Penetration Level of Photovoltaic in Distribution Network Considering Voltage Constraint

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Abstract. A large number of distributed PV connected to the distribution network may cause the voltage deviation of the grid to exceed the limit. Firstly, the calculation model of voltage loss caused by load under different distribution rules and the calculation model of voltage rise caused by photovoltaic are established. On the premise that the voltage deviation of the bus can reach the upper limit of the standard, the maximum allowable PV capacity of the line without overvoltage is derived. For a typical 10 kV line, the maximum PV permeability under the same distribution rule of PV and load and the voltage margin at the head of feeder without overvoltage are given. The results show that the overhead line can accommodate more PV capacity than the cable line, the voltage regulation of PV power can prevent overvoltage, and the bus voltage reduction can allow access to more PV capacity.

1. Introduction
Distributed photovoltaic access to power grid will inevitably change the power flow distribution of distribution network and the direction of power flow of some nodes, which affects the steady-state voltage distribution of distribution network [1]-[2]. On the one hand, the reasonable configuration of distributed photovoltaics can support the voltage of distribution network [3]. On the other hand, unconstrained access operation of distributed photovoltaics may lead to overvoltage of some nodes in distribution network [4]-[5]. To this end, domestic and foreign have promulgated the relevant technical regulations of distributed photovoltaic access to the grid [6]-[10], in order to guide and standardize the rational application of photovoltaic power supply.

In reference [8], an optimal access power calculation model is proposed. Considering the tap-changer adjustment of on-load tap-changer and given network structure, network load distribution and DG access location, the maximum capacity of DG satisfying voltage constraints is obtained by power flow calculation. Literature [9] Taking a given suburban residential power supply network as an example, assuming that the supply voltage is constant and moderate. Literature [10] studies the influence of photovoltaic power generation on line voltage distribution for radial networks, and suggests that DG reactive power control be used to participate in line voltage regulation. In reference [11], considering the power intermittence of photovoltaic power supply, the optimal allocation of intermittence DG in the whole period is obtained by dividing the time interval and according to the probability distribution of intermittence DG and system load power in each time interval, taking the comprehensive benefits of network loss and voltage quality as the objective function, using the chance-constrained programming method.
In this paper, based on the voltage deviation model, the DG admission capacity of medium voltage distribution network with multi-distributed photovoltaic power supply is studied under the typical distributions of load and DG along the feeder, such as concentration, incremental distribution, decreasing distribution and uniform distribution along the feeder terminal. The influence of reactive power loss of user distribution transformer on voltage distribution of feeder is also considered in the analysis. The results show that the admission capacity of DG can be estimated as long as the feeder parameters, the distribution law of load and DG and the load capacity are known. The conclusion of this paper has general adaptability and is especially suitable for the preliminary evaluation of distributed photovoltaic access capacity.

2. Voltage deviation analysis model

The connection of the power system above the distribution bus is very complicated. Because the system capacity is much larger than the total load capacity supplied by the distribution bus, the influence of load change on the upper system is small. Therefore, the system above the distribution bus can be equivalent to a voltage source. Under the control of system voltage regulating equipment, bus voltage varies, but it meets the requirements of grid voltage deviation.

There are several loads and distributed photovoltaic power sources distributed in different locations of the feeder. The static model of constant power is adopted for nodal load, and the three-phase load is assumed to be linear and symmetrical. Photovoltaic power supply is characterized by pure active power source, and does not participate in the regulation of distribution network voltage.

Under the above equivalent conditions, the voltage analysis model of distribution network with distributed photovoltaic power supply can be obtained as shown in figure 1. For the sake of generality, there are N nodes in a radiation connection, each node is connected with load and photovoltaic power supply. If a node does not have photovoltaic power supply or load, its power can be set to zero. In the figure 1, Node 0 represents the distribution bus, \( (R_k, X_k) \) represents the equivalent impedance of the k-th feeder, \( (P_{L,k} + jQ_{L,k}) \) represents the load power of the k-th node, and \( P_{PV,k} \) represents the photovoltaic power of the k-th node. It is worth pointing out that the active power flow direction of photovoltaic is opposite to that of load.

From figure 1, it can be concluded that the voltage loss from a node K to the distribution bus in the distribution network is as follows.

\[
\Delta U_k \% = \frac{\sum_{j=1}^{k} R_j \cdot \sum_{i=1}^{n} P_{L,i} + X_j \cdot \sum_{i=1}^{n} Q_{L,i}}{U_N^2} \times 100 - \frac{\sum_{j=1}^{k} R_j \cdot \sum_{i=1}^{n} P_{PV,j}}{U_N^2} \times 100
\]

\[ (1) \]

**Figure 1.** Circuit model of radial feeder with distributed loads and PV generators

Formula (1) shows that any point in the distribution network connected with distributed photovoltaics can help to reduce the voltage loss on the line and support the feeder voltage, and the closer the access position is to the end, the stronger the voltage support function is.
For the sake of generality, let the distribution function of active load along feeder length \( x \) be \( p_L(x) \), reactive load along feeder length \( x \) be \( q_L(x) \), distribution function of distributed photovoltaic along feeder length \( x \) be \( p_{pv}(x) \), total length of feeder is \( L \), then the voltage loss caused by load and photovoltaic at any distance from feeder bus line to bus line is \( l \).

