Analysis of the acceptance ability of distribution network to distributed PV

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Abstract. In this paper, the impact of distributed photovoltaic (PV) access on the power quality and fault current of distribution network is studied. First of all, the constant power output of photovoltaic power model is adopted and the influence of the access of distributed photovoltaic on distribution network voltage deviation and voltage harmonic are analyzed; secondly, the change of fault current is analyzed considering fault at the upstream, downstream and adjacent feeder of the distributed PV access location, respectively; finally, practical example is calculated based on above theoretical analysis, and the maximum penetration of PV is calculated in comprehensive consideration of power quality and existing protection setting value.

Keywords: Distribution Network; Distributed PV; Impact Analysis; Maximum Penetration.

1. Introduction

Under the situation of the gradual depletion of conventional energy and the increasingly serious environmental pollution, countries around the world actively develop and utilize renewable energy, and make photovoltaic power generation and television as an important development field. With the rapid development of photovoltaic power generation technology and large-scale commercial application, the existing power system continues to develop in the direction of high efficiency, clean and flexible, and the energy utilization efficiency of the whole society has improved. However, after the access of distributed photovoltaic, the distribution network will change from passive network to active network, which may lead to problems such as voltage over limit, relay protection device misoperation or misoperation, etc., which need to be quantitatively analyzed and the maximum access capacity of distributed photovoltaic will be obtained. At present, the research on the impact of distributed photovoltaic access on power quality mainly focuses on voltage deviation and voltage fluctuation. Literature [1-5] analyzes the voltage deviation of a large number of distributed photovoltaic power sources after they are connected to the distribution network, and establishes a mathematical model to calculate the access capacity of distributed power sources; literature [6-7] studies the harmonic pollution caused by distributed photovoltaic power sources after they are connected to the distribution network, and obtains the PV access power of the distribution network under the harmonic pollution limitation; literature [8] focuses on the voltage deviation and Based on the harmonic restraint,
the evaluation method of PV maximum permeability in distribution network is proposed. However, the access power of distributed photovoltaic should not only consider its impact on power quality, but also analyze its impact on current protection. Reference [9] analyzes the influence of photovoltaic grid connected power generation on protection and reclosing, and puts forward corresponding countermeasures. At present, there is no research on photovoltaic access capacity considering power quality and current protection of distribution network. In this paper, according to the capacity of distribution network to accept distributed photovoltaic, firstly, the constant power distributed photovoltaic and load model is adopted, the influence of distributed photovoltaic access on the voltage deviation of distribution network is deduced, and the influence of distributed photovoltaic on the voltage harmonic of distribution network is analyzed; secondly, the influence of distributed photovoltaic access on fault current is analyzed. The maximum access capacity of distributed photovoltaic (DVV) is calculated and obtained under the condition of power quality restriction and without changing the current protection setting value.

2. Influence of distributed photovoltaic access on power quality of distribution network

2.1. Influence of Voltage Deviation

Considering the distribution network as shown in Figure 1, each concentrated load is numbered as a node along the distribution network feeder. There are N nodes, the voltage of the first node is, the line start voltage is, the line standard voltage is, the voltage drop of node i relative to the line start node. The line impedance between each node is the same, and the line impedance between adjacent nodes is set to; the load of the distribution network system is evenly distributed at the point end of the line feeder, the load power is set to, and the capacity of the distributed photovoltaic system connected to the node is expressed in

\[ V_{i} - V_{0} = \frac{V_{0} - \Delta V_{0j} - V_{x}}{V_{N}} \]

\[ \Delta U' = \frac{V_{j} - V_{0}}{V_{N}} = \frac{V_{0} - \Delta V_{0j} - V_{x}}{V_{N}} \]

\[ \Delta U' = \frac{V_{0}}{V_{N}} - \frac{i(2N-i+1)}{2} \times P \times R + Q \times X \times V_{N}^2 - 1 \]

