A method based on the transmission line information for normal operation and fault of solving transfer impedance

Mengjiao Li1,2, Haifeng Yu1,2, Yuzheng Xie1,2, Zehong Chen3*, Xinran Li3 and Chunjing Lu3

1 State Grid Hunan Electric Power Company Limited Economic and Technological Research Institute, Changsha 410004, China
2 Hunan Key Laboratory of Energy Internet Supply-demand and Operation, Changsha 410004, China
3 College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
* Corresponding author: E-mail: Chenzehong@hnu.edu.cn

Abstract. Under the background of UHV project, the level of power system short-circuit current increasing has been one of the challenges of these power grid is facing. Therefore, it is necessary to analyze the characteristics of short-circuit current in power grid. The traditional method of calculating transfer impedance is to form node impedance matrix through network, and then calculate transfer impedance by formula. The precondition of the traditional method is to know the parameter information of each element in power grid, however, it is difficult to accurately give the parameter information of each element in engineering application. Based on the limitations of the traditional method, a method based on the transmission line information for normal operation and fault of solving transfer impedance is proposed, which treats the grid as a black box except for the short circuit point, so it is not necessary to know the parameter information of each element in the power grid as a known condition. Applying the method to solve for transfer impedance in a ring network, and the results are compared with the results of the traditional method to verify that the method is feasible.

1. Introduction
With the rapid development of economy, power demand keeps growing in China. From the completion of the first megavolt UHV transmission line in China by Wuhan High Voltage Research Institute in 1994, to the completion and operation of the "14 AC and 12 DC" UHV transmission project by the State Grid Corporation of China in 2021, in just over a decade, China's UHV power grid has achieved rapid development from nothing. On the one hand, the construction of UHV project improves the power transmission distance, increases the transmission power, reduces the transmission loss, realizes the high interconnection of power system, improves the economic benefits and power supply reliability of power grid operation. On the other hand, the construction of extra-high voltage projects has increased the voltage level and increased the electrical connections, making the problem of short-circuit current overruns in power grid more and more pronounced.

The power supply is the main source of short-circuit current in the grid, and the adjustment of the network structure will change the system impedance size, so the power supply and the network structure are the two main influencing factors of short-circuit current. In order to quantify and analyze
the influence of short-circuit current influencing factors on the size of the short-circuit current, an important electrical quantity in the short-circuit current calculation can be used, namely the short-circuit transfer impedance. In the study of short-circuit current-related problems, the complex power system network can be simplified to a radial network centered on the short-circuit point, and each radial branch contains only one power source connected to the short-circuit point through the short-circuit transfer impedance, which is an important electrical quantity that can represent the electrical distance between each point and the short-circuit point. For the solution of short-circuit transfer impedance, the literature [1] gives the formula of short-circuit transfer impedance by the condition of network equivalence transformation, combined with the node impedance matrix, which can accurately calculate the short-circuit transfer impedance on the premise of known impedance of each component in the network, but in practical engineering applications, for large-scale complex power networks, the node impedance matrix of the whole network is difficult to determine accurately. This paper combines the current calculation data of the network before the short-circuit and the short-circuit current decay curve of the line connected to the short-circuit point after the short-circuit, it proposes a calculation method to identify and solve the short-circuit transfer impedance, which does not require the impedance of each component in the whole network as a known quantity, and is more practical for solving the short-circuit transfer impedance in practical engineering.

2. Principle of application of the solution method

2.1. Complex network simplification method

In the short-circuit current calculation, the conventional solution method for the calculation of the short-circuit transfer impedance by network equivalence transformation, using the self impedance and mutual impedance of the network node impedance matrix to derive the equation. The literature [2] approximates a complex multi-machine power system as a radial-shaped network centered on a short-circuit point, as shown in Fig. 1.

