An accurate analysis method for transient characteristics of DC line faults in voltage source converter-based DC systems

Zhengguang Xiao1,2 | Xiaodong Zheng1,2 | Yangyang He1,2 | Nengling Tai1,2 | Chunju Fan1,2 | Ning Huang1,2 | Shan Jiang1,2

1 Key Laboratory of Control of Power Transmission and Conversion (Ministry of Education), Shanghai Jiao Tong University, Shanghai, China
2 Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China

Correspondence
Xiaodong Zheng, Key Laboratory of Control of Power Transmission and Conversion (Ministry of Education), Shanghai Jiao Tong University, Shanghai 200240, China.
Email: xiaodongzheng@sjtu.edu.com

Abstract
Voltage source converter-based DC systems face severe overcurrent problem under DC line faults, which causes significant influence on security, reliability and stability of the power system. As the theoretical basis for relay coordination and protection, the transient fault analysis of voltage source converter-based DC systems needs an in-depth study. Based on the conventional fault analysis, an accurate transient fault analysis method for the DC pole-to-ground fault and pole-to-pole fault through freewheeling diode switch state signals is proposed. In the capacitor discharge stage, fault current calculation error is reduced by taking into consideration the current fed from the grid side. In addition, through detailed analysis of the conduction condition and state of the freewheeling diode, clear calculation equations of transient fault currents are obtained. With the prior knowledge of fault response characteristics, definitions of freewheeling diode switch state signals assist in unifying calculation processes of different fault stages and simplifying transient fault calculation. Finally, a typical simulation model of the voltage source converter-based DC system was built in PSCAD/EMTDC software. The simulation results verified the conciseness and correctness of the proposed fault analysis method compared with the conventional fault analysis.

1 INTRODUCTION

With the rapid development of manufacture technology for power electronic devices and control technique for converters, DC systems are widely used and show great potential in the application of power transmission and distribution fields [1–3]. The advantages of DC systems include larger transmission capacity, less transmission loss, better power quality, more convenient access to DC loads, easier integration of renewable energy generations and energy storage systems, more reliable power supply and so on [4,5]. Therefore, the DC system is attracting more and more attention, and playing more and more important role in the power system [6–8].

The converter is a key component of the DC system, and the voltage source converter (VSC) is widely applied to engineering practice [9,10]. VSC-based DC systems show superior performance in independent control of the reactive and active power, avoidance of commutation failures, unchanged voltage polarity under power flow reversal, possibility to connect a weak system and so on [11,12]. However, there are still some challenges in VSC-based DC systems, one of which focuses on the severity of DC line faults. When DC side faults occur in the VSC-based DC system, DC-link capacitors will discharge rapidly. Consequently, fault currents will ramp up fast and reach an unbearably high value [13,14], which can damage power electronic devices in the converter. Therefore, it is of great significance to analyse DC line faults in VSC-based DC systems for the protection design, equipment selection, fault detection and location.

In the VSC-based DC system, DC line faults consist of pole-to-ground faults (PGF) and pole-to-pole faults (PPF). Through analysing equivalent circuits of DC line faults, literatures [15,16] divide the PGF into three stages: Capacitor discharge stage, grid-side current feeding stage and steady state. Meanwhile, for...
the PPF, capacitor discharge stage, diode freewheel stage and grid-side current feeding stage are included in the transient process. In [17,18], the PPF is studied and similar results are shown, while the fault response is described as a four-stage process. Another stage is introduced between capacitor discharge and diode freewheel stage when the DC-link voltage dips below the line-to-line voltage of the AC generator. Besides, short-circuit fault characteristics are investigated in [19] for VSC-based DC distribution networks connected with different distributed generators. Current-limiting capability of the VSC-based DC distribution system is considered in [20]. And it is found that, for the PPF, diode freewheel stage exists only when fault resistance is small enough and DC-link voltage is underdamped. On the contrary, when fault resistance is quite large, DC-link voltage is over damped and diode freewheel stage does not occur. In addition, literature [21] provides short-circuit fault analysis of multiterminal AC/DC hybrid distribution system with different network topologies, which is considerably valuable for topology determination. A new dq frame modelling of VSCs for DC fault study is proposed in [22], and it achieves good results while only the PPF is considered. In sum, there have been much research work involving fault characteristics of VSC-based DC systems, and the adopted analysis methods have shown reliability and effectiveness [23–25]. However, these analyses still expose some deficiencies, one of which lies in the thought that the capacitor discharge current dominates the capacitor discharge stage and thus the current fed from grid side is ignored. When the current fed from grid side is much smaller than capacitor discharge current, neglecting grid-side current can reasonably simplify fault circuits and fault characteristics can still be well expressed. But when the grid-side current is large enough to cause influence on fault calculation accuracy, it should be taken into account to obtain more accurate results. However, there have been few studies that provide a good solution to the aforementioned problem. Moreover, another deficiency may result from the grid-side current feeding stage. The derived fault calculation equations of grid-side current feeding stage are usually aimed at a certain fault circuit. It means that, with changing freewheeling diodes’ states, the fault response of grid-side current feeding stage cannot be solved continuously. As for lack of in-depth research on freewheeling diodes’ switch on-off states, there have been few methods that manage to obtain detailed calculation equations of the grid-side current feeding stage.