When considering the distributed photovoltaic system acting on the distribution network separately, firstly short-circuit the power supply side of the distribution network, and the impedance of the distribution network circuit is relatively small compared with the load, so the effect of the distributed photovoltaic system on the voltage deviation is mainly reflected in the section from the distributed photovoltaic system to the system power supply, that is, the circuit before point i; and for the circuit after point i, the distributed light The voltage system has no direct impact on the voltage deviation, but the access of the distributed photovoltaic system may raise the voltage, which will indirectly affect the voltage deviation of each point after point i, so it is specified that the effect of the distributed photovoltaic system on the voltage drop is negative. Therefore, under the independent action of the distributed photovoltaic system, the voltage drop of node j is as follows:

Figure 1. Multi node constant power distribution network
Using the circuit superposition theorem: \( \Delta V_j = \Delta V_{0,j} + \Delta V_{p,j} \) The voltage drop at any point \( j \) in the distribution network under the action of system power supply and distributed photovoltaic system is obtained:

\[
\Delta V_{p,j} = \begin{cases} 
\frac{j(R_p + X_Q)}{V_N} \cdot j \in [1,i] \\
\frac{i(R_p + X_Q)}{V_N} \cdot j \in [i+1,N]
\end{cases}
\]  

(2)

It can be seen from the above that if the line terminal voltage of this distribution network is \( V_0 \), then the voltage at any point in the line is:

\[
V_j = \begin{cases} 
V_0 - \frac{j(2N-j+1)}{2} \cdot \frac{R_p + X_Q}{V_N} + \frac{j(R_p + X_Q)}{V_N} & , j \in [1,i] \\
V_0 - \frac{j(2N-j+1)}{2} \cdot \frac{R_p + X_Q}{V_N} + \frac{i(R_p + X_Q)}{V_N} & , j \in [i+1,N]
\end{cases}
\]  

(3)

Then, the voltage deviation expression of the distribution network with distributed photovoltaic system at the node is as follows:

\[
\Delta U_j = \begin{cases} 
\frac{V_0 - j(2N-j+1)}{2} \cdot \frac{R_p + X_Q}{V_N^2} + \frac{j(R_p + X_Q)}{V_N^2} & -1, j \in [1,i] \\
\frac{V_0 - j(2N-j+1)}{2} \cdot \frac{R_p + X_Q}{V_N^2} + \frac{i(R_p + X_Q)}{V_N^2} & -1, j \in [i+1,N]
\end{cases}
\]  

(4)

It can be seen from equation (5) that the access capacity and location of distributed photovoltaic system will affect the voltage deviation of distribution network nodes.

2.2. Influence on the Distortion of Harmonic voltage

The distributed photovoltaic system with nonlinear model is connected to the low voltage side of the transformer. In harmonic analysis, the distributed photovoltaic system uses harmonic current source to simulate, and the second harmonic current amplitude is, expressed by the percentage of the fundamental current outflow based on the distributed photovoltaic system: the phase angle of the sub harmonic current is. A simplified harmonic network diagram for access to the distributed photovoltaic system is shown in Figure 2.

**Figure 2.** Distribution network for harmonic analysis

2.2.1. The influence of the Access Capacity of Distributed Photovoltaic System on the Distortion of Harmonic Voltage. The fundamental current amplitude of the distributed photovoltaic system is:
After derivation, it is concluded that the change of harmonic voltage amplitude of terminal nodes after access to distributed photovoltaic system is as follows:

\[ \Delta V_h = V_{h,x} - V_{h,x} \left[ \sqrt{r^2 + h^2 x^2} \right] \left[ I_{G,x} \right] \left[ G + I_{G,x} L \right] - L * \sqrt{r^2 + h^2 x^2} \left[ I_{a,x} \right] \left[ G + I_{a,x} L \right] \left[ V_{p,x} \right] \left[ G \right] > 0 \] (7)

2.2.2. The Influence of the Access Position of Distributed Photovoltaic System on the Distortion of Harmonic Voltage. It is assumed that the distributed photovoltaic system is connected to G1and G2 of the distribution network line respectively, and there are. The difference of distortion level of harmonic voltage is compared when the line is in two different positions:

3. Influence of distributed photovoltaic access on current protection of distribution network

The main effect of distributed photovoltaic on the current protection of distribution network is to provide fault current to the short circuit point. When the access location and capacity of distributed PV are not changed, the location of short-circuit point will also affect the short-circuit current provided by distributed PV, so it is necessary to consider the amount of fault current that distributed PV can provide in case of short-circuit fault in different locations of the line; in addition, when the same location of the line has short-circuit fault, with the change of access location and capacity of distributed PV The short-circuit current provided by distributed photovoltaic in power transformation and distribution network also has great changes. As the capacity of distributed photovoltaic increases, the fault current that can be provided increases; therefore, this section mainly studies the influence of the relative relationship between the location of short-circuit point and the access location of distributed photovoltaic on the fault injection current.