The network contains $m$ generators, generator $i$ is represented by the voltage source $E_i$ and the internal impedance $z_i$ in series, and the network is reduced to $m$ branches centered on the short-circuit point $f$. For any branch $i$, the total impedance of the branch is the short-circuit transfer impedance $Z_{if}$, and the impedance between the generator outlet bus $i$ and the short-circuit point $f$ is the external impedance $z_{fi}$, which satisfies the following equation.

$$Z_{yi} = z_i + z_{fi} \quad (1)$$

The short-circuit transfer impedance $Z_{if}$ of branch $i$ can also be derived from the intra-power impedance $z_i$, the self-impedance $Z_f$ of the short-circuit point $f$ in the network node impedance matrix, and the mutual impedance $Z_{fi}$ between power point $i$ and short-circuit point $f$ solved for.

$$Z_{if} = \frac{Z_{fi}}{Z_f} \cdot Z_i \quad (2)$$
Short-circuit transfer impedance conventional solution method is applied on the premise that the impedance of each component in the network is known, and the node impedance matrix is written and solved through the calculation of Equation (2). In the actual engineering application of power grid, the impedance information of each component in the network is not necessarily comprehensive and accurate, so the conventional solution method of short-circuit transfer impedance has some limitations in the actual engineering application of power grid, in order to solve this problem, the power grid other than the short-circuit point is regarded as a black box, which is connected to the short-circuit point through the line and outputs information to the short-circuit point, so the following network simplification is proposed, which will approximates a complex multi-machine power system as a radial-shaped network centered on a short-circuit point, as shown in Fig. 2.

![Network diagram](image)

Figure 2. Network sketch based on the line connected to the short-circuit point.

The network contains \( n \) lines connected to the short-circuit point, the network is centered on the short-circuit point \( f \) and reduced to \( n \) branches, each of which can be represented by a voltage source \( E_j \) and an equivalent impedance \( z_j \) in series, for any branch \( j \), the total impedance of the branch \( Z_{if} \) is the short-circuit transfer impedance, which satisfies the following equation.

\[
Z_{if} = z_j
\]  

(3)

Solving for the short-circuit transfer impedance means solving for the equivalent impedance \( z_j \) of the network after simplification.

2.2. Impedance parameters of the equivalent circuit before and after the short-circuit

In the practical application of the identification algorithm, the initial values of the parameters to be solved have an influence on the identification results. Therefore, this paper proposes to set the initial value of the short-circuit transfer impedance according to the value of the equivalent reactance before short-circuit.

According to the network simplification method shown in Fig. 2, an arbitrary line \( j \) connected to the short circuit point is simplified to an equivalent circuit with a voltage source and an equivalent impedance in series, as shown in Fig. 3.

Before a short-circuit fault occurs at short-circuit point \( f \), the power system in normal operation, according to the synchronous generator steady-state operation equivalent circuit, ignoring the resistance of the generator, transformer, and transmission line, the equivalent circuit shown in Fig. 3 can be reduced to an equivalent circuit with a voltage source and an equivalent reactance in series, as shown in Fig. 4.

The equivalent reactance \( x_j \) in Fig. 4 satisfies the following equation.

\[
x_j = x_j + x_e
\]  

(4)
Where $x_d$ is the direct shaft reactance of the synchronous generator and $x_e$ is the equivalent external reactance from the generator end to the short-circuit point.

After a short-circuit fault at short-circuit point $f$, the equivalent circuit shown in Fig. 3 can be transformed into an equivalent circuit with a voltage source and an equivalent reactance in series as shown in Fig. 5, based on the analysis of the physical process of a sudden three-phase short circuit in a synchronous motor with damped windings.

The equivalent reactance $x''$ in Fig. 5 is the short-circuit transfer impedance to be solved (ignoring the resistance), which satisfies the following equation.

$$x'' = x_d + x_e$$  \hspace{1cm} (5)

Where $x_{d''}$ is the synchronous generator direct shaft sub transient reactance and $x_e$ is the equivalent external reactance from the generator end to the short circuit point.

The external reactance is mainly composed of transformer and line parameters, the transformer and AC line are stationary components, according to the mathematical model of stationary components in the short-circuit current calculation, it is known that the steady-state parameters of the transformer and AC line before short-circuiting and the sub-transitory parameters after short-circuit remain the same, so the equivalent external reactance of Fig. 4 and Fig. 5 are equal.