This paper proposes an accurate and simple transient analysis method for both pole-to-ground and PPF in VSC-based DC systems. The proposed method makes a thorough investigation into switch on-off conditions and states of freewheeling diodes. And freewheeling diode switch state signals (FDSSSs) are defined to integrate fault calculation between AC and DC sides of the VSC. In capacitor discharge stage, current fed from grid side is considered and fault calculation accuracy is improved. Furthermore, fault circuits in different stages are represented by the changing FDSSSs. Transient fault responses of pole-to-ground and PPF are solved continuously. Finally, simulation results verified the superiority of the proposed method compared with the conventional method. The proposed fault analysis method can provide theoretical basis for protection design of VSC-based DC systems.

The rest of this paper is organised as follows. Section 2 presents the structure of VSC-based DC systems, and introduces the conventional fault analysis of DC line faults. Sections 3 and 4 propose the improved fault analysis method for the pole-to-ground and PPF, respectively. In section 5, the proposed fault analysis method is verified on the basis of simulation results. Finally, conclusions are drawn in Section 6.

## 2 | STRUCTURE OF VOLTAGE SOURCE CONVERTER-BASED DC SYSTEMS AND CONVENTIONAL FAULT ANALYSIS METHOD

### 2.1 | Structure of voltage source converter-based DC systems

A typical structure of the VSC-based DC system is shown in Figure 1. The AC utility grid is represented by a three-phase AC source with equivalent resistance and inductance. A two-level VSC is connected to the grid to achieve energy conversion between AC and DC power. The DC-link midpoint is selected as the grounding point, which regulates the DC output voltage at $\pm U_{dc}/2$. Pulse width modulation (PWM) is employed for the VSC to generate trigger signals, which control turn-on and turn-off of power electronic devices [9]. It means that trigger signals realize the energy conversion between AC and DC power by the control of power electronic devices. Besides, direct current control is selected as the control strategy for the VSC to fulfil active/reactive power control. In Figure 1, $F_1$ means the PGF, namely, the positive pole is grounded; $F_2$ means the PPF.

Considering the severity of DC line faults in VSC-based DC systems, rapidly rising fault currents will cause serious damage to the insulated gate bipolar transistors (IGBTs) in the VSC. In the engineering practice, the IGBTs will be blocked for self-protection when suffered from large fault current [14–16]. Given the self-protection of IGBTs, the VSC is assumed to be
2.2 Conventional fault analysis method

2.2.1 Pole-to-ground fault

As mentioned above, the transient process of PGF is divided into capacitor discharge stage and grid-side current feeding stage [15,16]. Brief introduction of these two stages is as follows, and detailed fault calculation is provided in Appendix.

Figure 2 illustrates the equivalent circuits of different stages in the PGF. The AC grid is represented by a three-phase AC source named $u_{sa,b,c}$; $R_s$ and $L_s$ mean its equivalent resistance and inductance respectively. The pole-to-ground DC-link capacitor is $2C$. $R$ and $L$ mean π-model equivalent resistance and inductance of DC lines from the VSC to the fault point. Owning to the large DC-link capacitor, the DC line grounding capacitor is omitted here.

1. Capacitor discharge stage: When the fault occurs, the positive pole-to-ground DC-link capacitor discharges and the voltage of positive pole drops rapidly. The capacitive discharge current is large, and thus the current fed from AC grid is ignored. The equivalent circuit of this stage is shown in Figure 2(a).

2. Grid-side current feeding stage: When positive DC voltage drops below any phase voltage of the AC grid, the grid feeds current to faulted DC lines through freewheeling diodes. Generally, inductance $L_s$ is much larger than resistance $R_s$ and therefore inductance is considered only. The equivalent circuit of this stage is shown in Figure 2(b). It needs to be mentioned that the fault calculation equations in Appendix are aimed at a certain fault circuit, while clear explanation of changing fault circuits is not given.

2.2.2 Pole-to-pole fault

In general, the transient response process of PPF is divided into capacitor discharge stage, diode freewheel stage and grid-side current feeding stage [15,16]. Relevant calculation can be found in Appendix.

Figure 3 shows equivalent circuits of different stages in the PPF. The equivalent pole-to-pole DC-link capacitor is $C$. $2R$ and $2L$ mean π-model equivalent resistance and inductance of DC lines from the VSC to the fault point.

1. Capacitor discharge stage: Similar to the PGF, equivalent DC-link capacitor $C$ discharges rapidly after the occurrence of PPF. Without the consideration of grid-side current, the equivalent circuit of this stage is represented by Figure 3(a).
2. Diode freewheel stage: Different from PGF, PPF in this stage is confronted with the diode clamping effect. When DC-link voltage drops to 0, the upper and lower phase-leg freewheeling diodes are all conducted, which results in the clamp of DC-link voltage as shown in Figure 3(b). Grid-side current feeding stage: Similar to PGF, both AC grid and DC-link capacitor provide fault current to DC lines in this stage, whose equivalent circuit is shown in Figure 3(c). It should be noted that the calculation results in Appendix are obtained by the approximation to a three-phase short-circuit fault.

3. IMPROVED ANALYSIS METHOD FOR TRANSIENT CHARACTERISTICS OF POLE-TO-GROUND FAULT

When the PGF occurs in the VSC-based DC system, the equivalent circuit is illustrated in Figure 4. The positive pole is short circuitted to ground, and negative pole is omitted for negligible fault current. IGBTs in the VSC are indicated by dotted lines to show that they are all blocked.

