

Evaluation of Photovoltaic Power Hosting Capability in Distribution Network with Energy Storage Systems

Xixiang Chen¹, Lifeng Liu², Weimin Zhen¹, Jian Lang², Quanming Le², Ke Sun^{1*}

¹State Grid Zhejiang Electric Power Co., Ltd., Hangzhou 310007, China

²State Grid Shaoxing Power Supply Company, Shaoxing 312000, China

*Ke Sun's e-mail: 1784882914@qq.com

Abstract. The access of photovoltaic (PV) power to the distribution network will affect the power flow and voltage distribution of the distribution network. A large number of PV accesses may cause the voltage fluctuation or even the voltage exceeding, which will affect the safety and operation reliability of the power grid. In view of the voltage exceeding caused by PV access, the influence of energy storage system on PV capacity in distribution network is studied in this paper. First, a distributed PV consumption model is established based on the constraints of voltage and power flow. Secondly, the influence of adding energy storage system on the capacity of distributed PV is analyzed. Finally, the maximum PV access capacity before and after adding energy storage is solved by trial method. Taking IEEE 30 node distribution system as a simulation example, the reasons for limiting the increase of PV capacity of each node are analyzed. The simulation results show that the energy storage system can effectively improve the capacity of distributed PV and avoid the occurrence of voltage exceeding.

1. Introduction

PV power generation, as the most abundant and less restricted form of power generation in new energy, is developing rapidly. As one of the fastest developing countries in PV industry, the government has introduced a series of related policies to support and encourage the development of PV power generation. However, due to the intermittent and fluctuating characteristics of PV power, access to the grid has caused a certain impact on the safe and stable operation of the power system, so large-scale PV grid connection and consumption are difficult, and there is serious PV abandon phenomenon. Therefore, it is of great practical significance to promote the research of grid connection and consumption of PV power generation.

Scholars at home and abroad have conducted active and effective research in these fields. The calculation of the maximum capacity of renewable energy is usually based on exploratory, analytical and mathematical optimization method. The tentative method proposed in [1]-[2] is to give the capacity and position of a renewable energy, and calculates the short circuit current and voltage distribution at various load levels. If the system short circuit current and voltage meet the requirements of safe operation, the capacity of renewable energy is increased, and the above calculation is repeated until the renewable energy is saturated. Reference [3] analyses the analytical method to calculate the hosting capacity of renewable energy, and to establish analytical equations to calculate the hosting capacity of renewable energy for the equation. In reference [4]-[5], the mathematical optimization method is used, that is, takes the maximum admittance power as the objective function, gives the



system parameters, considers a variety of constraints, and uses the optimization algorithm to solve the state variables and control variables, and provides guidance for the voltage adjustment measures.

In this paper, based on the constraints of the voltage and power flow, the model of distributed PV maximum hosting capacity is established, and the energy storage system is taken into consideration, so that the voltage can be kept in the restricted range, thus the purpose of increasing the distributed PV capacity can be achieved. In the case of IEEE 30 node distribution network, it is proved that the energy storage system can effectively improve the capacity of the distributed PV, and the reasons for limiting the increase of the PV capacity of each node without the storage system are also analyzed.

2. The influence of distributed PV access on voltage distribution

Currently, the most important factor restricting PV access is node voltage constraint. Suppose a radiant feeder has N nodes, and each node has distributed PV power and load. When PV is connected to a distribution network, due to its active and reactive power, the voltage loss on the feeder can be reduced, and the voltage loss of the k node to the bus line is shown by the formula (1):

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

where, (R_k, X_k) represents the equivalent impedance of section k feeder; $(P_{L,k}, Q_{L,k})$ represents the load power of node k ; $(P_{L,k}, Q_{L,k})$ represents PV power installed at node k .

3. Modeling of PV hosting capacity

3.1. Optimization Target

The connection of distributed PV to grid can effectively alleviate the impact of the shortage of power resources. The maximum hosting capacity of PV in the distribution network is related to the load level, permeability and line network loss. Grid connection of PV will cause the occurrence of voltage exceeding, power flow overload. Therefore, these constraints must be considered, the maximum PV admittance capacity is calculated, and the PV resolution model is established. In this paper, the maximum total capacity of PV in a feeder is taken as the objective function, as shown in (2):

$$f = \max P_{PV,i} \quad (2)$$

where $P_{PV,i}$ is the active power of distributed PV at node i .