According to the basic equation of synchronous generator and steady-state operation analysis, the synchronous generator direct shaft reactance consists of stator winding leakage reactance and direct shaft armature reaction reactance, which satisfies the following equation.

$$x_d = x_{a_d} + x_{a_d}$$  \hspace{1cm} (6)

According to the basic equation of synchronous generator and the analysis of the physical process of three-phase short circuit, it is known that the synchronous generator straight shaft sub transient reactance consists of stator winding leakage reactance, straight shaft armature reaction reactance, excitation winding leakage reactance and straight shaft damping winding leakage reactance, which satisfies the following equation.

$$x_{d'} = x_{a_d} + \frac{1}{x_{a_d} + \frac{1}{x_{a_d}} + \frac{1}{x_{a_d}}}$$  \hspace{1cm} (7)
Analysis of the mathematical expressions of $x_d$ and $x_{d''}$ shows that the equivalent reactance $x_j$ before the short-circuit and the equivalent reactance $x_{j''}$ after the short-circuit The difference in values is mainly due to the difference in parameters before and after the short circuit of the synchronous generator model, and $x_d > x_{d''}$, $x_j > x_{j''}$, so it is proposed to use the equivalent reactance $x_j$ before the short circuit to provide a numerical reference for solving the equivalent reactance $x_{j''}$ after the short circuit, and solving the equivalent reactance $x_j$ by identifying the power flow information in the normal operation of power grid. The initial value of $x_j$ is set by $x_j$, and the equivalent reactance $x_{j''}$ after short-circuit is solved by the short-circuit current decay curve of the grid connected to the short-circuit point $f$. Equivalent reactance $x_j$ is the short-circuit transfer impedance of the line connected to the short-circuit point $f$.

3. Short-circuit transfer impedance solution method based on line information before and after the short-circuit

3.1. Solving the mathematical model of the equivalent reactance $x_j$ before short-circuit

According to the equivalent circuit diagram shown in Fig. 3, the following equations can be written.

$$E = U + I \cdot z_j \quad (8)$$

Expanding equation (8) in detail as follows.

$$E_x + jE_y = U_x + jU_y + \left( \frac{P - jQ}{U_x + jU_y} \right) (r_j + jx_j) \quad (9)$$

The real and imaginary parts of equation (9) are separated, and to simplify the operation, the voltage at the short-circuit point $f$ in normal operation is taken as the amplitude $U$. We get as follow.

$$\begin{align*}
UE_x - U^2 - Pr_j - Qx_j &= 0 \\
UE_y + Qr_j - Px_j &= 0
\end{align*} \quad (10)$$

Using the power flow calculation module of the power system simulation software, we can obtain the bus voltage magnitude $U$ during normal operation at the short-circuit point $f$, the active power $P$ and the reactive power $Q$ at the receiving end of the line connected to the short-circuit point $f$ (with the short-circuit point $f$ as the receiving end). Therefore, $E_x$, $E_y$, $r_j$, $x_j$ are the parameters to be identified in equation(10).

The general form of the system of nonlinear equations is as follow.

$$\begin{align*}
f_1(x_1, x_2, \ldots, x_n) &= 0 \\
f_2(x_1, x_2, \ldots, x_n) &= 0 \\
\vdots
\ns_n(x_1, x_2, \ldots, x_n) &= 0
\end{align*} \quad (11)$$

Where, $x_1$, $x_2$, ...., $x_n$ are the $n$ unknown quantities to be solved, and the construction function $F_i$ as follows.

$$F_i = \sqrt{\frac{\sum_{i=1}^{m} (f_i)^2}{m}} \quad (12)$$

Then the process of solving the nonlinear system of equations is equivalent to solving the optimization problem of $\min F_i$.

Write equation (10) in the following form.

$$\begin{align*}
f_1 &= U_x E_x - U_x^2 - Pr_j - Qx_j \\
f_2 &= U_x E_y + Qr_j - Px_j
\end{align*} \quad (13)$$
Therefore, it is necessary to fine-tune the load size nearest to the short-circuit point \( f \) to obtain the results of multiple power flow calculations, and then construct a nonlinear system of equations by using equation (13) to construct a function \( F_1 \) to transform the solution of the nonlinear system of equations into an optimization problem, and use the optimization algorithm to solve the parameters \( x_j \), and this paper adopts the improved PSO algorithm to solve the equivalent reactance \( x_j \). Since the algorithmic work is not the focus of this paper, it will not be developed in detail here.

3.2. Solving the mathematical model of the equivalent reactance \( x_j'' \) after short-circuit

Using the power system transient stability calculation module can obtain the short-circuit current decay curves of the lines connected with the short-circuit point \( f \), as shown in Fig. 8.