As seen in Figure 2(a), the conventional method only considers the capacitive discharge current in capacitor discharge stage, thus ignoring the current fed from AC grid. To accurately obtain transient characteristics of the PGF, the current fed from AC grid is considered immediately after the fault occurs. According to Figure 4, fault calculation equations can be established based on Kirchhoff’s voltage law and Kirchhoff’s current law for AC side of the VSC:

\[
\begin{align*}
\dot{u}_{ia} - R_{ia}i_a - L_a\dot{i}_a &= u_nG_p(\phi_a) - u_nG_n(\phi_a), \\
\dot{u}_{ib} - R_{ib}i_b - L_b\dot{i}_b &= u_nG_p(\phi_b) - u_nG_n(\phi_b), \\
\dot{u}_{ic} - R_{ic}i_c - L_c\dot{i}_c &= u_nG_p(\phi_c) - u_nG_n(\phi_c), \\
\dot{i}_p &= i_pG_p(\phi_a) + i_bG_p(\phi_b) + i_cG_p(\phi_c), \\
\dot{i}_n &= i_nG_n(\phi_a) + i_bG_n(\phi_b) + i_cG_n(\phi_c).
\end{align*}
\]

(1)

Where the functions \(G_p(\phi)\) and \(G_n(\phi)\) are defined to judge switch on-off states of freewheeling diodes by the positive or negative value of phase current \(i_\phi\) (\(\phi = a, b, c\)). \(i_\phi\) means the derivative of \(i_\phi\), and other variables are denoted similarly.

Definitions of \(G_p(\phi)\) and \(G_n(\phi)\) are: \(G_p(\phi) = [1 + \text{sgn}(i_\phi)]/2\) and \(G_n(\phi) = [1 - \text{sgn}(i_\phi)]/2\), in which \(\text{sgn}(\cdot)\) means the signum function. When \(i_\phi > 0\), it is known that the upper phase-leg freewheeling diode is conducted and the lower is blocked. Based on the conduction of diodes, the related phase is conducted to the positive pole. At this point, from definitions of \(G_p(\phi)\) and \(G_n(\phi)\), \(G_p(\phi) = 1\) and \(G_n(\phi) = 0\). Then, it leads to the result that \(u_nG_p(\phi) + u_nG_n(\phi) = u_n\), which is consistent with the conduction of diodes. Contrariwise, When \(i_\phi < 0\), it is obtained that \(G_p(\phi) = 0\), \(G_n(\phi) = 1\) and \(u_nG_p(\phi) + u_nG_n(\phi) = u_n\), which means the related phase is conducted to the negative pole. Therefore, these analyses demonstrate that definitions of \(G_p(\phi)\) and \(G_n(\phi)\) can reflect the conduction of diodes and help to establish fault calculation equations.

As for DC side of the VSC, fault calculation equations are given in Equation (2) according to Figure 4.

\[
\begin{align*}
\dot{i}_n - i_i &= 2C\dot{u}_p, \\
\dot{i}_n &= 2Ci_L'\dot{i}_n, \\
u_p &= Ri_i + L_d\dot{i}_i.
\end{align*}
\]

(2)

Combine Equations (1) and (2), then the whole fault calculation equations are obtained as follows:

\[
\begin{align*}
\dot{i}_a &= [u_{ia} - R_{ia}i_a - L_a\dot{i}_a - u_nG_p(\phi_a) - u_nG_n(\phi_a)]/L_a, \\
\dot{i}_b &= [u_{ib} - R_{ib}i_b - L_b\dot{i}_b - u_nG_p(\phi_b) - u_nG_n(\phi_b)]/L_b, \\
\dot{i}_c &= [u_{ic} - R_{ic}i_c - L_c\dot{i}_c - u_nG_p(\phi_c) - u_nG_n(\phi_c)]/L_c, \\
\dot{i}_p &= i_pG_p(\phi_a) + i_bG_p(\phi_b) + i_cG_p(\phi_c), \\
\dot{i}_n &= i_nG_n(\phi_a) + i_bG_n(\phi_b) + i_cG_n(\phi_c). \\
\end{align*}
\]

(3)

There are 8 unknown quantities and 8 equations in Equation (3), and therefore the fault calculation equations can be solved. Considering the complexity of the derived differential equations, the numerical method can be utilized to solve Equation (3). From calculation results of Equation (3), how fault currents at AC and DC sides of the VSC change in transient process can be attained and analysed.

It is noteworthy that there exists a problem in Equation (3). The condition under which upper and lower diodes are both blocked is not considered in Equation (3). In this case, the phase current is always 0 and its derivative is also 0, which does not correspond to the equation of \(i_\phi\) in Equation (3). To solve this problem, a FDSSS called \(S_\phi\) is defined to describe the conduction state of upper and lower diodes. When \(S_\phi = 1\), it means that either the upper or lower phase-leg diode is conducted when \(S_\phi = 0\), it means that both of the two diodes are blocked. With the use of \(S_\phi\), updated calculation equations are shown in Equation (4).

