Analysis of single phase ground fault characteristics of low resistance ground active distribution network

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Abstract. A large number of distributed generators access to low resistance grounding system may have great influence on the fault characteristics of single phase ground. In view of low resistance ground active distribution network, the connection mode of Inverter-interfaced Distributed Generators (IIDG) is discussed comprehensively based on operation safety and protection requirements. The equivalent model of IIDG and simplified zero sequence network model of low resistance grounding system contain multi-IIDG for single phase ground fault are established. The amplitude and phase characteristics of zero sequence current in single phase grounding fault of the system and the characteristics of high-resistance ground fault are analyzed. Simulative results by MATLAB/Simulink verifies the correctness of the analysis results of fault characteristics. The conclusions could be provided as reference for solving the grounding protection of system with high penetration of distributed generator.

1. Introduction

The low resistance grounding system is popularized and applied in some heavy-load areas at home and abroad [1-2]. The large-scale integration of Distributed Generators (DG) into low resistance ground systems is the future development direction. It urgently needs to be analyzed and resolved.

Research on ground faults in low resistance ground systems is mainly concentrated in systems without DG: In [3-4] analyze the general characteristics of low resistance and high resistance single phase ground faults in passive distribution networks with low resistance grounding, but the system containing DG have different single phase ground fault characteristics. For the research of low resistance ground active distribution network, most of them stay at the single phase ground fault current characteristics of single inverter-interfaced distributed generator (IIDG) grid-connected system [5-7]. Under the mode of IIDG grounding through a low resistance, the overvoltage can be effectively controlled, and effective zero sequence current can be detected on both system and IIDG. However, the analysis is not suitable for the general situation of multiple DGs connected to the grid, and it does not consider the high resistance ground fault. At present, the research on the ground fault characteristics of the low resistance ground system with multiple DGs connected to the grid is still lacking.

In order to make up for the limitations of above research, the paper selects appropriate IIDG grid-connected method, establishes equivalent zero sequence network of multi-IIDG grid-connected system, and analyzes the zero sequence current amplitude and phase characteristics of low resistance ground distribution network containing multi-IIDG when single phase ground fault and high resistance ground fault. The conclusion provide basis for solving the problem of low resistance ground active distribution network ground protections.
2. IIDG equivalent model and grid connection method

2.1. IIDG equivalent model

Medium voltage distribution network is mainly connected with IIDG [8]. In the following paragraphs, DG is analyzed with IIDG as an example.

PQ control is usually adopted as the control strategy of IIDG [9]. The characteristics of the relationship between the active and reactive current component $I_d$ and $I_q$ and the positive sequence voltage change of parallel dots are shown in Fig.1. Both current and voltage are unit values of voltage and current ($I_N$). The output strategies of $I_d$ and $I_q$ also change with different degree of dot positive sequence voltage sag.

The change curve of the total output current $I_{dg}$ and the parallel node voltage satisfies the law as shown in Fig.2. Obviously, no matter what the voltage of parallel grid node is in case of failure, $I_{dg}$ is constant at $1 \sim 1.2I_N$. Considering the limitation of IIDG grid-connected capacity in the actual situation, and that the voltage of the node is clamped by the large system, IIDG is equivalent to the current source with only positive sequence component in the following analysis, and the output current is $1.2I_N$.

2.2. Grid connection method

Generally, IIDG is usually connected to the grid through a booster transformer [8]. When single phase grounding fault occurs in low resistance grounding system, if ungrounded grid-connection is adopted, the fault current on the IIDG side is too small to detect the fault. In principle, the ground resistance that is not less than the ground resistance value of neutral point is selected to ensure that both the grid and the IIDG can detect enough fault current to ensure the reliable operation of protection [9]. In order to suppress the harmonic injection generated by power electronic components in IIDG, the grid-connected booster transformer always keeps triangular connection as the connection mode of any end of grid-connected transformer. Grid grounding resistance is not less than 10Ω. It also needs to consider factors such as personal safety and fault features, will be discussed below.

