Preliminary Analysis of Voltage Grade Optimization and Transformation for Medium Voltage Distribution

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Abstract

With the rapid development of China's science and technology and social economy, it becomes more difficult for 10kV medium voltage distribution network to meet load development requirement. For the long-term development of State Grid, it must adopt measures to optimize and transform the existing medium voltage distribution network. According to the actual situation of State Grid, the voltage grade optimization program was put forward for a medium voltage distribution network. Then the models were established to make a comparison between the optimization program and current voltage grade program from the perspective of power grid scale, investment cost, and floor area to get the best optimization program: 500/220/20/0.4kV. Finally, according to different local conditions, concrete transformation methods are proposed..

Keywords: 20kV, voltage sequence, medium voltage power distribution, optimization and transformation

1. Introduction

With the rapid growth of the electric load's density and the increase of power supply radius, the 10kV power supply voltage used commonly in China's medium voltage distribution network now faces some increasing difficulties to meet load development requirement; the existing mode of power supply has a lot of problems in many places, so it needs to be improved[1-2]. Therefore, it is necessary to strengthen the transformation of a medium voltage distribution network. Boosting and transformation of a medium voltage distribution network is a systematic project, and its reformation scheme and implementation measures need systematic argument. At the same time, boosting and transformation can save energy, reduce loss, improve power supply capacity and reduce occupation of the space; its function in the aspects of saving energy and reducing loss is the best now when compared with other energy-saving and loss reduction measures[3-5]. It is very important for the operation and development of power networks in China.

The boosting and transformation of a medium voltage distribution network should not only consider whether it meets the needs of the modern society, but also take the various external factors of the boosting and transformation into consideration. In the 1950's, many countries abroad had completed the medium voltage distribution voltage level optimization and transformation, which generally chose 20kV as the new medium voltage distribution voltage[6-8]. In order to rationally configure the voltage rank sequence of China's power network, the literature [9] studied the status of voltage level distribution of power network at home and abroad, it proposed the substation level should be simplified and voltage distribution voltage should be improved. The literature [10] analyzed the

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main factors which influence the allocation of the voltage sequence; studied from two aspects of technology and economy, it was proposed that it is a general trend of the development of power grid voltage to enhance medium distribution voltage, and 20kV is proposed as the medium voltage in some areas. The literature [11] analyzed the technical and economic characteristics of three medium distribution voltages: 10, 20, 35 kV.

It shows that the advantages of enhancing medium distribution voltage, and obtaining the 20kV voltage level has more advantages than the other two voltage levels. The experience of the world power development shows that the advantages of choosing 20kV as the medium voltage in the economy and technology are obvious[12] since it has over 50 years' operating experience in the world, and many developed countries have used 20kV as a medium voltage[13-14]. Therefore, this paper mainly studies the 20kV as medium distribution voltage, proposes different optimization schemes, establishes evaluation model and evaluates the optimization scheme and the existing power supply from three aspects of technology and economy: power grid scale, investment cost and floor area, to verify the rationality of 20kV as a new medium distribution voltage in China to obtain the optimal sequence levels of boosting and transformation. Finally, according to different local conditions, concrete transformation methods are proposed.

2. The Main Problems Needed to be Solved in the Process of Boosting and Transformation

After many years' planning and construction in China's urban and rural distribution network, now it is the best period of development in history. To transform the existing power supply mode, the following questions need to be considered:

1). The problem of space resource occupancy. With the increase of population density in city, the floor area that can be used are becoming less and less, so the boosting and transformation of medium distribution voltage must adapt to the available land resources.

2). Timing problem of boosting and transformation. It requires us to combine the operation time of the different power supply area equipment to find the optimal boosting and transformation time and make full use of the existing power supply equipment.

3). The problem of economic benefits. The boosting and transformation should consider the minimum cost of the transformation process, and the electricity price has little effect on customers' electricity consumption after the transformation [15].

3. Proposed Optimization Scheme and the Establishment of Assessment Model

3.1 Optimization Scheme

1) The advantages of choosing 20kV voltage

The materials and construction costs of 10~20kV overhead lines are only slightly higher than the cost of0.4kV lines of the same length, and it is about 1/10 of the 110kV lines. The dramatic differences in costs show it is economic to join the 10kV and 20kV medium voltage distribution network between the ultra high/high voltage and low voltage distribution networks; even taking the cost of HV/MV substation into account, it can also get the same conclusion[16]. However, the construction cost of 35kV lines has reached the 1/5~1/3 costs of the 110kV lines; compared with the 20kV, although the power supply ability has been improved in the equivalent load density range, it has no advantage in economy.

