Calculating the maximum penetration capacity of distributed generation considering current protection

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Abstract: With significant increasing penetration of the inverter inter faced distributed generations(IIDG), the radial network turns into a multipower-supply network. Working as an additional source, IIDG may increase the total fault level and altering the magnitude and direction of the fault current, which compromise the correct operation of the overcurrent protection system. This paper presents a new method to calculate the optimal allocation of IIDG without any amendment of protection settings, which will make great convenience for operators to review the accessible capacity of IIDG reported by users. Under the consideration of low voltage ride through(LVRT), the method uses iterative correction to figure out the non-linear relationship between the fault current of IIDG and the fault voltage of the point of common coupling(PCC) in order to get the optimal capacity which meets the constraints of the current protection’s selectivity and sensitivity.

1. Introduction

The three-stage current protection is widely used in distribution network for its simplicity and reliability. Recently, the significant increasing penetration of IIDG (such as photovoltaic and wind power) does great effect on the stability and protection of distribution network especially in fault. Solutions to impact of IIDG have been proposed by researchers worldwide. In [1] and [2] where the authors propose an adaptive overcurrent protection scheme. The author of [3] proposes an adaptive relaying algorithm to detect the faults in the presence of IIDGs. A solution that caters for optimal capacity and accessible location of IIDG has been proposed in [4], where the author regards line loss minimum as the penetration level constraint. While in [5]-[6], the author takes several factors into account to get optimized capacity of IIDG by GA. Based on the static load model, [7] presents the functional relation between maximum penetration level and location.

This paper takes the LVRT strategy into consideration and build the control model of IIDG. In order to provide a standard for operators to review the capacity of IIDG reported by users, this method consists of two iterative cycle, the inner loop aims to figure out the non-linear relationship between current and voltage of PCC in fault. While the external dedicates in calculating the maximum capacity of IIDG with the constraints of selectivity of the current protection I and sensitivity of the current protection II without any change.
2. Equivalent model for IIDG

Taking photovoltaic as an example, in normal status, the maximum power point tracking (MPPT) strategy is adopted to calculate the MPPT operating voltage based on the photovoltaic output voltage and current. The grid-side inverter adopts active-reactive decoupling control, and the reactive power reference should be set to 0 which helps to improve the utilization of the inverter.

When fault occurs, the PCC’s voltage drops. During this situation, the newest code requires that the large and medium capacity IIDG should have LVRT capability. Furthermore, reactive current output is in priority to support voltage. The requirements for injection of reactive current of domestic PV power plants is as follows:

\[
I_{q,\text{ref}} = \begin{cases} 
0, & (U_{\text{pcc}}>0.9) \\
(0.9 - U_{\text{pcc}}) \times 1.5, & (0.1 \leq U_{\text{pcc}} \leq 0.9) \\
1.05, & (U_{\text{pcc}} < 0.1)
\end{cases}
\]

\[I_{q,\text{ref}}\] represents reactive power reference, \(U_{\text{pcc}}\) represents the PCC’s voltage. When asymmetrical fault happens, positive sequence voltage based strategy is purchased, which means that the active and reactive current is only related to the positive sequence voltage of PCC during the fault.

The reactive output is in priority during LVRT operation.

\[
I_{d,\text{ref}} = \min\{I_{d,\text{ref}0}, \sqrt{I_{\text{max}}^2 - I_{q,\text{ref}}^2}\}
\]

\(I_{d,\text{ref}0}\) is the normal active current reference, \(I_{\text{max}}\) is the maximum current of inverter. Usually, the overload capacity of photovoltaic is \(1.2I_{\text{rated}}\), while this current is in the range of two to three times of the rated load current for wind power[3]. In summary, the total fault current of IIDG can be expressed as:

\[
\hat{I}_{\text{df}} = (I_{d,\text{ref}} \cos \delta + I_{q,\text{ref}} \sin \delta) + j(I_{d,\text{ref}} \sin \delta - I_{q,\text{ref}} \cos \delta)
\]

3. IIDG capacity constraints

The three-stage current protection is widely used in the 10kV distribution networks. Working as an additional source, the IIDG’s connection may increase the total fault level such as altering the magnitude and direction of the fault current when fault occurs[1]. Since current protection III is based on the maximum load current, and need to cooperate with the current protection II and III of the next section in time delay. So the sensitivity of current protection III is guaranteed. The following section will discuss the constraints that limit the maximum capacity of IIDG connected to distribution networks. Figure 1 shows a typical distribution network with an IIDG.

3.1. A fault occurs in the downstream of PCC

As shown in Figure 1, IIDG is connected to the grid from bus C in T mode. When fault happens at \(f_1\) or \(f_2\), IIDG helps to increase the fault current that seen by the relays.

