Research on Dynamic and Thermal Effects Based on the Calculation of the Short-Circuit Current in Low-Voltage DC Distribution Systems for Civil Buildings

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Featured Application: The results of this research can be applied to DC distribution systems. The application of DC power distribution is becoming increasingly widespread. When a short-circuit fault occurs in a DC power system, accurate verification of the dynamic and thermal effects of the short-circuit current is crucial for the safety of equipment and system. This is a subject that must be studied in DC distribution systems.

Abstract: The verification of short-circuit effects is very important for ensuring the safety of equipment and power systems. Compared with that in alternating current (AC) systems, research on this issue in direct current (DC) systems is scarce, and it is urgently necessary to develop an accurate verification method for applications in DC systems. This research establishes an equivalent model of a pole–pole cable short-circuit according to the characteristics of low-voltage DC distribution systems in civil buildings. Through theoretical analysis and numerical simulation, the development process of a short circuit is summarized, and the methods of verifying dynamic and thermal effects based on the time-domain characteristics of the short-circuit current are specified. By calculating the peak value and Joule integral of the short-circuit current, in comparison with those in the IEC 61660 (1997) standard, this research points out that the method in the IEC 61660 (1997) standard is insufficient. Finally, the short-circuit peak current is greatly affected by the DC-link capacitance, the steady-state current is directly related to the filter inductance of the AC-link; and the verification of the thermal effect requires the calculation of the Joule integral in the transient and steady state.

Keywords: low-voltage DC; distribution system; short-circuit current; dynamic effect verification; thermal effect verification; Joule integral; civil building

1. Introduction

The application of photovoltaic power systems in buildings is increasingly widespread; more and more of the electrical equipment in buildings essentially uses direct current, and DC power distribution has many advantages over AC power. With the development and gradual maturity of the technology of power electronics, the application of DC systems has expanded from high-voltage transmission and medium-voltage distribution networks to low-voltage DC distribution systems in buildings. In order to ensure the safe operation of equipment and systems, it is very important to study short circuits currents and related issues in DC systems. Feng et al., Holbein et al., Lee et al., Pozzobon et al., Wang et al., and Xue et al. analyzed the development process and specific calculation of short-circuit currents [1–6]. Schau et al. analyzed the characteristics of a short-circuit arc [7]. Test benches and equivalent models for the study of short-circuit faults were built by Ravty et al. and Wang et al., respectively [5,8]. The authors of [9–12] studied the short-circuit protection of power electronic devices, and the authors of [13–18] conducted studies online protection.
and protection selectivity during short circuits. In [19–21], the researchers studied several fault location methods based on short-circuit currents. Methods of limiting the short-circuit current were proposed by [22–24]. Many scholars have also studied other related issues. Li and Park Zheyuan studied the calculation of various fault currents of ±750 V DC distribution grid [25]. Lim Seung-Taek et al. investigated a mid-point grounding system using capacitors to ensure electrical safety in a mono-polar LVDC system in household [26]. Ma Feiyoue et al. discussed the effects of grounding mode on fault characteristics in flexible DC distribution system [27]. Pavel et al. presented a fundamental building block for LVdc for different applications in meshed dc grids, which is capable of achieving the given control objectives [28]. Wang et al. proposed a time domain piecewise approximate analytical calculation method for AC–DC hybrid system, when the AC system fails at the receiving end [29]. Wu et al. developed a comprehensive isolation protection device that can quickly cut off the short circuit, and can limit the fault in the fault branch [30].

However, there are some issues that have not been fully studied, and the verification of the dynamic effects and thermal effects of short circuits is one of them. To the best of the authors’ knowledge, no published papers have addressed this issue, except for the IEC 61660 (1997) standard [31,32], which has relevant provisions. If the verification of dynamic effects or thermal effects fails, the devices will be damaged; the accident range will expand when a short circuit occurs, and the system safety will also be destroyed. Therefore, it is a key issue to the power system.