2) Concrete plan

The optimal method of medium voltage distribution voltage should achieve the minimum of total investment cost as the target, and meet the requirements of social, economic and other aspects. Therefore, according to voltage sequence of China's urban power network and methods of installation and considering capacity and load density, it determines viable alternative of the new voltage sequence, namely 500/220/110/20/0.4kV, 500/220/20/0.4kV.

3.2 Assessment Model

The evaluation of medium voltage distribution voltage level optimization and transformation needs to be considered from the two aspects of technology and economy, which are based to establish technical and economic evaluation model, including grid scale estimation model, investment cost estimation model, and floor area estimation model; the investment cost includes substation investment cost, lines reconstruction cost, power cable renovation costs. The concrete model is: **the grid scale model.**

3.2.1 High Voltage Substation Scale

Total number of substations in the whole regions

$$n_{HV} = \begin{cases} INT\left[\dfrac{P\times K}{C_{HV}\times T_{HV}}\right] & MOD\left[\dfrac{P\times K}{C_{HV}\times T_{HV}}\right] < 0.25 \\ INT\left[\dfrac{P\times K}{C_{HV}\times T_{HV}}\right]+1 & MOD\left[\dfrac{P\times K}{C_{HV}\times T_{HV}}\right] \geq 0.25 \end{cases}$$

Where P stands for total load of the whole regions, ten thousand kW, and K is capacity-load ratio; C_{HV} stands for capacity of single main transformer, ten thousand kVA; T_{HV} is the number of main transformer in the station; INT（X） stands for the X rounded; MOD (X) indicates that takes its decimal number of the X.

The power supply area of single high-voltage Substation (km^2) is as follows:

$$A_1 = \frac{\sqrt{3}}{2} d_{ss}^2$$

Where d_{ss} stands for the distance of any two high voltage substations, and average length of high voltage feed lines of substation, L_{HV} ,is expressed as follows:

$$L_{HV} = [\frac{d_{ss}}{2} + \frac{\sqrt{3}}{6} d_{ss}] \times 2 + \frac{\sqrt{3}}{3} d_{ss} = [\frac{2\sqrt{3}}{3} + 1] \times d_{ss} = 2.155 d_{ss}$$

The total length of high voltage lines in substations is expressed as follows:

$$L_h = n_{HV} \times L_H$$

3.2.2 Medium Voltage Substation Scale

The total capacity of medium voltage distribution transformer (ten thousand kVA) is expressed as follows:

$$S_{MV} = \frac{P}{R_{MV} \cdot \cos\varphi}$$

Where R_{MV} stands for the load change ratio; $\cos\varphi$ is the load power factor.

The total number of medium voltage distribution transformer is expressed as follows:

$$T_z = \begin{cases} \frac{TC_M}{C_{M1}} \times 10000 & MOD\left[\frac{TC_M}{C_{M1}} \times 10000\right] = 0 \\ INT\left[\frac{TC_M}{C_{M1}} \times 10000\right] + 1 & MOD\left[\frac{TC_M}{C_{M1}} \times 10000\right] > 0 \end{cases}$$

Where TC_M is the total capacity of medium voltage distribution transformer. C_{M1} is the capacity of single distribution transformer.

The total length of middle voltage lines.(km) is expressed as follows:

$$L_z = \left(\frac{N}{n_{HV}} \times L_c\right) \times n_{HV}$$

Where N is the total back number of middle voltage lines, and L_c is the main length of the outlet.

Investment cost model

Using the scale of the power network to estimate the network size, the computational formula of the investment cost is expressed as follows: :

$$M = SV_H + L_h V_1 + T_z V_{M1} + L_z V_{M2}$$

Where S is the total power capacity of the whole regions; L_h is the total length of high voltage feed lines of substation. T_z is the total number of medium voltage distribution transformer. L_z is the total length of the whole region's medium voltage feeders; V_H is the comprehensive cost of unitary substation capacity; V_1 is the comprehensive cost of high-voltage lines per km; V_{M1} is the comprehensive cost of single distribution transformer; V_{M2} is the comprehensive cost of medium voltage main trunk per km.

Floor area model

By the calculation results from the grid scale estimation model, the floor area scale of different alternatives can be calculated, and it is equal to the product of the grid scale multiplied by the floor area of unitary equipment or the width of lines corridor; the calculation formula of the floor area is expressed as follows:

$$Q = n_{HV} Q_{H1} + L_h Q_{H2} + T_z Q_{M1} + L_z Q_{M2}$$

Where n_{HV} is the total number of substations in the whole regions; L_h is the total length of high voltage feed lines of substation; T_z is the total number of medium voltage distribution transformer; Q_{H1} is the floor area of each substation; Q_{H2} is the corridor width of high voltage lines; Q_{M1} is the floor area of single distribution transformer; Q_{M2} is the corridor's width of medium voltage lines.

