Analysis about Power Supply Capability, Economy and Reliability on Voltage Level Sequence of Urban DC Distribution Power System in Integrated Energy System

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Abstract. With the development of DC power transmission technology, it is possible to develop a multilevel urban DC distribution system in integrated energy system. With the basic principle and main constraints of designing for DC distribution voltage level sequence, a sequence of voltage levels of DC distribution power system in different voltage levels is proposed, and the power supply capability, economy evaluation and reliability on voltage level sequence of multilevel DC distribution is discussed in detail through a specific example.

1. Introduction

Due to the development of DC load recently, the distribution power system with DC transformers and DC circuit breakers is prospective in China. Current studies [1-3] mainly focus on the voltage level of low voltage and ultra-low voltage DC distribution network at the end of the system. Research in [4] considers that 400V as the voltage level of power supply system in data center has high efficiency. European scholars have studied 326, 230, 120 and 48V DC voltage classes according to the existing 230V AC distribution network voltage classes in Europe. The results show that the voltage drop and power loss will increase rapidly with the decrease of DC distribution network voltage. When the voltage drops to 48V, both voltage drop and current exceed the limit [5]. Based on the actual situation of Korean power grid, Korean scholars analyzed the fault characteristics of 1.5kV and 400V DC distribution network [6]. The formulas of DC distribution line loss and energy conversion loss is deduced, and analyzed in a medium-voltage 16kV and low-voltage 326V systems [7]. It is concluded that the efficiency of DC system is higher than that of AC system when semiconductor device loss is reduced by half.

Research in [8,9] mainly focuses on the problem of HVDC voltage grade for long distance transmission in China. It is proposed to establish 1000, ±800, ±660, ±500 kV HVDC voltage grade sequence for transmission network, and its economy is analyzed. The relationship between transmission capacity and voltage level of flexible HVDC transmission is studied in [10], and analyses the economy of (±80kV) and (±150kV) flexible HVDC transmission. Although none of the above papers deals with the sequence of DC voltage levels in distribution systems, the related problems of DC voltage levels are studied from the perspective of power grid planning and equipment.
manufacturing level, which provides ideas for the study of this paper. Distribution network is obviously different from transmission network in structure and function. Compared with HVDC transmission network, HVDC distribution network has the characteristics of large load fluctuation, strong flexibility of power supply, more distributed power access and high cost of land conversion. Therefore, its DC voltage level sequence needs to be specially studied and calculated.

This paper aim to study the urban power grid in the integrated energy system as the development of DC load, DC power transmission voltage transformation in urban power system is usually rapid. Based on a feasible voltage level sequence of DC distribution network from the aspects of load demand, grid structure, technical feasibility and economy, the power supply capability, economic evaluation and reliability is discussed in detail.

2. Design of DC voltage level sequence
Figure 1 illustrates the multilevel DC urban distribution power system with a sequence of voltage levels. The block diagrams show the connection of generation, transmission and distribution both AC and DC power system.

![Figure 1. Topology of multilevel DC distribution power grid](image)

Based on the block diagram shown in Figure 1, the capability of power supply with different voltage level in DC distribution power system are listed in Table 1.

| Distribution Level | Voltage Level | Distance | Capacity  |
|--------------------|---------------|----------|-----------|
| High voltage I     | > 180 kV      | 150-850 km | 800-1200 MW |
| High voltage II    | 90-180 kV     | 50-300 km | 50-500 MW  |
| Medium voltage I   | 16-90 kV      | 20-100 km | 2-15 MW   |
| Medium voltage II  | 1.5-16 kV     | 3-40 km   | 1-4 MW    |
| Low voltage I      | < 1.5 kV      | < 3 MW    | < 1 MW    |
| Low voltage II     |               |          |           |
Based on Table 1, the specific voltage level sequence of DC distribution power system can be designed below.

2.1. **High voltage distribution level I: ±320kV**

The main task of this voltage level is to distribute power to cities or large industrial parks with high load ratio (greater than 40MW/km$^2$) and connect it with the upper transmission network as the voltage level of high voltage distribution. ±320kV is the voltage level adopted by Dalian Flexible Direct Current Transmission Project in China. It is also the preferred voltage level for large capacity Flexible Direct Current Transmission Project under construction in the world. It meets the requirements of high voltage I in Table 1. Its power supply capacity is comparable to that of 500 kV AC, but the voltage is low and the area of substation is small, which breaks through the limitation of high voltage entering urban area and meets the demand of load growth.

2.2. **High voltage distribution level II: ±150kV**

The main task of this voltage level is to distribute power in the area with load rate not more than 40MW/km$^2$, as the voltage level of high-voltage distribution to connect the regional high-voltage transmission network. ±150 kV is a typical voltage level used in flexible HVDC transmission project, and the related technology and equipment are relatively mature. Its transmission capacity range is 99-707MW, which meets the requirements of high voltage II in Table 1.