For DC system, the IEC 61660-1 (1997) standard [31] provides the calculation method of short-circuit currents, the IEC 61660-2 (1997) standard [32] provides the calculation method of the dynamic effect and thermal effect of short-circuit currents. For AC system, the IEC 60909-0 (2016) standard [33] provides the calculation method of short-circuit currents. However, the method of the IEC 61660 (1997) standard is flawed, which will be explained in detail later.

This research analyzes the various stages of short-circuit currents according to the characteristics of low-voltage DC distribution systems in civil buildings, and it provides accurate verification methods for the dynamic and thermal effect according to the time-domain characteristics of the short-circuit current. For a DC distribution system, the peak short-circuit current is greatly affected by the DC-link capacitance, the steady-state current is directly related to the filter inductance of the AC-link, and the verification of the thermal effects requires the calculation of the Joule integral in the transient and steady state.

This study is organized as follows: Section 2 outlines the characteristics of DC distribution systems in civil buildings, establishes the equivalent models of each stage of a short-circuit fault, and summarizes the calculation process for the short-circuit current. The time-domain characteristics of a short-circuit current are explained through a theoretical analysis and numerical simulation. Section 3 explains the verification process for dynamic and thermal effects according to the time-domain characteristics of a short-circuit current. Sections 4 and 5 compare the methods and results of the IEC61660-1, 2 (1997) standards and those of this research, and provide some useful discussions and summaries.

2. Materials and Methods

2.1. Material: DC Power Distribution Systems for Civil Buildings and Their Characteristics

Civil buildings refer to non-productive residential and public buildings, as opposed to industrial buildings. The system diagram of a typical DC distribution system in civil building is shown in Figure 1. VSC stands for AC–DC converter.

As a user, a civil building is always located at the end of the grid, and its substation is called an “end-user substation”. Compared with the entire grid, its capacity is small and the “electrical distance” from the power plant is long. When the load in a building changes, or even a short-circuit fault occurs, it generally does not cause changes of the grid structure or operation mode, and the output of power plants in the grid changes slightly and slowly. In this way, it can be considered that the parameters of related components in the whole system are fixed within a few seconds after the short circuit occurs, and the
grid outside the building can be replaced equivalently by a series connection of an ideal voltage source and an impedance. At the same time, for the sake of safety and convenient operation and maintenance, the bus structure of a unipolar and the radial network structure are appropriate for the building distribution system. The DC voltage is usually 1500 V, 750 V, 375 V, 220 V, 110 V, etc. In this research, 750 V is used.

Figure 1. Diagram of a DC power distribution system in a building.

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2.2. Equivalent Model of Lumped Parameters

The system shown in Figure 1 can be expressed as the equivalent model shown in Figure 2 by lumped parameters, when the distribution parameters of equipment and lines are ignored.

Figure 2. Equivalent model with lumped parameters.

\[ V_g \] denotes the rated voltage (line–line) of the grid, VSC stands for an AC–DC converter, \[ V_d \] is the rated voltage of the DC bus, \[ i_s \] stands for the short-circuit current, and \[ S \] denotes the short-circuit fault point.

2.3. Theoretical Analysis of the Short-Circuit Current

For verifying the dynamic and thermal effects of short-circuit current and identifying whether it will damage the equipment and destroy the system safety, it is only necessary to verify the situation that the short-circuit current is the maximum, i.e., the line suddenly experiences a short-circuit fault when there is no load.
In this subsection, a prospective short-circuit current is reviewed while ignoring the influence of protective devices. Protective devices reduce the amplitude of the fault current. As a result, the prospective short-circuit current is a necessary basis for Section 3.

Two-level voltage-source AC–DC converters (VSC) are commonly used in the DC distribution in buildings, and a protective circuit blocks the insulated gate bipolar transistor (IGBT) within 1 ms when a short circuit occurs. For a DC system, the short-circuit current is the highest and the situation is the most serious when a pole–pole cable short circuit occurs, and the equivalent model of a VSC and fault circuit is shown in Figure 3.

![Figure 3. Equivalent model of a VSC and short-circuit fault circuit.](image)

$R_g$ and $L_g$ are the total resistance and inductance of the AC-link, including the resistance and inductance of the grid and transformer, as well as the filter inductance of the VSC. $C$ is the capacitor on the DC-link of the VSC. $R$ and $L$ are the total resistance and inductance of the DC-link conductors within the fault circuit, including the bus-bars and cables.