3. Single phase ground fault model of low resistance earth active distribution network

3.1. Fault equivalent model

Multiple IIDGs should be distributed as uniformly as possible in each outlet of the distribution network. At this time, the permeability based on the rated capacity of the main transformer should not exceed 33.3% at most [10]. According to this principle, take the 10kV system shown in Fig.3 as an example to analyze. In Fig.3, line I contains n IIDGs, and the rest lines total m IIDGs. The composite sequence network diagram of single phase ground fault occurring at any position in I is shown in Fig.3. Composite sequence network diagram of any outgoing line with single phase ground fault is shown in Fig.4.
Where, $Z_{p10}$ and $Z_{p10}$ denote positive and negative sequence impedance of main transformer. $Z_{p1i}$ ($i = 1, 2, \ldots, n+1$), $Z_{p2i}$, $Z_{p0i}$ mean positive, negative and zero sequence impedance of fault point upstream respectively. $I_{10}$, $I_{1i}$ ($i = 1, 2, \ldots, n$), $I_{in+1}$, $I_0$ represent positive sequence current of adjacent line’s IIDGs, the fault point upstream’s IIDG, fault point downstream’s IIDG and zero sequence current of system. $R_n$, $R_f$ denote neutral ground resistance and transition resistance. $R_{dg0}$, $R_{dg}$ ($i = 1, 2, \ldots, n$), $R_{dgn+1}$ are IIDG grid-connected grounding resistances of $I_{10}$, $I_{1i}$ ($i = 1, 2, \ldots, n$), $I_{in+1}$ respectively. The fault current is composed of zero sequence current provided by system and all IIDGs, and it satisfies

$$I_0 = I_s + I_{dg} = \frac{U_s + \sum_{i=0}^{n+1} I_{1i} (\sum_{i=0}^{n+1} Z_{pi})}{Z_s + Z_n + 3R_f} \quad (1)$$

Where, $U_s$ represent system voltage, $Z_s$, $Z_n$ and $Z_0$ are the equivalent positive, negative and zero sequence impedance of network respectively.

It can be seen that the changes of composite sequence diagram after multiple IIDGs are mainly reflected in positive sequence current component of IIDG and the introduction of ground resistance of grid-connected transformer in the zero sequence network. Due to the control strategy’s control of the output current and the limitation of the maximum permeability, the influence of IIDG grid-connected on the amplitude of the total fault zero sequence current is limited under different capacities.

### 3.2. Simplified zero sequence network model

The line impedance of low resistance grounding system has certain influence on the amplitude of zero sequence current in the case of low resistance fault, will not have substantial influence on the action of grounding protection. The line impedance is ignored in the following analysis. In conclusion, the zero sequence network in Figure 4 is equivalent to the simplified network as shown in Fig.5.

According to 2.1, the fault current in (1) can be expressed as

$$I_0 = \frac{U_s + \sum_{i=0}^{n+1} I_{1i} (\sum_{i=0}^{n+1} Z_{pi})}{Z_s + Z_n + 3R_f}$$
\[ i_0 = K_{dg} i_s = \frac{K_{dg} \hat{U}_s}{Z_1 + Z_2 + Z_0 + 3R_e} \tag{2} \]

Where, \( K_{dg} \) denote grid-connected current coefficient of IIDG. The appropriate value is 1\textasciitilde1.2. It is concluded that the fault point current can be basically determined when single phase ground fault occurs at any position under the condition of the system structure is determined.

4. Single phase ground fault analysis of small resistance earth active distribution network

4.1. Selection of grid-connected grounding resistance and analysis of fault zero sequence current amplitude characteristics

In multi-IIDG system, the zero sequence current distribution caused by complex distribution of IIDGs is not conducive to the protection work, and its specific value needs further analysis. The results show that increasing the ground resistance has little effect on overvoltage. It is also necessary to ensure that both the system and IIDG can detect large enough current to ensure the sensitivity of protection on each side. The zero sequence current at the export of line can be obtained from the network in Fig. 5.

\[ I_{dgn} = KI I = \frac{R_{dgn}^2}{R_{dgn} + R_{dgm/n}} I_0 \tag{3} \]

\( K \) represents shunt coefficient, \( R_{dgm/n} \) denotes equivalent resistance of all \( R_{dg} \) of this circuit, and \( R_{dgm/n} \) means equivalent total resistance of \( R_{dg} \) and \( R_n \) of the other circuits except this circuit.

