

The Evaluation of Ultimate Capacity for Distributed Photovoltaic Access Distribution Network Considering Uncertainty

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Abstract. Aiming at the problem of the increasing voltage over limit risk by a large number of distributed PV access network, firstly by analyzing the volatility and time-series property of the PV output, a probability model of PV output based on the clearance model is established in this paper. Then the risk assessment index of system voltage exceeding the limit based on the probability and severity of node voltage at each time interval is established. Based on this, using the hybrid approximation to solve the ultimate capacity of distributed PV access network is proposed. Finally, a typical IEEE 33-node power distribution system is taken as an example to analyze the risk of system voltage under different load characteristics, load levels and line types. From these three aspects, the ultimate capacity of distributed PV access network is evaluated.

1. Introduction

A large number of distributed photovoltaic (DPV) accesses to distribution network (DN), making the original single-source radiation DN into an active distribution network, which also changes the power flow and voltage distribution of DN and increases the risk of voltage over-limit (VOL) [1-4]. However, due to the uncertainty of PV output and load, it is difficult to measure their impacts on the voltage of DN accurately by certain power flow assessment method, which is mainly related to the location and capacity of the PV. Therefore, how to assess the voltage over limit risk of DN caused by PV access and determine the ultimate capacity of PV will be an urgent problem to be solved.

At present, lots of references have studied the influence of DPV access on the voltage of DN [5-8]. Reference [5] proposed using Thevenin's equivalent model based on DG to analyze the effect of DG access on voltage stability of the system. Reference [6] proposed using sensitivity analysis method to analyze the influence of DG output and access location on the system voltage. Reference [7] established the probability model of DPV power generation system based on Beta distribution of solar radiation and analyzed the influence law of the steady-state voltage distribution and voltage amplitude fluctuation of DN after PV access. Reference [8] proposed solving the problem of VOL in DN by PV power supply active/reactive power integrated control scheme. The above references all analyze the impact of PV access on DN voltage from the perspective of static power flow. However, in fact, PV output has uncertainties and time-series property, that is to say, the risk of system VOL caused by the fluctuation of PV output during different periods of the day is not the same. Therefore, when assessing the risk of VOL caused by PV access, the model considering the uncertainty and time-series of load and PV output simultaneously is more practical.



In this paper, based on the analysis of the PV output characteristics, a probability model of PV output based on the clearance model is established. The risk assessment index of VOL in DN considering the uncertainty and time-series property of PV output and the ultimate capacity of PV access network are proposed. Taking the IEEE33-node standard power distribution system as an example, this paper evaluates the ultimate capacity of DPV from three aspects of load characteristic, load level and line type.

2. Probabilistic model of PV and load

2.1. Time-series model of PV output based on clearance theory

Related researches show that there is a strong positive correlation between PV output and solar irradiance. But the intensity of sunlight varies greatly with different weather types and seasons. Therefore, in order to show the differences of PV output due to different solar irradiance in different weather types, the eigenvector is constructed in this paper according to the indexes that describe the average output and volatility of PV, and then the generalized weather types are classified by cluster analysis. Then, the time-series models of PV output under different weather types are established.

The PV output contains both deterministic and uncertain components, the deterministic property mainly reflects the time-series characteristics of PV output due to the sunrise and sunset of the sun, while the uncertainty mainly reflects the PV output due to cloud changes fluctuation characteristics. This paper refers to the analysis method of reference [9], the relative output at each moment breaks down into the day's benchmark output and fluctuation coefficient at each moment. Finally, for PV output benchmark data and fluctuation coefficient data of different weather types, the least square method is used to fit the PDF of the PV benchmark output and the fluctuation coefficient under different weather types. The fitting function is:

$$f(x) = \sum_{i=1}^n \alpha_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{1}{2\sigma_i^2}(x-\mu_i)^2} \quad (1)$$

In (1), α_i , σ_i and μ_i are fitting parameters whose values are related to the type of weather and the type of fitting variables.

2.2. Probabilistic model of load

The errors of load forecasting and load measuring are inevitable. Therefore, its active power P_L and reactive power Q_L should be described as random variables. Many researches demonstrate that these two random variables obey normal distribution function.

3. The evaluation of ultimate capacity for DPV access distribution network

PV access generally raises the voltage of DN, resulting in the risk of VOL. And the PV output is generally larger in sunny days and the risk of VOL in DN will be higher. Therefore, the following analysis uses the probability model of PV output in sunny days as an example to analyze the ultimate penetration (ultimate capacity) of PV access. The PV penetration mentioned in this article is the ratio of the total installed capacity of DPV in the DN to the maximum power supply capacity of the feeder.

