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CALCULATION METHOD OF MAXIMUM LOAD RATIO OF TRANSFORMER CONSIDERING DISTRIBUTED PV AND STORAGE

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ABSTRACT

The load ratio of transformers could be improved with the integration of distributed generators. A calculation method for the maximum load ratio of transformer is proposed considering the distributed PV and storage. The feature of the method is that the distributed PV and storage system is handled as a special transformer, whose power supply capability is zero while improving other transformers' load ratio. Taking power supply reliability as core index, the maximum load ratio values of transformers are explored. The effectiveness of the proposed method is verified by simulation results.

Keywords: transformer, the maximum load ratio, distributed PV, storage, power supply reliability

1. INTRODUCTION

In order to achieve sustainable development of society and the environment, many countries are developing PV power generation[1]. Distributed PV (PV) is an important part of renewable energy power generation, it is likely that a huge number of PV equipment will integrate into urban power distribution system[2]. At the same time, with the rapid reduction in price, storage may have a rapid development.

To calculate the maximum load ratio of transformer, there are several traditional calculation methods, including capacity ratio method[3], maximum network current method[4], maximum load multiple method[5], and so on. These methods highly rely on experiences and cannot obtain accurate results in some cases. Differing from traditional methods, an innovative method is developed in [6], an analytical calculation method based on main transformer interconnection. Taking power supply reliability index as core index, the maximum load ratio values of transformer are determined. In [7-9], above calculation method is further improved. And, a calculation model based on linear programming is established in [10, 11]. However, in existing research, distributed PV and storage have yet not been given enough consideration.

Distributed PV and storage are handled as a special transformer. The own load ratio of the special transformer is zero, while they can improve other transformers' load ratio. During the calculation, power supply reliability under "N-1" criterion is a staff gauge. With different power supply reliability standard, different maximum load ratio values are achieved. The impact of storage equipment is also analyzed in Monte Carlo simulation process.

2. IMPROVEMENT INFLUENCE OF DISTRIBUTED PV AND STORAGE

2.1 Calculation method of the maximum load ratio

2.1.1 The main transformer connection matrix and the maximum load ratio matrix [6]

There are n substations in one power supply area and they are numbered in sequence 1, 2, ..., n. To each substation, the transformer numbers are denoted as N_1, N_2, ..., N_n. For the ith substation, the jth main transformer number is $\sum_1^{i-1} N_{i+j}$. As a result, the total number of transformers is $N_\Sigma = N_1 + N_2 + ... + N_n$. The main transformer connection matrix, denoted as L_{link}, is

$$
\boldsymbol{L}_{link}=\begin{bmatrix} L_{1,1} & \cdots & L_{1,j} & \cdots & L_{1,N_\Sigma} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ L_{i,1} & \cdots & L_{i,j} & \cdots & L_{i,N_\Sigma} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ L_{N_\Sigma,1} & \cdots & L_{N_\Sigma,j} & \cdots & L_{N_\Sigma,N_\Sigma} \end{bmatrix} \tag{1}
$$

Among which, $L_{i,j}$ is the contact relationship between the ith main transformer and the jth main transformer. When there is connection, $L_{i,j}$ =1, otherwise $L_{i,j}$ =0. Each row corresponds to a main transformer connection unit.

The maximum load ratio matrix $\boldsymbol{T}$ is closely related to the connection matrix $\boldsymbol{L}_{\text{link}}$.

$$
\boldsymbol{T}=\begin{bmatrix} T_{1,1} & \cdots & T_{1,j} & \cdots & T_{1,N_\Sigma} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ T_{i,1} & \cdots & T_{i,j} & \cdots & T_{i,N_\Sigma} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ T_{N_\Sigma,1} & \cdots & T_{N_\Sigma,j} & \cdots & T_{N_\Sigma,N_\Sigma} \end{bmatrix} \tag{2}
$$

When the ith main transformer does not connect with the jth main transformer, $L_{i,j}$ and $T_{i,j}$ are 0. Otherwise, $L_{i,j}$ is 1 and $T_{i,j}$ is:

$$
T_{i,j}=\left(\frac{\sum_{j=1}^{N_\Sigma} L_{i,j}R_j - R_i}{\sum_{j=1}^{N_\Sigma} L_{i,j}R_j}\right)L_{i,j} \tag{3}
$$

Among which, R_i is the rated capacity of ith main transformer.