The variation process of the short-circuit current $i_s$ goes through 2 or 3 stages depending on the resistance, capacitance, and inductance of the fault circuit [21].

2.3.1. Under the Condition $R < 2\sqrt{\frac{C}{L}}$, When It Is Under-Damped, the Short Circuit Current Goes through Three Stages [21]

Stage 1: At the moment in which a short circuit occurs, as the impedance of the DC-link plummets, the AC-link voltage is lower than the DC-link voltage, and the diodes are cut off. The capacitor is discharged in an oscillation. The equivalent circuit is shown in Figure 4a. It can be seen that the capacitor discharging current $i_c$ (i.e., $i_s$) rapidly increases, and the capacitor voltage decreases. The state equation and its solution are shown in the following equations:

$$\frac{d^2V_c}{dt^2} + \frac{R}{L} \frac{dV_c}{dt} + \frac{1}{LC} V_c = 0 \quad (1)$$

$$i_c = C \frac{dV_c}{dt} = \frac{V_0}{\omega L} e^{-\delta t} \sin(\omega t) \quad (2)$$

$$\delta = \frac{R}{2L}, \quad \omega^2 = \frac{1}{LC} - \left(\frac{R}{2L}\right)^2$$

where $V_0$ is the initial voltage of the capacitor. The time for the discharge current to reach its peak is:

$$t_p = \frac{\beta}{\omega}, \quad \beta = \arctan\left(\frac{\delta}{\omega}\right) \quad (3)$$
Figure 4. Equivalent model of each stage of a short circuit. (a) Stage 1, capacitor discharge. (b) Stage 2, diodes turn on because of the inductor freewheeling. (c) Stage 3, uncontrolled rectification.

The peak of the discharge current \( i_p \), i.e., the peak of the short-circuit current, can be obtained by bringing Equation (3) into Equation (2).

Stage 2: When the capacitor voltage drops to zero, the diodes are turned on under the action of inductor freewheeling. The AC-link is equivalent to a three-phase short circuit, and the DC-link is an R-L first-order circuit; it is noted that the capacitor voltage at the moment is zero. The equivalent circuit in this stage is shown in Figure 4b. How long this stage lasts depends on the attenuation of the inductor freewheeling; this is difficult to calculate with a formula and can only be roughly determined through simulation.

Stage 3: The equivalent circuit of the entry into a state of uncontrolled rectification and a tendency toward the steady state is shown in Figure 4c; this is a third-order circuit. At this time, the voltage and current \( i_g \) of the DC-link are 6 positive pulsating waveforms. The total impedance \( Z \) in the fault circuit is:

\[
Z = \left[ (R + j\omega_g L)\frac{1}{\omega_g C} \right] + (2R_g + j2\omega_g L_g)
\]

where \( \omega_g \) is the synchronous angular frequency of the grid. The amplitude of the DC-link current \( i_g \) is

\[
I_g = \frac{\sqrt{2V_g}}{|Z|}
\]

In addition, \( i_s = \frac{i_g}{1 - \omega_g^2 LC + j\omega_g RC} \)

Therefore, the amplitude of \( i_s \) is

\[
I_s = \frac{I_g}{\sqrt{(1 - \omega_g^2 LC)^2 + (\omega_g RC)^2}}
\]

Steady-state value of each pulse of short-circuit current is:

\[
i_s = I_s \cdot \sin(\omega_g t), \quad \omega_g t \in \left[ \frac{\pi}{3}, \frac{2\pi}{3} \right]
\]
It can also be approximated that the steady-state value is DC, \((3/\pi)I_s\). The steady-state short-circuit current can be found with Equations (4)–(7), but it is complicated to manually calculate and can be obtained through simulation.