2.3. **Medium voltage distribution level I: ±30kV**

The main task of this voltage level is to supply power to regional distribution stations and medium voltage loads, and to undertake the access tasks of large capacity distributed power sources and electrified railways. As the ratio of adjacent two-stage voltage should be greater than 5 when the voltage is 50-150 kV, and (±30 kV) is the voltage level adopted by Shanghai Nanhui Project. Therefore, the choice of (±30 kV) is more reasonable. At the same time, in the traction power grid of electrified railway, the current 25 kV single-phase AC network can be simply transformed into the DC (±30 kV) voltage level, or can be incorporated into the higher voltage level [11] according to the capacity. Due to the difference of catenary structure after modification, ±30 kV traction DC power grid has half of the original impedance and twice the power supply distance, which can reduce the number of traction substations and line losses.

2.4. **Medium voltage distribution level II: ±10kV**

The main task of this voltage level is to supply power to terminal distribution stations or large loads, and its power supply capability and economy need to be fully considered. The power supply capacity of <10kV is equivalent to that of 20kV AC, but the insulation requirement of the line does not exceed that of 10kV AC. Therefore, the use of DC (±10kV) distribution can not only reduce the investment cost greatly by using the 10kV line in the original AC distribution network, but also improve the distribution capacity greatly.

2.5. **Low voltage distribution level I: ±750V, 400V**

The main task of this voltage level is to provide a reasonable interface for rail transit and small-scale distributed energy. It is the core voltage level for the economic and stable connection between micro-grid and large power grid, and also provides power for most household loads. The bus voltage of charging station of electric vehicle is about 690V DC, and the outlet voltage of small fan is 700V DC. It can be connected to 750V DC voltage level. Therefore, +750 is a reasonable voltage level for small capacity distributed power generation. 750V voltage level can also meet the mainstream 400 V three-phase AC load supply demand, only need a first-level DC/AC conversion.

400V is a more standard DC voltage level, which can be directly applied to all kinds of terminal electrical equipment, including power supply to 220V AC load. Therefore, the voltage level can be used as the user's entry voltage. In the enterprise data center and other occasions, this voltage level is
also more appropriate. In some special occasions, 400V can also be converted into (±200V) power supply in order to take into account the access of DC system composed of various kinds of security batteries. In addition, for the direct access of power or load to unipolar bipolar DC power supply network, reasonable planning is needed to balance the load of each polarity.

2.6. Low voltage distribution level II: 48V

This voltage level is mainly used for household or commercial loads. Household distribution has the characteristics of short power supply distance, low load power and high security requirements. The working voltage of most household DC loads is below 48V, and 48V is a safe voltage level which can be directly contacted without protection measures, so it is reasonable to choose 48V. This voltage level is the voltage level obtained by converting 400 V after entering the house. It is used to supply domestic or commercial indoor power together with 400 V voltage (which is responsible for supplying power to high-power load).

3. Analysis on power supply capability

The analysis of power supply capability mainly includes the calculation of capacitance and distance. The ratio of the voltage difference between the head and the end of the DC bipolar distribution line and the supply voltage can be expressed as:

$$e_U = \frac{\Delta U}{U} \approx \frac{P_{dc} R_d}{U_{dc}}$$  \hspace{1cm} (1)

The loss rate of DC distribution line can be given by:

$$e_{dc} = \frac{\Delta P}{P_{dc}} = \frac{2 \Delta U I_{dc}}{2 U_{dc} I_{dc}} = e_U$$  \hspace{1cm} (2)

The loss rate of DC distribution line can also be expressed as:

$$e_{dc} = \frac{\rho DL}{U_{dc}}$$  \hspace{1cm} (3)

It can be seen that in the DC distribution network, the voltage loss rate and line loss rate are in numerical agreement. Assuming that the voltage at the end of the line is rated, the deviation of the voltage at the end of the line is equal to the voltage loss rate of the line. As a result, the power supply capacity and distance of different voltage level can be calculated and listed in Table 2.

| Voltage level | Line dimension | Transmission capacity | Distance |
|---------------|----------------|-----------------------|----------|
| ±320 kV       | 1200 mm²       | 1024 MW               | 408 km   |
| ±150 kV       | 600 mm²        | 225 MW                | 204 km   |
| ±30 kV        | 300 mm²        | 18 MW                 | 51 km    |
| ±10 kV        | 200 mm²        | 7 MW                  | 6.8 km   |
| ±0.75 kV      | 90 mm²         | 0.04 MW               | 3 km     |
| 0.4 kV        | 60 mm²         | 0.01 MW               | 2 km     |

4. Analysis on economy and reliability

Compared with AC distribution network, DC distribution network has the characteristics of small substation area, low cost of line construction, low line loss and no reactive power compensation device. It has better economic benefits in theory. This section will estimate the investment cost of equipment related to each voltage level of multilevel DC distribution network based on the data provided in some
documents, determine the power loss rate of each level, and finally compare the economy of DC distribution network and AC distribution network through the analysis of specific examples.