Hence, the condition under which the two phase-leg diodes are both blocked can be well expressed in Equation (4). As for the calculation of \(S_\phi\), it should change...
with the conduction state of the two phase-leg diodes.

\[
\begin{aligned}
\dot{S}_a &= S_a[u_{sa} - R_s i_a - u_p G_p(i_a) - u_n G_n(i_a)]/L_s \\
\dot{S}_b &= S_b[u_{sb} - R_s i_b - u_p G_p(i_b) - u_n G_n(i_b)]/L_s \\
\dot{S}_c &= S_c[u_{sc} - R_s i_c - u_p G_p(i_c) - u_n G_n(i_c)]/L_s \\
\dot{S}_d &= \dot{S}_a G_p(i_a) + \dot{S}_b G_p(i_b) + \dot{S}_c G_p(i_c) \\
\dot{S}_f &= \dot{S}_a G_n(i_a) + \dot{S}_b G_n(i_b) + \dot{S}_c G_n(i_c) \\
\dot{S}_i &= (u_p - u_n)/L \\
\dot{S}_i' &= (i_p - i_n)/2C \\
\dot{S}_i'' &= i_n/(2C).
\end{aligned}
\] . (4)

By solving Equation (4), the transient process of PGF is calculated interval by interval, in which every interval corresponds to a fixed fault circuit. With the switch on and off of phase-leg diodes, the equivalent fault circuit will change accordingly and \(S_\phi\) should be updated as well. When the phase current drops to 0, \(S_\phi\) should be determined whether to update by the comparison of phase voltage \(u_{\phi p}\) to positive phase voltage \(u_a\) and negative phase voltage \(u_n\). If \(u_a < u_{\phi p} < u_n\), the two phase-leg diodes are not conducted according to the conduction condition of diodes, and \(S_\phi\) should be set as 0. If \(u_{\phi p} \geq u_a\) or \(u_{\phi p} \leq u_n\), the upper or lower diode are conducted, and \(S_\phi\) should be set as 1. The update of \(S_\phi\) means the change of the equivalent circuit. Therefore, solving process of the former circuit should be ended and that of the latter circuit should be started. Meanwhile, the end values of the former solving process should be set as the initial values of the latter solving process. The flow chart of transient fault calculation for PGF is shown in Figure 5, where \(S_\phi = \lvert\text{sign}(i_{\phi 0})\rvert\) and \(t_{\phi 0}\) means the specified calculation time for the transient process.

With the consideration of grid-side current in capacitor discharge stage, the improved analysis method is more accurate. Moreover, the introduction of \(S_\phi\) solves the aforementioned problem that the fault calculation equations only apply to a certain fault circuit in grid-side current feeding stage. The changing equivalent fault circuit is described by the changing \(S_\phi\). Besides, the definition of \(S_\phi\) assists in unifying calculation processes of capacitor discharge stage and grid-side current feeding stage. As a result, the transient fault response of PGF can be solved continuously using Equation (4) and the flow chart in Figure 5.

4  IMPROVED ANALYSIS METHOD FOR TRANSIENT CHARACTERISTICS OF POLE-TO-POLE FAULT

When the PPF occurs and all IGBTs are blocked, the equivalent circuit is shown in Figure 6. The system parameters are same with those of the PGF.

Like the analysis method of PGF, fault calculation equations for AC and DC sides of the VSC are studied and derived according to Figure 6. In addition, the FDSSS called \(S_\phi\) is added to describe the conduction state of upper and lower diodes. Finally, differential equations of the PPF can be written as

\[
\begin{aligned}
\dot{i}_a &= S_a[u_{sa} - R_s i_a - u_p G_p(i_a) - u_n G_n(i_a)]/L_s \\
\dot{i}_b &= S_b[u_{sb} - R_s i_b - u_p G_p(i_b) - u_n G_n(i_b)]/L_s \\
\dot{i}_c &= S_c[u_{sc} - R_s i_c - u_p G_p(i_c) - u_n G_n(i_c)]/L_s \\
\dot{i}_d &= \dot{i}_a G_p(i_a) + \dot{i}_b G_p(i_b) + \dot{i}_c G_p(i_c) \\
\dot{i}_f &= \dot{i}_a G_n(i_a) + \dot{i}_b G_n(i_b) + \dot{i}_c G_n(i_c) \\
\dot{i}_i &= (u_p - u_n - 2R_i i_i)/2L \\
\dot{i}_i' &= (i_p - i_n)/2C \\
\dot{i}_i'' &= (i_p + i_n)/2C.
\end{aligned}
\] . (5)
When DC-link voltage drops to 0, the diode freewheel stage starts for the diode clamping effect. However, the diode freewheel stage is not taken into account in Equation (5). In this stage, the upper and lower diodes are all conducted, and the voltages of positive and negative poles remain constant. Consequently, it is deduced that $u_{p} = 0$ and $u_{n} = 0$, which are not consistent with the expressions of $u_{p}$ and $u_{n}$ in Equation (5). Similar to the FDSSS called $\mathcal{S}_{p}$, another FDSSS called $\mathcal{S}_{d}$ is defined to describe the condition when the upper and lower diodes are all conducted. When $\mathcal{S}_{d} = 0$, it means that the upper and lower diodes are all conducted, and the diode freewheel stage starts. When $\mathcal{S}_{d} = 1$, it means that the diode freewheel stage ends and grid-side current feeding stage starts. The fault characteristics of different fault stages can be applied to the determination of $\mathcal{S}_{d}$. Thus, $\mathcal{S}_{d}$ is added and Equation (5) is modified as Equation (6):