2.3.2. Under the Condition \(R > 2\sqrt{\frac{1}{L}}\), When It Is Overdamped, the Short Circuit Current Goes through Two Stages

Stage 1: Similarly to Stage 1 in Section 2.3.1, the capacitor discharges, and the equivalent circuit is shown in Figure 4a. The state Equation (1) is solved as follows:

\[
i_C = C\frac{dV_C}{dt} = -\frac{V_0}{L(P_2 - P_1)}(e^{P_1t} - e^{P_2t})
\]

\[
P_1 = -\frac{R}{2L} + \frac{1}{\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}}
\]

\[
P_2 = -\frac{R}{2L} - \frac{1}{\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}}
\]

The time for the discharge current to reach its peak is

\[
t_p = \frac{\ln\left(\frac{P_2}{P_1}\right)}{P_1 - P_2}
\]

The peak of the discharge current \((i_p)\), i.e., the peak of the short-circuit current, can be obtained by bringing Equation (9) into Equation (8).

Stage 2: When the capacitor voltage drops below the AC-link voltage, the diodes turn on, the circuit enters a stage of uncontrolled rectification, and it tends to be steady. The equivalent circuit is shown in Figure 4c. Note that the capacitor voltage at this time is not zero, which is different from Figure 4b. Because it is overdamped, the short-circuit current does not go through the stage in Figure 4b. The analysis and calculation in this stage are the same as those in Stage 3 in Section 2.3.1.

2.3.3. Under the Condition \(R = 2\sqrt{\frac{1}{L}}\), When It Is Critically Damped, the Short Circuit Current Goes through Two Stages

Stage 1: Similarly to Stage 1 in Section 2.3.1, the capacitor is discharged, and the equivalent circuit is shown in Figure 4a. The state Equation (1) is solved as follows:

\[
i_C = \frac{V_0}{L}e^{-\delta t}; \delta = \frac{R}{2L}
\]

Stage 2: The stage is the same as that in Stage 3 in Section 2.3.1. Critical damping can hardly be encountered in practice but exists only in theory.

2.4. Numerical Simulation

As mentioned in the first paragraph of Section 2.3, it is only necessary to verify the situation that a circuit experiences a short circuit when there is no load. Assuming that a short circuit occurs at point S in the circuit shown in Figure 2, Figure 5 shows the equivalent model of the fault circuit for simulation.

Assuming the DC-side includes a 6 m-long bus-bar \((50 \times 5\) rectangular copper bar) and a 30 m-long cable \((2 \times 50\) mm² copper core). By consulting their resistance and inductance values per unit length, the total resistance \(R\) and inductance \(L\) can be calculated. For the bus-bar: \(R = 2 \times 0.087\) m\(\Omega\)/m, \(L = 2 \times 0.64\) \(\mu\)H/m. For the cable: \(R = 2 \times 0.435\) m\(\Omega\)/m,
L = 2 × 0.256 μH/m. C is the voltage regulator capacitor of the VSC, and the initial voltage of the DC-bus is \( V_0 = 750 \) V. It can be calculated that \( R < 2 \sqrt{\frac{L}{C}} \).

**Figure 5.** Equivalent model of the short circuit for simulation.

For the AC side, \( R_g \) and \( L_g \) denote the total resistance and inductance of the AC side, including the resistance and inductance of the grid and transformer (4.2 mΩ and 48 μH), as well as the filter inductance of the VSC (1 mH). The parameters of the transformer are 10/0.4 kV, 400 kVA, and \( U_K = 4\% \). Obviously, these parameters are very consistent with the actual situation.

The rated power of the converter is 250 kW, and proportional–integral control is adopted. The frequency of pulse width modulation (PWM) is 5 kHz. The IGBTs will be blocked after a fault occurs.

MATLAB/Simulink was used to simulate this faulty circuit, and the results are listed in Table 1. The waveforms of the short-circuit current \( i_s \) and DC bus voltage \( V_c \) are shown in Figure 6.