In case of short circuit at point F1, only the system power supply provides short-circuit current to the fault point through protection R1, while the distributed photovoltaic provides short-circuit current to the fault point through protection R2. For the case of three-phase short circuit, it can be equivalent to the simple circuit as shown in Figure 3. The distributed photovoltaic is represented by a controlled current source. The load on the right side of node 3 is represented by ZL, which is the line impedance between node 1 and node 2, which is the impedance from the short circuit to the beginning of the line, and.

\[ I_{k,1} = \frac{E_s}{aZ_{t-2}} \] (8)
According to Fig. 4, the expression of distributed photovoltaic terminal voltage can be obtained by using node voltage method:

\[
\left( \frac{1}{Z_L} + \frac{1}{(1-a)Z_{1-2} + Z_{2-3}} \right) U = \left( \frac{S}{U} \right)
\]

As the distributed photovoltaic adopts the maximum power output mode and often operates at the unit power factor, it can be obtained from equation (9) and further expansion:

\[
\left( 1 + \frac{|Z_{2-3}|}{(1-a)|Z_{1-2}| + |Z_{2-3}|} \right) U^2 = P|Z_{2-3}| \cos \beta
\]

Thus, the voltage of the distributed photovoltaic terminal and the short-circuit current flowing through the protection R2 can be solved:

\[
U = \sqrt{\frac{PR_c ((1-a)|Z_{1-2}| + |Z_{2-3}|)}{(1-a)|Z_{1-2}| + |Z_{2-3}|}}
\]

From the above analysis, it can be seen that protection R1 can accurately cut off the fault within its protection range, but protection R2 may detect the fault current and act first, so that the right side of distributed photovoltaic will form island operation state. When \( f_2, f_3 \) and \( f_4 \) are short circuited, the analysis method is consistent with that of \( f_1 \). The specific derivation process will not be described here.

4. Example analysis

The actual distribution network in an area shown in Figure 5 is used for simulation analysis. The distribution network consists of two branches and six nodes, each of which has a certain power load at the end. The distributed photovoltaic system is mainly connected to the distribution network through the end of the branch node. The system side voltage level is 110kV, the system impedance value is h; the capacity of 110kV main transformer is 63MVA, the transformer transformation ratio is 110/10.5, the capacity load ratio is 2.56, the power factor is 0.95, 110kV bus voltage unit value is 1.0, 110kV bus voltage reference value is 110kV, the 10kV line voltage reference value is 10.5kV; the capacity of 10kV public distribution transformer is 0.8MVA, the transformer transformation ratio is 10/0.4. The line parameters are: resistance is 0.125/km, reactance is 0.08 \( \Omega \)/km, susceptance is 2S × 10\(^{-6}\)S/km, and the length of each line section is 1 km. The load conditions of each node are as follows: the load values of node 2, node 3 and node 4 are 2.23MW, the limit capacity of 10kV public distribution transformer is 0.8MW for node 5 load, and node 6 is used to simulate the load of other 10kV lines in 110kV substation, and the load value is 12.02MW.

![Figure 5. A typical distribution network](image)

4.1. Access Capacity of Distributed Photovoltaic considering Power Quality

Select 5%, 25%, 50%, 75% and 100% (0.669MW, 3.345MW, 6.69MW, 10.035MW and 13.38MW) of the limit capacity of the line as the access capacity of distributed photovoltaic. When the access capacity of photovoltaic changes, the voltage deviation of each node is shown in Table 1.
4.1.1. Voltage deviation.

