The impact of load transfer on transmission and distribution costs

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Abstract. This article analyses the impact of the load transfer on the transmission and distribution costs from the N-1 security check of the distribution network and the total supply capacity, and proposes a capacity expansion planning model for the distribution network to obtain the best investment time for the generator, and then further studies the impact on the cost of transmission and distribution after the expansion of the distribution network.

1. Introduction
Load transfer means that when a fault occurs, the load on the faulty main transformer or feeder can be transferred to its directly connected main transformer or feeder through a switch action. This process is related to the maximum power supply capacity. Total supply capacity (TSC) is an important index to evaluate the distribution network. Similar to the total transfer capacity (TTC) of the power transmission system, the total supply capacity of the grid refers to the maximum load supply capacity under the conditions of the N-1 criteria and the actual operation constraints of the distribution network in a certain power supply area [1].

After considering the load transfer, total supply capacity will change, which will have a certain impact on the transmission and distribution costs. Therefore, an effective analysis of this part of the cost should be carried out.

In the literature [2], the boundary of distribution system security region (DSSR) is observed. Literature [3, 4] proposes an analytical calculation method for the power supply capacity based on the interconnection relationship between the main transformers of the substation, taking the N-1 criteria of the main transformer into account. Literature [5] established a rigorous mathematical model for total supply capacity, modeling TSC as a linear programming problem, and able to find the optimal solution of the problem space. Literature [6] proposed a long-term incremental cost model of transmission, which determines the best investment time by comparing the balance point of the annual congestion cost and the investment cost curve.

The above literature does not consider the impact of TSC on the operating cost of the distribution network and the investment decision-making issues that result from it. Thus, this paper considers the load transfer, and analyzes the safety cost of the distribution network in order to meet the N-1 security check and the optimal investment time of the generator through the TSC model and the expansion planning model of the distribution network, which is conducive to the long-term economic and stable operation of the distribution network.
2. N-1 Security check of distribution network

The N-1 criteria is an important criterion in the planning and operation of the distribution system. It requires that when the distribution network is in operation and an independent element in the distribution network, such as the main transformer, feeder, etc., fails, there will be no power outages that should not be occurred to users. There are mainly two types of N-1 security check: main transformer N-1 and feeder N-1.

Main transformer N-1 means that under a given load condition, when a main transformer fails, the load can be carried out through the tie line inside or outside the station under the premise of meeting other main transformer capacity constraints and feeder capacity constraints. The main transformer N-1 needs to follow the following principles:

1) Priority is given to the main transformers in the same substation for transfer. For substations containing more than two main transformers, priority is given to the main transformer with a large load margin for transfer.

2) If the main transformer inside the station fails to transfer successfully, the load transfer will be performed outside the station. Among them, feeders with low load outside the station are given priority to transfer, and the transfer rules adopt the feeder N-1 criteria.

3) For loads directly connected to the bus (such as radial feeder loads), they can only be transferred through the main transformer in the station.

Feeder N-1 is to examine whether a fault occurs at any position of the feeder, whether the fault can be isolated, and the load that needs to be restored to supply power can be transferred to other connected feeders. The feeder outlet failure is the most serious situation. Due to the large scale of the distribution network, the N-1 security check of the entire network in the planning is often only for the feeder outlet failure. When performing N-1 security check on a certain feeder, the load carried by each feeder after the transfer should be less than its own feeder capacity.

3. TSC model

Total supply capacity of the distribution network is defined as the maximum load that the distribution network can carry when the feeder N-1 security check and the substation main transformer N-1 security check are satisfied. N-1 security check should consider the actual operation constraints of the distribution network such as the load transfer between the main transformers and feeders, the connection relationship between the main transformers and feeders in the network, the capacity of the main transformers and feeders, and the overload coefficient of the main transformers. In the calculation process of the TSC model, in addition to the overall TSC of the distribution network, it also needs to calculate the load distribution of each main transformer and feeder when the TSC is reached.

3.1. Power distribution system security domain

The Distribution System Security Region (DSSR) refers to the collection of all operating points where the distribution network can operate safely and stably under the constraints of the main transformer N-1 and feeder N-1 of the distribution network. In the distribution system, the operating point refers to the collection of all state quantities at a certain moment in the distribution network, which is represented by the load carried by the main transformer. The working point can be expressed as an n-dimensional vector:

\[ T = (T_1, T_2, \ldots, T_n)^T \]  

Where \( T \) represents the working point vector based on the main transformer load, and \( T_i \) represents the load carried by the i-th main transformer.

