DC Distribution Power Grid Voltage Level Sequence for Urban Power System in Integrated Energy System

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Abstract. The development of HVDC technology makes it possible to build a multistage HVDC distribution power system. Firstly, the basic principles and main constraints of voltage level sequence for DC distribution are analyzed in detail. Based on the analysis of the DC distribution capacity of each voltage level, a series of voltage levels of DC distribution network with high voltage, medium voltage, low voltage and ultra-low voltage are proposed, taking the load demand as the basic foundation, considering the manufacturing level of relevant equipment and the need of power grid structure optimization. Finally, the specific voltage level sequence of DC distribution network is proposed.

1. Introduction
With the increasing load demand, the increasing power quality requirements of users and the access of a large number of distributed generators, the traditional distribution system is facing challenges. Using DC-based distribution system shows the advantages that AC system does not have in improving the operation efficiency of distribution network, improving the reliability and quality of power supply, and realizing flexible and safe access to distributed generation [1-3].

At present, with the continuous development of flexible HVDC transmission technology, the development level of DC transformer and DC circuit breaker has been continuously improved, and the technical feasibility of DC distribution network has been significantly improved [4]. Relevant research results show that China's existing distribution network only accounts 1/3 for the future new network [5]. Therefore, it has broad prospects to actively promote the application of DC distribution technology to solve the drawbacks of the existing distribution mode.

Similar to AC distribution, the future development direction of DC distribution should also be the cooperation and complement of multilevel distribution network. Therefore, how to determine the voltage level of all levels of DC power grid is a key issue. At the same time, the formulation of voltage level sequence is the basis of power grid planning, which needs to be highly forward-looking, not only to meet the increasing load demand, but also to adapt to the future changes in power grid structure. Taking AC distribution system as an example, with the rapid growth of load, its mature distribution voltage level sequence gradually appears the problems of insufficient power supply capacity and excessive low-voltage distribution loss. In some areas, 220 kV AC has been used as the voltage level of medium voltage distribution. In some load-intensive areas (such as Shanghai), 500 kV AC direct
power supply has even appeared in the load center. This has brought about a series of security and economic problems [2-5]. As a mode of future distribution network, how to formulate a reasonable sequence of DC distribution voltage levels is an urgent problem to be solved in the application of DC distribution technology.

Different from the previous research on DC transmission, this paper is based on the urban power grid in the integrated energy system. From the perspective of voltage level coordination, a reasonable DC distribution voltage system is constructed and its rationality is analyzed. Considering the actual situation of high load density, multi-access of distributed generators and rapid development of DC transmission and distribution technology in the future, this paper proposes a feasible voltage level sequence of DC distribution network from the aspects of load demand, grid structure, technical feasibility and economy.

2. Principles of power grid voltage level sequence

According to the voltage standard [6], the keys for formulating voltage level are the ratio of adjacent two levels of voltage is not less than 2, and the ratio of adjacent two levels of voltage should be greater than 5 when the voltage is 50-150kV. Throughout the analysis and study of the voltage level of power grid at home and abroad, the voltage level sequence configuration mainly includes the principle of "geometric mean" and "rounding two to three".

The "geometric mean" can be given by:

$$U_j = (U_i U_{j+1})^{0.5}$$  \hspace{1cm} (1)

The "geometric mean" can be expressed as: Each voltage level in the optimal voltage level sequence should be "geometric mean" to each other. Only in this way can each voltage in the voltage level sequence be an economic voltage, which can effectively reduce the overall cost of power grid operation [7].

The principle of "two to three" can be expressed as follows: in the selected sequence of voltage levels, the multiples between adjacent voltage levels should be close to or exceed "3", and at the same time, one of the two levels whose multiples are close to or less than "2" should be discarded (i.e., the multiples between adjacent voltage levels should be greater than "2"). This can not only avoid the problems of excessive low-voltage outgoing circuit, long transmission distance and large loss caused by excessive gradient, but also avoid the problems of overlapping power supply range and redundancy of equipment caused by excessive gradient.

3. Constraints on voltage level of DC distribution system

In addition to the above principles, some constraints need to be taken into account in formulating the voltage level of DC distribution network. For example, the continuous expansion of urban scale leads to excessive load density in some areas; in the future power grid, solar energy, wind energy, fuel cells and other distributed energy are connected to the grid in large quantities, and demand for electricity consumption and power quality is constantly rising. Electric vehicles, uninterrupted power supply, rail transit and other things closely related to DC charging and power supply enter the social life, and multilevel DC power grid needs. To provide a reasonable access voltage level. These constraints impose many constraints on the selection of voltage levels in DC distribution networks.