3.1.1. Selectivity constraints of downstream relay for the current protection I.

For protection 3, the settings of the current protection I should be set by escaping the maximum fault current at the exit of next section.

\[
I_{\text{op3}}^I = K_{\text{rel}}^I \times I_{\text{CD,max}}^{(3)}
\]

\(K_{\text{rel}}^I\) is the reliable coefficient of the current protection I, take \(K_{\text{rel}}^I = 1.2\).

\[
|\hat{I}_1| < I_{\text{op3}}^I
\]

\(\hat{I}_1\) is the fault current when a three-phase short-circuit occurs at the end of CD section in maximum operational mode.
3.1.2. Sensitivity constraints of upstream protection
IIDG’s connection has a drain effect on fault current seen by the relay 2, which results in sensitivity loss. However, the sensitivity must meet the following condition.

\[ K_{\text{sen}} = \frac{I_{\text{II, min}}^{(2)}}{I_{\text{II, op}}^{(2)}} \geq 1.3 \]  \hspace{1cm} (6)

\( I_{\text{II, op}}^{(2)} \) is the current protection II setting of relay 2, \( I_{\text{II, min}}^{(2)} \) is the fault current when two-phase fault happens at the end of BC section in the minimum operational mode.

3.2. A fault occurs in the upstream of PCC
The capacity constraint is that the fault current does not exceed the setting of the current protection II.

\[ I_{\text{II, op}}^{(2)} = K_{\text{rel}}^{\text{II}} \times K_{\text{rel}}^{1} \times I_{\text{CD, max}}^{(5)} \]  \hspace{1cm} (7)

\[ |\hat{I}_{\text{dg}}| \leq I_{\text{II, op}}^{(2)} \]  \hspace{1cm} (8)

\( I_{\text{II, op}}^{(2)} \) is the second current protection setting of relay 2, \( \hat{I}_{\text{dg}} \) is the reverse current provided by IIDG.

It is recommended to establish simple communication between the upstream relay and IIDG. When any upstream protection trips, IIDG exits.

3.3. Fault on adjacent feeder
When fault occurs at \( f_1 \), IIDG will contribute to the fault current seen by the following relays.

3.3.1. Reverse current constraint
According to the principle of the protection setting, since \( I_{\text{II, op}}^{(2)} > I_{\text{II, op}}^{(5)} \), the constraints can be set as that do not exceed the setting of the second current protection.

\[ |\hat{I}_{\text{dg, f}}| \leq I_{\text{II, op}}^{(5)} \]  \hspace{1cm} (9)

3.3.2. Adjacent feeder protection constraint
Regarding the influence of additional fault current supported by IIDG on protection 5, it is similar to section(A). Therefore, the constraint can be set as:

\[ |\hat{I}_{5}| \leq I_{\text{II, op}}^{(5)} \]  \hspace{1cm} (10)

![Figure 1. typical distribution network with IIDG](image1)

![Figure 2. Malfunction equivalent network with photovoltaic power supply](image2)

4. The calculation admittance capacity
In the practical calculation, the load can be calculated by the instantaneous load and voltage. The fault model of IIDG can be regarded as a voltage controlled current source, and its mathematical expression can be written as:
\[ I_{d_g,f} = f(U_{\text{PCC},f}) \] (11)

\[ Y_{LD,k} = \frac{S_{LD,k}}{U_k^2} \] (12)

Taking the fault happening at \( f \) as an example, the equivalent network is shown in Figure 2.

When the distribution network fails, the node voltage equation is:

\[ YU = I \] (13)

\( Y \) is the admittance matrix, \( I \) is the injection current matrix. In order to figure out the nonlinear relationship between PCC voltage and the current supported by IIDG\(^{[13]} \), this paper use the iterative method to correct the current of IIDG until the PCC voltage is stabilized. The iterative equation, the correction equation and the convergence criterion are as follows:

\[
\begin{bmatrix}
I_{d_g,f}^{(k)} \\
I_{d_g,f}^{(k)}
\end{bmatrix} = \begin{bmatrix}
I_{s,f}^{(k-1)} \\
K(U_{\text{PCC}} - U_{d_g,f}^{(k)})
\end{bmatrix}
\] (14)

\[
I_{d_g,f}^{(k)} = \min \left\{ I_{d_g,f}^{(k-1)}, \sqrt{I_{d_g,f}^{(k-1)} + I_{d_g,f}^{(k-1)}} \right\}
\]

\[ I_{d_g,f}^{(k)} = (I_{d_g,f}^{(k)} \cos \theta^{(k)} - I_{d_g,f}^{(k)} \sin \theta^{(k)}) + j(I_{d_g,f}^{(k)} \sin \theta^{(k)} - I_{d_g,f}^{(k)} \cos \theta^{(k)}) \]

\[ \theta = \arctan(\text{Im}(U_{d_g,f}^{(k)}) / \text{Re}(U_{d_g,f}^{(k)})) \]

\[ \max(\left| U_{s,f}^{(k)} - U_{d_g,f}^{(k-1)} \right| \left| U_{d_g,f}^{(k-1)} - U_{d_g,f}^{(k-1)} \right|) < \varepsilon \] (16)

There are two iterations in the program, one is to iterate over the capacity of IIDG and the other is to iteratively correct the fault current provided by IIDG. Specific procedures are as Figure 3:

5. Simulation

5.1. Case study

The simulation of the distribution system topology is shown in Figure 1. The impedance parameters are: \( r = 0.13 \Omega / \text{km} \), \( L = 1.1332 \text{mH/km} \), the length of each line is: \( L_{AB} = 3 \text{km} \), \( L_{BC} = 2 \text{km} \), \( L_{CD} = 4 \text{km} \),
$L_{DE} = 2\text{km}$, $L_{AF} = 2\text{km}$, $L_{FG} = 2\text{km}$, the load parameters are: $LD_1 = 3 + j2\text{MVA}$, $LD_2 = 2 + j1\text{MVA}$. The system baseline capacity is: $S_B = 10\text{MVA}$, the system reference voltage is: $U_B = 10\text{kV}$. Take IIDG connected to bus C as example, the optimal capacity that meets each constraint is shown in the Table 1.

