Method Article

A fast fault current calculation method for distribution networks connected with inverter interfaced distributed generators

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ABSTRACT

The integration of the inverter interfaced distributed generation (IIDG) challenges the conventional fault current calculation methods. The existing fault current calculation methods for distribution networks with IIDG connection generally use nodal admittance matrix and its implicit inverse, which take a longer calculation time and are not suitable for electrical engineering. To simplify the calculation process and reduce the calculation time, a new method was proposed. The new method can estimate fault currents of the feeders with IIDG connection with a higher computation speed, using fault current values obtained in networks without IIDG connection as the initial values in the procedure. The proposed method can obtain results without modifying the node impedance matrix and the calculation time was not affected by the nodes number, which can be used for fast short-circuit current calculation in radial distribution networks with IIDG connection. The new method can be conveniently integrated into software packages for power system analysis and relay protection evaluation.

- The proposed method can estimate fault currents of the feeders with IIDG connection with a higher computation speed, which is beneficial for electrical engineering.
- The new method has advantages in calculation time and accuracy of the results in comparison with the conventional bus-oriented methods.
- The method proposed in this paper can be conveniently integrated into software packages for power system analysis and relay protection evaluation.

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Method details

Fault current calculation is one of the basic calculations in electrical engineering [1]. As the penetration level of the inverter interfaced distributed generators (IIDGs) increases, it is necessary to develop new fault current calculation methods in distribution networks [1,2]. The calculation time of the conventional bus-oriented methods depends on the scale of the network [3,4] and it is not suitable for electrical engineering. To simplify the calculation process and reduce the calculation time, a new fault current calculation method was proposed, based on the composite-sequence network analysis [5].

The new method uses fault current values obtained in networks without IIDG connection as the initial values to estimate fault currents of the feeders connected with IIDGs. The procedure of the proposed method contains four main steps, which is shown in Fig. 1.

To illustrate the proposed method, a representative distribution network is presented in Fig. 2. The topology of the network is radial and IIDGs are integrated into the system. A fault is assumed to occur at $f_1$ and $f_2$, respectively.

STEP 1: Calculate the newly defined coefficients in terms of the fault location and IIDG coupling point

$k_i$ and $l$ are defined coefficients in this paper, which are shown in (1) and (2), respectively.

$$k_i = \frac{Z_{S-DG_i}}{Z_{Sfn_i}} \quad (1)$$

$$l = \frac{Z_{1}}{Z_{Sfn}} \quad (2)$$

where, $Z_1 S-DG_i$ denotes the positive impedance between the upstream network and IIDG $i$, $Z_{Sfn}$ denotes the total positive impedance between the upstream network and the fault location.

STEP 2: Estimate the fault currents of the feeders connected with IIDGs by using $k_i$, $l$, and the fault current values obtained in networks without IIDG connection.

The phase components of the fault currents during symmetrical and asymmetrical faults can be estimated through Table 1 and 2, respectively.

The expressions in Tables 1 and 2 are used for symmetrical and asymmetrical faults, respectively. The coefficients, superscripts and subscripts in Tables 1 and 2 are illustrated as the following.

(1) The coefficient $\alpha$ depends on the fault type and can be express as

$$\alpha = \begin{cases} 
\frac{1}{\beta_1} & \text{three phase fault} \\
\frac{1}{1 + \beta_1} & \text{line-to-line fault} \\
\frac{1}{2 + \beta_2} & \text{single line-to-ground fault} \\
(1 + \beta_2)/(1 + 2\beta_2) & \text{double line-to-ground fault} 
\end{cases} \quad (3)$$
Fig. 1. A diagram of the proposed fault current calculation method.
Fig. 2. A simplified distribution network connected with IIDGs.

Table 1
Calculation method of fault currents during symmetrical faults.

| $f_1$ | $f_2$ |
|-------|-------|
| $i_3$ | $i_2$ |
| $i_4$ | $i_1$ |

\[
\begin{align*}
\beta_1 &= 1 + Z_f/Z_{\text{Sf}1} \\
\beta_2 &= Z_{\text{Sf}1}^0/Z_{\text{Sf}1} + 3Z_f/Z_{\text{Sf}1} \\
\end{align*}
\]  
(4)

(2) The constant $a$ is a vector which can be expressed as 
\[ a = e^{j2\pi/3} \]
(5)

(3) The superscript A, B, and C denotes the phase components. 
(4) The subscript (pre) represents the previous fault currents in networks without IIDG connection.

It is noted that the initial value of $I_{DG}$ can be set as its rated current.

STEP 3: Calculate the IIDG coupling voltages

The phase components in Tables 1 and 2 can be transformed into the sequence components according to the symmetrical component transformation [6] shown as
\[
I^{0,1,2} = S^{-1}I^{A,B,C}
\]
(6)

where,
\[
S = \begin{bmatrix}
1 & 1 & 1 \\
1 & a^2 & a \\
1 & a & a^2
\end{bmatrix}
\]
(7)

The expressions for calculating IIDG coupling voltages are expressed in Table 3. $U_{1(0)} \ DG$ represents the pre-fault voltage of the coupling point with IIDG connection, which can be obtained through the power flow estimation.