3.1. System voltage over-limit risk assessment index

Risk index not only need to reflect the possibility of fault occurred in the system, but also need to reflect the severity of the fault occurred. In this paper, we use the voltage probability distribution model to quantify the probability, use the severity function to quantify the severity and establish the system VOL risk assessment based on the voltage probability distribution and severity function of each node in each period. Therefore, the definition of the system VOL risk assessment R_{vs_max} is the maximum VOL risk of all nodes in the system during the operation period (generally 24h), that is:

$$R_{vs_max} = \max \{R_{vs}(1), R_{vs}(2), \dots, R_{vs}(t), \dots, R_{vs}(24)\} \quad (2)$$

Where $R_{vs}(t)$ is the sum of VOL risk for all nodes at time t and its calculation method is as follows:

$$R_{vs}(t) = \sum_i \int_0^{V_{\min}} f(V_i^t) U_{dl}(V_i^t) dV_i^t + \sum_i \int_{V_{\max}}^{\infty} f(V_i^t) U_{ul}(V_i^t) dV_i^t \quad (3)$$

In (3), V_{\max} and V_{\min} are upper limit and lower limit of the node voltage respectively; $f(V_i^t)$ is the probability density function of node i voltage at time t ; $U(V_i^t)$ is the function of the severity of the VOL as follows:

$$U_{dl}(V_i^t) = \frac{e^{V_{\min} - V_i^t} - 1}{e - 1} \quad U_{ul}(V_i^t) = \frac{e^{V_i^t - V_{\max}} - 1}{e - 1} \quad (4)$$

3.2. The calculation of the assessment index

In this paper, R_{vs} is calculated by the method of probabilistic power flow calculation based on cumulant method [10], in which the probabilistic power flow model uses the linearization model [11] of the AC power flow and the Polar-Newton-Raphson method is used as the power flow calculation method.

3.3. Assessment process

In order to ensure the safe operation of the power grid and improve the power quality of the consumer, if given the limiting value R_{vs_limit} of the risk of the DN VOL in actual operation, we can use the hybrid approximation method to obtain the ultimate capacity H_{limit} of the DPV access DN. The main steps of the assessment process are as follows and the process is shown in Figure 1.

- 1) Entering the original data, building simulation network model;
- 2) Collecting the historical data of PV output and load in the target area to construct the probabilistic model of load and PV output;
- 3) Given the initial PV penetration rate H ;
- 4) Calculating R_{vs_max} : calculate the risk assessment index of DN VOL at a given PV penetration rate according to the calculation method of risk assessment index of VOL in Section 3.1 and 3.2;
- 5) Judging whether R_{vs} is greater than R_{vs_limit} , if not, let $H=H*(k+1)$, where k is the penetration rate adjustment coefficient and $0 < k < 1$, and return to step 4; if yes, go to step 6;
- 6) Reducing the penetration rate H and penetration rate adjustment coefficient k : let $H = H*(1-k)$ and $k = k/2$;
- 7) Judging whether k is less than the accuracy e , if yes then return to step 4; if no, then output the ultimate capacity H_{limit} of PV.

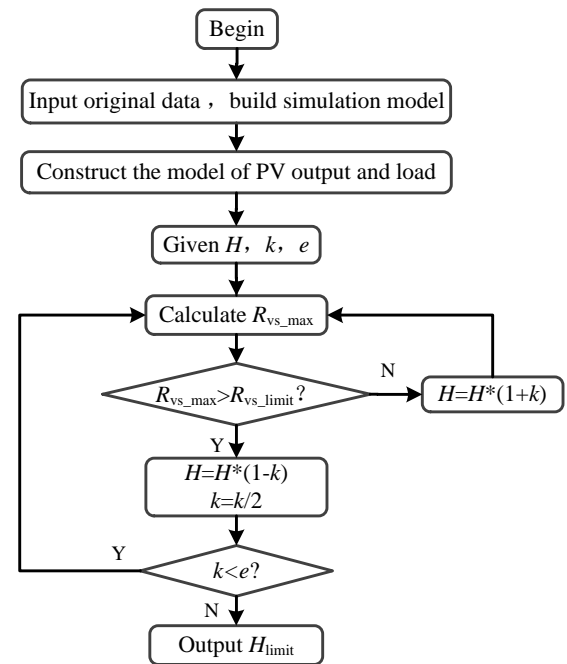


Figure 1. Assessment process for H_{limit}

4. Case study

The IEEE 33-node distribution system is chosen for simulation. As the main line, Node 2 to Node 19 selects the 10kV line model LGJ-240, which is commonly used in China currently. Node 1 is a balance bus, its voltage is set to 1.05pu. The system equivalent reactance X_s is 0.32Ω and DPV connected to Node 19 equivalently and centrally at the end of system. The improved network model is shown in Figure 2.