3.2. Constraint Condition

3.2.1. Power balance constraint. On the premise of safe and stable operation of the power grid, the power balance equations of PV distribution network are shown in (3) and (4), and are used as the equality constraint of the PV maximum admittance capacity calculation model.

$$P_{PV,i} - P_{Li} - U_i \sum_{j=1}^n U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \quad (3)$$

$$Q_{PV,i} - Q_{Li} - U_i \sum_{j=1}^n U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \quad (4)$$

where $P_{PV,i}$ and $Q_{PV,i}$ are the active and reactive power of distributed PV at node i , respectively; P_{Li} and Q_{Li} are the active and reactive power of load at node i , respectively; U_i and U_j are the voltage amplitude at node i and j ; θ_{ij} is the voltage phase angle at node i and j .

3.2.2. Node voltage constraints. When PV is connected to the distribution network, it will inevitably cause the node voltage to change. Therefore, node voltage must be required within a certain range of constraints, as shown below.

$$U_{i,min} \leq U_i \leq U_{i,max} \quad (5)$$

where $U_{i,min}$ and $U_{i,max}$ are the minimum and maximum voltage value through node i , respectively.

3.2.3. Line power flow constraint. After the PV is connected to the grid, the node voltage will change, which will cause the change of the power flow. Therefore, the power flow must be controlled within a reasonable range, as shown below:

$$S_l \leq S_{lmax} \quad (6)$$

where S_l and S_{lmax} are the apparent power and maximum transmission power of line l , respectively.

3.2.4. PV output constraint. The maximum capacity of PV is not infinite because of the influence of light intensity and ambient temperature. In order to keep the active power output of PV maximum, the PV output constraint can be expressed as:

$$P_{PV,i} \leq P_{PV,i,max} \quad (7)$$

where $P_{PV,i,max}$ is the maximum value of active power output from PV at node i .

3.3. Solution Based On Exploratory Method

In this paper, the established model is solved according to the exploratory method combined with the power flow calculation. The maximum PV hosting capacity that each node can bear before and after adding energy storage system is calculated, and the main solution steps are as follows:

- Based on the power flow algorithm, the PV hosting capacity of each node without energy storage system is obtained within the constraint of voltage and power flow of each node.
- The PV capacity connected to power grid is increased using exploratory method, and the voltage amplitude and branch power of each node are obtained and judged, if both of them are in the scope of security constraints, the PV capacity will continue to increase until the voltage exceeding occurs, and the reasons that limit the PV capacity of each node to continue to increase are recorded. The schematic diagram of the solution before adding the energy storage system is shown in Figure1.
- After obtaining the maximum PV hosting capacity of each node without adding energy storage system, the energy storage system is added, and then the PV capacity of the nodes is continuously increased.

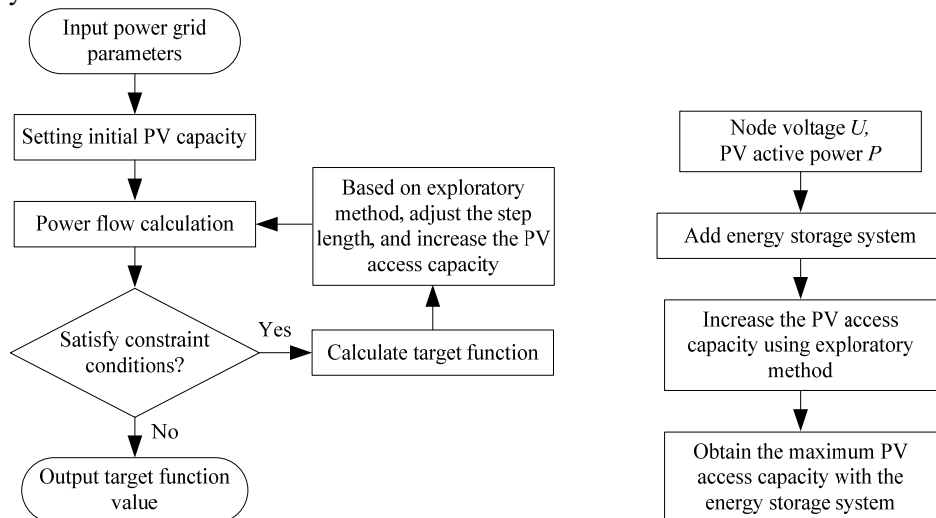


Figure 1. Before adding energy storage system Figure 2. After adding energy storage system

- The maximum PV capacity of each node is obtained by continuously increasing the energy storage system using the exploratory method. Then the maximum PV capacity after installing the

energy storage system is recorded, and the schematic diagram of the solution after adding the energy storage system is shown in Figure 2.

