Load Distribution Constraints Based Power Supply Capacity Calculation for a Distribution Network

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Abstract. Starting from the application purpose of real distribution network planning, for the high-voltage distribution network connected by medium-voltage tie lines, the power supply capacity is predicted according to current feeder loads and their changing trends, so that the results are more realistic. Based on the above calculation process, the weakness of a distribution network can be identified intuitively and conveniently, which can be used as the basis for generating the measures or schemes to improve power supply capacities. Numerical examples show that the presented model and method are intuitive, simple, and stable and effective compared with the existing methods, and are convenient for application in practice.

1. Introduction
The total supply capability (TSC) of a distribution network generally refers to the total load supply capacity of the distribution network to meet the “N−1” safety criterion in a certain power supply area. At present, most of the methods for calculating the power supply capacity of a distribution network is to obtain the ideal load distribution based on a network structure and element capacities under the condition of unknown loads or incremental loads[1~3]. Among them, Reference [1] is to calculate the maximum power supply load of a distribution network with the element capacity constraints being satisfies under the condition of unknown loads. References [2, 3] consider the existing load distribution but residue supply capability (i.e. the incremental power supply capacity) is obtained under the condition that incremental loads are unknown. It is noteworthy that the ideal load distribution resulting from the above-mentioned references probably will not happen in practice. This is because the loads of a distribution network are those of feeders or feeder sections, which cannot be adjusted arbitrarily according to the optimization result of power supply capacity. Moreover, loads need to be connected to a nearby feeder [4], so it is unrealistic to adjust the load distribution between
feeders or feeder sections on a large scale. Therefore, for a definite load distribution, only the local adjustment of loads between feeders or feeder sections [3, 4] and the connection modes between main transformers [4] can be adjusted or optimized.

Aiming at engineering application, in this paper two kinds of power supply capacity (i.e. safe power supply capacity and quasi-safe power supply capacity) are defined for the calculation of power supply capacity of a distribution network, which can take into account the normal maximum power supply load for the local network which does not meet the "N-1" in a network structure. A method is proposed for calculating the power supply capacity based on current load distribution and its growth characteristics, so that the results are more realistic. Examples show that the presented model and method are intuitive, simple and practical.

2. Calculation Model of Power Supply Capacity

With the load transfer between in-stations and inter-stations being considered, the calculation of power supply capacity involves the capacity and the number of main transformers, the tie-connection modes between main transformers, the current loading of feeders and their changing trends. For the "N-1" safety need of feeders, their power supply outage is the most serious and thus only the main transformer need to be considered for the safety check. Therefore, with the maximum total load of feeders as the target, the calculation model of power supply capability can be expressed as

\[
\begin{align*}
\max f_t &= \sum_{l \in N_l} S_l \\
\text{s.t.} & \quad \sum_{l \in N_l} S_l + \sum_{j \in N_j} S_l \tau_f \leq S_{N_{i,j}}, j \in N_f, k \in N_{j TT} \\
& \quad S_{c,l} \leq S_{c,j}, \quad l \in N_{c,l}, l' \in N_{c,j}, l \text{ can be supplied through } l' \\
& \quad S_l = S_{0,l} + \Delta S_l, \quad l \in N_l
\end{align*}
\]

(1)

Where \( S_{N_{i,j}} \) is the rated capacity of main transformer \( j \), \( N_i \) and \( N_L \) are the sets of all main transformer numbers and feeder numbers, \( N_{j TT} \) is the number set of the transformers that are directly connected with main transformer \( j \), \( N_{j TL} \) is the number set of the feeders from main transformer \( j \), \( N_{j TL} \) is the number set of the feeders that are transferred to main transformer \( j \) when main transformer \( k \) is out of service, \( S_{0,l} \), \( \Delta S_l \). And \( S_l \) are respectively the current load power, load power variation and total load power of feeder \( l \).

3. Calculation Method of Power Supply Capacity

3.1. Annual Load Forecasting Based Method

If the annual load forecasting results of feeders in formula (1) are known, the "N-1" check of main transformer outage can be carried out year by year until the capacity of any main transformer or feeder is violated, and the corresponding maximum allowable load power of substations is the overall power supply capacity.