$$
\begin{align*}
S_{d} &= S_{a0} - R_{s}i_{c} - u_{p}C_{p}(i_{c}) - u_{n}C_{n}(i_{c}) / L_{s} \\
S_{d} &= S_{b0} - R_{s}i_{c} - u_{p}C_{p}(i_{c}) - u_{n}C_{n}(i_{c}) / L_{s} \\
S_{d} &= S_{c0} - R_{s}i_{c} - u_{p}C_{p}(i_{c}) - u_{n}C_{n}(i_{c}) / L_{s} \\
i_{p} &= i_{a}C_{p}(i_{c}) + i_{b}C_{p}(i_{c}) + i_{c}C_{p}(i_{c}) \\
i_{n} &= i_{a}C_{n}(i_{c}) + i_{b}C_{n}(i_{c}) + i_{c}C_{n}(i_{c}) \\
i_{f} &= (u_{p} - u_{n} - 2R_{s}i_{c}) / (2L_{s}) \\
i_{f} &= S_{p}(i_{f} - i_{f}) / (2L_{s}) \\
i_{f} &= S_{d}(i_{f} + i_{f}) / (2C) \\
i_{f} &= S_{d}(i_{f} + i_{f}) / (2C)
\end{align*}
$$

$\mathcal{S}_{d}$ should be adjusted according to the start and end of different stages. The DC-link voltage and relevant fault currents can reflect the fault characteristics of different stages. After the occurrence of PPF, $\mathcal{S}_{d}$ is set as 1 because there does not exist the condition when the upper and lower diodes are all conducted in the capacitor discharge stage. When the DC-link voltage drops to 0 ($u_{p} - u_{n} = 0$), the diode freewheel stage starts and $\mathcal{S}_{d}$ should be set as 0, which means that all freewheeling diodes are conducted. When the sum of upper diode currents fed from AC grid exceeds the DC fault current ($i_{p} > i_{f}$), the diode freewheel stage ends and the grid-side current feeding stage starts, and $\mathcal{S}_{d}$ should be set as 1. The flow chart of transient fault calculation for PPF is similar to that of PGF. With the consideration of the diode freewheel stage, the differential Equation (6), instead of Equation (4), are solved to achieve fault calculation. In addition, the part of state judgement and signal adjustment in Figure 5 needs to be updated with a new one, which is given in Figure 7. Besides, the initial values of FDSSSs are modified to $\mathcal{S}_{d} = (S_{a0}, S_{b0}, S_{c0}, S_{d0})$, where $S_{d0} = 1$.

Similar to the analysis of PGF, the improved analysis method for PPF considers the grid-side current immediately after the fault occurrence. Therefore, the transient fault calculation accuracy is improved in the capacitor discharge stage. Meanwhile, instead of the approximation to three-phase short-circuit fault, the exact fault circuit in the grid-side current feeding stage is described by $\mathcal{S}_{p}$. The changing $\mathcal{S}_{p}$ can represent the changing fault circuit, and thus the fault response is solved continuously. Besides, on the basis of $\mathcal{S}_{p}$, the definition of $\mathcal{S}_{d}$ further unifies the fault calculation processes of capacitor discharge stage, diode freewheel stage and grid-side current feeding stage. In brief, the transient fault calculation of the PPF is more accurate and more concise.

**5.1 Simulation Results and Analyses**

A typical VSC-based DC system model shown in Figure 1 has been built using PSCAD/EMTDC, whose detailed system parameters are presented in Table 1. Direct current control is selected for the VSC to fulfill active/reactive power control. This
TABLE 1  Simulation system parameters

| Parameters                              | Values |
|-----------------------------------------|--------|
| Rated voltage of AC grid, \( u_{\text{sa,b,c}} \) (kV) | 11.5   |
| Equivalent resistance, \( R_s \) (Ω)    | 0.2    |
| Equivalent inductance, \( L_s \) (mH)  | 2      |
| Pole-to-ground capacitor, \( 2C \) (µF) | 4000   |
| Current-limiting inductance, \( L_C \) (mH) | 1     |
| Rated voltage of DC lines, \( U_{\text{dc}} \) (kV) | ±10    |
| Resistance per length, \( R_{\text{line}} \) (Ω km\(^{-1}\)) | 0.014  |
| Inductance per length, \( L_{\text{line}} \) (mH km\(^{-1}\)) | 0.16   |

Control consists of inner current controller loop and outer voltage controller loop. Constant DC voltage and reactive power control are employed as the control strategy of the VSC. The DC voltage reference is set as the rated voltage of DC lines, and the reactive power reference is set as 0 Mvar. PWM technique is used to develop the gating pulses for the VSC. DC line faults occur 5 kilometres away from the converter with the fault resistance of 0.01 Ω. The DC line is represented by a π-model equivalent resistor and inductor. Due to the large DC-link capacitor, the DC line grounding capacitor is omitted here [14–16].

Considerable simulations of pole-to-ground and PPF have been carried out to make the comparison between the conventional and improved methods. The simulation step is 25 μs, and the fault occurrence time is 4.0 s. The VSC is blocked immediately after the fault initiation. The superiority of the proposed transient fault analysis method is verified by the simulation results.

5.1  Simulations of pole-to-ground fault

5.1.1  Calculation results of DC fault current in capacitor discharge stage

Figure 8 presents calculation results of DC fault current in the capacitor discharge stage. The end time \( t = 4.0023 \) s means that, in the simulation case, the voltage of pole-to-ground capacitor is lower than any phase voltage of AC grid. In Figure 8(a), calculated DC fault currents via the conventional and improved methods (\( i_{\text{f,CM}}, i_{\text{f,IM}} \)) are shown with the results in simulation case (\( i_{\text{f,SIM}} \)). In Figure 8(b), calculation errors of the conventional and improved methods are compared. In the following figures, SIM relates to the results of simulation; CM relates to the results of the conventional method; and IM relates to the results of the improved method.