- Drawing the maximum PV capacity curve of each node without considering the energy storage system and taking into account the energy storage system.
- Comparing the curves mentioned above, the influence of adding energy storage system on the PV capacity is analyzed, and the corresponding conclusions are drawn.

4. Case analysis

4.1. System description

In this paper, the IEEE 30 node distribution network system is used as an example. The voltage level of this system is 12.66 kV, the base power is 20 MW, the total active load power is 6.5 MW, the total reactive power is 4.5 MVar, the branch power is 12 MW, $U_{(i,min)}=0.95U_N$, $U_{(i,max)}=1.05U_N$, the first node voltage is set at 1.035 p.u., and the specific structure of the system is shown in Fig. 3.

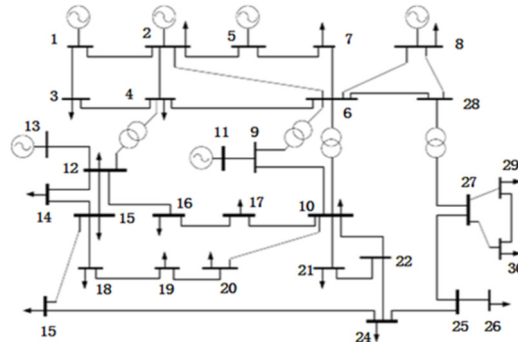


Figure 3. IEEE 30 node system structure diagram.

4.2. PV Hosting Capacity Without Energy Storage System

In order to study the influence of different access location of single PV on PV hosting capacity, this paper selects 2, 9, 20, and 30 nodes at the front, middle, and back of the feed line as the research object, and does not consider the energy storage system at this time. According to the method of this paper, the admittance capacity of distributed PV is calculated. The result is shown in Table 1.

Table 1. Access capacities of single PV without energy storage system

Connection node	2	9	20	30
Access capacity/MW	13.5	5.01	4.7	4.3

It can be seen from Table 1 that the hosting capacity of the distributed PV system becomes smaller and smaller as the node moves backward from the system bus to the feeder terminal. When the maximum capacity of PV systems is connected to the 4 nodes, the trend diagram of the system voltage distribution is shown in Figure 4. Except node 2 that has no voltage exceeding, the node voltage is close to the upper limit of 1.05 when the other nodes are connected with the maximum capacity of PV systems.

From the voltage distribution diagram of Figure 4, we can see that for the above distribution network, the main reason for restricting the PV hosting capacity is the voltage limit. When the distributed PV is connected closely to the bus bar, the voltage rise of the system is limited, while the distributed PV supports the system voltage significantly when the PV is connected gradually away from the bus. Therefore, it can be seen that the PV capacity that the system can hold will decrease as the connection node moves backward with the power flow of the system within limitation. In addition, this paper finds out the reasons that limit the PV capacity of each node by calculating, as shown in Table 2.

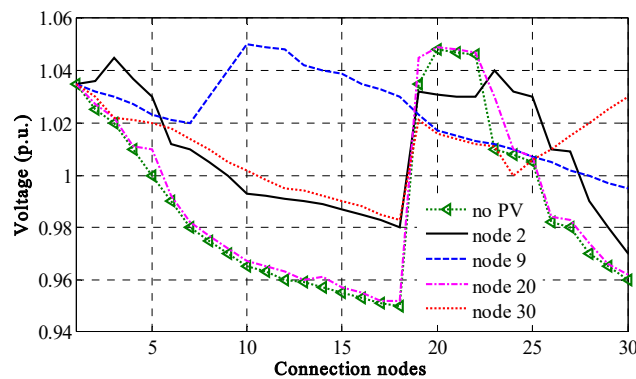


Figure 4. Voltage distribution trend diagram at PV connection point.

Table 2. Reasons that limit the PV capacity of each node

Connection node of PV	Constraint factor
2,3,4,19,23	Branch power overload
5,6,7,8,9,10,11,12,13,14,15,16,17,18	Voltage exceeding
20,21,22,24,25,26,27,28,29,30	Voltage exceeding

As can be seen from Table 2, the capacity of the PV near the system bus is limited by the branch power constraints, while the rest of the nodes are restricted by voltage constraints so that their capacity cannot continue to grow. This is consistent with the conclusion of the above analysis that the voltage limit is the main reason to limit the increase of PV capacity. Therefore, different measures can be taken to improve the hosting capacity of PV according to the restriction factors of each node. For the nodes near the bus bar, the lines in the front end of the feeder can be reformed to increase the line size to improve the capacity of the PV. For the nodes far away from the bus line, the active management measures of voltage control can be added to raise the capacity of PV. Figure 5 is the maximum PV hosting capacity distribution map of the IEEE 30 node before the energy storage system is added. When the distributed PV is connected closely to the system bus node, the PV hosting capacity is the largest and the curve is relatively stable. When the connection location gradually far away from the system bus node, the hosting capacity of PV is becoming smaller and smaller, which shows that the voltage constraints of these nodes become more and more obvious.

