Research on the Load Rate of Substation Considering Distributed Photovoltaics

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Abstract. The load rate of the substation can be increased after the distributed power source is connected to the distribution network. This paper proposes a calculation method of distribution network substation load rate that can effectively take into account distributed photovoltaic output. By simplifying distributed photovoltaic into a special transformer, the complexity of distribution network substation load rate analysis is reduced; The probabilistic effect of distributed photovoltaic on the load rate of substations is evaluated by the verification of “N-1”. Through the analysis of examples, the effectiveness of the method in this paper is proved.

Keywords. Distribution substation; distributed photovoltaic; load rate; energy storage; reliability.

1. Introduction
An important feature of the smart grid is to allow a large amount of renewable energy generation to connect to the power system. Distributed photovoltaic is an important part of renewable energy, whose large-scale connection to the urban power distribution system is the future development trend [1-2].

The method of determining the maximum load rate of distribution network substations mainly adopts N-1 simulation verification [3]. The traditional calculation methods include capacity-load ratio method [4], network maximum current method [5], maximum load multiple method [6], etc. These methods are relatively complex. And in some cases, accurate results cannot be obtained. Ref. [7] analyzed the influence of the low-voltage side connection mode of the medium-voltage distribution network on the total power supply capacity (TSC). Ref. [8] proposed the concept and mathematical model of the distribution network safety domain, power supply capacity model and power supply capacity curve, and analyzed the difference and connection between the safety domain and the power supply capacity under N-0 and N-1, as well as the method of use in operation and planning; Ref. [9] studied the effect of PV-energy-storage charging station on power supply capacity of the distribution network, which is evaluated by the continuous power flow method of load growth; Ref. [10] proposed an evaluation model of the maximum power supply capacity of the distribution network considering multiple transfers, with the maximum sum of system loads as the objective function. Based on the N-1 safety verification criterion of the distribution network as a constraint, the specific calculation example was used to verify that this method can fully tap the power supply potential of the distribution network, and at the same time, it can propose corresponding the method on the loss load transfer for various main transformer faults, which broke the limitations of traditional evaluation methods; Ref. [11] puts
forward the analytical calculation method of power supply capacity based on the main transformer interconnection of the substation. The method is improved in Refs. [12-14]. However, the existing research has not fully considered the impact of equipment such as distributed PV, or their confidence capacity is considered to be zero. The idea of treating distributed PV as a special transformer is put forward in this paper. The “N-1” criterion is used as the verification standard to determine the maximum load rate of the distribution network substation taking into account the distributed PV output and the auxiliary function of the energy storage. The focus was on the analysis of PV access capacity and the impact of energy storage equipment in the process of Monte Carlo simulation.

2. Influence of Distributed PV on Substation Load Rate
If the distributed PV system is equivalent to a special substation containing only one transformer, the special transformer is connected to the main transformers of other substations through the tie line, as shown in figure 1. Without considering the transmission capacity constraints of the tie line, the distributed PV system does not directly supply power to any load. It only transmits the uncertain power generated by the PV system to the 2 main transformers of substation 1 through the tie line.

Before distributed PV accesses to the system, there is a relationship between power output and load demand as shown in figure 2 when a main transformer breaks down. The red line is the time series load curve, and the blue line is the capacity of the original distribution system under the fault condition. After distributed PV is increased, the available capacity of the distribution system under the same fault will be shown by the green curve. Due to the uncertainty of the output of PV, the available power of the system may also be shown by the black curve, and the system will lack power supply. It can be seen that the distributed PV system has a probabilistic effect on the improvement of power supply capacity, and this statistical value can be obtained by simulation. At this time, it can effectively reduce potential power shortages by adding an energy storage system (ESS) as a backup.
In order to quantify the role of distributed PV and ESS in improving the power supply capacity, the following indicators for possible power shortages is defined in this article.

\[
IN = \frac{\sum_{i=1}^{N_{\text{simu}}} \sum_{j=1}^{8760} N_{\text{ush}}(i, j)}{8760 N_{\text{simu}}}
\]  

(1)

In formula (1): \(N_{\text{simu}}\) is the total number of years of simulation; \(N_{\text{ush}}(i, j)\) is the power shortage situation in the \(j_{th}\) hour of the simulation year \(i\). If a power shortage occurs, \(N_{\text{ush}}(i, j)=1\), otherwise \(N_{\text{ush}}(i, j)=0\).

