Research on power grid technical reform planning model based on overall cost constraint

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Abstract. For a long time, the technical reform of the power grid has improved or updated the existing power grid facilities to achieve the effect of low-cost and improved grid operation efficiency. In recent years, the development of power grid has entered a high-quality development stage, the technical reform of the power grid has been continuously improved. In the actual compilation, the grid technical reform plan usually uses historical data for qualitative analysis, which lacks quantitative optimization analysis considering power constraints and improvement indicators. Based on the power grid planning mathematical optimization model, this paper establishes a technical reform optimization model that comprehensively considers the power grid technical reform planning cost and load shedding cost, and uses the improved IEEE 30-node example to verify the model. The verification results show that the model can obtain the optimization of the technical reform route planning and can effectively guide the preparation of power grid technical reform planning, which has practical significance.

1. Introduction

In recent years, the development of power grids has altered from high-speed growth to high-quality development. Under this circumstance, the development trend of power grids has gradually changed from incremental development to stock improvement. Due to this, the power grid technical reform investment has a growing trend in the future.

Power grid planning is based on load forecasting and power source planning. Power grid plan determines when and where to build the transmission line and its type and circuits connection, in order to achieve the required transmission capacity during the planning period, and minimize the cost of transmission system on the premise of meeting various technical standard [1]. The technical reform of power grid refers to the improvement, support or overall renovation of existing old electrical equipment, facilities and supporting auxiliary facilities by using mature and applicable advanced technologies, equipment, processes and materials from home and abroad[2]. In recent years, foreign countries have paid more and more attention to the portion optimization of power grids. In the reference 3, the way of replacing transmission lines by gas pipelines has expanded and enhanced the reliability of energy transmission channels and enhanced the resilience of the system. Reference 4 identifies the critical loads of the power system, modeling and evaluating the line strength to improve the ability to supply heavy and negative loads in extreme weather. Reference 5 proposes a strategy for grid line reinforcement and intelligent control. Reference 6 uses the distribution network contact switch control method to improve the recovery capacity of the distribution network. In the reference 7, the distribution network is adjusted through the grid, and is decomposed into a plurality of microgrid-level small grids to achieve self-
healing effect. Reference 8 proposes a three-stage planning model that considers line reinforcement. However, there are few studies on the improvement of the operation effect by using power grid technical reform in China. The technical reform of the power grid usually proposes several given technical solutions based on the judgement of engineers and adopts the technical and economic comparison method to obtain the recommended scheme [9]-[15]. In general, the plan to participate in the comparison is proposed by the planner based on experience, and does not necessarily include the objective optimal plan. Therefore, the final recommendation plan contains quite subjective factors. Reference [10] links the technical reform of power grids with the reduction of line losses, and proposes measures to reduce line losses, but does not combine linear loss quantitative analysis with technical reform planning. Reference [11] proposed a method to use the line loss theory to guide the grid technical reform planning, focusing on the explanation of the workflow, but did not analyze the theoretical model of the technical reform planning.

Based on the advanced research results at home and abroad, this paper analyzes the principle of grid optimization mathematical optimization method, and characterizes the effect of grid technical reform by reducing the amount of system load shedding, establishes the grid technical reform planning model, and adopts the improved IEEE 30 node. The case analysis is proposed to verify the effectiveness of the model and provide reference for the practical use of the making the grid technical reform plan.

2. Power grid planning mathematical optimization model

The mathematical optimization method of power grid planning is to summarize the requirements of power grid planning into mathematical programming models in operations research, and then solve them through certain optimization algorithms to obtain the optimal planning scheme that satisfies the constraints. The mathematical optimization model of power grid planning mainly includes three elements: variables, constraints and objective functions:

(1) Variables. Variables have two types: decision variables and state variables. The decision variable indicates whether the transmission line is selected to join the network and is therefore an integer variable. It determines the topology of the planning network. State variables represent the operating state of the system, such as line flow, node voltage, and so on. State variables are generally real variables.

(2) Constraints. Constraints include construction condition constraints of decision variables, upper and lower bounds of each state variable, and constraint relationships that each variable should satisfy. At present, most power grid mathematical planning models consider constraints such as line overload and power flow equations.