Table 1. The optimal capacity of IIDG.

| Location of IIDG | Downstream | Upstream | Adjacent | Admittance capacity |
|-----------------|------------|----------|----------|---------------------|
| B               | 21.05      | 39.74    | 59.23    | 19.16               |
| C               | 10.75      | 27.18    | 32.71    | 10.87               |
| D               | 5.05       | 6.31     | 24.42    | 10.01               |
| E               | /          | /        | 20.74    | 19.75               |
| F               | 39.78      | 69.26    | 61.75    | 30.68               |
| G               | /          | /        | 54.6     | 29.91               |

5.2. Verification

A distribution network simulation system considering the newest code was established in PSCAD. Taking IIDG being connected from bus C as an example to verify the above method.

A three phase fault occurs at the end of section CD at 1 second. The fault current seen by the relay 3 and its setting are shown in Figure 4. Because of inrush transient current, the fault current increases sharply at 0.01s after fault occurs, exceeding the setting value. We labeled ‘X’ for the fault current peak. However, the action time is usually less than 10ms, which is helpful to escape from the inrush transient current. During the following time, the fault current seen by the relay 3 is less than its set value.

When a fault occurs at the beginning of the BC section, the comparison between the fault current seen by the relay 2 and current protection II setting is shown in Figure 5.

Figure 6 depicts the comparison of the fault current seen by the relay 5 and current protection I setting when a fault occurs at the end of section AF in adjacent feeder. The Figure 7 shows that the reverse fault current seen by relay 2 increases.

6. Conclusion

By analyzing the impact of IIDG’s penetration on the stability and protection of distribution network, this paper proposes a calculation method of admittance capacity of IIDG considering current
protection constraints. This method takes LVRT control strategy into account and provides a standard to audit the installation capacity of IIDG reported by users without changing the existing protection settings, which greatly simplifies the work of the operation and maintenance department.

Figure 6. The comparison between fault current and protection I setting of relay 5

Figure 7. The comparison between fault current and current protection II setting of relay 2

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References
[1] Coffele F, Booth C, Dyško A. An Adaptive Overcurrent Protection Scheme for Distribution Networks[J]. IEEE Transactions on Power Delivery, 2014, 30(2):561-568.
[2] Mahat P, Chen Z, Bak-Jensen B, et al. A Simple Adaptive Overcurrent Protection of Distribution Systems With Distributed Generation[J]. IEEE Transactions on Smart Grid, 2011, 2(3):428-437.
[3] Haj-Ahmed M A, Illindala M S. The Influence of Inverter-Based DGs and Their Controllers on Distribution Network Protection[J]. IEEE Transactions on Industry Applications, 2014, 50(4):2928-2937.
[4] ZHONG Jia-qing, YE Zhi-ge, LU Zhi-gang. Analysis of Optimal Allocation of Penetration Level and Interconnected Location of DG[J]. Power System Protection and Control, 2012, 40(7):50-55.
[5] ZHANG Yuankai. Siting and Sizing of Distribute Generation Based on Genetic Algorithm[D]. Northeastern University, 2013.
[6] ZHENG Li. Study on the Locating and Sizing of Distributed Generation in Distribution Network. South China University of Technology, 2012.
[7] WEN Sheng, GU Jie, CHENG Haozhong, CHEN Bin, ZHANG Gonglin. Maximum Penetration Level and Optimal Placement of Distributed Generation[J]. Electric Power Automation Equipment, 2012, 32(10):109-114.
[8] PAN Guoqing, ZENG Dehui, WANG Gang, et al. Fault analysis on distribution network with inverter interfaced distributed generations based on PQ control strategy[J]. Proceeding of the CSEE, 2014, 34(3):555-561.
[9] WU Lijie, CHEN Xingying, XU Shiming, et al. Calculating the maximum penetration capacity of distributed generation considering current protection[J]. Power System and Clean Energy, 2015, 31(3):35-39.
[10] ZENG Dehui, WANG Gang, GUO Jingmei, et al. Adaptive current protection scheme for distribution network with inverter-interfaced distributed generators[J]. Automation of Electric Power System, 2017, 41(12):86-92.
[11] WU Zhengrong, WANG Gang, LI Haifeng, et al. Fault characteristics analysis of distribution networks considering control scheme of inverter interfaced distributed generation[J]. Automation of Electric Power System, 2012, 36(18): 92-96.