer spiral coil as presented in [26]:

$$ L_c = \frac{a^2 n^2}{8a + 11c} \text{ (µH)} $$

$$ a = 0.5 \times (R_o + R_i), \quad c = (R_o - R_i) $$ (20)

where $n$, $a$, and $c$ are the turn number of the coil, the average radius and the thickness of the coil, respectively.

Table 2 compares the results of analytical approach, measurement and COMSOL design for 5 kV UFD. As expected, when the holder is included, the inductance increases owing to the holder magnetic material. Also, when the armature is added, the total inductance of the coil is decreased because of the negative impact of the mutual inductance. Since the COMSOL FEM model is verified, the self and mutual inductances are calculated for a range of gap distances as presented in Fig. 9. It is seen that as the distance of the armature increases, the mutual inductance is decreasing (from $M_0 = 0.047$ µH) at a specific rate of $M' = 0.0044$.

Table 1  TC and driver design parameters for 5 and 320 kV UFD

<table>
<thead>
<tr>
<th>Parameters</th>
<th>5 kV</th>
<th>320 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacitor bank ($C_{tc}$)</td>
<td>2.7 mF</td>
<td>11 mF</td>
</tr>
<tr>
<td>voltage ($V_{tc}$)</td>
<td>300 V</td>
<td>900 V</td>
</tr>
<tr>
<td>$R_C$</td>
<td>15 mΩ</td>
<td>20 mΩ</td>
</tr>
<tr>
<td>disk radiiuses ($R_d$)</td>
<td>25 mm</td>
<td>65 mm</td>
</tr>
<tr>
<td>disk thickness ($T_d$)</td>
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<td>30 mm</td>
</tr>
<tr>
<td>disk material</td>
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<td>Aluminum</td>
</tr>
<tr>
<td>thickness of holder ($H_t$)</td>
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<td>6 mm</td>
</tr>
<tr>
<td>height of holder ($H_h$)</td>
<td>7 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>holder martial</td>
<td>carbon steel</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>number of turns</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>coil width ($C_w$)</td>
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<td>2 mm</td>
</tr>
<tr>
<td>coil height ($C_h$)</td>
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<td>4 mm</td>
</tr>
<tr>
<td>inner radiuses of coil ($R_i$)</td>
<td>6.5 mm</td>
<td>27.5 mm</td>
</tr>
<tr>
<td>outer radius of coil ($R_o$)</td>
<td>21 mm</td>
<td>47.5 mm</td>
</tr>
</tbody>
</table>

5 UFD model verification in normal operation

The UFD model is implemented in PSCAD, considering two test systems: 5 kV laboratory hardware and 320 kV commercial UFD.

Fig. 6 Photograph of the laboratory 5 kV UFD

Table 1  TC and driver design parameters for 5 and 320 kV UFD

<table>
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<td>disk radiiuses ($R_d$)</td>
<td>25 mm</td>
<td>65 mm</td>
</tr>
<tr>
<td>disk thickness ($T_d$)</td>
<td>10 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>disk material</td>
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<td>Aluminum</td>
</tr>
<tr>
<td>thickness of holder ($H_t$)</td>
<td>4.5 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>height of holder ($H_h$)</td>
<td>7 mm</td>
<td>10 mm</td>
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<tr>
<td>holder martial</td>
<td>carbon steel</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>number of turns</td>
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<td>20</td>
</tr>
<tr>
<td>coil width ($C_w$)</td>
<td>1.4 mm</td>
<td>2 mm</td>
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<tr>
<td>coil height ($C_h$)</td>
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<tr>
<td>inner radiuses of coil ($R_i$)</td>
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</tr>
<tr>
<td>outer radius of coil ($R_o$)</td>
<td>21 mm</td>
<td>47.5 mm</td>
</tr>
</tbody>
</table>

Fig. 7  Laboratory TC (coil, holder and armature)
µH/mm. Table 3 shows the final calculated electrical parameters. Table 4 presents the mechanical data of the 5 kV UFD.

To verify the 5 kV UFD electrodynamic model, the experiments have been conducted where the position of each contact is measured using the Hall effect sensor. The experiments are repeated for different charging voltages of TC capacitor, i.e. 300, 200 and 180 V. Fig. 10 presents the measured and simulated motion curves \( z_g \). As can be seen, the armature reaches its final position (3 mm) at about 1.5 ms in case of 300 V capacitor voltage. Some bounce is observed since no dampers are used, which is not included in the PSCAD model. With lower voltages, the stroke is incomplete because of high friction and bi-stable force. Good agreement between experiments and simulations is evident.

### 5.2 320 kV test UFD

The parameters of a 320 kV UFD have been estimated based on the work in [6, 18, 19], considering the reported opening time, contact velocity, dimensions of the armature and developed forces. Key design parameters are summarised in Table 4 while the calculated TC and TC driver parameters are given in Table 1. 33-mF capacitor banks with charging voltage of 900 V provides the required energy for two 20-turn TC to reciprocally move of the contacts and push/pull rod with the weight of about 3.5 kg. The peak voltage of 1.5 p.u. is considered resulting in the total gap distance of about 60 mm assuming one bar SF₆. Five breaking points are assumed, as shown in [19]. Considering 4.25 mm overlap, the maximum stroke travel is about 8.5 mm. Table 3 presents the calculated electrical parameters.