**Table 1.** Simulation result.

<table>
<thead>
<tr>
<th>Initial Value (When ( t = 0 ))</th>
<th>Simulation Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_g = 380/220 ) V</td>
<td>( V_0 = 750 ) V</td>
</tr>
<tr>
<td>( i_s = 0 ) A</td>
<td>( i_p = 895 ) A</td>
</tr>
<tr>
<td>( V_c = 25 ) V</td>
<td></td>
</tr>
</tbody>
</table>

\[ V_g = 380/220 \text{V} \]
\[ R_g = 4.2 \text{mΩ} \]
\[ L_g = 1.05 \text{mH} \]
\[ V_0 = 750 \text{V} \]
\[ C_g = 1 \text{mF} \]
\[ R = 27.1 \text{mΩ} \]
\[ L = 23.0 \mu\text{H} \]
Table 1. Simulation result.

<table>
<thead>
<tr>
<th>Initial Value (When t = 0)</th>
<th>Simulation Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_g = 380/220$ V</td>
<td>Peak current $i_p = 4345$ A</td>
</tr>
<tr>
<td>$V_0 = 750$ V</td>
<td></td>
</tr>
<tr>
<td>$t_p = 0.23$ ms</td>
<td></td>
</tr>
<tr>
<td>$i_s = 0$ A</td>
<td></td>
</tr>
<tr>
<td>$i_s = 895$ A</td>
<td></td>
</tr>
<tr>
<td>$V_c = 25$ V</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Waveforms of the short-circuit current $i_s$ and DC-bus voltage $V_c$. (a) The waveforms of $i_s$. (b) The waveforms of $V_c$.

3. Results

Short-circuit effect verification includes the verification of dynamic effects and thermal effects. The peak current $i_p$ should be used for dynamic effect verification; thermal effect verification requires the calculation of the thermal effect with the Joule integral ($\int i^2 dt$) [32]. The IEC61660-1, 2 (1997) standards provide calculation methods for the short-circuit current and its thermal effect, which will be discussed in Section 4. The methods proposed in this research are introduced first.
3.1. Dynamic Effect Verification

After obtaining the short-circuit peak current $i_p$ according to the method in Section 2 or through simulation, the dynamic effects of the electrical equipment and conductors are verified accordingly. For example, the main bus is two parallel rectangular copper bars, and when the short-circuit peak current $i_p$ flows, the electromagnetic force $F$ between the bars is [32]:

$$ F = \frac{\mu_0 i_p^2}{2\pi a_m} $$

where, $\mu_0$ is the vacuum’s magnetic permeability;

$l$ is the center distance between the pillars;

$a_m$ is the effective distance between bus-bars.

The rest of the steps are as specified in the IEC61660-2 (1997) standard [32].

3.2. Thermal Effect Verification

Based on the analysis and the results of the simulation of the short-circuit variation process described in Section 2, the Joule integral can be accurately calculated.

Assuming that the short-circuit duration is $T_k$, according to the process of change in the short-circuit current shown in Figure 6, the calculation of the Joule integral can be divided into two stages: $0$~$T_1$ is the capacitor discharge stage ($i_c$), and $T_1$~$T_k$ is the steady-state current stage ($i_s$). After the two stages are calculated, the total Joule integral is obtained through summation:

$$ \int_0^{T_k} i^2 dt = \int_0^{T_1} i_c^2 dt + \int_{T_1}^{T_k} i_s^2 dt $$

(10)

It is difficult to directly calculate the Joule integral of the capacitor discharge process, but it can be easily obtained from an energy perspective analysis. Figure 7 shows the capacitor discharge circuit.

![Capacitor discharge circuit](image)

Figure 7. Capacitor discharge circuit.

The energy stored in the capacitor is eventually consumed by the resistor R. Therefore [18],

$$ \frac{1}{2} CV_0^2 = \int_0^\infty i_c^2 R dt $$

According to the analysis in Section 2.3.1 and Figure 6b, when the short-circuit current enters Stage 3, uncontrolled rectification occurs, and the AC-link starts to inject the short-circuit current into the DC-link. At this time, the discharge current of capacitor C and the freewheeling of inductor L can be neglected, and the value of $T_1$ can be obtained as 2 ms, as shown in Figure 6b; therefore,

$$ \int_0^{T_1} i_c^2 dt = \frac{1}{2R} CV_0^2 $$

(11)