3.2. Equal Load Growth Rate Based Method

Load forecasting involves many factors so that it is difficult to predict loads accurately. In the absence of accurate load forecasting results, if the current load distribution of a feeder is known, the power supply capacity can be estimated according to the changing trend of feeder load, which is presupposed by experience. For the calculation of power supply capacity under the condition of equal load growth rate, the specific method is as follows.
4. Computational Model
Assuming that the load of each feeder increases with the same load growth rate, model (1) can be changed to the following model.

\[
\begin{align*}
\max \gamma & \\
\sum_{i \in N_j^T} S_i + \sum_{i \in N_j^T} S_i \tau_i & \leq S_{i,j}^T, \quad j \in N_t, k \in N_j^T \\
S_i + S_i \tau_i & \leq S_{c,i}, \quad l \in N_j^T, l' \in N_j^T, \ l \text{ can be supplied through } l' \\
S_i & = \eta_{0,l} S_{c,i}, \quad l \in N_l
\end{align*}
\]

(2)

Where \(\gamma\) the proportional is factor of load variation of feeders and \(\eta_{0,l}\) is the current load rate of feeder \(l\).

5. Calculation Method
According to (2), the sum of the loads for all feeders of main transformer \(j\) and all feeder loads transferred to main transformer \(j\) through tie lines after the outage of main transformer \(k\) is not allowed to be greater than the capacity of main transformer \(j\). The sum of the load for any feeder of main transformer \(j\) and the load transferred to the feeder through the tie-line after the outage of main transformer \(k\) is not allowed to be greater than the capacity of the feeder. Therefore, for the outage of main transformer \(k\), the maximum allowable proportional factor needs satisfy the following expression.

\[
\begin{align*}
\gamma_{j,k} \left[ \sum_{i \in N_j^T} (\eta_{0,i} S_{c,i}) + \sum_{i \in N_j^T} (\eta_{0,i} S_{c,i}) \tau_i \right] & \leq S_{n,i}^T \\
\gamma_{j,k} (\eta_{0,i} S_{c,i} + \eta_{0,i} S_{c,i} \tau_i) & \leq S_{c,i}
\end{align*}
\]

(3)

Where \(\gamma_{j,k}\) is the proportion factor to meet the capacity constraints of related equipment when main transformer \(k\) transfers loads to main transformer \(j\) and corresponding feeders through the tie line after the main transformer \(k\) is out of operation. When the current load satisfies the "N-1" safety criterion, \(\gamma_{j,k} \geq 1\).

From (3)

\[
\gamma_{j,k} = \min \left\{ \frac{S_{n,i}^T}{\sum_{i \in N_j^T} (\eta_{0,i} S_{c,i}) + \sum_{i \in N_j^T} (\eta_{0,i} S_{c,i}) \tau_i} \right\}
\]

(4)

Where

\[
\gamma_{j,k}^L = \min \left\{ \frac{S_{c,i}}{\eta_{0,i} S_{c,i} + \eta_{0,i} S_{c,i} \tau_i} \right\}
\]

(5)

Considering all the main transformers and the main transformers connected with one of them, \(\gamma_{j,k}\) of different main transformers is obtained and its minimum value is taken, which is the maximum allowable growth rate of feeder load variation, as shown in (5).
\[ \gamma_{\text{max}} = \min_{j \in N_i} \left\{ \min_{k \in N_j} \{ \gamma_{j,k} \} \right\} \]  
\[ (5) \]

The power supply capacity of substation \( i \) can be expressed as

\[ C_{\text{Sub},i} = \gamma_{\text{max}} \sum_{j \in N_i} \sum_{l \in N_j} \eta_{h,l} S_{C,l} \]  
\[ (6) \]

Where \( C_{\text{Sub},i} \) is the power supply of substation \( i \), \( N_{T,j} \) is the number set of the main transformers for substation \( i \).