![Figure 8. The decay curve of short-circuit current.](image)

From the Fig.8, it can be seen that the amplitude of the AC component of the short-circuit current can be approximately divided into two components that decay according to different time constants, the rapider one is the sub-transient component, corresponding to the time constant of \( T_{d'} \); the more slowly one is the transient component, whose time constant is \( T_d \), from which the complete mathematical expression of the short-circuit current decay curve can be given.

\[
I_m(t) = (I_m' - I_m) e^{-t/T_{d'}} + (I_m' - I_{m0}) e^{-t/T_d} + I_{m0} \tag{14}
\]

Eq. (14) can be further expressed as

\[
I_m(t) = \left( \frac{E_q}{x_d} - \frac{E_{q0}}{x_d} \right) e^{-t/T_{d'}} + \left( \frac{E_q}{x_d} - \frac{E_{q0}}{x_d} \right) e^{-t/T_d} + \frac{E_q}{x_d} \tag{15}
\]

After using the power system transient stability calculation module to set the simulation step, we can get the data \((t, I_m(t))\). Combined with equation (15), the mathematical expression coefficients of the short-circuit current decay curve can be solved by means of parameter identification. However, in the actual solution process, considering both sub-transients and transients increases the difficulty of the solution, which is not conducive to the accuracy of the parameter identification results. In this paper, the main parameter solved by equation (15) is the sub transient reactance \( x_{d''} \). Therefore, without considering the transient component, equation (15) is further simplified.

\[
I_m(t) = \left( \frac{E_q}{x_d} - \frac{E_{q0}}{x_d} \right) e^{-t/T_{d'}} + \frac{E_q}{x_d} \tag{16}
\]

It should be noted that the curve corresponding to equation (16) is the rapidly decaying part of the short-circuit current decay curve, not the whole short-circuit current decay curve. Shift the term of equation (16) to obtain,
\[ I_n(t) = \left( \frac{E' - E_q}{x_d} \right) e^{-t/\tau_d} - \frac{E_q}{x_d} = 0 \]  \hspace{1cm} (17)

Equation (18) is as below.

\[ g_i = I_{m}(t_i) \left( \frac{E' - E_q}{x_d} \right) e^{-t_i/\tau_d} - \frac{E_q}{x_d} \]  \hspace{1cm} (18)

According to the power system transient stability calculation module to obtain \( n \) data pairs \((t, I_n(t))\), according to equation (18) can write \( n \) equations to form a nonlinear system of equations, the function \( G_i \) is as below.

\[ G_i = \sqrt{\frac{\sum_{i=1}^{n} (g_i)^2}{n}} \]  \hspace{1cm} (19)

Then the process of solving the nonlinear system of equations is equivalent to solving the optimization problem of \( \min G_i \). The initial values of the \( x_d \) and \( x_d'' \) are set according to the equivalent reactance \( x_j \) before the short-circuit, and the parameters \( x_{d''} \) are solved by the optimization algorithm, the optimization algorithm used in this paper is the same as above. The coefficient \( x_{d''} \) of mathematical expression of the short-circuit current decay curve is the equivalent reactance \( x_{j''} \) after the short-circuit.

4. Flowchart of the implementation of the solution method

The proposed method uses the power flow calculation module and transient stability calculation module of PSASP to obtain the required data, and uses Matlab for programming recognition algorithm to solve the short-circuit transfer impedance. The overall flow of the method is shown in Fig. 9.

![Flowchart of solution method](image-url)
5. Simulation verification of short-circuit transfer impedance solution method based on line information before and after short-circuit

5.1. Establishing the simulation calculation network
To verify the method proposed in this paper, a 3-machine and 6-node system is constructed as shown below, and the short-circuit transfer impedance of each line connected to bus #1 is calculated by using the method proposed in this paper, and the short-circuit transfer impedance results are compared with those calculated by hand calculation method.

The 3-machine and 6-node system shown in Fig. 10 is used as the study object. 1# bus is the main load center of the grid, 4# bus unit is the synchronous generator power supply at the sending end, set as PQ node; 5# bus unit is the synchronous generator power supply at the sending end, set as PV node; 6# bus unit is the synchronous generator power supply at the main load center, set as balancer, line and transformer reactance parameters are shown in the Fig.10.

![Figure 10. Three-machine and six-node system diagram.](image)

5.2. Solving for the equivalent reactance before short-circuit $x_j$
According to the 3-machine and 6-node system constructed as shown in Fig. 10, the following data are obtained through the tide calculation by using the tide calculation module of PSASP to calculate the steady-state operating state parameters of each part of the power system based on the given parameters and operating conditions of the generator, transformer, line, load and other components.