\[
\Delta U(\% ) = \frac{\int_0^L \int_0^l p_L(x)dx \, dy + \int_0^L \int_0^l q_L(x)dx \, dy + \int_0^L \int_0^l p_{pv}(x)dx \, dy}{U_N^2} \times 100\% - \frac{\int_0^L \int_0^l p_L(x)dx \, dy}{U_N^2} \times 100\% \tag{2}
\]

For high voltage trunk overhead lines, the line reactance is usually larger than the line resistance, so the reactive power on the line is the main factor affecting the node voltage. But for urban cable distribution network and low voltage small cross-section overhead lines, the line resistance is similar to the line reactance, or even the line resistance is larger than the line reactance, so the influence of active power on the feeder voltage cannot be ignored.

Due to the installation of reactive power automatic compensation equipment in the low voltage side of users, the load power factor of urban 10kV distribution network is relatively high. The following analysis is considered as 0.95. In addition, the no-load reactive power loss of 10 kV distribution transformer is considered separately. The rated capacity of distribution transformer at the first load point is set as \( S_{NT,i} \), and the no-load reactive power loss rate of transformer is considered as 2.5% of the average value. If the active load rate of the node transformer is \( \alpha_i \), the active power and reactive power of the node can be expressed as

\[
P_{li} = \alpha_i S_{NT,i}
\]

\[
Q_{li} = 0.025 S_{NT,i} + \tan^{-1}(0.95) P_{li} (0.025 / 0.32) P_{li}
\]

(3)

Considering that the typical capacity-load ratio of medium-voltage distribution system is about 2 (i.e. transformer load ratio is 0.5), for convenience of analysis, the formula can be approximated as follows.

\[
P_{li} = \alpha_i S_{NT,i}
Q_{li} = 0.37 P_{li}
\]

(4)

The relationship between total feeder load and nodal load is as follows

\[
S_{NT} = \sum S_{NT,i}
\]

\[
P_L = \sum P_{li} = \alpha S_{NT}
\]

(5)

\[
Q_L = \sum Q_{li} = (0.025 + 0.32 \alpha) S_{NT}
\]

Formula (3) shows that the relationship between reactive power distribution and active power distribution of feeder is as follows.

\[
q_L(x) = 0.37 p_L(x)
\]

(6)

By substituting Formula (5) into Formula (2), a general formula for calculating voltage loss at any point from the distribution bus to the feeder line can be obtained.

\[
\Delta U(\% ) = \frac{\int_0^L \int_0^l p_L(x)dx \, dy + \int_0^L \int_0^l q_L(x)dx \, dy + \int_0^L \int_0^l p_{pv}(x)dx \, dy}{U_N^2} \times 100\% - \frac{\int_0^L \int_0^l p_L(x)dx \, dy}{U_N^2} \times 100\% \tag{7}
\]
3. Access Capacity of Distributed Photovoltaic

Formula (6) shows that for feeders without distributed generators, the voltage loss caused by load is positive, so long as the supply voltage does not exceed the upper limit of voltage deviation, the feeder will not appear overvoltage. However, if there is a distributed photovoltaic power supply in the feeder, due to the voltage lifting effect of distributed photovoltaic, overvoltage may occur at a node in the middle of the feeder or at the end of the feeder.

Because of the randomness of load distribution and load utilization, it is difficult to draw a general conclusion about voltage deviation. For this reason, several typical regular distributions of photovoltaic and load are analyzed, such as terminal concentration, increasing distribution, uniform distribution and decreasing distribution.

Assuming the total length of the feeder is \( L \), the total active power is \( P \), and the position of a point on the feeder is \( x \) (i.e. the distance between the point and the bus). For different typical distribution laws, the power distribution functions can be obtained as follows, in which the \( \delta(L - x) \) is the impulse function.

\[
p(x) = \frac{P}{\delta(L - x)}
\]  

Thus, from equation (6), it can be concluded that the voltage loss at any point of the feeder with a distance of \( L \) from the busbar caused by the load under different distribution laws is as follows.

\[
\Delta U_{L(i)} \% = \frac{P_i (r_0 + 0.37x_0)}{U_N^2} l \times 100\%
\]  

Similarly, from equation (6), it can be obtained that the voltage elevation at any point of the feeder with a distance of \( L \) from the bus bar caused by photovoltaic energy under different distribution laws is as follows:

\[
\Delta U_{PV(i)} \% = \frac{P_{PV} r_0}{U_N^2} l \times 100\%
\]  

If the voltage deviation at the distribution bus is qualified and assumes that the bus voltage reaches the upper limit of the voltage deviation, the condition that no overvoltage occurs on the feeder is as follows:

\[
\Delta U_{(i)} \% = \Delta U_{L(i)} \% - \Delta U_{PV(i)} \% > 0
\]  

According to equation (10), the conditions under which no overvoltage occurs at any point on the feeder under the combination of load and photovoltaic distribution laws can be obtained. The results are shown in Table 1.