### 3. Evaluation of Substation Load Rate with Distributed PV

Distributed PV equipment increases the capacity of other transformers through joint operation of networks, and obtains the maximum load rate matrix \(T\).

\[
T = \begin{bmatrix}
T_{1,1} & \ldots & T_{1,n} & 0 \\
\vdots & \ddots & \vdots & \vdots \\
T_{n,1} & \ldots & T_{n,n} & 0 \\
0 & \ldots & 0 & 0
\end{bmatrix}
\]

(2)

Among which, \(n\) represents the total number of transformers, the meaning of each parameter in the \(T\) matrix and the calculation method can refer to Ref. [11].

The maximum load rate of the transformer is calculated by 3 steps. (1) Select the \(i_{th}\) contact unit in the main transformer contact matrix. Assuming the transformer \(i\) fails, calculate the initial value of the load that the \(i_{th}\) contact unit can supply, that is, the sum of the rated capacity of the other transformers recorded it as \(L_0\); (2) Increase the load according to the step \(\Delta L\) on the basis of \(L_0\). By calculating the \(IN\) indicator of the simulation statistical system, the load increases \(X\) steps to the search upper limit \(L_{\text{max}}\); (3) According to the set \(IN\) upper limit (such as 0.5%), determine the available load limit of \(i\) contact unit corresponds to step \(x\) (\(x < X\)), then the load rate limit of all transformers of the contact unit is calculated by the following formula:

\[
T_{i,j} = \left\{ \frac{\sum_{i=1}^{n} L_{i,j} R_i - R_i + x\Delta L}{\sum_{i=1}^{n} L_{i,j} R_i} \right\}
\]

(3)

By repeating the above process, each row in the maximum load rate matrix \(T\) can be obtained. From equation (1), it can be seen that the calculation of \(IN\) index needs to use Monte Carlo simulation.

### 4. Example

The transformer capacity of each substation in figure 1 is shown in table 1. The load data of IEEE RTS system [9] is used in load curve. Taking the contact unit centered on the main transformer 2 as an example, in the case of considering only the PV system, the statistical result of the indicator \(IN\) at \(E = 0.6G\) is shown in figure 3. It should be noted that the ration of the load increase and the PV capacity is recorded as the load capacity ratio.

| Substation | Voltage level (kV) | Capacity (MVA) |
|------------|-------------------|---------------|
| 1          | 35                | 2×20          |
| 2          | 35                | 2×20          |
| 3          | 110               | 2×31.5        |
Figure 3. Statistical results of indicator IN when $E = 0.6G$.

According to the simulation method in section 2, if the IN index is required to be less than 0.5%, the maximum load rate matrix $T_{0.5\%}$ is obtained under the premise of $G = 10$, $E = 0.2G$:

$$
T_{0.5\%} = \begin{bmatrix}
0.63 & 0.63 & 0 & 0 & 0 & 0 & 0 \\
0.87 & 0.87 & 0.87 & 0 & 0.87 & 0 & 0 \\
0 & 0.92 & 0.92 & 0.92 & 0.92 & 0.92 & 0 \\
0 & 0 & 0.89 & 0.89 & 0.89 & 0.89 & 0 \\
0 & 0.82 & 0.82 & 0.82 & 0.82 & 0.82 & 0 \\
0 & 0 & 0.77 & 0.77 & 0.77 & 0.77 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

The maximum load rates allowed for each main transformer are 63%, 63%, 77%, 77%, 77% and 77%.

5. Conclusion
This paper proposes a calculation method for the maximum load rate of substations taking into account the distributed PV system. This method considers the severe conditions which occurs that a main transformer fails on the day of maximum load. The main characteristics of this method are: (1) distributed PV system is equivalent to a special transformer; (2) The load capacity directly supplied by the PV system is zero; (3) The Monte Carlo analysis method of distributed PV and ESS is used to improve the power supply capacity. According to the analysis results, it can be seen that distributed PV can increase the load rate of substations and provide auxiliary decision-making information for planners.

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