1. 1# bus voltage amplitude;
2. In line 2-1, the active power and reactive power at the receiving end with the 1# bus side as the receiving end;
3. In line 3-1, the active power and reactive power at the receiving end with the 1# bus side as the receiving end;
4. In line 6-1, the active power and reactive power at the receiving end with the 1# bus side as the receiving end.

The tide calculation results obtained using the PSASP tide calculation module are shown in the table below.

| Busbar name | Voltage amplitude | Voltage phase angle | Base voltage(kV) |
|-------------|-------------------|--------------------|-----------------|
| 1           | 1.00689           | 0.03057            | 230             |

| Line name | Sending busbar | Receiver busbar | Active power at receiving end | Reactive power at receiving end |
|-----------|----------------|-----------------|-------------------------------|---------------------------------|
| 2-1       | 2              | 1               | 1.94153                       | 0.73883                         |
| 3-1       | 3              | 1               | 1.89606                       | 0.16775                         |
| 6-1       | 6              | 1               | -0.03379                      | 2.89772                         |
Take the result of the tide calculation as the basic tide calculation result, and get multiple tide calculation results by changing the power of the load connected to 1# bus, and the power change of the tide calculation result should not be too much relative to the basic tide calculation result after adjusting the load power. The specific adjustment method is: adjusting the active power and reactive power of the load connected to 1# bus to increase by 0.1% until it increases by 1%; adjusting the active power and reactive power of the load connected to 1# bus to decrease by 0.1% until it decreases by 1%; performing a power flow calculation after each adjustment and recording the required data, totaling 21 sets of data. Based on the data obtained from the power flow calculation, the improved particle swarm algorithm is used to identify the parameters $E_x$, $E_y$, $r_j$, and $x_j$ according to Eqs. (12) and (13), and the identification results are shown in the following table.

| Line name | $E_x$ | $E_y$ | $r_j$ | $x_j$ | Root mean square error |
|-----------|-------|-------|-------|-------|------------------------|
| 2-1       | 2     | 1     | 1.94153 | 0.73883 | 2.1679*10^-4          |
| 3-1       | 3     | 1     | 1.89606 | 0.16775 | 1.9909*10^-4          |
| 6-1       | 6     | 1     | -0.03379 | 2.89772 | 1.1998*10^-4          |

$x_j$ is the equivalent reactance before the short-circuit of line 2-1, line 3-1 and line 6-1.

5.3. Solving for the equivalent reactance $x_j^{''}$ after short-circuit

According to the 3-machine and 6-node system constructed as shown in Fig. 10, using the transient stability calculation module of PSASP, a three-phase circuit fault is set to occur at bus #1, the fault starts at 1s, and it lasts 0.3s, and the following data are obtained by transient stability calculation.

1. The short-circuit current decay curve of line 2-1 flowing to the short-circuit point 1# bus;
2. The short-circuit current decay curve of line 3-1 flowing to the short-circuit point 1# bus;
3. The short-circuit current decay curve of line 6-1 flowing to the short-circuit point 1# bus;

The short-circuit current decay curves obtained by the PSASP transient stability calculation module are shown in Fig. 11-13.

Figure 11. Decay curve of short-circuit current of line 2-1.
Figure 12. Decay curve of short-circuit current of line 3-1.
Figure 13. Decay curve of short-circuit current of line 6-1.

According to the obtained short-circuit current decay curves, the sampling time is from 1.001s to 1.060s, using the interval of 0.001s to obtain a total of 60 data pairs ($t$, $I_m(t)$), based on the obtained equivalent reactance of line 2-1, line 3-1 and line 6-1 before the short-circuit to set the initial values of the corresponding short-circuit current decay curve coefficients $x_d$ and $x_d^{''}$, the initial values of $x_d$ can be determined directly according to $x_j$. The initial value of $x_d^{''}$ should be given according to $x_j$. The initial value range is not fixed, but should be considered in conjunction with the obtained short-circuit current decay curve. In order to speed up the convergence of the improved particle swarm algorithm, the initial values are set as the following table.
Table 4. Initial value setting of coefficient the static reactance and sub transient reactance.

| Line name | $x_j$ | $x_d$ | $x_d''$ (lower limit) | $x_d''$ (upper limit) |
|-----------|-------|-------|-----------------------|-----------------------|
| 2-1       | 0.1621| 0.1621| 0.0811                | 0.1621                |
| 3-1       | 0.2045| 0.2045| 0.1023                | 0.2045                |
| 6-1       | 0.0663| 0.0663| 0.0332                | 0.0663                |

Combining Eq. (18) and Eq. (19), the improved particle swarm algorithm is used to identify the parameters $E_q$, $E_d$, $x_d$, $x_d''$, and $T_d''$. The identification results are shown in the following table.

