Short-circuit Current Calculation Method for Distributed Power Distribution Network with Control Strategies

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Abstract. In recent years, large-scale distributed generation (DG) with control strategies, such as photo-voltaic and wind power generation, is connected to the distribution network, making the traditional short-circuit current calculation method for distribution network no longer applicable. This paper establishes the mathematical model of DG piece-wise function with control strategies based on the control objectives of new DG grid connection. On this basis, this paper proposes an iterative calculation method for short-circuit current with DG distribution network with control strategies by taking the piece-wise function equation as the modified equation. This method can accurately calculate the short-circuit current value of the DG distribution network with control strategies, which provides a basis for the study of the influence of DG access on relay protection and the corresponding countermeasures.

1. Introduction

As distributed generation equipment is connected to the distribution system, its impact on the protection of the entire distribution system is also emerging. In order to study its influence, it is important to establish a new DG model with the new DG grid connection with control strategies, and to propose a short-circuit current calculation method suitable in this situation.

At present, since most papers simplify the DG model to a constant voltage source, a constant current source, or a linearly varying current source, the calculation of the short-circuit current with DG is still performed using the traditional method. Some articles have proposed complicated circuit equations of simple faults of distribution network with DG based on the established DG model with control strategies. However, the calculation is too complicated to be applied in complex distribution network, and it also poses difficulties for computers to manipulate programmatically \cite{1,3}.

2. DG modeling with new grid connection regulations

Recent years have seen new regulations for IIDG grid connection both at home and abroad. State Grid Corporation of China (SGCC) pointed out in Technical Specifications for PV Power Plants Connecting to Power Grids that in order to maintain the power grid stability, the medium-to large-sized PV power plants should have the capability of low voltage ride-through (LVRT), give priority to provide reactive power to the system, and keep running for a certain period with grid-connection in the event of grid failure. \cite{4,5}.

When there is a grid failure, the voltage drop of the point of common coupling (PCC) of the distributed generation is less than a\%, and the IIDG provides the active reactive power according to...
the active and reactive currents specified by the original system. Therefore, the active reactive current fault model of the IIDG operates normally:

\[
\begin{align*}
I_d &= \frac{P}{U_{pcc}} \\
I_q &= \frac{Q}{U_{pcc}}
\end{align*}
\]  

In the formula (1), \(I_d\) and \(I_q\) represent the active current and the reactive current supplied by the distributed power source to the grid; \(P\) is the maximum capture power of IIDG or the maximum output active power set by IIDG; \(Q\) represents the reactive power set by the system; \(U_{pcc}\) is the actual voltage of PCC.

When the voltage of PCC of IIDG drops between \(a\%\) and \(b\%\), the reactive current supplied by the IIDG is \(I_q' + k_1 \left( \frac{U_N - U_{pcc}}{U_N} \right) I_N\), or the reactive current of the previous system plus the \(k_1\) times of the reactive current provided by IIDG every time when the PCC voltage is reduced by 1% when there is a fault. The active current provided by IIDG to the system is the minimum function between the maximum output active current allowed and \(\frac{P}{U_{pcc}}\), the active currents required to be delivered by IIDG, excluding the reactive current delivered by IIDG to the grid under the limiting requirements of the power electronics being \(k_2 I_N\) (\(k_2\) is the maximum allowable overcurrent multiple of the inverter distributed power supply). The model is:

\[
\begin{align*}
I_q &= I_q' + k_1 \left( \frac{U_N - U_{pcc}}{U_N} \right) I_N \\
I_d &= \min \left[ \sqrt{k_2^2 I_N^2 - I_q'^2}, \frac{P}{U_{pcc}} \right]
\end{align*}
\]  

In the formula (2), \(U_N\) is the rated power of the PCC; \(\frac{U_N - U_{pcc}}{U_N}\) is the ratio of the voltage drop of PCC when a fault occurs; \(I_q'\) is the reactive current supplied to the grid before the PCC voltage drops by \(a\%\); \(k_1\) is the ratio of the reactive power of the IIDG output.

When the PCC voltage drop of IIDG is greater than \(b\%\), IIDG is required to deliver the reactive current \(k_2 I_N\), with the maximum current limit of the power electronic device. At that time, the active current is zero. Under this circumstance, the fault model of IIDG is

\[
\begin{align*}
I_q &= k_2 I_N \\
I_d &= 0
\end{align*}
\]  

In the formula (3), \(k_2\) is the maximum allowable overcurrent multiple of IIDG.

\(I_{DGC}\), the fault equivalent model of the converter distributed power supply is:

\[
\begin{align*}
I_{DGC} &= I \angle \varphi_{DG} \\
I &= \sqrt{I_d^2 + I_q^2} \\
\varphi_{DG} &= \tan^{-1} \left( \frac{I_q}{I_d} \right) + \arg(\dot{U}_{pcc})
\end{align*}
\]  

In the formula (4), the active current component of the IIDG is oriented to the phase of the PCC voltage, and the phase angle of the IIDG current is the sum of \(\tan^{-1} \left( \frac{I_q}{I_d} \right)\), the angle between the active and reactive currents, and \(\arg(\dot{U}_{pcc})\), the phase angle of the grid-connected voltage.