4. Empirical Analysis

The paper takes the industrial park of Suzhou as an example to verify the feasibility and the economy of 20kV. The mainly voltage level sequence of the Suzhou industrial park is 500/220/110/10/0.4kV; taking the existing voltage level sequence of 500/220/110/10/0.4kV of this city as shown in scheme 1 into consideration, the new voltage level sequence of 500/220/110/20/0.4kV is shown in scheme 2, 500/220/20/0.4kV is shown in scheme 3, and the three schemes are compared in grid scale estimation and economy.

4.1 Load Situation

The utilization areas of the planning areas of Suzhou industrial park are 196.95km ^{2} , and the utilization areas of construction areas are 122km ^{2} . Forecast of load and floor area in 2020 is shown in Table 1.

From the Table 1, the load of Suzhou industrial park in 2020 is 1064MW; the load density is 8.72MW/km; the perspective saturation in the annual load is about 1817MW; the load density reaches 14.9MW/km.

Table 1: Forecast of load and floor area in 2020

Time	Year of 2020	The perspective saturation year
Load Prediction（MW）	1064.25	1817.16
The utilization areas of construction areas (km ^{2})	122	122
Average load density of construction areas (MW/km ^{2})	8.72	14.9
The utilization areas of planning areas(km ^{2})	196.65	196.65
Average load density of planning areas (MW/km ^{2})	5.41	9.24

4.2 Grid Scale Assessment

According to the results from estimation model of the grid scale, power transformation and power transmission scale have three construction programs:220/110/10/0.4kV, 220/110/20/0.4kV and 220/20/0.4kV as listed in Table 2.

From the Table 2, the number of 220kV substation in this three schemes of 220/110/10/0.4kV, 220/110/20/0.4kV and 220/20/0.4kV, was 6, 6 and 11, respectively; the number of 110kV substation was 19, 16 and 0, respectively; the number of 10(20)kV medium voltage distribution transformer was 6224, 3734 and 3734, respectively, so the total number is decreased in turn between the substation of 220kV and below in three schemes, and the total length of the lines is also decreased.

4.3 Economic Assessment

By establishing from program 1 to program 3, namely the investment estimation model is 220/110/10/0.4kV, 220/110/20/0.4kV and 220/20/0.4kV. Meanwhile, considering the two sub schemes of entire cable power lines and overhead power lines, the detailed results are shown in Table 3.

Table 2: Power transformation and power transmission scale estimation of three construction programs

The scheme name(kV)	220/110/10/0.4(kV)	220/110/20/0.4(kV)	220/20/0.4(kV)
Power transformation scale			
Substation of 220kV (seat × ten thousand kVA × tower)	2160MVA =6 × 18 × 2	2160MVA =6 × 18 × 2	1980MVA =11 × 9 × 2
Substation of 110kV (seat × ten thousand kVA × tower)	1900MVA =19 × 5 × 2	2016MVA =16 × 6.3 × 2	0
Distribution transformer of 20(10)kV(seat)	6224	3734	3734
Power transmission scale			
220kV lines(km)	62.64	62.64	84.81
110kV lines(km)	111.53	105.6	
20(10)kV lines(km)	1387.5	888	888

Table 3: Investment estimation of three construction programs (unit: CNY ten thousand)

Scheme name（kV）	220/110/10/0.4(kV)	220/110/20/0.4(kV)	220/20/0.4(kV)
Total investment of substation(CNY ten thousand)	154504.8	154596	102990
Total investment of cable lines(CNY ten thousand)	427329.5	369564	304191
Total investment of aerial lines(CNY ten thousand)	56382.35	52270.8	47617.95
Total investment(the substation + the aerial lines, CNY ten thousand)	210887.15	206866.8	150607.95
Total investment(the substation + the cable lines, CNY ten thousand)	581834.3	524160	407181

From the Table 3, we can see that all the three schemes above:

(1) No matter what kind of erection is, the scheme 3, namely 220/20/0.4kV, saves most in the investment.

(2) In the aerial mode, the scheme of 220/20/0.4kV can save 28% of the investment, compared with the scheme of 220/110/20/0.4kV and 220/110/10/0.4kV.