2.1.2 The maximum load ratio of each main transformer of the system

The ith column of the $\boldsymbol{T}$ matrix is the maximum load ratio that can be achieved under the condition that the ith main transformer is connected with other transformers of different connection units and ensure operation security. As the actual load ratio can only be one value, it is the minimum value of the load ratios in the column, denoted as $T_{\text{i(N-1)}}$.

$$
T_{i(N-1)}=\min_{1\le j\le N_\Sigma, T_{i,j}\ne 0}\left\{T_{j,i}\right\} \tag{4}
$$

A detailed description of this method can be found in [6].

2.2 The influence of distributed PV and storage

The maximum load ratio of a transformer is closely related to rated capacity and the power transmission capacity of power lines or feeders. When there is no distributed generators, a transformer receives electric power from the upper-level power grid. As long as the premise that the upper-level power supply is sufficient, the capacity of each transformer and the tie-line capacity determine the maximum load. That is to say, the distribution network can satisfy changing load under the premise of "N-1" security.

Distributed PV gives intermittent output, for example, the output at night is generally close to zero. As a result, distributed PV system cannot supply end load alone, or it is understood that the distributed PV system does not meet "N-0" security, and be out of the question of N-1" security. In the framework of ref [6], the maximum load ratio of distributed PV system is zero. This handle method will seriously underestimate the importance of distributed PV to distribution grid. In fact, the power load is not a constant value. No matter in day period or in year period, there are peak load and valley load. What's more, the output of PV reaches it maximum value at noon and the load demand also reach a peak at noon [12]. In addition, with a small capacity of storage the power supply reliability can be greatly improved. Therefore, this paper will make a detail analyses on the maximum load ratio when there are distributed PV and storage in distribution grid.

3. CALCULATION METHOD OF THE MAXIMUM LOAD RATIO OF TRANSFORMERS

3.1 Simplification of the distributed PV and storage

If the distributed PV system is equivalent to a special transformer, the method in [6] can be used to calculate the maximum load ratio of the transformer. Under this assumption, the special transformer is connected to the main transformer located in other substations with tie-line, as shown in Fig. 1. The distributed PV system does not directly supply any load, but only transmits the uncertainty power generated by the PV system to the 2 main transformers of the substation numbered 1 through the tie-line. That is to say, the capacity of the distributed PV system itself is zero, but the capacity of other transformers is increased by the joint operation. The maximum load ratio matrix $\boldsymbol{T'}$ is obtained:

$$
\boldsymbol{T}'=\begin{bmatrix} T'_{1,1} & \cdots & T'_{1,j} & \cdots & T'_{1,N_\Sigma} & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ T'_{i,1} & \cdots & T'_{i,j} & \cdots & T'_{i,N_\Sigma} & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ T'_{N_\Sigma,1} & \cdots & T'_{N_\Sigma,j} & \cdots & T'_{N_\Sigma,N_\Sigma} & 0 \\ 0 & \cdots & 0 & \cdots & 0 & 0 \end{bmatrix} \tag{5}
$$