3. **short-circuit current iterative calculation method**

Assume that a three-phase short-circuit fault occurs at \(f_3\), the end of the CD segment of the distribution network, as shown in the figure.
Figure 1  Schematic diagram of three-phase short circuit at the end of CD segment of the distribution network

The equivalent circuit diagram of the above figure is shown as follows (Rf is the transition resistance)

\[ Z_{AB} Z_{BC} Z_{CD} R_f Z_{AF} Z_{FG} Z_S E S I = f \left( U_{PCC} \right) \]

Figure 2  Equivalent circuit diagram of three-phase short circuit at the end of the CD segment of the distribution network

Based on the circuit diagram, the node voltage equation is shown as follows by using the node impedance equation.

\[ \mathbf{U} = \mathbf{IZ} \]
\[ \mathbf{I}_i = \begin{bmatrix} \dot{U}_{sf} & \dot{U}_{BF} & \dot{U}_{CF} & \dot{U}_{DF} & \dot{U}_{EF} & \dot{U}_{GF} \end{bmatrix}^T \]
\[ \mathbf{I}_f = \begin{bmatrix} I_{sf} & 0 & I_{DGf} & 0 & 0 & 0 \end{bmatrix}^T \]

(5)

It can be seen from the above equation (5) that the node impedance matrix \( Z \) can be obtained from the parameters of the distribution network. To solve the voltage value of each node, and to further find out the current of each branch when the fault occurs, we only need to know \( I_{DGf} \), the short-circuit current of the IIDG output, and \( I_{sf} \), the short-circuit current output by ES when the distribution network fails. If the two are constant or are in a linear function with the voltage at each point, the above node voltage equation can be obtained directly or through corresponding changes. According to the modeling of \( I_{DGf} \), the fault current output by IIDG in this equation is a piece-wise function of \( U_{PCC} \), the change of the PCC voltage. Therefore, it cannot be obtained using the traditional method.

Iterative methods can be used to solve such equations. Firstly, set the initial iteration value of \( I_{DGf} \) and \( I_{sf} \). As the setting of the initial value of the iteration, \( I_i \) and \( I_{DG} \), the normal current value can be obtained using the tidal current method with DG distribution network. Obtain the initial calculated voltage value of each node by using the node voltage equation as the iterative equation. Then, based on the calculated value range of the voltage drop of PCC, use the modification equation of \( I_{DGf} \), the fault current provided by inverter distributed power source for correction. For example, the PCC voltage of \( U_{PCC} \) is \( U_{CF} \) in this figure, which is used to obtain the voltage drop range. When the voltage drop value is less than a%, choose \( I_d = \frac{P}{U_{PCC}} \) to correct the fault current value of the distributed power.
source; when the voltage drop value is between a% and b%, choose $I_d = \frac{p}{u_{pcc}}$, $I_q = \frac{Q}{u_{pcc}}$; when the voltage drop is greater than b%, choose

$$I_d = \frac{p}{u_{pcc}}, \quad I_q = \frac{Q}{u_{pcc}}.$$  

After correction, substitute it into the node voltage equation for calculation to obtain a new node voltage value. When the absolute value of the difference between the calculated node voltage value and the previous node voltage value is not less than $\varepsilon$, it indicates that the calculation result converges, and calculation can come to an end since the accurate node voltage value when fault occurs has been obtained. The voltage of each node at the last calculation is the voltage when the required IIDG distribution network fails, based on which the current of each branch can be obtained. If the absolute value of the difference between the calculated node voltage value and the previous node voltage value is not less than $\varepsilon$, then continue to iterate using the corresponding IIDG fault model according to the value range of the PCC voltage of IIDG, so as to obtained the new voltage value of each node. Compare them with the value their previous node, and the calculation stops until all the voltage differences are less than $\varepsilon$.