STEP 4: Achieve the calculation results
Table 2
Calculation method of fault currents during asymmetrical faults.

| Line-to-line fault (phase B and phase C) | Single line-to-ground fault (phase A) | Double line-to-ground fault (phase B and phase C) |
|-----------------------------------------|--------------------------------------|--------------------------------------------------|
| $f_1$                                   |                                      |                                                  |
| $i_3 = i_3^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha_k) - (1 - a^2)/3]i_{DG}^k$ | $i_3 = i_3^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha_k) - (1 - a^2)/3]i_{DG}^k$ | $i_3 = i_3^{(pre)}$ |
| + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ |
| + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ |
| $i_4 = i_4^{(pre)} - j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ | $i_4 = i_4^{(pre)} - j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ | $i_4 = i_4^{(pre)} - j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ |
| + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha_k) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha_k) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha_k) - (1 - a^2)/3]I_{DG}^k$ |
| $i_1 = i_1^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ | $i_1 = i_1^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ | $i_1 = i_1^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} \alpha_k i_{DG}^k$ |
| + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ | + $j\sqrt{3} \sum_{l=1}^{m} [(1 - \alpha) - (1 - a^2)/3]I_{DG}^k$ |
| $f_2$ | $f_2^{(pre)} = f_2^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} (1/2)I_{DG}^k$ | $f_2^{(pre)} = f_2^{(pre)} + j\sqrt{3} \sum_{l=1}^{m} (1/2)I_{DG}^k$ | $f_2^{(pre)} = f_2^{(pre)} - \sum_{l=1}^{m} \alpha_k I_{DG}^k$ |

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Table 3
IIDG Coupling voltages during asymmetrical faults.

| $f_1$ | $i \in [1, n]$ | $U_{DG_i}^{(1)} = U_{DG_i}^{(1)(0)} - kZ_i I_i^1$ |
|-------|----------------|----------------------------------|
| $f_2$ | $i \in [n + 1, m]$ | $U_{DG_i}^{(1)} = U_{DG_i}^{(1)(0)} - Z_{i} I_i^1$ |

According to the control strategy and low voltage ride-through (LVRT) capability of IIDG [4,7], the output currents of IIDG are controlled by the coupling voltages, which can be presented as

$$I_{DG} = (I_d \cos \theta + I_q \sin \theta) + j(I_d \sin \theta - I_q \cos \theta)$$  \hspace{1cm} (8)

$$\begin{cases} 
I_q = \min (\alpha (U_N - U^1) I_N, I_{max}) \\
I_d = \min \left(\frac{P}{U^1}, \sqrt{I_{max}^2 - I_q^2}\right)
\end{cases}$$  \hspace{1cm} (9)

where, $I_d$ and $I_q$ are the active current value and reactive current value, respectively, $U_N$ and $U^1$ are the normal voltage and fault voltage of the common coupling point, respectively, $I_N$ is the IIDG rated current, $I_{max}$ is the maximum output current of IIDG, and $\theta$ is the angle between $U_d$ and the reference direction.

The progress can be programmed as an iteration procedure and the iteration number $\lambda$ increases in the next iteration. The procedure is terminated when the difference between $I(\lambda)$ DG $i$ and $I(\lambda+1)$ DG $i$ is less than the convergence $\varepsilon$ ($\varepsilon$ is set as 0.0001 in this paper), and the latest results are accepted as the output.

Case study

The effectiveness of the proposed calculation method has been investigated on the thirty-three-node system. The thirty-three-node system is extended to contain four IIDGs, which is shown in Fig. 3. The feeder and load data are tabulated in [8], and the feeder zero impedance is selected as two times of the positive impedance [9]. The output powers of IIDG 1 to IIDG 4 are 1.0, 1.0, 0.5, and 0.5 MW, respectively.

Different cases have been studied by using the proposed method and the conventional bus-oriented method in [4]. The comparison of the calculation procedure is shown in Fig. 4. It can be seen that the conventional method uses node impedance matrix in an iteration procedure and the calculation time depends on the scale of the network. In comparison with the conventional method, the new method uses fault current values obtained in networks without IIDG connection as the initial values to estimate the fault currents of the feeders connected with IIDGs, simplifying the calculation process and improving the calculation time.
Fig. 4. The calculation procedure comparison between the proposed method and conventional method.

Fig. 5. Calculation time of the method in [4] and the proposed method when faults occurring at (a) \( f_1 \), (b) \( f_2 \), (c) \( f_3 \), and (d) \( f_4 \).
It has been verified that the maximum magnitude and phase angle errors of the proposed method are 0.005 p.u. and 2.8°, respectively, while the maximum errors of the method in [4] are 0.015 p.u. and 15.1°, respectively. To validate the effectiveness of the proposed method in calculation time, the CPU time of the calculation procedure is observed as well as the time of the conventional method in [4]. The comparisons are presented in Fig. 4, which has verified the improvement of the proposed method in calculation time. It is noted that the time of the initial input estimation is 30 milliseconds and is not contained in Fig. 5. The proposed method can be conveniently programmed and integrated into software packages for power system analysis and relay protection evaluation in electrical engineering.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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