After the load transfer is completed, it is necessary to ensure that all main transformers are not overloaded. In the model of the security domain of the distribution system, the load transfer is also affected by the capacity of the tie line. In the operation of the distribution network, the main transformer load is subject to the above-mentioned series of constraints. These constraints determine
the security domain boundary of the distribution system. Therefore, the model of the security domain of the distribution system can be expressed as:

$$\Omega_{\text{DSSR}} = \left\{ \begin{array}{l}
P_i = \sum_{F_m \in T_i} F_m (\forall i) \\
tr_{ty} = \sum_{F_m \in T_i} trF_{mk} \\
trF_{mk} + F_k \leq RF_k(m) (\forall m, k) \\
tr_{ty} + P_j \leq R_j (\forall i, j)
\end{array} \right. \quad (2)$$

In the formula, $F_m$ represents the feeder outlet load carried by the $m$ feeder; $trF_{mk}$ represents the load transferred to the feeder $k$ when the N-1 fault occurs on the feeder $m$, $P_i$ represents the load carried by the main transformer $i$; $tr_{ty}$ represents when the main transformer $i$ occurs N-1 The load transferred to the main transformer $j$ when a fault occurs; $F_m \in T_i$ means that the feeder $m$ is out of the autonomous variable $i$, $T_i$ means the main transformer $i$; $RF_k(m)$ is the capacity of the feeder $k$, which also reflects the difference between the feeder $m$ and the feeder $k$. There is a transfer relationship between; $R_j$ represents the rated capacity of the main transformer $j$.

In the security domain model of the distribution system as described above, Equation 1 is the equation constraint between the main transformer and the feeder, which shows that the sum of the feeder load of the autonomous transformer $i$ is equal to the load carried by the primary transformer $i$; Equation 2 When the main transformer N-1 fault occurs, the feeder load is transferred to the equation constraint, which means that when the main transformer $i$ is out of operation due to a fault or overhaul, the load transferred to the main transformer $j$ when a fault occurs; $F_m \in T_i$ means that the feeder $m$ is out of the autonomous variable $i$, $T_i$ means the main transformer $i$; $RF_k(m)$ is the capacity of the feeder $k$, which also reflects the difference between the feeder $m$ and the feeder $k$. There is a transfer relationship between; $R_j$ represents the rated capacity of the main transformer $j$.

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In the above model, the left side of each inequality represents the load of feeder $i$; the right side of the inequality $RF_{u}^{(1)} - F_u$ is the N-1 constraint condition of the line, $R_u = \sum_{F_m \in T_i} F_m - \sum_{F_m \in T_i} F_m$ is the N-1 constraint condition of the main transformer. Taking the minimum of them can make the load on the feeder meet the constraints of the feeder N-1 and the main transformer N-1.

Each inequality in the DSSR model is equivalent to a safety boundary in the load space. The safety domain of the distribution network is surrounded by the hyperplane of n feeder section loads. The intersection of n inequalities forms the boundary of the safety domain.

### 3.2. TSC model based on main transformer interconnection

After comprehensively considering the faults of the main transformer N-1 and the feeder N-1, the TSC model based on the main transformer interconnection is established.
The objective function is:

$$\text{max} \ TSC = \sum_i P_t$$

(4)

The constraints are:

$$P_t = \sum_{i \in c_{ij}} F_m (\forall i)$$

$$tr_t \leq \sum_{m \in c_{ij}} trF_{mk}$$

$$trF_{mk} + F_i \leq RF_{k}^{(m)} (\forall m, k)$$

$$tr_{ij} + P_j \leq R_j (\forall i, j)$$

(5)

Among these constraints, the first equation is main transformer-feeder load constraint; the second equation is main transformer-feeder load transfer constraint; the third inequality is feeder N-1 constraint and the last inequality is main transformer N-1 constrain.

The above model considers the long-term operation after a fault. When the main transformer fails, the automatic switch-on of the substation will start first. The main transformer has short-term overload capacity, and the shorter the time, the stronger the overload capacity. After the realization of distribution automation under the background of smart grid, the medium voltage distribution network has the ability to realize faster load transfer, and the main transformer overload time will be greatly shortened. At this time, the non-faulty main transformer of the same substation will be able to accept the full load of the failed main transformer and the value of the overload coefficient $k$ will not affect the TSC calculated by the model.

3.3. Distribution network expansion planning model

Total supply capacity of the distribution network will be affected by factors such as network structure, transformer capacity, line capacity, etc. Therefore, this section will establish a capacity expansion planning model for the distribution network [7]. The main idea is to increase the maximum power supply capacity and reduce the operation cost of distribution network by connecting wind turbines under the constraints of transformer capacity and line capacity.

In the actual investment year $t$, the current value of the future investment cost of wind turbines in the distribution network is:

$$C_{now} = \frac{C_{Asset}}{(1+d)^t}$$

(6)

In the formula, $C_{Asset}$ is the investment equivalent cost of the wind turbine.

If the expansion plan of the distribution network is not carried out, the power supply capacity of the distribution network will be restricted by total supply capacity. With the increase of residential electricity load, lines and transformers also need to operate beyond the safe power supply range of the distribution network during peak load times. The current value of the short-term over-limit cost resulting from this is:

$$C_s = \frac{\sum P_r \times c \times T}{(1+d)^t}$$

(7)

In the formula, $P_r$ is the over-limit part of the power that exceeds total supply capacity of the distribution network, $c$ is the penalty price corresponding to the over-limit power, the price of this part will be higher than the general price level, $T$ is the time when the power supply capacity of the distribution network exceeds total supply capacity.