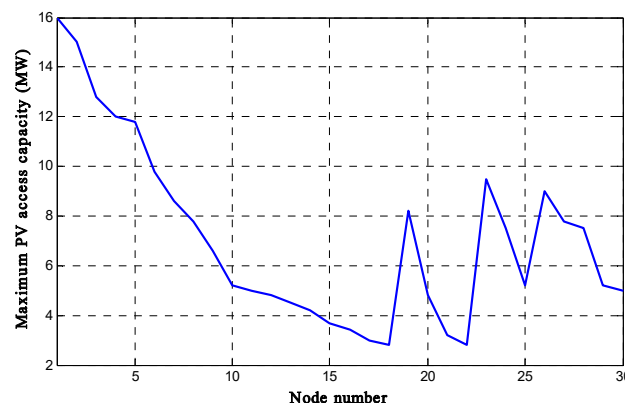


Figure 5. Maximum PV hosting capacity distribution map without energy storage system.

Through the above analysis, it can be seen that the maximum capacity of the single PV power source that IEEE 30 nodes can access is less than 16 MW before any energy storage system is added, and the hosting capacity of the distributed PV is significantly reduced after the middle of the feeder.

When the terminal node voltage of the distribution network is low, an appropriate amount of PV can be selected to support the voltage. When a large number of PV needs to be consumed in the distribution network, the PV can be considered in the front node of the distribution network.

4.3. PV hosting capacity with energy storage system

In order to improve the hosting capacity of the PV system, relevant measures must be added. From the above analysis, it is known that the limit of node voltage is the most important factor that restricts the PV capacity. Therefore, this paper considers adding energy storage system. Based on the previous analysis, in the case of adding the energy storage system, the nodes in the middle are chosen to connect the PV, and compare it with that without the energy storage system. The calculation results of the maximum PV hosting capacity are shown in Table 3.

Table 3. Access capacities of single PV with energy storage system.

Connection node	14	17	18	23
Access capacity without energy storage system	3.46	3.2	4.5	2.9
Access capacity with energy storage system	4.5	4.1	5.2	3.9

As can be seen from Table 3, when the energy storage system is added, the maximum PV hosting capacity at the center or back is obviously improved.

5. Conclusion

The influence of energy storage system on PV capacity in distribution network has been studied in this paper. A distributed PV hosting model has been established based on the constraints of voltage and power flow. Then, the influence of adding energy storage system on the capacity of distributed PV has been analyzed. Finally, the maximum PV access capacity before and after adding energy storage has been solved by exploratory method. Taking IEEE 30 node distribution system as a simulation example, the reasons for limiting the increase of PV capacity of each node have been analyzed. The simulation results have shown that the energy storage system can effectively improve the capacity of distributed PV and avoid the occurrence of voltage exceeding.

References

- [1] H. Pezeshki, A. Arefi, G. Ledwich, and P. Wolfs, "Probabilistic voltage management using OLTC and dSTATCOM in distribution networks," *IEEE Trans. Power Delivery*, vol. 33, no. 2, pp. 570-580, Apr. 2018.
- [2] F. Rolim, F. Trindade, "Use of batteries to voltage regulation in distribution systems with deep penetration of photovoltaic generation," in *Proc. 2018 Simposio Brasileiro de Sistemas Eletricos*, Niteroi, Brazil, May 2018.
- [3] L. Macedo, J. Franco, R. Romero, and etal, "Increasing the hosting capacity for renewable energy in distribution networks," in *Proc. 2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference*, DC USA, Apr. 2017.
- [4] V. Klonari, J. Toubeau, J. Lobry, and F. Vallee, "Photovoltaic integration in smart city power distribution: A probabilistic photovoltaic hosting capacity assessment based on smart metering data," in *Proc. 2016 5th International Conference on Smart Cities and Green ICT Systems*, Rome Italy, Apr. 2016.
- [5] F. Lamberti, V. Calderaro, V. Galdi, and etal, "Long-term performance in providing voltage support by PV and storage systems in distribution networks," in *Proc. 2016 IEEE Power and Energy Society General Meeting*, Boston USA, Jul. 2016.