Table 1. Node voltage deviation when the PV capacity changes

| PV access capacity | node 1 | node 2 | node 3 | node 4 |
|--------------------|--------|--------|--------|--------|
| 0.669MW            | -0.41% | -5.01% | -8.00% | -9.69% |
| 3.345MW            | -0.40% | -3.23% | -4.48% | -6.11% |
| 6.69MW             | -0.39% | -1.27% | -0.57% | -2.14% |
| 10.035MW           | -0.40% | 0.50%  | 2.99%  | 1.48%  |
| 13.38MW            | -0.41% | 2.12%  | 6.28%  | 4.82%  |

It can be seen from Table 1 that when the line power flow direction does not change, the node voltage deviation of the distribution network decreases with the increase of the distributed photovoltaic access capacity; however, when the distributed photovoltaic access capacity exceeds 6.69MW, the line power flow direction changes, and the node voltage deviation of the distribution network changes from negative to positive. As the access capacity of the distributed photovoltaic system continues to increase, the distribution network savings. The point voltage deviation began to increase, and under the selected photovoltaic access capacity, the node voltage deviation did not exceed the limit. Node 2, node 3 and node 4 are selected as the access location of distributed photovoltaic, and the access capacity of distributed photovoltaic is set as 13.38MW.

Table 2. Node voltage deviation when the PV location changes

| position | node 1 | node 2 | node 3 | node 4 |
|----------|--------|--------|--------|--------|
| 2        | -0.40% | 2.33%  | -0.78% | -2.35% |
| 3        | -0.41% | 2.12%  | 6.28%  | 4.82%  |
| 4        | -0.43% | 1.71%  | 5.49%  | 10.87% |

It can be seen from Table 2 that as the access position of distributed photovoltaic is closer to the end of the line, the voltage deviation of distribution network node 4 is larger. When the access capacity of distributed photovoltaic access node 4 is 13.38MW, the voltage deviation of distribution network node 4 exceeds ± 7% of the range specified in GB/T 12325-2008 allowable deviation of power quality supply voltage. At this time, the maximum access of distributed photovoltaic of access node 4 is The capacity is 10.41MW.

4.1.2. Voltage harmonics. The same way is used to study the total distortion rate of voltage harmonic. When the photovoltaic access capacity changes, the total distortion rate of voltage harmonic of each node is shown in Table 3. It can be seen from Table 3 that the total voltage harmonic distortion rate of nodes in the distribution network is positively related to the photovoltaic access capacity. With the increase of photovoltaic access capacity, the total voltage harmonic distortion rate of nodes in the distribution network increases accordingly. When the distributed photovoltaic access capacity is 13.38MW, the total voltage harmonic distortion rate of nodes 2, 3 and 4 in the distribution network exceeds the power quality public grid harmonic (GB/T 14549-2008) The maximum access capacity of the corresponding access node 3 is 11.78MW.

Table 3. Node voltage deviation when the PV capacity changes

| PV access capacity | node 1 | node 2 | node 3 | node 4 |
|--------------------|--------|--------|--------|--------|
| 0.669MW            | 0.2    | 0.32   | 0.337  | 0.329  |
| 3.345MW            | 0.200  | 0.601  | 0.885  | 0.643  |
| 6.69MW             | 0.200  | 0.803  | 1.571  | 0.887  |
| 10.035MW           | 2.353  | 3.166  | 3.436  | 3.301  |
| 13.38MW            | 3.07   | 4.154  | 4.515  | 4.334  |
When the access position of distributed photovoltaic changes, the total harmonic distortion rate of each node is shown in Table 4.

| Position | Node Voltage Deviation |
|----------|------------------------|
| 2        | 3.337                  |
| 3        | 3.07                   |
| 4        | 2.559                  |