6. Calculation Steps

1. Let \( M_T = N_T \) and \( M_T^{\text{TT}} = \emptyset \);
2. Let \( j \) be an element in \( M_T \);
3. Let \( j \) be an element in \( M_T^{\text{TT}} \) and calculate \( \gamma_{j,k} \) according to formula (4);
4. Delete \( k \) from \( M_{T,TT} \), and if \( M_{T,TT} \) is not an empty set, go back to step 2;
5. Delete \( j \) from \( M_T \), and if \( M_T \) is not an empty set, go back to step 1;
6. Calculate and output \( \gamma_{\text{max}} \) according to formula (5).

7. Selection of Improvement Schemes

In order to guide the distribution network planning, the calculation of power supply capacity can be used as the basis for analysis. Through analyzing the weak network links for power supply capacity, the planning scheme that can improve power supply capacity can be found. For a certain load change mode, the improvement scheme selection of power supply capacity can be expressed as follows.

\[ \max f_{c,i} = \max_{k \in \Omega_{i,i}} \{ C_{i,k} \} \]  
\[ (7) \]

Where \( C_{i,k} \) is the power supply capacity corresponding to the \( k \)-th improvement scheme of power supply capacity under the load change mode \( i \), \( \Omega_{i,i} \) is the number set of the improvement schemes under load change mode \( i \).

8. Examples

In order to perform the result comparison, the example of Reference [3] is used.

8.1. Reference Example and Its Adjustment

9. Reference Example

The network structure of the used reference example is shown in Figure 1.
In Figure 1, there are two substations, four main transformers, 20 10-kV feeders of JKLYJ-185, with a maximum capacity of 11.30 MVA, 20 feeder outlet switches numbered 1~20, 11 tie-connection switches numbered 100-110, two segmented switches numbered 000 and 001. The 20 feeders or feeder segments are numbered as 1~20, and their load values are shown in Reference [2] (The total load is 88.97MVA). For each of the four main transformers, the ratio is 35kV/10kV and the capacity is 40MVA.

10. Adjustment of Reference Example
Considering that the calculation method of power supply capacity in this paper is based on the fact that the current power grid meets the "N-1" safety criterion and that the power grid for the example in Reference [2] does not meet the "N-1" safety criterion (for example, when main transformer 3 or 4 is out of operation, the load of feeder 6 will exceed its capacity), load S21 and S22 are deleted in this paper from the original examples, the corresponding total load is 81.73 MVA, and the current load distribution and line loading rates are shown in Table 1.

### Table 1. Current load distribution without the S21 and S22 of Reference [2]

| Feeder /Feeder Section No. | Load /MA | Current Load Rate | Max Safe Load Rate | Feeder /Feeder Section No. | Load /MA | Current Load Rate | Max Safe Load Rate | Feeder /Feeder Section No. | Load /MA | Current Load Rate | Max Safe Load Rate |
|----------------------------|----------|------------------|-------------------|----------------------------|----------|------------------|-------------------|----------------------------|----------|------------------|-------------------|
| 1                          | 3.04     | 0.27             | 0.50              | 8                          | 3.84     | 0.340            | 0.50              | 15                         | 3.42     | 0.303            | 0.50              |
| 2                          | 1.01     | 0.09             | 0.40              | 9                          | 4.13     | 0.365            | 0.50              | 16                         | 6.77     | 0.599            | 0.60              |
| 3                          | 5.98     | 0.529            | 0.53              | 10                         | 4.50     | 0.398            | 0.47              | 17                         | 3.46     | 0.306            | 0.50              |
| 4                          | 4.10     | 0.363            | 0.50              | 11                         | 3.45     | 0.305            | 0.50              | 18                         | 3.68     | 0.326            | 0.50              |
| 5                          | 4.65     | 0.412            | 0.50              | 12                         | 4.77     | 0.422            | 0.50              | 19                         | 5.07     | 0.449            | 0.50              |
| 6                          | 3.19     | 0.282            | 0.50              | 13                         | 3.77     | 0.334            | 0.50              | 20                         | 4.77     | 0.422            | 0.50              |
| 7                          | 3.32     | 0.294            | 0.50              | 14                         | 4.81     | 0.426            | 0.50              | Total                       | 87.13    |                  | /                  |