3.1. Load demand in the future

According to the situation of domestic economic development, research in [8] predicts that the saturated load density of economically developed cities will be 10-40 MW/km² in 2020, 5-10 MW/km² in moderately developed cities and 3-5 MW/km² in underdeveloped cities. In order to cope with the load growth, in the AC distribution system, Shanghai has seen the situation of high voltage entering the urban area and 500 kV entering the distribution link; Suzhou Industrial Park will also upgrade the AC medium voltage distribution voltage level to 20 kV.
The following two points should be paid attention to when the load demand restricts the voltage level of DC distribution.

Firstly, at the same corresponding voltage level, DC has larger capacitance than AC. DC power distribution has no eddy current loss and skin effect, so its transmission capacity is higher than that of AC power transmission of the same grade. The DC bipolar system and three-phase AC transmission system can be given by:

\[ \frac{P_{dc}}{P_{ac}} = k_1 \frac{2U_{ac}I_{dc}}{aU_{ac}I_{ac}\cos\phi} = 1.2 \times \frac{2\sqrt{2}U_{ac}I_{ac}}{3\times0.9U_{ac}I_{ac}} = 1.25 \]  

(2)

Hence, under the same cable insulation strength and current RMS, the power transmitted by DC bipolar system is 1.25 times that of the corresponding three-phase AC transmission system.

Secondly, the transmission capacity of DC underground cable is larger than that of AC underground cable. Due to the influence of capacitance to ground, the reactive power of AC underground cables is difficult to be compensated, which makes it difficult to realize large capacity and long distance power transmission. DC cable has no such problem. In urban areas where the load is concentrated, the demand can be met by DC low voltage and high current transmission. Therefore, DC underground cable can realize medium-to-low voltage transformation and large capacity transmission, and the medium-voltage distribution level of DC distribution network need not be set too high.

3.2. Equipment Manufacturing Level

Flexible DC transmission technology based on voltage source converter can directly supply power to passive network without minimum active power transmission restriction, and can supply power to isolated load; Flexible DC only reverses current direction while DC voltage polarity remains unchanged when power flow reverses, which is suitable for multi-section DC connection; its converter station occupies small area and can be built in land-intensive cities, block design, short production debugging cycle. Distribution network has the characteristics of large load variation, multi-segment connection and high demand for power quality. Therefore, flexible HVDC transmission technology is particularly suitable for the construction of HVDC distribution network. The current level of equipment manufacturing and the development trend of technology are of reference significance for the formulation of voltage level sequence of DC distribution network.

Research in [9] points out that the industry has the ability to produce (±300 kV) DC cables and converter stations. Other key equipment in DC distribution network, such as DC transformer, DC circuit breaker and DC protection device, have developed to some extent, but the overall level needs to be further improved. Some of them are still in the stage of research and development. This brings difficulties to the formulation of voltage level and economic evaluation. At present, 10 kV AC electronic power transformer has entered the stage of industrial test, which can be used as high-power DC transformer through transformation. A 1.5kV marine DC circuit breaker has been developed successfully [10], and a 320kV voltage class DC circuit breaker has also been developed, which can interrupt the DC current by 16kA [11].

The direction of equipment development is to meet the load demand. Therefore, the voltage level sequence formulated by forecasting load and power grid development will also have guiding significance for equipment development. The development level of equipment should be taken into account in the formulation of voltage level sequence, but not limited to it.

3.3. Power grid structure optimization

DC load in distribution network mainly includes rail transit, electrified railway, enterprise data center and some household appliances. In the AC system, a large number of converters derived from such loads consume a large amount of electricity. In the future, 60% of the low voltage load will be DC load [12,13], and the application of DC distribution network will have higher energy efficiency. In addition, most distributed generators are DC or can be simply converted to DC output; energy storage devices and batteries of electric vehicles generally work under DC system, so the application of DC
distribution network can simplify the structure of power grid. The formulation of DC distribution network voltage level should start from reducing the commutation link effectively, and provide reasonable access voltage level for these loads and power sources.

3.4. Distribution Mode Constraints
There are two main modes of DC transmission and distribution: unipolar transmission and bipolar transmission. The capacity of unipolar transmission is easy to be restricted by the size of ground current, but the cost of transformation is low; the capacity of bipolar transmission is large, flexible and reliable, but the construction cost is high. In the long run, it is more reasonable to adopt bipolar transmission mode in DC distribution network. In addition, bipolar transmission provides more voltage level options, such as $\pm 750V$ for $1.5kV$ and $\pm 325V$ for $750V$. This level setting can effectively reduce the variable pressure link.