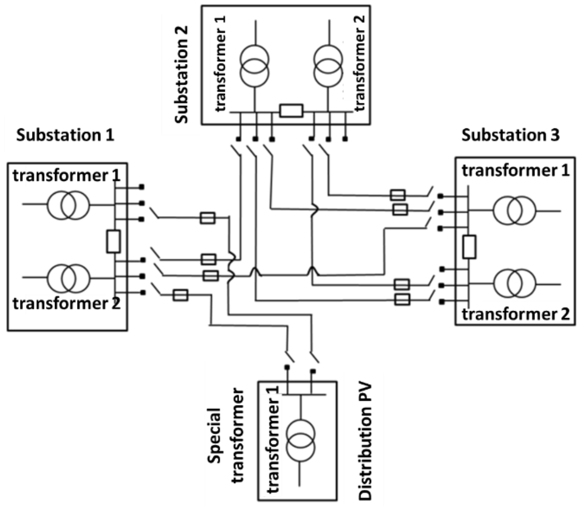

Fig.1 Schematic diagram of equivalent distributed PV system

Before the integration of distributed PV to the power distribution, the maximum load ratio of the transformer is T_0. If any transformer fails during the annual peak load day, the load may be equal to the rated capacity of the transformer, as shown in Fig. 2. The red line is the time-series load curve, and the blue line represents available capacity, with a constant value, of the original power distribution system. After integration of the distributed PV system as shown in Fig. 1, the available capacity of the distribution system occurring above fault will be the green curve. The curve is the combination of constant capacity of the original power distribution system with the uncertainty output of distributed PV. The green curve shows the excellent nature of distributed PV output as "golden power". In a word, it can increase the total load supply compared to the original distribution system.

When the system operator realizes the potential power supply capability, the load of the original power distribution system will be increased to the purple curve in Fig 2. As the uncertainty of PV output, the PV equipment may output unideal power in the peak load period of a year. At this situation, the available capacity of the system is shown as the black curve in Fig.2 and some power demand will not be satisfied. The distributed PV system has a probabilistic effect on the improvement of the maximum load ratio of transformers. A statistic result can be obtained by simulation. To reduce the unserved energy, some storage may make a big difference. The storage system as a backup can compensate the power supply shortage and it is also a probabilistic improvement on the power supply capability.

In order to quantify the improved effect of distributed PV and energy storage on the maximum load ratio of transformer, this paper defines the following indicators for possible power shortages.

$$IN = \frac{\sum_{i=1}^{N_{simu}} \sum_{j=1}^{8760} N_{ush}(i,j)}{8760 * N_{simu}} \tag{6}$$

Among which, N_{simu} is the total simulation year number, $N_{\text{ush}(i,j)}$ represents the condition of the lack of power supply in the jth hour of the ith year. If there is a power shortage, $N_{\text{ush}(i,j)}=1$, otherwise $N_{\text{ush}(i,j)}=0$. It should be emphasized that the physical meaning of the above indicators is a reliability statistic when a main transformer is out service. It is different from the commonly used power supply reliability index.

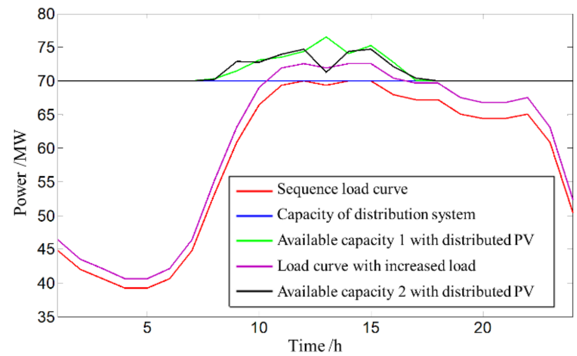

Fig.2 Distributed PV and storage could improve the power supply capability

3.2 Maximum load ratio of the transformer

The maximum load ratio of the transformer can be calculated by three steps. (1) Choosing the ith connection unit in the main transformer connection matrix and assuming that the ith transformer is out of service, the initial value of the load could be supplied in ith connection unit can be estimated, that is, the sum of the rated capacity of the remaining transformers, denoted as L_0. (2) Increasing the load with a small step ΔL on the basis of L_0, calculate the IN index by simulation. (3) According to the setted lower limit of the false power supply reliability rate (1-IN , such as 99.5%), determine the available load limit of the ith contact is L_{ex}.

Each row in the maximum load ratio matrix $\boldsymbol{T'}$ can be got by repeating above process. According to "N-1" security requirement, each main transformer is out of operation in turn, the statistical IN index is used to determine the maximum load ratio of the transformer of each main transformer connection unit.

4. CASE STUDY

4.1 Simulation and analysis of distributed PV and energy storage systems

A distribution network is shown as Fig. 1. The transformer capacity values are shown in Table 1. Taking the connection unit centered with main transformer numbered 1 as an example, the statistical results of the index *IN* when *E*=0, and *E*=0.2*G* are shown in Fig. 3 and Fig. 4. It should be noted that the abscissa is the ratio of the increased load to the distributed PV capacity, short for load capacity ratio.