Table 5. Steady state parameter identification results.

| Line name | $E_q$  | $E_q''$ | $x_d$  | $x_d''$ | $T_d''$ | Root mean square error |
|-----------|--------|---------|--------|---------|---------|------------------------|
| 2-1       | 0.9857 | 0.9423  | 0.1584 | 0.1029  | 0.0307  | 2.9312*10^-4           |
| 3-1       | 0.9056 | 1.1816  | 0.1905 | 0.1585  | 0.0237  | 4.8295*10^-4           |
| 6-1       | 0.9214 | 1.0915  | 0.0737 | 0.0423  | 0.0221  | 7.9451*10^-4           |

The sub-transient reactance coefficient $x_d''$ is the short-circuit transfer impedance of each line connected to the short-circuit point.

5.4. Calculation results by hand calculation method

The 3-machine and 6-node system shown in Fig. 10 is transformed into an equivalent circuit.

![Figure 14. Equivalent circuit diagram of a three-machine and six-node system.](image)

System base capacity is 100MVA.

For generators.

\[
X_1 = x_d' \times \frac{S_g}{S_{N_1}} = 0.1 \times \frac{100}{460} = 0.0217
\]

(20)

\[
X_2 = x_d' \times \frac{S_g}{S_{N_2}} = 0.1 \times \frac{100}{363} = 0.0275
\]

(21)

\[
X_3 = x_d' \times \frac{S_g}{S_{N_3}} = 0.1 \times \frac{100}{250} = 0.0400
\]

(22)

For transformer.

\[
X_4 = 0.015
\]

(23)

\[
X_5 = 0.015
\]

(24)

\[
X_6 = 0.030
\]

(25)

For transmission lines.

\[
X_7 = X_8 = X_9 = 0.0754
\]

(26)

The equivalent network obtained by network transformation is as shown in the Fig. 15.
Figure 15. Simplified equivalent circuit diagram of a three-machine and six-node system.

Transforming the upper circuit of equivalent circuit shown in Fig. 14 to a star, then the equivalent calculation is performed by the unit current method for the transformed part. The results are as the following table.

Table 6. Calculation results of manual calculation method.

| Impedance name | Reactance value |
|----------------|-----------------|
| $X_{21}$       | 0.1032          |
| $X_{31}$       | 0.1588          |
| $X_{61}$       | 0.0426          |

Comparing the identification results $x_d''$ and the results of the hand calculation method in Table V, it can be seen that there is a certain deviation with an acceptable degree, thus the proposed short-circuit transfer impedance solution method has the feasibility of practical application, the method can calculate the short-circuit transfer impedance of each line connected to the short-circuit point.

6. Conclusion

This paper proposes a method of solving short-circuit transfer impedance. Compared with the existing general short-circuit transfer impedance solution method, it doesn’t require the information of each component in power grid as known condition, and has more applicability in the engineering of the power grid. The short-circuit transfer impedance of each line connected to the short-circuit point can be used as a measure to analyse the short-circuit current influence factor.

Acknowledgements

This paper is supported by the Science and Technology Project (5216A2200003) of State Grid Hunan Electric Power Co., Ltd. and the Hunan Provincial Science and Technology Innovation Platform and Talent Program (2019TP1053), for which we would like to express our sincere thanks.

References

[1] TAO Sudong. The Calculating Method of Shifting -impedance[J]. Shandong Electric Power, 2003(03): 73-75.
[2] CAO Wei, CHEN Chunyang, ZHOU Ming. Study on Practical Calculation Method of Attenuated Short-Circuit Current With the DC Component Considered[J]. Power System Technology, 2017, 41(12): 4054-4060.
[3] LI Guangqi. Transient Analysis of Power System[M]. China Electric Power Press, 2010, 3-4.
[4] HE Yangzan, WEN Zengyin. Power System Analysis[M]. Huazhong University of Science & Technology Press, 2002. More references
[5] Short-circuit current calculation in three-phase A.C.systems : GB/T 15544.1—2013[S]. Beijing:China Standard Press, 2013.
[6] LIAO Guodong, XIE Xintao, HOU Yiling, et al. Analysis on the problems of three-phase short-
circuit current over-limited of 500 kV bus when UHV connected to Hunan Power Grid[1]. High Voltage Engineering, 2015(3):47-75 (in Chinese).