The performance of 320 kV UFD model is evaluated in the case of 900, 700 and 500 V voltage of the TC capacitor bank. Fig. 11 presents the results for the operation speed, motion, coil current, and the electromagnetic force. Theoretically, this UFD could operate within 2–3 ms for considered voltages, while the speed, TC coil current and the force would lie within the range of 1.5–6 m/s, 5–7 kA and 5–25 kN, respectively. The results are compatible with the ranges of these parameters reported in [6, 19]. Considering the reported opening time of 2 ms [4] the charging voltage of 900 V is adopted.

### 6 UFD failure mode validation and verification

#### 6.1 Air insulated UFD

The validation of the air arc model from Section 4.2 has been performed on the downscale 5 kV UFD prototype. The arc model parameters are summarised in Table 5. Fig. 12 shows the experimental results with two test cases – opening at a current of 200 A (high) and opening at a current of 2.5 A (low). The arc voltages are calculated using (16), based on the current (Figs. 12b and c) and position sensor (Fig. 12a) measurements. These comparisons show a very good accuracy which validates the proposed air arc model.
The PSCAD test system for validating the SF$_6$ arc model based on (19) is shown in Fig. 13. It consists of two variable DC voltage sources $V_1$ and $V_2$ with series RL impedance. $V_1$ and $V_2$ represent two DC terminals in a VSC-based DC grid while the RL impedance represents a DC cable with a terminating inductor. In practice, the two DC voltages at cable ends can take a wide range of dynamically changing values, depending on the type of VSC converters, type of faults, and the protection system employed. Two tests are performed to demonstrate the applicability of the SF$_6$ arc model as shown in Table 6.

The results of the first test, simulating spurious opening under load current, are shown in Fig. 14. $V_1$ and $V_2$ are kept constant throughout the test while the series inductance is set to zero to speed up the current transient. The UFD opening command is given at 20 ms while the contact separation starts around 21.1 ms. The model enters arcing mode and the arc voltage increases with the gap distance and reaches 158 V at full separation. As the arc resistance increases, the current through the UFD decreases from 2 to 1.85 kA. Without corrective action from the control system (a change in source voltages), it is visible that the arcing in the UFD can cause a substantial change in the steady-state load current because the voltage difference between the terminals is typically low. However, in the actual HVDC system, this change may be slower because of the cable and DC CB inductances.

The second test, shown in Fig. 15, is developed to verify: (i) entering arc mode on high current; then (ii) exiting on low current; and (iii) entering failure mode on high voltage. A DC fault condition with negative pre-fault current of −2 kA is assumed at 21 ms. At 21.1 ms, the UFD’s contacts separate but, because $I_{\text{UFD}} > I_{\text{chop}}$, an arc is initiated between the contacts. The current is increasing at 3.2 kA/ms. At 21.63 ms, $I_{\text{UFD}}$ falls below $I_{\text{chop}}$ and the arc is temporarily extinguished, as seen by the spike in UFD voltage. However, at this point the contacts have not separated sufficiently to provide blocking voltage to satisfy $V_{\text{UFD}} > V_{\text{max}}$ and a restrike occurs due to dielectric breakdown. The arc is reignited and then the arc voltage continues to rise until full contact separation. Fig. 15e shows the net source voltage ($V_1 - V_2$),

6.2 SF$_6$ insulated UFD

The PSCAD test system for validating the SF$_6$ arc model based on (19) is shown in Fig. 13. It consists of two variable DC voltage sources $V_1$ and $V_2$ with series RL impedance. $V_1$ and $V_2$ represent two DC terminals in a VSC-based DC grid while the RL impedance represents a DC cable with a terminating inductor. In practice, the two DC voltages at cable ends can take a wide range of dynamically changing values, depending on the type of VSC converters, type of faults, and the protection system employed. Two tests are performed to demonstrate the applicability of the SF$_6$ arc model as shown in Table 6.

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---

**Table 5** Electric arc parameters in air for a 5 kV UFD

<table>
<thead>
<tr>
<th>Current, A</th>
<th>Gap distance, mm</th>
<th>A</th>
<th>B</th>
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<tbody>
<tr>
<td>&lt; 100</td>
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</tr>
<tr>
<td>1</td>
<td>36.32</td>
<td>−0.124</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>71.39</td>
<td>−0.186</td>
<td></td>
</tr>
<tr>
<td>&gt; 100</td>
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</tr>
<tr>
<td>1</td>
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<td>0.098</td>
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<tr>
<td>5</td>
<td>14.13</td>
<td>0.211</td>
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**Table 6** Test parameters for a 320 kV UFD arc model

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test 1</th>
<th>Test 2</th>
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</thead>
<tbody>
<tr>
<td>series inductance</td>
<td>$L_s$</td>
<td>0 mH</td>
<td>100 mH</td>
</tr>
<tr>
<td>series resistance</td>
<td>$R_s$</td>
<td>1 Ω</td>
<td>1 Ω</td>
</tr>
<tr>
<td>UFD chopping current</td>
<td>$I_{\text{chop}}$</td>
<td>1 A</td>
<td>1 A</td>
</tr>
</tbody>
</table>
The UFD model is verified for both normal operation and failure mode using a 5 kV laboratory UFD and results show very good matching. The parameters for 320 kV SF₆ UFD model are presented and the model is evaluated using limited reported results from manufacturers.

9 Acknowledgments
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10 References