IIDG grid-connection will cause a large zero sequence current flowing through each output line under the gold-attribute single phase ground fault. The fault line has the largest amplitude of zero sequence current. The smaller equivalent resistance is, the larger zero sequence current is. When the number of non-fault line IIDG is large, if \( R_{dg} \) value is too small, the line current will be close to the fault line current, especially when the transition resistance is large, fault characteristics are not obvious. To solve the above problems, below \( R_{dg} \) value will be taken for 20\textasciitilde100 \( \Omega \) resistance. In principle to ensure qualification of the system total control in 10\textasciitilde50 \( \Omega \) equivalent resistance.

Based on above, the amplitude characteristics of single phase ground faults in active distribution networks with small resistance can be concluded: IIDG grid-connected makes non-fault lines flow through large zero sequence current. The amplitude of zero sequence current of each line has a fixed proportional relation, and the zero sequence current of fault line is obviously larger than that of non-fault line. In addition, when the line does not contain IIDG, a greater zero sequence current will appear at the outlet of the line when a single phase ground fault occurs than before the grid connection.

4.2. Analysis of fault zero sequence current phase characteristics

In the zero sequence network of low resistance ground system without IIDG, the non-fault lines are generally equivalent to the total grounding capacitance of the line and capacitive current. The zero sequence current leads the zero sequence voltage by about 90\(^\circ\), and the amplitude far less than 1/10 of the fault current \[4\]. The grid-connection of a large number of IIDGs with grounding resistors results in the characteristic of approximate resistance for the zero sequence current of sound lines with IIDGs. Zero sequence voltage and current phase difference close to 0\(^\circ\). At this point, the zero sequence current \( I_{f0} \) at the fault point is opposite to the current vector and of all other lines, which satisfies (4).

\[ \hat{i}_{f0} = -(\hat{i}_{c0} + \hat{i}_{b0} + \hat{i}_{dg0}) \tag{4} \]

Where, \( I_{c0}, I_{b0}, I_{dg0} \) represent total zero sequence current of the line to the ground, system neutral point resistance and IIDG grid-connected grounding resistance. Since \( C_0 \) is no higher than 10\(^{-5}\), amplitude of \( I_{c0} \) is far less than \( I_{b0}, I_{dg0} \). \( I_{c0} \) will not have substantial influence on the properties of \( I_{b0} \), so \( I_{b0} \) is approximately reverse resistance. Similarly, the phase of zero sequence current at the export of fault line is basically the same as that of \( I_{b0} \), and there is a phase difference of about 180\(^\circ\) between zero sequence voltage and current. The zero sequence voltage and current phase relationship of each line is shown in Figure 6, which is also an important feature of IIDG grid.
4.3. Analysis of zero sequence current characteristics of high resistance grounding fault

In practice, the fault of high resistance grounding often occurs, which will cause serious economic and personal loss, so we must pay attention to it.

Take the network in Fig.3 for example. IIDG total capacity from 0 to 15 MVA, calculate each line can be obtained when single phase ground fault occurring at different positions of export of zero sequence current changing with transition resistance curve as shown in Fig.7. The setting value of zero sequence overcurrent protection is calculated as 30A.

\[
\begin{align*}
\text{Figure 6} & \quad \text{Zero sequence voltage & current phase relationship} \\
\text{Figure 7} & \quad \text{Single phase ground fault zero sequence current curve with transition resistance}
\end{align*}
\]

It can be seen that when F11 and F1k points of I’s fail, the fault current attenuates greatly with the increase of transition resistance, which is slightly faster than when it is not connected to the grid, and is almost not affected by grid-connected capacity. At this time, the traditional protection setting value cannot identify the fault with high resistance. In the case of changing the number of IIDG, line length, etc., similar conclusions are drawn, which will not be repeated here. According to (3)(4), the relationship between the zero sequence current of the fault line and the non-fault line is independent of the transition resistance. When the non-fault line does not contain IIDG, its capacitive current is still much smaller than that of fault line. According to (5), the phase relationship in figure 6 is still satisfied.