3.5. Transitional transformation of AC distribution network
In addition to the new distribution network using direct current system, there is also the situation of transforming the existing AC distribution system into direct current distribution system. In this case, the DC system will continue to use the original AC distribution network lines, the set DC voltage level on the line insulation requirements are not higher than the original AC distribution. The greatest advantage of using the existing AC lines is that the investment and construction cost of the lines can be saved, especially for medium-voltage distribution networks with more feeder loops (such as 10kV AC distribution network), whose line cost accounts for a larger proportion of the total investment cost.

4. Design of voltage level sequence
In this paper, the sequence of voltage levels and their coordination are analyzed based on the topological structure of multistage DC distribution network [3], as shown in Figure 1.
level sequence, and fully consider the manufacturing level and development trend of DC-related equipment. At present, the relationship between the voltage level of AC distribution network and its capacitance and distance is shown in Table 1. In recent years, the voltage level of most urban and regional power grids has been simplified to 500/220/110/10/0.4 kV.

Table 1. Distance and capacity of AC voltage system.

| Voltage level | Transmission Distance | Transmission Capacity |
|---------------|-----------------------|-----------------------|
| 500 kV        | 150-850 km            | 1000-1500 MW          |
| 330 kV        | 200-600 km            | 200-800 MW            |
| 220 kV        | 100-300 km            | 100-500 MW            |
| 110 kV        | 50-150 km             | 10-50 MW              |
| 35 kV         | 20-70 km              | 1-10 MW               |
| 20 kV         | 12-40 km              | 0.4-4.0 MW            |
| 10 kV         | 6-20 km               | 0.2-2.0 MW            |
| 0.4 kV        | < 0.6 km              | < 0.1 MW              |

Based on the data in Table 1 and considering the development of load, the power supply objectives of each voltage level in DC distribution network proposed in this paper are shown in Table 2.

In Table 1, the voltage level of 220 kV and the above is the voltage level of transmission network. Because of the increase of load and the expansion of city scale, the voltage of high voltage distribution has been extended to 220 kV. In some areas, 500 kV is even used to enter the load center directly. The distribution capacitance of 110-220 kV in HV AC distribution network is less than 100 MW, the maximum distribution range is 100 km; the distribution capacity of 10 kV in medium voltage AC distribution network is several MW, and the distribution range is 10 km; the distribution capacity of low voltage AC distribution network (0.4 kV) is less than 100 kW, and the distribution range is less than 1 km.

Table 2. Power supply of voltage levels in DC distribution system

| Distribution Level | Voltage Level | Distance | Capacity   |
|--------------------|---------------|----------|------------|
| High Voltage Distribution Level I | > 180 kV | 150-850 km | 800-1200 MW |
| High Voltage Distribution Level II | 90-180 kV | 50-300 km | 50-500 MW   |
| Medium Voltage Distribution Level I | 16-90 kV | 20-100 km | 2-15 MW     |
| Medium Voltage Distribution Level II | 1.5-16 kV | 3-40 km | 1-4 MW      |
| Low Voltage Distribution Level I    | < 1.5 kV | < 3 MW | < 1 MW      |
| Low Voltage Distribution Level II    |          |         |            |

Combines the requirements of load on supply voltage level and the current voltage level of flexible HVDC transmission project under construction, Table 2 proposes the following specific voltage level sequence of DC distribution network.

The sequence of DC distribution network could be listed as

High Voltage Distribution Level I: ±320kV;
High Voltage Distribution Level II: ±150kV;
Medium Voltage Distribution Level I: ±30kV;
Medium Voltage Distribution Level II: ±10kV;
Low Voltage Distribution Level I: ±750V, 400V;
Low Voltage Distribution Level II: 48V;
5. Conclusions
In this paper, the basic principles and influencing factors of voltage level setting for DC distribution network are analyzed. Considering the requirements of distribution capability, equipment manufacturing level and future load growth, and aiming at realizing distribution function, the voltage grading configuration of (±320kV, ±150kV, ±30kV, ±10kV, ±750V, 400V, 48V) DC distribution network is proposed systematically. In cities with high load rate, the sequence of (±320/±150/±30/±0.75/0.4 kV or (±320/±150/±10/±0.75/0.4 kV) can be used; in areas with lower load rate and long-term stability, the sequence of (±150/±30/±10/0.4 kV) can be used.

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