[7] T. Omata and K. Uemura, "Effects of series impedance on power system load dynamics," in IEEE Transactions on Power Systems, vol. 14, no. 3, pp. 1070-1077, Aug. 1999, doi: 10.1109/5.780926.

[8] G. Xu and X. Liu, "Equivalent substitution method-based failures analysis for electromagnetic loop," 2012 11th International Conference on Environment and Electrical Engineering, 2012, pp. 317-322, doi: 10.1109/EEEIC.2012.6221395.

[9] D. Sweeting, "Applying IEC 60909, Fault Current Calculations," in IEEE Transactions on Industry Applications, vol. 48, no. 2, pp. 575-580, March-April 2012, doi: 10.1109/TIA.2011.2180011.

[10] B. L. Robertson and T. A. Rogers, "External impedance vs. short-circuit currents," in Electrical Engineering, vol. 53, no. 2, pp. 252-254, Feb. 1934, doi: 10.1109/EE.1934.6539939.

[11] Y. Jin, Y. Chen, Z. Lu, Q. Zhang and R. Kang, "Cascading Failure Modeling for Circuit Systems Using Impedance Networks: A Current-Flow Redistribution Approach," in IEEE Transactions on Industrial Electronics, vol. 68, no. 1, pp. 632-641, Jan. 2021, doi: 10.1109/TIE.2020.2967672.

[12] R. Bleilevens and A. Moser, "Simplified Short Circuit Current Calculation for DC Distribution Grids based on a Superposition Approach using Approximated Current Courses," 2020 5th IEEE Workshop on the Electronic Grid (eGRID), 2020, pp. 1-8, doi: 10.1109/eGRID48559.2020.9330643.

[13] Z. Čonka, K. Mášlo and B. Bátor, "Short circuit current calculations," 2018 19th International Scientific Conference on Electric Power Engineering (EPE), 2018, pp. 1-4, doi: 10.1109/EPE.2018.8396040.

[14] C. Jäger, I. Grinbaum and J. Smajic, "Dynamic Short-Circuit Analysis of Synchronous Machines," in IEEE Transactions on Magnetics, vol. 53, no. 6, pp. 1-4, June 2017, Art no. 8103304, doi: 10.1109/TMAG.2017.2661580.

[15] S. A. Eroshenko, A. O. Egorov, M. R. Zagidullin and M. D. Senyuk, "The indicators system for the short circuit currents levels assessment in the power systems," 2017 15th International Conference on Electrical Machines, Drives and Power Systems (ELMA), 2017, pp. 144-148, doi: 10.1109/ELMA.2017.7955419.

[16] B. Niersbach, I. Ghourabi and J. Hanson, "Suitability of Simple Methods Based on the Standard IEC 60909-0 for the Calculation of Three-Phase Short-Circuit Currents in Distribution Grids," NEIS 2020; Conference on Sustainable Energy Supply and Energy Storage Systems, 2020, pp. 1-6.

[17] C. Zhiqin et al., "Calculation and Analysis of Online Short Circuit Current in a Regional Power Grid based on the Actual Operation Data (CICED 2020)," 2021 China International Conference on Electricity Distribution (CICED), 2021, pp. 191-195, doi: 10.1109/CICED50259.2021.9556842.

[18] Y. Zhang, Y. Zhang, J. Han and M. Wang, "Accuracy of Calculation Method for DC Component of Short-circuit Current," 2021 4th International Conference on Energy, Electrical and Power Engineering (CEEP), 2021, pp. 26-32, doi: 10.1109/CEEP51765.2021.9475771.

[19] O. Chiver, L. Neamt and O. Matei, "Comparative study on sudden short-circuit currents of a synchronous generator," 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), 2015, pp. 1688-1693, doi: 10.1109/EEEIC.2015.7165426.

[20] C. Han, X. Wu and P. Ma, "Identification of synchronous generator parameters based on 3-phase sudden short-circuit current," 2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011, pp. 959-962, doi: 10.1109/DRPT.2011.5994032.