### Table 1. Maximum PV penetration level under same distribution rule of load and PV along the line

| Types and specifications of feeders | \( r_0 \) (Ω/km) | \( x_0 \) (Ω/km) | \( \beta \) (\( P_{PV} / P \)) |
|------------------------------------|------------------|-----------------|------------------|
| Overhead line                      |                  |                 |                  |
| LGJ-70                             | 0.425            | 0.34            | 1.35             |
| LGJ-150                            | 0.198            | 0.34            | 1.59             |
| LGJ-240                            | 0.120            | 0.36            | 1.98             |
| Cable                              |                  |                 |                  |
| YJV-70                             | 0.255            | 0.124           | 1.54             |
| YJV-150                            | 0.134            | 0.101           | 1.32             |
| YJV-240                            | 0.084            | 0.075           | 1.63             |

As far as overvoltage is concerned, the data in the table show that:

1. For the same kind of lines, the larger the conductor cross section, the higher the permissible photovoltaic permeability.

2. Under the same conductor cross-section, overhead wires can carry higher photovoltaic permeability than cables.
In the actual system, the load and photovoltaic power are random. If the $P_L$ in Tables 1 is considered as the minimum load and the photovoltaic power supply is considered as the rated power, the photovoltaic power can still meet the requirements, then there will be no overvoltage on the feeder.

Figure 2 shows the simulation results of node voltage distribution of 5-node load feeder under different photovoltaic capacity and load distribution. The simulation environment is PSCAD, and the distribution law of load and photovoltaic along the line is the same. The feeder is designed to use LGJ-150 with a length of 5 km, and a load and distributed photovoltaic power supply are connected every 1 km. The total load power is 3000 kW and the power factor are 0.95. From figure 2, we can see that: (1) the larger the photovoltaic capacity (or the greater the permeability $\beta$), the higher the voltage rise; (2) For the four typical distribution laws, the probability of overvoltage caused by the photovoltaic focusing on the terminal installation is the greatest; (3) When $\beta < 1.68$, the voltage at each point of the feeder will not be higher than the voltage at the head, but when $\beta > 1.68$. There will be a point voltage higher than the head voltage on the feeder, which may lead to overvoltage.

![Figure 2. Line voltage profile under different distribution of load and PV](image)

### 4. Overvoltage Solution

If the photovoltaic power and load power cannot always meet the conditions of the preceding section, the necessary measures should be taken.

1. **Limiting the output capacity of photovoltaic power supply**

   Assuming that only one photovoltaic power supply is connected to a certain section of the line with distributed load, if there is a point in the line where the voltage is higher than the voltage at the end of the power supply side, this point must be the photovoltaic grid-connected point. Generally speaking, if there are many photovoltaic power sources distributed on a feeder, if there is overvoltage in the feeder, then the most serious overvoltage must also be a grid-connected point. Therefore, it can be concluded that if there is no overvoltage at each photovoltaic grid-connected point, there will be no Overvoltage on the feeder.

2. **Adjusting bus voltage and reserving margin**

   If the distributed photovoltaic system on the feeder does not have the ability to limit the overvoltage and power or cannot be controlled according to the high voltage side voltage, it is necessary to take on-load voltage-regulating transformer and other bus voltage-regulating measures to keep a certain space between the bus voltage and the upper voltage limit.

   If the total photovoltaic power is $P_{PV}$ and is concentrated at the end of the feeder, the maximum voltage rise that the photovoltaic power supply may cause on the feeder is calculated.

   $$\Delta P_{PV,\text{MAX}} \% = \frac{P_{PV} \cdot r_t L}{U_N^2} \times 100\% \quad (12)$$

   If the internal impedance of the power supply system above the bus is neglected and only the feeder impedance is taken into account, the short-circuit capacity of the grid-connected point at the end of the feeder is as follows
According to the access system principle of Q/GDW480-2010 "Technical Regulations for Distributed Generation Access to Power Grid": if the ratio of short-circuit current of grid-connected point of distributed generation to rated current of distributed generation is not less than 10, it can be obtained by formula (11) and formula (13).

\[
\Delta P_{PV,max} \% < \frac{1}{10 \sqrt{1 + (x_0 / r_0)^2}} \times 100\%
\]

If the upper reserve of bus voltage deviation is larger than the maximum voltage rises of photovoltaic, there will be no problem of overvoltage caused by photovoltaic in feeder. For LGJ-240 overhead line, the \( x_0 / r_0 \) is about 3, and the maximum voltage rise or bus voltage regulation margin is 3.16%.

5. Conclusion

In the feeder of distributed photovoltaic access distribution network, overvoltage may occur in the feeder, so it is necessary to limit the access capacity of distributed photovoltaic. When the approximate distribution law of photovoltaic power supply and load on the feeder is known, the maximum photovoltaic capacity allowed to access can be calculated by the proposed algorithm. In the actual system, the load and photovoltaic power vary randomly. If the conditions are not always satisfied, distributed photovoltaic power supply is required to adjust the output power according to the grid-connected point voltage, or to install voltage-regulating equipment at the bus, so that there is a certain margin between the bus voltage and the upper limit of voltage deviation.

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