Table 1 The detail parameters of all substations

Substation	Voltage /kV	Rated capacity/(MVA)
1	35	2×20
2	35	2×20
3	110	2×31.5

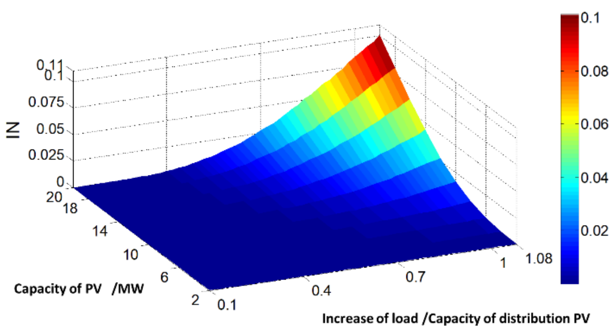

Fig.3 The statistical results of index IN with *E*=0

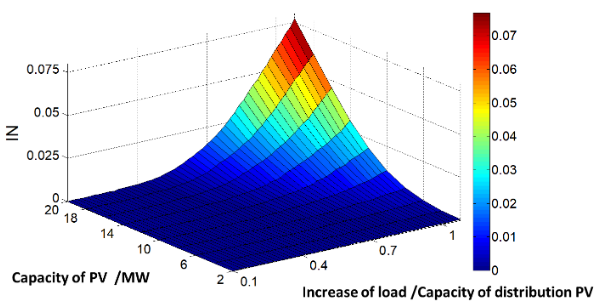

Fig.4 The statistical results of index IN with *E*=0.2*G*

Followings can be found. When the PV capacity is relatively small, even if the load capacity ratio is larger than 1, the reliability of the power supply is bigger than 99.9%. When the PV capacity is relatively large, the reliability of the power supply has dropped below 99.0%.

4.2 Maximum load ratio of transformer

According to the simulation method in Section 3, under the premise of *G*=10 and *E*=0.2*G*, the maximum load ratio matrix $\boldsymbol{T'}_{100\%}$ and $\boldsymbol{T'}_{99.5\%}$ can be achieved, representing that the false power supply reliability ratio values are 100% and 99.5% respectively. $\boldsymbol{T'}_{100\%}$ is equivalent to a load ratio matrix that strictly satisfies the "N-1" principle in [5], and $\boldsymbol{T'}_{99.5\%}$ is a reference index for system planners.

The maximum load ratio of each transformer is:

$$\boldsymbol{T}_{(N-1)100\%} = [T_{1(N-1)}, T_{2(N-1)}, T_{3(N-1)}, T_{4(N-1)}, T_{5(N-1)}, T_{6(N-1)}] \\ = [0.54 \quad 0.54 \quad 0.7194 \quad 0.7194 \quad 0.7194 \quad 0.7194]$$

$$\boldsymbol{T}_{(N-1)99.5\%} = [T_{1(N-1)}, T_{2(N-1)}, T_{3(N-1)}, T_{4(N-1)}, T_{5(N-1)}, T_{6(N-1)}] \\ = [0.63 \quad 0.63 \quad 0.7738 \quad 0.7738 \quad 0.7738 \quad 0.7738]$$

The maximum load ratio is higher than that in [6]

$$\boldsymbol{T}_{(N-1)} = [T_{1(N-1)}, T_{2(N-1)}, T_{3(N-1)}, T_{4(N-1)}, T_{5(N-1)}, T_{6(N-1)}] \\ = [0.5, 0.5, 0.69, 0.69, 0.69, 0.69].$$

5. CONCLUSION

An improved calculation method of the maximum load ratio of transformer is proposed. The method is with several unique features. (1) Distributed PV and storage are handled as a special transformer. (2) False power supply reliability rate index is defined to analyze the probabilistic effect of the distributed PV and energy storage. According to the analysis results, distributed PV and storage can improve the load ratio of traditional transformers. If this potential is completely ignored, the value of distributed PV cannot be reflected properly.

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