With regard to the related construction cost of DC distribution network, the investment cost of related equipment with voltage levels of (±7.5kV) and (±15kV) is specifically analyzed in [12]. In multi-stage DC distribution network, the main equipment (such as DC transformer and circuit breaker) is usually realized by modular combination technology, so its cost can be roughly considered to be linear with voltage level or capacity. At the same time, the unit cost of high voltage cables above 30 kV is obtained in proportion to the data in [11], while the voltage levels below 30 kV are evaluated with reference to AC single-phase cables. Accordingly, the unit price of equipment investment cost estimation under each voltage level of DC distribution is shown in Table 3.

| Voltage level | Capacity cost/kW | Circuit breaker cost/m | Line cost/m |
|---------------|------------------|------------------------|-------------|
| ±320 kV       | 1000 CNY/kW      | 10870000 CNY           | 560         |
| ±150 kV       | 1000 CNY/kW      | 5200000 CNY            | 610         |
| ±30 kV        | 1000 CNY/kW      | 1200000 CNY            | 120         |
| ±10 kV        | 1000 CNY/kW      | 530000 CNY             | 180         |
| ±0.75 kV      |                  | 25000 CNY              | 20          |
| 0.4 kV        |                  | 2000 CNY               | 20          |

Operation cost mainly considers maintenance cost and loss cost, the latter includes power transformation loss and line loss. Variable energy loss is mainly DC voltage loss in multilevel DC system. At present, the efficiency of DC transformer is about 90%, which is much lower than that of AC transformer. However, researchers have developed a DC converter with 99% efficiency, and with the mature application of wide band gap devices, the efficiency of DC transformer is expected to be greatly improved. Therefore, in the loss analysis, the efficiency of DC transformer is regarded as equivalent to that of AC transformer.

The loss rate of AC distribution line can be given by:

$$\eta_{ac} = \frac{3I_{ac}^2R_t}{\sqrt{3}U_{ac}^2\cos\varphi} = \frac{P_{ac}R_t}{U_{ac}^2\cos^2\varphi}$$

(4)

Combine (1), (2) and (4) by assuming the material and length of AC and DC cables are the same:

$$\eta_{dc} = \frac{P_{dc}U_{dc}^2\cos^2\varphi}{2(1+k)P_{ac}U_{ac}^2}$$

(5)

The total cost of multilevel distribution power system can be given by:

$$F_{dc} = F_c + P_{dc}c\eta_{dc} + F_m = F_c + (F_{dc} + F_c)n$$

(6)

If the load is distributed in a circular power supply area with an area of 100m² and a forward load density of 40W/km², it will be 4000MW in the long run.

The voltage level sequence of AC distribution scheme recommended in [5] is 220/20/0.4 kV. Among them, there are 22 substations with voltage level 220 kV with total capacity 7920 MVA, capacity-load ratio 1.98; 3732 distribution transformer in 20 kV with total capacity 5971 MVA, load rate 67%; the lines is 846 km. The total cost of investment and operation is:

$$F_{ac} = 173.8 + (1.17 + 0.22)n$$

(7)

By applying the DC distribution power system, the load density will be 40MW/km² in the future. Hence, it is necessary to use HVDC distribution to go deep into the load center when the voltage level is ±150 kV. Therefore, the three-level network is also used to realize DC power supply in this area.
High-voltage DC power distribution is ±150 kV medium-voltage DC power distribution is ±10 kV and low-voltage DC power distribution is 400 V. Therefore, the investment and construction cost of DC distribution can be estimated as shown in Table 4.

| Voltage level | Transformer cost | Circuit breaker cost | Line cost | Total |
|--------------|------------------|----------------------|-----------|-------|
|              | Cost/kW No./MW   | Cost/billion         | No.       | Cost/billion |
| ±150 kV      | 1000             | 7900                 | 7.9       | 0.05   |
| ±10 kV       | 1000             | 5900                 | 5.9       | 0.0053 |
| Total        | -                | -                    | 13.8      | 2.08   |

As mentioned above, assuming that the efficiency of DC transformer is the same as that of AC transformer, the energy conversion cost of AC and DC distribution network is the same, the cost will be 1.17 million. With the power factor 0.9 and the DC line loss is 81% of the AC line loss, the total investment of a multilevel DC distribution system can be given by:

\[ F_{dc} = 160.3 + (1.17 + 0.178)n \]  

The comparisons between (7) and (8) show that the investment cost of DC distribution equipment is slightly lower than that of AC distribution because the voltage level of DC distribution is lower than that of AC distribution. When DC transformer efficiency reach the level of AC transformer efficiency, its operating cost will also be slightly lower than that of AC because of the low DC line loss.

5. Conclusions

In this paper, the sequence of voltage levels of DC distribution network in different voltage levels is proposed in detail, and the power supply capability, economy evaluation and reliability on voltage level sequence of multilevel DC distribution is discussed in detail by comparing with a traditional AC distribution power grid. The analysis and calculation results show that the DC distribution power system is with better performance in power supply capability, economy evaluation and reliability.

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