In Figure 8(a), it can be seen that there are some errors between the calculation results \( i_{\text{f,CM}} \) and the simulation results \( i_{\text{f,SIM}} \). The maximum error of the calculation results \( i_{\text{f,CM}} \) is about −10% from Figure 8(b). It reveals that some calculation error will occur if using the conventional method. By contrast, using the improved method, the calculation results \( i_{\text{f,IM}} \) are very close to the simulation results \( i_{\text{f,SIM}} \) after taking the current fed from grid side into account. At the end of the capacitor discharge stage, the DC fault current calculation error of the conventional method is −9.86%, and that of the improved method is −0.42%. The superiority of the improved method to the conventional method is verified. It needs to be noted that the fault calculation of capacitor discharge stage is an extremely important issue in the protection design of DC systems. The fault detection and isolation requires to be accomplished in several milliseconds, which corresponds to the capacitor discharge stage. Thus, an accurate fault calculation method within the capacitor discharge stage is the necessary prerequisite for system protection.

5.1.2  Comparison between capacitor discharge current and grid-side current

As for the capacitor discharge stage shown in Figure 8, the current fed from AC grid \( i_{\text{p,SIM}} \) and the capacitor discharge current \( i_{\text{C,SIM}} \) are given together in Figure 9 to make a further comparison. It can be found that, in the built VSC-based DC system, the current fed from AC grid is at a high value compared with the capacitor discharge current in a short period after the fault occurs, which lasts for 0.81 ms. The period during which \( i_{\text{p,SIM}} \) is larger than \( i_{\text{C,SIM}} \) is indicated by the red area in Figure 9. In such a situation, omitting the fault loop at AC side of the VSC in the conventional method may cause certain calculation error,
which explains the reason for higher accuracy of the improved method.

5.1.3 Calculation results of phase currents and DC fault current in transient state

Based on Equation (4) and the flow chart in Figure 5, transient fault currents within 0.04 s (two periods) after PGF occurs are calculated, and these results together with simulation results are shown in Figure 10. Comparison between calculation and simulation results of phase currents is made in Figure 10(a). Besides, calculation and simulation results of DC fault current are plotted in Figure 10(b). In these two subfigures, simulation results are presented by the thin and solid curves; while calculation results are presented by the heavy and dashed curves. From Figure 10(a), the simulation results and calculation results of phase currents are nearly identical. The improved method shows high calculation accuracy of phase currents. In Figure 10(b), the error between calculated and simulated curves of DC fault current is quite small. The peak value of DC fault current in simulation is 20.04 kA and the calculated result is 20.01 kA, whose error is $-0.15\%$. Therefore, the conclusion is that the improved method has high calculation accuracy of the DC fault current. Moreover, it needs to be mentioned that the improved method solves the transient process of the PGF continuously.

5.1.4 Changes of freewheeling diode switch state signals in transient state

As for the transient stage shown in Figure 10, the changes of FDSSSs $S_a$, $S_b$ and $S_c$ involved in Figure 5 are displayed in Figure 11. Besides, with the consideration of the FDSSS $S_d$ involved in Figure 7, the change of $S_d$ is also calculated and shown in Figure 11. It can be seen that $S_d$ is constantly 1, which means that the diode freewheel stage does not exist in the transient state of the PGF. And it is consistent with the actual fault response. In addition, the period under which $S_a$, $S_b$ or $S_c$ is 0 corresponds to the condition when the upper and lower diodes of phase A, B or C are both blocked. It is consistent with the period in Figure 10(a) when the phase current is always 0. The results prove that the definitions of FDSSSs promote the transient fault calculation of the PGF.
5.2 | Simulations of pole-to-pole fault

5.2.1 | Calculation results of DC fault current in capacitor discharge stage

In Figure 12(a), the calculation and simulation results of DC fault current are compared. And calculation errors of the conventional and improved methods are presented in Figure 12(b). It indicates that the improved method has little calculation error; and the conventional method may cause larger error. The maximum error of the conventional method exceeds $-10\%$ as shown in Figure 12(b). The short vertical line in every curve in Figure 12(a) means the corresponding end point of the capacitor discharge stage. It shows that the conventional method may obtain an inaccurate end point of the capacitor discharge stage. As a result, faster protection speed is required for isolation devices in the conventional method, which hurts the system economy. By contrast, the improved method exhibits much better calculation performance, and has less error in calculating the end point of the capacitor discharge stage. Furthermore, using the improved method, the fault response of the capacitor discharge stage and diode freewheel stage is solved continuously. The calculation complexity of the PPF in transient state is greatly simplified.

5.2.2 | Comparison between capacitor discharge current and grid-side current

As for the capacitor discharge stage shown in Figure 12, the current fed from AC grid $i_{p,SIM}$ and the capacitor discharge current $i_{C,SIM}$ are given together in Figure 13 for further analysis. It is found that, in the early period of capacitor discharge stage, the current fed from AC grid is at a high value compared with the capacitor discharge current. Based on the calculation results of the conventional method in Figure 12, it is indicated that ignoring the grid-side current in capacitor discharge stage may cause error accumulation problem, and affect the fault calculation accuracy.