The actual investment time of the wind turbine generator should be the time corresponding to the present value $C_{now}$ of the future investment cost less than or equal to the present value $C_s$ of the short-term over-limit cost. The objective function of distribution network expansion planning model is:

$$\min t$$

(8)
The constraint is:

\[
\frac{C_{\text{load}}}{(1 + \delta)^t} \leq \frac{\sum P_e \times c \times T}{(1 + \delta)^t} \tag{9}
\]

4. Case analysis

The grid structure diagram of the calculation example is shown in Figure 1:

![Figure 1. Schematic diagram of calculation example.](image)

In the calculation example, there are 2 110kV substations and 16 10kV feeders. The total capacity of the substation is 80MVA, the rated capacity of each transformer is 20MVA, the total feeder capacity is 144MVA, and the capacity of all feeders is 9MVA.

4.1. Calculation of TSC

On the basis of the model established in 3.2, using Lingo software to solve it, the TSC is 58MVA and the average load rate of the transformer is 72.5%. The operating point when TSC is reached is \( T = [13.5, 13.5, 15.5, 15.5] \). When the TSC operating point is taken, the system is in a critical passing state, that is, the N-1 security check of the system is just in the critical state of passing and failing. If the feeder changes or the feeder adds a little more load, the system cannot pass the N-1 security check.

When reaching the TSC operating point, the load distributed by each feeder is shown in the following table:

| Feeder segment | Load(MVA) | Feeder segment | Load(MVA) |
|----------------|----------|----------------|----------|
| 1              | 2.5      | 9              | 6.5      |
| 2              | 4.5      | 10             | 4.5      |
| 3              | 4        | 11             | 0        |
| 4              | 2.5      | 12             | 4.5      |
| 5              | 6.5      | 13             | 4.5      |
| 6              | 0        | 14             | 0        |
| 7              | 4.5      | 15             | 4.5      |
| 8              | 2.5      | 16             | 6.5      |

Table 1 shows the load of each feeder outlet section when the substation reaches TSC. From the table, it can be seen that the load carried by feeders 6, 11, and 14 is 0. This is because the solution obtained by Lingo is a feasible distribution plan, but not unique.
Since the power system is composed of thousands of devices, from the perspective of reliability, there is bound to be a certain failure rate. In order to meet the load transfer constraints of the main transformer and feeder when N-1 fault occurs, the transformer cannot be fully loaded, and the remaining unused 22MVA capacity is equivalent to the capacity reserved for backup, thereby improving the stability of the system and the reliability of power supply. What this part of the capacity produces is the safety cost in the transmission cost, that is, the cost paid by the unit to ensure safety and the loss due to safety issues.

According to the analysis of the two-part electricity price, the capacity electricity fee is calculated according to the capacity of the transformer. Assuming that the capacity electricity price is 23 yuan/kVA \cdot month, after considering the load transfer once, the total safety cost of the calculation example is 6.072 million yuan per year.

Therefore, after considering the N-1 criteria that needs to be met for one transfer, the cost of transmission and distribution has increased due to safety requirements.

Consider connecting a generator at bus S1. This article does not consider the issue of time-of-use electricity prices for the time being. The on-grid electricity price for all periods is 0.38 yuan/kWh, and the penalty price for over-limit power in the distribution network is 1.5 times the on-grid electricity price, which is 0.57 yuan/kWh. Assuming that a 2MW generator set is invested in bus S1, the capacity cost is 2,800,000 yuan/MW, the unit installation cost is 600,000 yuan/MW, and the discount rate \( d = 6.5\% \).

According to formulas (9) and (10), it can be obtained from Figure 2 that the present value of the investment cost of generator decreases with the increase of year \( t \), while the present value of short-term over-limit cost increases with the increase of year \( t \). The intersection point of the two curves is 6.7 years.

![Figure 2. Curves of present value of investment cost and short-term over-limit cost.](image)

After 6.7 years of investment and access to a 2MW generator, assuming that the predicted output per unit of the generator is 1.574MW, the TSC obtained by Lingo software is 59.5743MVA, and the operating point when TSC is reached is \( T = [18.5743 \ 19 \ 12 \ 10] \). Total supply capacity of the distribution network has increased by 1.5743MVA, and the annual safety cost has been reduced to 5.6375 million yuan, which is 434,500 yuan less than before the installation of generator.
5. Conclusions

TSC is the maximum load supply capacity of the distribution network to meet the N-1 criteria, but the existing literature does not analyze the impact of TSC on the operating cost of the distribution network. To solve this problem, this paper studies the impact of load transfer and TSC on the cost of transmission and distribution. After considering the compliance with load transfer, total supply capacity of the distribution network will be reduced accordingly, and the distribution network needs to undertake a certain safety cost to meet the needs of N-1 security check. This part of the security cost is high, reaching 6.072 million yuan per year, so the expansion plan for the distribution network is considered.

This article then compares the present value of the future investment cost of the connected generator with the present value of the short-term over-limit cost, which will help to further determine the optimal investment time of the distribution network and minimize the cost. The results of test case show that the connection of generators increases the total supply capacity of the distribution network by about 3%. Under the premise of maintaining the safe and stable operation of the distribution network, it will reduce the safety cost and provide an effective reference for the optimal planning of the distribution network.

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