10.1. Calculation and Analysis of Power Supply Capacity
Based on the equal load growth rate based method of power supply capacity, the maximum allowable load ratio factor \( \gamma_{\text{max}} \) is 1.07824, the power supply capacity \( C_{\text{Sub,A}} \) and \( C_{\text{Sub,B}} \) of substation A and B are 40.714 MVA and 47.418 MVA respectively, and the corresponding power supply capacity is 88.132 MVA.
10.2. Optimization of Power Supply Capacity

11. Line Load Balancing Measures
As indicated above feeder 3 and 16 are of relatively heavy loads. Based on the principle of uniform load distribution and nearest transfer, 2MVA load of feeder 3 is transferred to adjacent feeder 2, and 2MVA load of feeder 16 is transferred to adjacent feeder 2 and feeder 17. The load distribution and line load rates after load adjustment are shown in Table 2.

Table 2 Load distribution with the feeder loads being adjusted

| Feeder Sector No. | Load /MV A | Current Load Rate | Max Safe Load Rate |
|------------------|------------|-------------------|--------------------|
| Feeder Sector No. | Load /MV A | Current Load Rate | Max Safe Load Rate |
| 1                | 3.04       | 0.27              | 0.50               |
| 2                | 4.01       | 0.35              | 0.50               |
| 3                | 3.98       | 0.35              | 0.50               |
| 4                | 4.10       | 0.36              | 0.50               |
| 5                | 4.65       | 0.41              | 0.50               |
| 6                | 3.19       | 0.28              | 0.50               |
| 7                | 3.32       | 0.29              | 0.50               |

12. Transformer Load Balancing Measures
According to Reference [4], the fewer the tie-lines between two main transformers are, the larger the maximum safe load rates of a main transformer and the larger the power supply capacity is. In this example, each main transformer is of five outgoing lines, while the total number of main transformers is four, so that the number of tie-connection lines between two main transformers may be set to 1 or 2. After the adjustment, the maximum number of tie-connection lines between two main transformers is 2 and the minimum number is 1, as shown in the network topology of Figure 2.

Figure 2. Schematic diagram of the distribution network with the tie-connection being adjusted

13. Calculation and analysis of power supply capacity
After using the above-mentioned load balancing measures, according to the equal load growth rate based calculation method, the maximum load ratio factor \( \gamma_{max} \) is 1.22, the safe power supply capacity \( C_{Sub,A} \) and \( C_{Sub,B} \) of substation A and B are respectively 47.29 MVA and 52.42 MVA. The safe power supply capacity is increased from 88.132 MVA to 99.71 MVA.
13.1. Comparisons and Analysis of Examples
In Reference [2] and [3] the power supply capacity of a distribution network is calculated with a known current load distribution, but the reasonable load growth trend is neglected. In this paper, the calculation of power supply capacity is based on the reasonable load distribution and changing trend, and the optimization of power supply capacity is also based on practical and feasible measures. So that the results are in line with the reality and have more practical guiding significance.

13.2. Conclusion and Discussion
Based on the idea of using simple methods to solve large-scale complex problems, a practical model and method is proposed for calculating the power supply capacity of a distribution network. The main conclusions are as follows.

(1) The power supply capacity can be obtained according to the existing load distribution and its changing trend, instead of the ideal feeder load with the load or incremental load distribution is unknown.
(2) Example shows that load balancing measures can significantly improve the power supply capacity of a distribution network. Among them, line and transformer load balancing measures can make full use of feeder capacity and main transformer capacity respectively.
(3) Different from the existing calculation methods of power supply capacity, the proposed model and method are more realistic, intuitive, simple, fast, stable and effective, and easy to be applied in practical projects. As long as the basic ideas and methods of this paper are mastered, planners can use simple computing tools or even only rely on manual to complete this specific work.

References
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