(3) In the cable mode, the scheme of 220/20/0.4kV can save 17% and 28% of investment, respectively, compared with the scheme of 220/110/20/0.4kV and 220/110/10/0.4kV.

(4) The investment of the 220/20/0.4kV scheme in the substation engineering is the lowest, so it can save 33% and 33.4% of the investment respectively.

(5) In the transmission engineering, the overhead erection mode is about 13% of the cable mode in investment, and the investment of the 220/110/0.4kV overhead erection mode is the lowest in the three schemes.

4.4 Floor Area Estimation

The floor area results from scheme 1 to scheme 3 are shown in Table 4.

From the Table 4, we can see that all the three schemes above:

(1) The floor area of transmission and distribution of scheme 3 is the smallest, and it can save 35.9% floor area and 2.43% floor area, respectively, compared with the scheme of 220/110/10/0.4kV and 220/110/20/0.4kV.

(2) In the transmission engineering, the least occupied area is scheme 3, and it can save 36.3% floor area and 6.7% floor area, respectively, compared with the scheme of 220/110/10/0.4kV and 220/110/20/0.4kV.

(3) In the transformation engineering, the least occupied area is scheme 2, and it can save 12.2% floor area and 11.9% floor area, respectively, compared with the scheme of 220/110/10/0.4kV and 220/110/20/0.4kV.

Through the comparison and analysis of the above three models, scheme 3, namely 220/20/0.4kV, has the best total investment of boosting and transformation and the optimal floor area, so choosing the 20kV as new medium voltage distribution voltage is reasonable in technology and economy.

5. Boosting and Transformation of 10kV Distribution Network

5.1 Boosting and Transformation in Different Stages

The 10kV distribution network needs to consider many factors, including the timing of the boosting and transformation, the region of transformation and the equipment of boosting and transformation[17-19].

In the early stage of boosting and transformation, it not only needs us to study the regions and equipment of boosting and transformation, but also focus on the regions of shortage power supply and equipment to be scrapped to carry out boosting and transformation; in the middle stage of boosting and transformation, we should focus on the cities that the development of power networks is better to carry out boosting and transformation of the 10kV power network; in the latter stage of boosting and transformation, mainly carrying out boosting and transformation to the regions which haven’t finished the boosting and transformation completely. Finally, all the regions would be operated in 20kV.

5.2 Boosting and Transformation in Different Regions

After dividing the different stages of boosting and transformation, the concrete power supply areas need to be carried out in boosting and transformation, according to the differences of development of power grid scale in each region, in general, the areas of boosting and transformation can be divided into urban areas and rural areas[20-21].

In urban areas, it should gradually carry out boosting and transformation of 20kV in the original mode of 10kV power supply, and finally make 20kV completely take the place of 10kV; in rural areas, generally, keeping the mode of 10kV power supply unchanged, and carrying out the boosting and transformation of 20kV according to the concrete circumstances.

5.3 Make Full use of Existing Equipment

In the process of boosting and transformation of the 10kV power distribution equipment, the existing stock equipment should be used to carry out the boosting to save the cost of rebuilding.

For the unavailable equipment, including the equipment which achieved the desired life, they should be replaced to adapt to the power distribution equipment of 20kV voltage level as soon as possible; for the equipment that can be directly used after testing, under the condition of considering economy, they should be reformed by technical measures to meet the operation requirements of 20kV; for the sites in the transition period of boosting and transformation, they can be gradually reformed by using connecting transformers, and the concrete measures are as follows: First, expand one connecting transformer of 10/20kV(No.2) to supply power for the 10kV load of transformer 1 which is not boosting; then with the deepening of boosting and transformation, expand main transformer of 110/20kV(No.3), and supply power for 20kV load together; after the gradual replacement of 10kV network by 20kV, reform transformer 1 to the main transformer of 110/20kV, and the transformer 1 works together with transformer 3 to supply power, transformer 2 can be out of operation, and the illustration is shown in Figure 1.

6. Conclusions

1) The boosting and transformation of medium voltage distribution network is suitable for the economic and social development in China. It can improve the power supply, reduce the occupancy of land resources, and save energy and reduce loss. After demonstration, 20kV power supply has more advantages in technology and economy; compared with 10kV power supply, it can meet the needs for future economic development of the city better. Therefore, adopting 20kV voltage level is the first choice of transformation of the existing medium voltage distribution network, meanwhile, the power supply voltage level of 500/220/20/0.4kV is recommended.

2) In the process of boosting and transformation, the practical difficulties and the economic benefits should be taken into account, including seizing the opportunity, adjusting measures to local conditions, and boosting and transforming the medium voltage distribution network duly.

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