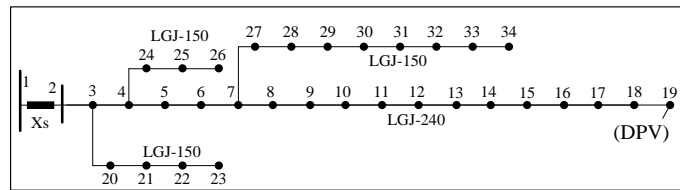
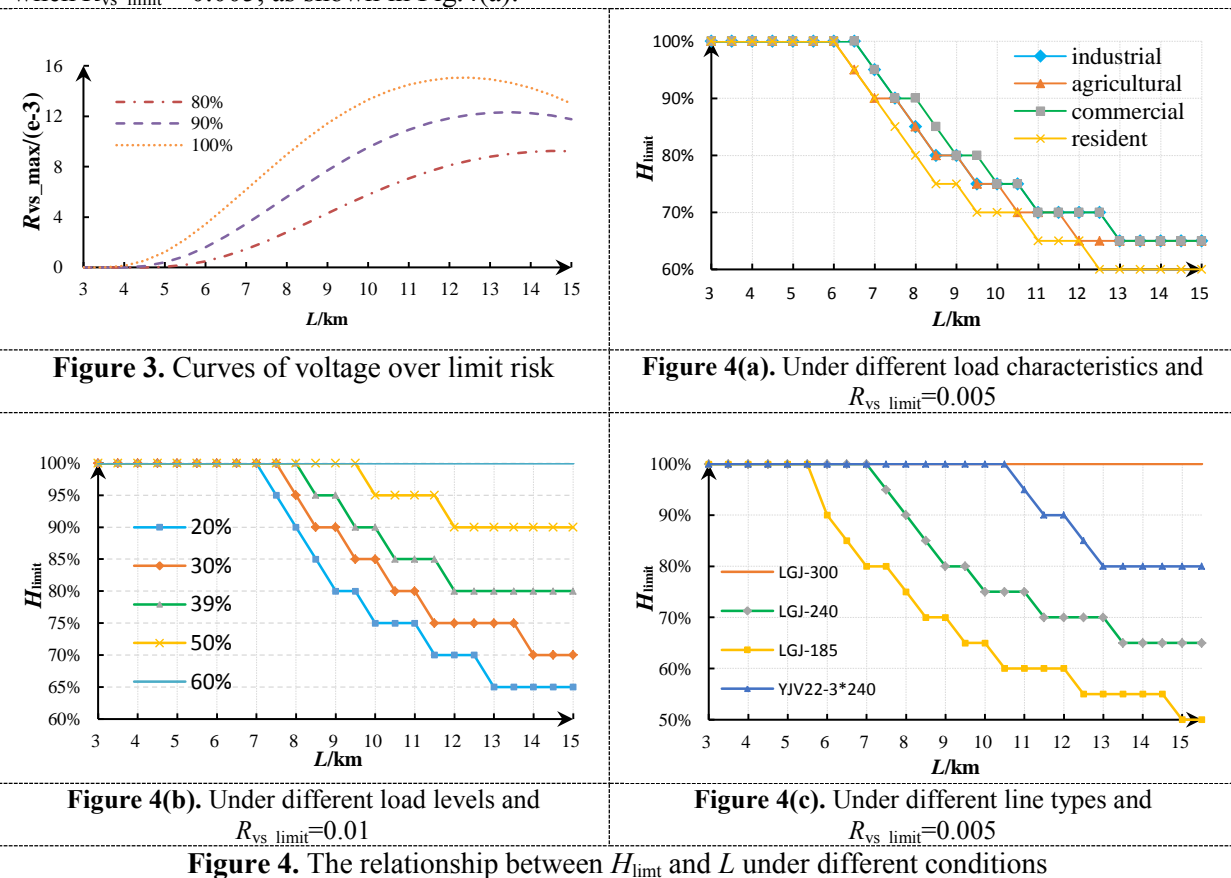


Figure 2. DPV access distribution grid structure

The main line of main simulation is LGJ-240. According to the current carrying capacity, its maximum power supply capacity P_{Lmax} is 9.509MW. Because the DN is a single radiation network, its upper limit of PV penetration rate is 100%, only need to ensure that the current of main line is not overloaded.