It can be seen from Table 4 that the total voltage harmonic distortion rate of the distributed photovoltaic access point is independent of the access location of the distributed photovoltaic, only related to the access capacity of the distributed photovoltaic; and the closer the access location of the distributed photovoltaic is to the end of the line, the farther the distributed photovoltaic harmonic propagation distance is, the greater the degree of harmonic attenuation is, and the smaller the total voltage harmonic distortion rate of the other nodes in the distribution network. When the distributed photovoltaic is connected to node 2, node 3 and node 4 respectively and the access capacity is 13.38MW, the total distortion rate of voltage harmonics of node 2, node 3 and node 4 in the distribution network exceeds ± 4% of the range specified in GB / T 14549-2008 power quality public grid harmonics. At this time, the maximum access capacity of the distributed photovoltaic connected to node 2, node 3 and node 4 is 11.78MW. By comparing Table 3 and table 4, it can be seen that the maximum access capacity of distributed photovoltaic when the voltage deviation of distribution network nodes with distributed photovoltaic when the total harmonic distortion rate of distribution network nodes with distributed photovoltaic exceeds the limit is smaller than the maximum access capacity of distributed photovoltaic when the node voltage deviation of distributed photovoltaic exceeds the limit. Therefore, when the node voltage deviation and the total harmonic distortion rate of node voltage exceed the limit at the same time, the problem of node voltage deviation exceeding the limit should be given priority.

### 4.2. Access Capacity of Distributed Photovoltaic considering Current Protection

In this paper, the current protection setting value of distribution network before distributed photovoltaic access is taken as the constraint, and the maximum capacity of distributed photovoltaic access under this condition is analyzed. Among them, the setting of three section current protection R1, R2, R3 and R4 current quick break protection shall be based on the maximum short circuit current that may occur when avoiding the short circuit at the bus side of the lower line protection. The reliability coefficient of section I is 1.2, that of section II is 1.1, that of section III is 1.15, that of self starting is 1.3, and that of current relay is 0.85. It is assumed that the line end protection is equipped with current quick break protection and over-current protection, and the rest of the line protection is equipped with current quick break, time limited current quick break and over-current protection. Without considering the distributed photovoltaic access, the setting calculation results of protection 1-4 are shown in Table 5.

| Position | Instantaneous Current Quick Break Setting Value | Setting Value of Time Limited Current Quick Break |
|----------|-----------------------------------------------|-----------------------------------------------|
| 1        | 30.190                                        | 21.066                                        |
| 2        | 17.151                                        | 15.27                                         |
| 3        | 13.883                                        | —                                             |
| 4        | 30.190                                        | —                                             |
Table 6. Short circuit current effective value of each protection when the PV capacity changes

| PV access capacity | R1    | R2    | R3    | R4    |
|--------------------|-------|-------|-------|-------|
| 0.669MW            | 17.703| 15.800| 15.187| 0.722 |
| 3.345MW            | 17.242| 15.647| 17.775| 0.722 |
| 6.69MW             | 16.777| 15.432| 19.846| 0.722 |
| 10.035MW           | 16.312| 15.244| 21.450| 0.722 |
| 13.38MW            | 15.943| 15.082| 22.456| 0.722 |

Table 6 is a combination of table 5 and table 6. When the short-circuit point is f3 and the distributed photovoltaic access capacity is 10.35MW, the fault current flowing through protection R2 (15.244kA) is less than its time limit current quick break setting value (15.27kA), so that the two-stage protection of protection R2 cannot be used as the remote backup protection of R3. At this time, the maximum distributed photovoltaic access capacity of the corresponding access node 3 is 10.01MW.

Table 7. Short circuit current effective value of each protection when the PV location changes

| position | name | R1    | R2    | R3    | R4    |
|----------|------|-------|-------|-------|-------|
| 2        |      | 14.282| 17.703| 17.703| 0.703 |
| 3        |      | 15.943| 15.082| 22.456| 0.722 |
| 4        |      | 11.353| 11.294| 11.264| 0.765 |

According to table 5 and table 7, when the short-circuit point is F3 and the distributed photovoltaic access capacity is 13.38MW, the fault current (17.703kA) flowing through the protection R2 is less than its time limit current quick break setting value (17.151kA), which makes the protection R2 and the protection R3 act at the same time to remove the fault and lose selectivity. At this time, the maximum access capacity of the corresponding access node 2 is 12.96MW.

5. Conclusion

This paper analyzes the changes of power quality and fault current of distribution network after the access of distributed photovoltaic, and obtains PV access capacity considering voltage deviation, voltage harmonic and current protection respectively through practical examples, and obtains PV access capacity considering the above factors. The analysis conclusion of this paper can not only judge the PV access capacity of a certain node in the distribution network, but also draw the corresponding restrictions of the access capacity, which provides reference for the adjustment and transformation of the distribution network.

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