5.2.3 | Calculation results of phase currents and DC fault current in transient state

Based on Equation (6) and the flow chart in Figure 7, transient currents within 0.04 s after the PPF occurs are calculated and presented in Figure 14. Calculation and simulation results of phase currents are compared in Figure 14(a). Calculated and simulated curves of DC fault current are plotted together in Figure 14(b). It can be seen from Figure 14(a) that the calculation results of phase currents are sufficiently close to the simulation results. The improved method exhibits high accuracy in phase current calculation. From Figure 14(b), the DC fault current in simulation peaks at 17.20 kA and the calculated result is 17.24 kA, whose error is 0.23%. Thus, it comes the conclusion that the improved method has high calculation accuracy of the DC fault current.

5.2.4 | Changes of freewheeling diode switch state signals in transient state

Furthermore, the changes of FDSSs $S_a, S_b, S_c$ and $S_d$ are plotted in Figure 15. It shows that $S_b$ is constantly 1 which means that there is no such a period when the phase B current is
always 0. And this is demonstrated by the results of phase B current in Figure 14(a). Moreover, it is observed that there exist two periods when $S_d$ is constantly 0 which means the diode freewheel stage occurs twice. And the two occurrences of the diode freewheel stage is verified by the simulation results of the DC-link voltage shown in Figure 15(b). This figure also compares the simulation and calculation results of DC-link voltage, and effectiveness of the improved method is validated. From Figure 15, it is concluded that the improved method using FDSSSs can grasp firmly the transient characteristics of the PPF. In addition, the diode freewheel stage may happen more than once, which is not mentioned in the conventional method.

5.3 Comparison analysis under different parameters

To analyse the influence of different parameters, considerable simulation cases under different parameters have been carried out. The peak of DC fault current and the peak time are chosen to compare the calculation accuracy of the conventional and improved methods.

$I_{cm}$ and $T_{cm}$ mean peak current and peak time of the conventional method; $I_{im}$ and $T_{im}$ mean those of the improved method; $I_{sim}$ and $T_{sim}$ mean those in the simulation. The fault occurrence time is assumed to be 0 to calculate the peak time.

5.3.1 Different DC-link capacitors

The simulation and calculation results under different DC-link capacitors are shown in Figure 16. In PGFPGF with DC-link capacitors between 500–6000 $\mu$F, and in PPF with these between 500–2000 $\mu$F, the peak currents occur in the grid-side current feeding stage. Due to small DC-link capacitor, the capacitor discharge current is small while the grid-side current is relatively large. The conventional method ignores the large grid-side current, and so it gets incorrect peak times $T_{cm}$, which are in the capacitor discharge stage. These cases are shown by “incorrect $T_{cm}$ cases” in Figure 16. For other cases, the conventional method still shows more error than the improved method, especially for the peak current. With consideration of grid-side current, the improved method shows high accuracy for both peak current and peak time under different DC-link capacitors.
5.3.2 | Different fault resistances

Simulation cases under different fault resistances have been investigated. These results are given in Figure 17. For PGF, DC fault current reaches its peak in the grid-side current feeding stage when the fault resistance is relatively small ($R_f = 0.005$, 0.01 and 0.05 Ω). In these cases, the conventional method provides incorrect peak times $T_{cm}$ for omitting grid-side current. When the fault resistance is relatively high ($R_f = 5$ and 20 Ω), the RLC circuit in the conventional method is overdamped. The calculated peak current $I_{cm}$ is the initial value, and the calculated peak time $T_{cm}$ is 0. It is clearly inconsistent with simulation results. From Figure 17, it is indicated that the improved method shows much less error, and has high accuracy for both pole-to-ground and PPF.

5.3.3 | Different source parameters

This part considers different source parameters (source resistance $R_s$ and source inductance $L_s$) in simulation. Figure 18 shows the simulation and calculation results. It needs to be noted that changing source parameters has no effect on calculation results of the conventional method. From simulation results, when source impedance is relatively small, peak currents occur in the grid-side current feeding stage. The reason for this is that, with small impedance of AC source, the grid-side current feeding effect is obvious. In this situation, the conventional method will underestimate the peak current and peak time. With consideration of grid-side current from AC source, accurate peak current and peak time are obtained in the improved method for both pole-to-ground and PPF.

5.3.4 | Different line parameters

In this part, simulation cases under different line parameters have been discussed. From Figure 19, for all the cases of PGF, the peak currents happen in the grid-side current feeding stage. For PPF, DC fault current experiences its peak in the grid-side current feeding stage when the line resistance is relatively small and impedance relatively large. With small resistance $R$ and large impedance $L$ in grid-side current loop, time constant $L/R$ is large, and grid-side current attenuates slowly. It means that grid-side current feeding effect is obvious under small line resistance and large line impedance. The conventional method cannot cope with these cases. It is observed that, under different line parameters, the improved method keeps high calculation accuracy. And it shows much better performance than the conventional method.
6 | CONCLUSIONS

An accurate analysis method for transient characteristics of pole-to-ground and PPF using FDSSSs is proposed in this paper. The FDSSS is defined and utilized to describe fault characteristics of the VSC. The current fed from grid side is considered in the capacitor discharge stage. Besides, the fault calculation processes of different stages are unified with the definitions of FDSSSs. By the simulation validation, the improved method shows high calculation accuracy for phase currents and DC fault current. Moreover, comparison analysis under different parameters indicates that the improved method has much better calculation performance than the conventional method. In this study, simulation results show that the diode freewheel stage may occur more than once in the PPF. And it is found that the peak of DC fault current may happen in the grid-side current feeding stage. With consideration of grid-side current feeding effect, the proposed method can accurately describe the fault response characteristics and obtain good results.