The Joule integral of the steady-state stage $T_1$~$T_k$ is

$$ \int_{T_1}^{T_k} i_s^2 dt = i_s^2 (T_k - T_1) $$
As shown in Figure 6a, due to the DC component of the short-circuit current on the AC side, at the beginning of Stage 3, \( i_s \) has a fluctuation of the grid’s synchronous frequency. This will make the Joule integral larger, and it can be corrected by referring to Equation (108) in the IEC 60909-0 (2016) standard [33]:

\[
\int_{T_1}^{T_k} i_s^2 dt = i_s^2 (m + n) (T_k - T_1)
\]

(12)

where \( m \) is taken according to Figure 18 in the IEC 60909-0 (2016) standard [33], and \( n \) is taken as 1 according to Figure 19 in the IEC 60909-0 (2016) standard and the discussion in Section 2.1. By bringing Formulas (11) and (12) into Formula (10), the total Joule integral of 0~\( T_k \) can be obtained as follows:

\[
\int_{0}^{T_k} i^2 dt = \frac{1}{2RC} CV_0^2 + i_s^2 (m + 1) (T_k - T_1)
\]

(13)

The rest of the verification steps are as specified in the IEC61660-2 (1997) standard [32]. The thermal effect verification of electrical equipment shall hold the following relation:

\[
\int_{0}^{T_k} i^2 dt < I_{thr} T_k
\]

where \( I_{thr} \) is the rated short-term current of the electrical equipment that can be withstood.

The thermal effect verification of conductors shall hold the following relation [32]:

\[
\int_{0}^{T_k} i^2 dt < \left( S_{thr} A \right)^2 T_k
\]

where \( S_{thr} \) and \( A \) denote the rated short-term current density that can be withstood and the cross-section of the conductor, respectively.

4. Discussion

The circuits shown in Figures 1 and 5 are common and typical for low-voltage DC distribution systems in civil buildings, and the parameters of each component are in line with those in actual projects, so they have great referential significance. By analyzing the resistance and inductance of commonly used cables and the voltage regulator capacitors of converters in practice, it can be found that fault circuits almost always satisfy the condition \( R < 2\sqrt{L} \) when a polar–polar metallic short-circuit occurs in a civil building’s low-voltage distribution system. In actual engineering calculations or simulations, the converter manufacturer should be requested to provide data on the AC-link inductance and DC-link capacitance.

4.1. Comparison and Analysis of Short-Circuit Currents

In the IEC 61660-1 (1997) standard [31], when calculating, the short-circuit current of the rectifier output is simplified and approximated. Figure 8 shows the equivalent circuit that adopts, in which there is no capacitor for stabilizing voltage on the DC-link; therefore, a large deviation may arise. Figure 9 shows the approximated waveform of the short-circuit current used in this standard.

For the system shown in Figure 5, Table 2 shows the results of calculating the short-circuit currents according to the method of the IEC 61660-1 (1997) standard, according to Equations (2) and (3) in this research, and according to the simulation.

It can be seen that the results from the method of the IEC 61660-1 (1997) standard had a large deviation. According to the analysis of the calculation Formulas (13)–(15) and the equivalent circuit in the IEC 61660-1 (1997) standard, the quasi-steady-state current \( I_k \) and peak current \( t_p \) were mainly affected by the impedance of the AC-link.
Figure 8. Equivalent circuit of the rectifier in the IEC 61660-1 (1997) standard.

Figure 9. The approximated waveform of the short-circuit current in the IEC 61660-1 (1997) standard.

Table 2. Short-circuit currents obtained with the three methods.

<table>
<thead>
<tr>
<th>IEC 61660-1 (1997)</th>
<th>According to Formulas (2) and (3)</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi steady-state short-circuit current, ( I_k = 1540 ) A</td>
<td>( t_p = 0.226 ) ms; ( i_p = 4329 ) A</td>
<td>( t_p = 0.23 ) ms; ( i_p = 4345 ) A</td>
</tr>
</tbody>
</table>

According to Formulas (2) and (3) in this research, the short-circuit peak current was mainly influenced by the components on the DC-link. In order to output a stable DC voltage and reduce the ripple in it, the capacitance for stabilizing voltage \( C \) is usually relatively large, and the capacitor discharges at the moment of a short circuit to form an impulse current, so the peak current \( i_p \) is greatly affected by the capacitor \( C \).