(3) Objective function. The objective function is a function of decision variables and state variables, which mainly includes the investment cost and operating cost of the power transmission and transformation construction of the power grid. For long-term planning, the time value of various costs must also be considered. The goal of the plan should be to minimize the total discounted cost.

The objective function of the grid planning is usually shown in equation (1).

$$\min \left( \sum_{i \in N_g} C_i P_{Gi} + \sum_{j \in A} K_j Z_j \right)$$

During the equation, $C_i$ refers to the Node i issues a discounted charge for unit power power throughout the planning period; $P_{Gi}$ refers to the active power injected to the network by the generator in node i; $K_j$ refers to the investment cost of line j construction; $Z_j$ refers to the decision variables of line j construction when $Z_j = 1$ indicates that line j is selected for construction, when $Z_j = 0$ indicates that line j is not selected for construction; $N_g$ refers to the generator node set; $A$ refers to the set of lines to be selected.

The constraints of power grid planning usually include node power balance equation, line power flow equation and upper and lower bound constraints of each variable, and sometimes new constraints are added according to the difference of actual problems.
3. Grid technical reform planning optimization model

3.1 Objective function

The grid technical reform planning model is designed based on the mathematical optimization model of the power grid planning. To minimize the total cost of the planning period, the objective function is set as follows:

\[
\min \left( C_1 \sum_n P_n^c + C_2 \sum \pi_{ij} \right)
\]  

During the equation, \( C_1 \) refers to the load shedding penalty factor; \( C_2 \) refers to the cost of single line technical reform; \( P_n^c \) refers to the switching load of node \( n \); \( \pi_{ij} \) refers to the decision variable characterizing whether the line \( ij \) connecting node \( i \) and node \( j \) is technically reformed, if the technical transformation is carried out, it is 1 and vice versa.

3.2 Constraints

Considering the improvement effect of technical transformation on the reliability of power grid power supply, the selection of technical transformation planning scheme needs to select a balance point between the reliability improvement benefit of the power grid and the cost of power loss before the transformation. Therefore, in addition to the generator output and system power flow in the power system, the constraints of the model should also consider the total amount of technical transformation. The power constraints of the model include:

1. Generator power output constraint:

\[
g_g P_g \leq P_g \leq u_g P_g
\]  

During the equation, \( P_g \) refers to the reactive power output of generator \( g \); \( P_g \) and \( P_g \) refer to the minimum and maximum technical output of generator \( g \); \( u_g \) refers to the decision variable characterizing whether generator \( g \) is online. If generator \( g \) is online, it is 1 and vice versa.

2. Excision load power limit constraint:

\[
0 \leq P_n^c \leq P_n^d
\]  

Whereas \( P_n^d \) refers to the total load capacity of node \( n \).

3. Power flow limit constraint:

\[
P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}}
\]  

Whereas \( P_{ij} \) refers to the power flow of transmission line \( ij \). \( x_{ij} \) refers to the impedance of line \( ij \).

4. Line power constraint:

\[
P_g + \sum_{i \in \text{(n)}} P_{ij} - \sum_{i \in \text{(n)}} P_{ij} = P_n^d - P_n^c
\]  

During the equation, \( P_g \) refers to the active power output of generator \( g \); \( \sum_{i \in \text{(n)}} P_{ij} \) refers to the sum of the line powers flowing into node \( n \); \( \sum_{i \in \text{(n)}} P_{ij} \) refers to the sum of the line powers flowing out of node \( n \).

5. Technical reform capacity constraint:
\[-((1-\pi_{ij})\bar{P}_{ij} + \pi_{ij}\hat{P}_{ij}) \leq P_{ij} \leq (1-\pi_{ij})\bar{P}_{ij} + \pi_{ij}\hat{P}_{ij}\]  

(7)

Whereas $\bar{P}_{ij}$ refers to the power capacity of transmission line $ij$ before technical reform; $\hat{P}_{ij}$ refers to the power capacity after technical reform.

In addition, there is voltage phase angle constraint of node $n$:

$$\theta_n \leq \theta_n \leq \bar{\theta}_n$$  

(8)

Whereas $\theta_n$ and $\bar{\theta}_n$ refers to the lower and upper limits of the voltage phase angle of node $n$ respectively.