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APPENDIX
The pole-to-ground fault:

1. Capacitor discharge stage

\[
\begin{align*}
\eta_p &= A_1 e^{3t'} + A_2 e^{2t'}, \\
\eta_1 &= -2C \frac{du_p}{dt}, \\
\eta_{1,2} &= -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{2LC}}. \\
A_1 &= \frac{1}{p_2 - p_1} \left(\frac{p_2 V_0}{2} + \frac{I_0}{2C}\right), \\
A_2 &= \frac{1}{p_1 - p_2} \left(\frac{p_1 V_0}{2} + \frac{I_0}{2C}\right).
\end{align*}
\]  

(A1)

2. Grid-side current feeding stage

\[
\begin{pmatrix}
\eta_p \\
\eta_1 \\
i_{a,b,c}
\end{pmatrix}
= 
\begin{pmatrix}
0 & -\frac{1}{2C} & \frac{1}{2C} \\
1 & -\frac{R}{L} & 0 \\
-\frac{1}{L_\alpha} & 0 & 0
\end{pmatrix}
\begin{pmatrix}
\eta_p \\
i_1 \\
i_{a,b,c}
\end{pmatrix}
+ 
\begin{pmatrix}
0 \\
0 \\
\frac{1}{L_\gamma}
\end{pmatrix}
\eta_{a,b,c}.
\]

(A2)

The pole-to-pole fault:

1. Capacitor discharge stage

\[
\begin{align*}
\eta_{dc} &= \frac{V_0}{\omega} (\omega_0 - e^{-\delta t} \sin(\omega t + \beta)) - \frac{I_0}{\omega C} e^{-\delta t} \sin \omega t, \\
\eta_1 &= -\frac{I_0}{\omega} e^{-\delta t} \sin(\omega t - \beta) + \frac{V_0}{2\omega L} e^{-\delta t} \sin \omega t, \\
\delta &= \frac{R}{2L}, \omega = \sqrt{\frac{1}{2LC} - \left(\frac{R}{2L}\right)^2}, \\
\omega_0 &= \sqrt{\delta^2 + \omega^2}, \beta = \arctan(\omega / \delta).
\end{align*}
\]  

(A3)

2. Diode freewheel stage

\[
i_i = I_i(0) e^{-\frac{\gamma t}{\tau}}, \quad \gamma = \alpha - \phi, \quad \beta = \arctan(\omega_0 / \delta).
\]

(A4)

3. Grid-side current feeding stage

\[
\begin{align*}
i_f &= I_f \sin(\omega_f t + \alpha - \phi) + I_{f0} e^{-\frac{\gamma t}{\tau}}, \\
\eta_{NSC} &= \left(\eta_{d,(>0)} + \eta_{b,(>0)} + \eta_{c,(>0)}\right), \\
i_t &= A \sin(\omega t + \gamma) + B e^{-\frac{\gamma t}{\tau} + \frac{1}{\omega}[C_1 \omega_0 e^{-\delta t} \sin(\omega t + \beta) + C_2 e^{-\delta t} \sin \omega t]}, \\
I_{g0} &= I_{a0} \sin(\alpha - \phi_0) - I_{b0} \sin(\alpha - \phi), \\
\tau &= \frac{L_\gamma + 2L}{2R}, \phi = \arctan(\omega_0 t), \\
A &= \frac{I_{g0} \left(1 - 2\omega_0^2 L C \right)^2 + (2R \omega_0)^2 \right)^{1/2}, \\
\gamma &= \alpha - \phi - \delta, \delta = \arctan\left(\frac{2R \omega_0}{1 - 2\omega_0^2 L C}\right), \\
B &= \frac{I_{g0} \tau^2}{\tau^2 - 2R \tau + 2LC}, \quad C_1 = -A \sin \gamma - B, \\
C_2 &= B / \tau - \omega_0 A \cos \gamma.
\end{align*}
\]  

(A5)

In the conventional method, transient process of the pole-to-pole fault is divided into capacitor discharge stage and grid-side current feeding stage; besides, transient process of the pole-to-pole fault is divided into capacitor discharge stage, diode freewheel stage and grid-side current feeding stage. The faulted pole in pole-to-ground fault is selected as the positive pole here and the analysis method can also be applied to the scenario when the negative pole is faulted.

Fault current expressions or calculation methods in different stages are given in (A1–A5). Where \( \eta_p \) means the voltage of positive pole, \( i_t \) means DC fault current, \( i_{a,b,c} \) means phase currents, \( \eta_{dc} \) means DC-link voltage, \( V_0 \) means the initial value of DC-link voltage, \( I_0 \) means the initial value of DC fault current, \( I_{g0} \) means the value of DC fault current at the end of capacitor discharge stage, \( I_{a0} \) means the current of phase A at the end of diode freewheel stage, \( \alpha \) means the voltage angle of phase A at the end of diode freewheel stage, \( \phi_0 \) means load angle, \( I_g \) means steady-state current of three-phase short-circuit fault, \( \omega_1 \) means angular frequency of AC grid.