According to the analysis of Equations (4)–(7) in this research, the short-circuit steady-state current depends on the total impedance \( Z \) of the fault circuit. The filter inductance on the AC-link of the converter is usually relatively large, so the steady-state current is greatly influenced by the filter inductance \( L_g \).

4.2. Comparison and Analysis of the Joule Integral

The IEC 61660-2 (1997) standard [32] adopts the product of the square of the thermal equivalent of the short-term current \( (I_{th}) \) and short-circuit duration \( (T_k) \), and it assumes
According to the analysis of Equations (4) –(7) in this research, the short-circuit current is calculated according to Formula (13). In engineering practice, the case is almost always Tk > T1.

Table 3. Joule integrals obtained with the three methods.

<table>
<thead>
<tr>
<th>IEC 61660-2 (1997)</th>
<th>According to Formula (13)</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_p = 11.7 ms; T_k = 100 ms</td>
<td>T_1 = 2.0 ms; T_k = 100 ms; m = 0.3</td>
<td>T_k = 100 ms</td>
</tr>
<tr>
<td>A_1 = 402,843 (A^2 S)</td>
<td>∫_0^{T_k} i^2 dt = 112,428 (A^2 S)</td>
<td>∫_0^{T_k} i^2 dt = 107,450 (A^2 S)</td>
</tr>
</tbody>
</table>

The calculation results of the first method differed significantly from those of the latter two. Analyzing Formula (24) for A_1 and its coefficients in the IEC 61660-2 (1997) standard, it can be seen that A_1 is only related to t_p, but not to the steady-state current. Equation (13) in this research calculates the thermal effects of the capacitor discharge and steady-state current at the same time, so it was more accurate and consistent with the results of the simulation. In addition, the t_p value calculated with Formula (15) in the IEC 61660-1 (1997) standard [31] was much larger than that calculated with Formula (3) in this research. Therefore, the “equivalent rectangular function” (A_i) was much larger than the Joule integral obtained with the second and methods.

According to Figure 6, the calculation of the Joule integral is related to the short-circuit duration T_k. When T_k < T_1, it is calculated according to Formula (11); when T_k > T_1, it is calculated according to Formula (13). In engineering practice, the case is almost always T_k > T_1.

4.3. Consequences of the Different Methods

By analyzing and comparing the results of different methods for the example shown in Figure 5, it can be seen that different calculation or verification methods lead to different verification results.

If the prospective peak value and steady-state value of a short-circuit current by calculation are smaller than the actual values, or the verification method causes the verification
result is smaller than the actual value, the electric equipment may be damaged and the system safety may also be destroyed when the short circuit occurs. Conversely, if the prospective values are larger than the actual values, it will increase the investment and cause a waste.

5. Conclusions

According to the characteristics of low-voltage DC distribution systems in civil buildings, this research established an equivalent model of a polar–polar short-circuit; through a theoretical analysis and numerical simulation, the change process and the peak and steady-state values of the short-circuit current were studied. Then, the results were applied to the verification of the dynamic effects and thermal effects of equipment selection.

The most serious short-circuit fault in a DC system is a metallic short circuit between two poles when there are no loads. In the low-voltage DC distribution systems of civil buildings, fault circuits generally satisfy the condition $R < 2\sqrt{\frac{L}{C}}$. The short-circuit peak current is calculated according to Formula (2), the time to reach the peak is calculated according to Formula (3), and the short-circuit steady-state current is calculated according to Formula (7) or obtained through a numerical simulation.

Dynamic effect verification should use the short-circuit peak current calculated according to Formula (2), and thermal effect verification should involve the calculation of the Joule integral according to Formula (13).

The short-circuit peak current is greatly affected by the DC-link capacitance of the converter which is for stabilizing voltage, and the steady-state current is greatly affected by the AC-link filter inductor of the converter; these two parameters should be ascertained before calculations or simulations. The thermal effects of short-circuit currents require separate calculations of the Joule integrals for the transient and steady-state stages.

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