4.1. The ultimate penetration rate of PV under different load characteristics

To study the influence of PV access on voltage level under different penetration rates, based on the DN structure shown in Fig.2, we assume that load types of all nodes are industrial load and the peak value of total load is 3.715MW, (that is, the maximum load rate of line is 39.07%). The assessment index of VOL risk R_{vs_max} in DN is calculated under different line lengths and different PV penetration rates, as shown in Figure 3. The load characteristics of different load types are different. So the load types of nodes are set as agricultural load, commercial load and resident load respectively. The maximum risk of VOL of system node under different line lengths and PV penetration rates is studied under different load types. The PV penetration rate is obtained under different lengths of main line when $R_{vs_limit} = 0.005$, as shown in Fig.4(a).



From Fig.3 and Fig.4(a), we can see that: 1) When the penetration rate is less than 80%, the risk of VOL in DN will increase with the increase of PV penetration rate and main line length. When the penetration rate is more than 80% and the length of the overhead line is too long, the reactive power

loss of the line will increase significantly if the direction of the active and reactive power flow in the line is opposite, which leads to lower voltage at some nodes in the front part of the line. Therefore, under the condition of large PV penetration rate, the risk of voltage over-upper-limit will slightly decrease as the length of the main line increases. 2) When the line length does not exceed 6km, the ultimate penetration rate of PV access is mainly limited by the line current carrying capacity, and its ultimate penetration rate is 100%. 3) When the line length is more than 6km and $R_{vs_limit} = 0.005$, the accessible PV capacity in DN with the characteristics of resident load is the smallest under different load types, which is mainly the residents load curve and PV output curve does not match well, leading to the maximum risk of VOL when in the same penetration rate. When $R_{vs_limit} = 0.01$, the maximum over-limit probability constraint is relaxed, and the ultimate PV penetration rate increases under a certain length, but the overall trend remains unchanged.

4.2. The ultimate penetration rate of PV under different load levels

Based on the grid structure and line parameters in Fig.2, assuming that all nodes are industrial load types, their peak loads are set at 1.9, 2.9, 3.7, 4.8 and 5.7MW respectively, that is, the corresponding maximum load rates of the line are respectively 20%, 30%, 39%, 50% and 60% respectively. The maximum risk of VOL of the system node under different line lengths and different PV penetration rate is studied, and the PV penetration rates under different main line lengths are obtained when $R_{vs_limit} = 0.01$, the result is shown in Fig.4(b).

The figure shows that: 1) When the line length does not exceed 7km, the PV access ultimate penetration rate is mainly limited by the line safety current, and its ultimate penetration rate is 100%. When the line length is more than 7km but not more than 15km, the PV access ultimate penetration rate is affected by the limit of the risk of VOL, and remains above 60%. 2) Under the same line length, the penetration rate of PV access increases with the increase of line load rate.

4.3. The ultimate penetration rate of PV under different line types

Based on the grid structure in Fig.2, assuming that all nodes are industrial loads and the peak of total load is 3.7MW, we study the maximum risk of VOL of the system node under different line lengths and different PV penetration rates, and the PV penetration rates under different line types are obtained when $R_{vs_limit} = 0.005$, the result is shown in Fig.4(c).

The figure shows that: 1) For overhead lines with the length between 5.5km and 15km, the ultimate penetration rate of PV access increases as the wire diameter of the line increases. 2) Under the same line length and the same diameter conditions, the cable line can access larger penetration rate of PV than overhead line.

5. Conclusions

In this paper, a time-series model of PV output is established, and an evaluation method of ultimate capacity for DPV access DN considering uncertainty based on the risk index of voltage over-limit is proposed. The simulations show that:

(1) When the other conditions are the same, the distribution network with the majority of industrial load has the highest receiving capacity of photovoltaic power. Therefore, it is a reasonable choice to install DPV on the roof of a factory and realize local consumption.

(2) When the line length and load type are the same, the penetration rate of photovoltaic access increases with the increase of the line load level. Therefore, the DPV should be given priority to access to the heavy-load medium voltage feeder.

(3) In general, the ultimate penetration rate of PV access can reach 100% when the length of medium-voltage line does not exceed 5km, and the ultimate penetration rate of photovoltaic access can reach at least 50% or so when the line length is more than 5km and less than 15km.

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