5. Simulation verification

10kV low resistance grounding system model with multi-IIDG was built in MATLAB/Simulink. Its structure was shown in Fig.8, and IIDG was equivalent to the current source model in 2.1.

\[
\text{Figure 8} \quad \text{System simulation structure diagram}
\]

The permeability of IIDG is 30%, and the total grid-connected capacity of IIDG is 15MVA. IIDG ground resistances of Line I, II are 60 Ω and 40 Ω respectively. Table 1 shows the simulation results of single phase ground fault with different fault points and transition resistance. 3I_{10}, 3I_{20}, 3I_{30} represent zero sequence current of each line export, δU_0 means zero sequence voltage phase of the bus, δ1, δ2, δ3 denote zero sequence voltage phases of line I~III zero sequence current leading bus.
It can be seen from Table 1 that the amplitude of zero sequence current at export of corresponding fault line during F₁~F₃ failure is the largest, and zero sequence current at each line decreases with the increase of transition resistance. However, as long as the fault occurs in the same line, the ratio of zero sequence current at each line and the phase difference of fault zero sequence voltage and current are basically the same. The zero sequence current leading zero sequence voltage of the fault line is about 180°, the phase difference between the zero sequence current and the zero sequence voltage of the non-fault line with IIDG is less than 3°, and the zero sequence voltage leading zero sequence current of the non-fault line without IIDG is about 90°, which is consistent with the theoretical analysis above.

### 6. Conclusion

Low ground resistance active distribution network has different characteristic when single phase ground fault. Magnitude of the zero sequence current of each outlet line mainly depends on \( R_{dg} \) and \( R_n \). Zero sequence current of the fault line is larger than that of the non-fault line, and its amplitude ratio is determined when the network structure is determined, and it is not affected by the transition resistance and the grid-connected capacity. Zero sequence current of the line including IIDG is approximately resistive, and the current of the fault line is reverse resistive and is not affected by the transition resistance. When a high-resistance fault occurs, zero sequence current at the outlet of the fault line attenuates greatly with the increase of transition resistance, and its amplitude fluctuates slightly under the influence of grid-connected IIDG.

### References

[1] Liu Yuquan, Cai Yanchun, Deng Guohao, et al. Operation and protection in distribution system with small resistance grounding mode[J]. Distribution & Utilization, 2015, 32(6): 30-35.

[2] Yang Jun, Xu Jiazhui, Che Hongwei, et al. Schematic design and application study on low resistance grounding system[J]. Journal of Electric Power Science and Technology. 2012, 27(2):81-85.

[3] Lin Zhichao, Wang Yang, Luo Busheng, et al. Configuration and Tuning of High-sensitivity Grounding Fault Protection for Low-resistance Grounding[J/OL]. Automation of Electric Power Systems. http://doi.org/10.19635/j.cnki.csu-epsa.000267

[4] Wang Yang, Xue Yongduan, Xu Bing-yin. Zero sequence inverse-time overcurrent protection in low resistance grounding system with grounding fault[J]. Automation of Electric Power Systems, 2018, 42(20): 150-157.

[5] Guo Liwei, Xue Yongduan, Zhang linli, et al. Analysis of Single phase Earth Fault in Low Resistance Grounded Distribution Network Containing DG.

[6] Xu Yuqin, Yang Hao, Li Peng. Earth fault analysis on low resistance grounded distribution network with inverter interfaced distribution generation[J], Electrical Measurement & Instrumentation, 2018,55(16):57-63+71.

[7] Wang Tao, Shi Rong. Influence of distributed generation on grounding method of distribution network[J]. Journal of Xi’an Polytechnic University,2018,32(5):567-580.

[8] Yang Hao, Research on Neutral Grounding Modes Selection in Urban Distribution Network. Baoding: North China Electric Power University.
[9] Zhang W Y, Zhu S J, Zheng J H, et al. Impacts of Distributed Generation on Electric Grid and Selecting of Isolation Transformer[J]. Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005.

[10] Liu Zhiwen, Dong Xuzhu, Huang Yu. et al. Calculation Method for Maximum Penetration of Distributed Generations Considering Multiple Constrain[J]. Proceedings of the CSU - EPSA, 2019, 31(06): 85-92.

[11] Zhao Weiqi. Research of improving the reliability in zero sequence protection of small resistance grounding system[D]. Guangzhou: South China University of Technology, 2012.