The equations for the iteration of the short-circuit current of the IIDG distribution network with the subdivision control strategies are as follows:

$$\begin{align*}
\begin{bmatrix} U_{t+1}^i \\ I_{t+1}^i 
\end{bmatrix} &= \begin{bmatrix} U_{sf}^t \\ I_{sf}^t 
\end{bmatrix} + \begin{bmatrix} \frac{U_{Bf}}{u_{pcc}} & \frac{U_{Bf}}{u_{pcc}} & \frac{U_{Cf}}{u_{pcc}} & \frac{U_{Cf}}{u_{pcc}} & \frac{U_{DF}}{u_{pcc}} & \frac{U_{DF}}{u_{pcc}} & \frac{U_{GF}}{u_{pcc}} & \frac{U_{GF}}{u_{pcc}} 
\end{bmatrix} \begin{bmatrix} I_{t+1}\\ I_{t+1}\\ I_{t+1}\\ I_{t+1}\\ I_{t+1}\\ I_{t+1}\\ I_{t+1}\\ I_{t+1} 
\end{bmatrix}^T
\end{align*}$$ (6)

$$\begin{align*}
\begin{cases}
I_{d_{t+1}} = \frac{p}{u_{pcc}} \\
I_{q_{t+1}} = \frac{Q}{u_{pcc}} \\
I_{d_{t+1}} = \min \left[ \frac{k_2 I_{t+1}^N}{\sqrt{2} U_{pcc}}, \frac{k_2 I_{t+1}^N}{u_{pcc}} \right] \\
I_{q_{t+1}} = k_2 I_{t+1}^N \\
I_{d_{t+1}} = 0
\end{cases}
\end{align*}$$ (7)

$$\varphi_{DG} = \tan^{-1} \left( \frac{I_{q_{t+1}}}{I_{d_{t+1}}} \right) + \arg(\tilde{U}_{pcc}^{t+1})$$

$$|\max(U_{t+1}^i - \tilde{U}_i)| \leq \varepsilon$$ (8)

Equation (6) is an iterative equation for calculating the short-circuit current of the IIDG distribution network, in which $t$ is the number of iteration, and $B'$ indicates the short-circuit point. If there is a bus that the current of the system and DG cannot pass through due to the fault, take the bus node voltage as zero. Equation (7) is a modification equation for calculating the short-circuit current of the IIDG distribution network. Equation (8) is the criterion of convergence.

4. Case verification

The simulation verification of the short-circuit current calculation method of IIDG with control strategies shown in Figure 1.
The power supply of the system has a rated voltage of 10.5 KV, a capacity of 500 MVA, and an equivalent impedance of j1.2 Ohm. Set the active power output of the IIDG as 10 MW during normal operation; its reactive power, 0 MW; Its rated current, 0.45 KA; the rated PCC voltage, 7.964KV. Set $k_1$, the proportional coefficient of reactive power of IIDG output as 2; $k_2$, the maximum allowable overcurrent multiple of IIDG, 1.2; $a\%$, the first PCC grid drop, 10%; $b\%$, the second PCC grid drop, 40%. The line impedance is $(0.2+0.41j)$ Ohm/km and the lengths of AB, BC, CD, DE, AF, FG are 2 km, 4 km, 2 km, 11 km, 15 km, 4 km, respectively.

The allowable error of the short-circuit current value when three-phase short circuit occurs at f1, f2, f3, f4, f5, and f6 of each branch. Allowable error is 0.0001. Build the simulation model based on PSCAD/EMTDC, and obtain the short-circuit current value of each branch when f1, f2, f3, f4, f5, and f6 fail under the same conditions. Compare the result with the calculation result, as shown in Table 1.

| Short-circuit point | Calculated current value and stimulated current value of each branch when IIDG distribution network fails at different points |
|---------------------|---------------------------------------------------------------------------------------------------------------------|
| f1                  | Calculated value: 6.5376, 0.0206, 0.0329, 0.0329, 0.0693, 0.0693; Stimulated value: 6.5369, 0.0247, 0.0336, 0.0336, 0.0699, 0.0699 |
| f2                  | Calculated value: 3.3175, 3.3175, 0.0268, 0.0268, 0.0737, 0.0737; Stimulated value: 3.3183, 3.3183, 0.0267, 0.0267, 0.0748, 0.0748 |
| f3                  | Calculated value: 1.3964, 1.3964, 1.7592, 0.0229, 0.0815, 0.0815; Stimulated value: 1.3962, 1.3962, 1.7681, 0.0247, 0.0834, 0.0834 |
| f4                  | Calculated value: 1.4500, 1.4500, 1.6992, 1.6992, 0.0889, 0.0889; Stimulated value: 1.4504, 1.4504, 1.6983, 1.6983, 0.0886, 0.0886 |
| f5                  | Calculated value: 0.1873, 0.1873, 0.0573, 0.0573, 3.4124, 0.0272; Stimulated value: 0.1875, 0.1875, 0.0574, 0.0574, 3.4122, 0.0279 |
| f6                  | Calculated value: 0.0182, 0.0182, 0.0626, 0.0626, 3.0041, 3.0041; Stimulated value: 0.0188, 0.0188, 0.0637, 0.0637, 3.0016, 3.0016 |

It can be seen that the calculated and stimulated values of the short-circuit current of the distribution network of IIDG with control strategies and low voltage ride-through characteristics are basically consistent with each other, and the errors are three digits after the decimal point. Therefore, the validity of the calculation method and the reliability of the calculation result can be proved.
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