Limited by the regional grid network conditions, the number of grid technical transformations meet the following constraints:

$$\sum \pi_{ij} \leq M$$  

(9)

In the formula, $M$ is the maximum number of technical transformation lines.

4. Case analysis

4.1 Case introduction

The improved IEEE 30-node example is used to verify the power grid technical transformation planning model. In order to reflect the effectiveness of the technical transformation, the capacity of the line technology before and after the transformation is given. The specific parameters are shown in Table 1, where node type 1 is a PQ node, 2 is a PV node, and 3 is a balanced node. The generator parameters in the example are shown in Table 2.

| Node number | Node type | Node load (MW) | Node number | Node type | Node load (MW) |
|-------------|-----------|----------------|-------------|-----------|----------------|
| 1           | 3         | 0              | 16          | 1         | 7.5            |
| 2           | 2         | 21.7           | 17          | 1         | 9.1            |
| 3           | 1         | 12.4           | 18          | 1         | 14.6           |
| 4           | 1         | 7.6            | 19          | 1         | 9.5            |
| 5           | 1         | 3.6            | 20          | 1         | 9.2            |
| 6           | 1         | 4.5            | 21          | 1         | 17.5           |
| 7           | 1         | 12.8           | 22          | 2         | 2.5            |
| 8           | 1         | 20.4           | 23          | 2         | 4.2            |
| 9           | 1         | 6.8            | 24          | 1         | 8.7            |
| 10          | 1         | 5.8            | 25          | 1         | 10.4           |
| 11          | 1         | 7.6            | 26          | 1         | 3.1            |
| 12          | 1         | 11.2           | 27          | 2         | 6.5            |
| 13          | 2         | 8.6            | 28          | 1         | 6.5            |
| 14          | 1         | 6.9            | 29          | 1         | 2.4            |
| 15          | 1         | 8.2            | 30          | 1         | 6              |

Table 1. Parameter of IEEE 30 node study example

| Generator node | Minimum technical output (MW) | Maximum technical output (MW) |
|----------------|-------------------------------|-------------------------------|
| 1              | 30                            | 70                            |
| 2              | 30                            | 60                            |
| 13             | 10                            | 40                            |
4.2 Case calculation

When \( C_1 \) equals to 100 and \( C_2 \) equals to 300, That is, when the cutting load is greater than 3MW, it is considered that the technical transformation investment will reduce the overall system cost. If the value of \( C_2 \) is increased, the cost of the technical reform of a single line will be increased, indicating that the grid has a smaller tolerance for the allowable load shedding, correspondingly the cost is even greater.

Table 3 shows the results of sensitivity analysis of the technical reform line under this boundary condition.

| Amount of technical reform line | 3  | 5  | 7  | 8  | 9  |
|---------------------------------|----|----|----|----|----|
| Load cutting (MW)               | 30.99 | 18.9 | 11.84 | 5.79 | 0  |
| Total cost (ten thousand Yuan)  | 3998.7 | 3390 | 3284.4 | 2979.3 | 2700 |

It can be seen that in the case of the example, when the maximum number of technical reform lines is 3, the load shedding is 30.99 MW, and the cost is 39.987 million yuan. As the number of lines for technical transformation increases, the line is blocked. The load shedding is reduced and the overall cost is also reduced. When the capacity is 9, the load shedding can be completely avoided and the reliability of the power supply is greatly improved. The results of the example verify the validity of the model.

5. Conclusion

(1) Based on the optimization of the mathematical model of power grid planning, this paper designs the grid technical transformation planning model innovatively. The model is based on the power grid cut-off load cost and the technical transformation overall cost design objective function, and the constraints are set by parameters such as grid power and phase angle. It can reflect the quantitative coupling relationship between grid technical transformation and system operation indicators.

(2) The improved IEEE 30-node example is used to verify the design of the grid technical transformation planning model. The results of the example show that the optimal balance point between the grid technical transformation cost and the grid load-cutting cost can be obtained through this model. The selection of technical transformation points under the system power constraints is used to guide the preparation of the grid technical transformation plan.

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