The Research and Engineering Practice in Air Clearance of Valve Hall and DC Field in VSC-HVDC Converter Station with High Voltage and Large Capacity

Libin Zhang, Xiangyu Chen, Shouqiang Fu, Hongjian Li and Min Zhao

Economic and Technical Research Institute of State Grid Jibei Electric Power Company, room 611, Yangfangdian East Road #21, Haidian District, Beijing, China. Email: chenxiangyu-cxy@163.com

Abstract. The value of air clearance is an important basis for the design of the converter station, which affects the layout and safe operation of the converter station. In this paper, the calculation method of minimum air clearance based on improved clearance shape coefficient is proposed, and the g-parameter method is used to correct the discharge characteristics of air gap under non-standard meteorological conditions. The method is applied to the valve hall and DC field air clearance design of Zhangbei ±500 kV flexible DC converter station. The Zhangbei converter station is used as a typical representative to empirically analyze the influence of temperature and humidity changes on the air gap, and we can get the temperature and humidity value when air clearance are at the maximum value, and we calculate the air clearance of different gap shape coefficients. This paper can provide method guidance and data for the selection of air clearance for other similar projects.

1. Introduction
Flexible DC transmission technology is a new type of DC transmission technology based on voltage source converter, fully controlled shutdown device and pulse width modulation technology. It has strong controllability, little impact on the environment, and low requirements on system short circuit capacity. It can improve the dynamic stability of the system and has broad application prospects, including asynchronous grid interconnection, renewable energy grid connection, urban grid power supply, island power supply, and distributed generation grid connection [1-4].

The value of air clearance is an important basis for the design of the converter station, which affects the layout and safe operation of the converter station [5]. At present, because of the shortage of land resources and environmentally friendly requirements, the layout of the converter station becomes more and more compact, especially in some key position, therefore, the check of the charging distance is critical. Flexible DC transmission, due to its flexibility, wide range of applications, and various voltage levels, there is no specification or standard which can provide the air clearance value corresponding with each voltage level, so the air clearance needs to be calculated in every specific projects.

2. Air Clearance Calculation Method
There are mainly two types of calculation methods of air clearance in valve hall of DC converter station [6-9]
1) According to the actual gap structure discharge test curve provided by the engineering construction manufacturer, and the air clearance value of the valve hall is obtained from the query curve of the overvoltage calculation result.
2) Using the method provided in the IEC standard, the \( U_{50} \) is corrected for atmospheric density, humidity, temperature and altitude of DC converter station conditions, and then calculated according to operation shock and lightning impulse valve air clearance formula provided by IEC.

Assume that the 50% impulse flashover voltage in the valve hall weather conditions is \( U_{50}^{(calculated \ by \ SIWL \ and \ LIWL)} \), and this voltage is corrected to 50% flashover voltage of standard atmospheric conditions, \( U_{50-corr} = k_a U_{50}/K_t \), and then we can get the minimum safe clearance which is calculated according to the clear distance formula under standard meteorological conditions.

Among them, \( k_a \) is the altitude correction coefficient, \( K_t = k_1 k_2 \) is the atmospheric correction coefficient, \( k_1 \) is the atmospheric density correction coefficient, and \( k_2 \) is the atmospheric humidity correction coefficient.

Thus, the 50% impulse flashover voltage corrected to standard atmospheric conditions is

\[
U_{50-corr} = \frac{k_a \cdot U_{50}}{k_1 \cdot k_2} = \frac{k_a \cdot U_w}{k_1 \cdot k_2 \cdot (1 - 2\sigma)}
\]  

In order to accurately calculate the minimum air clearance of the valve hall, the actual discharge characteristic curve of the air gap between the overhead flexible conductor, the tubular hard busbar and the frame, and between the tubular busbar and the valve hall steel column are generally required. When there is no an actual discharge test curve, the determination of the minimum air gap distance of the converter station can be calculated from the relevant empirical formula:

Switching impulse:

\[
U_{50-corr} = k \times 500 \times d^{0.6}
\]  

Lightning impulse:

\[
U_{50-corr} = k \times 540 \times d
\]

\( D \) is the air gap distance, and this \( d \) is the same value as the \( L \) in the parameter \( g \) formula used in calculating the atmospheric density and humidity correction coefficient. Actually, it needs to be iterated until \( d = L \); \( k \) is the gap factor which can reflects the shape characteristic of the electrode, the different coefficients represent different electrode shapes.

Usually, the larger of the minimum air clearance values determined by lightning impulse and switching impulse is taken as the minimum air clearance value. It should be noted that as the voltage level increases, in general, due to the saturation characteristics of the gap under the switching impulse, the gap distance determined by the switching impulse in the valve hall is much larger than the gap distance determined by the lightning impulse. Therefore, in the DC converter station, the dominant effect on the air clearance is the switching impulse.

2.1. Altitude Correction Method

IEC 60071-2:1996 proposes an altitude correction method related to the altitude and impulse voltage type, and specifies the calculation formula for the correction factor of altitude 2000m and below:

\[
k_a = e^{m(\frac{H}{8150})}
\]

\( H \)—Altitude unit, m; \( m \)—Correction factor related to voltage type and air gap structure

2.2. Atmospheric Correction Method

The national standard GB/T 16927.1-2011 proposes an atmospheric correction method related to the experimental meteorological conditions. The test voltage under different test meteorological conditions can be corrected with the standard meteorological conditions, and the atmospheric correction factor \( K_t \) is given as follows:

\[
K_t = k_1 k_2
\]
Where $k_1$ - air density correction factor, $k_1 = \delta_m$; $k_2$-humidity correction factor, $k_2 = k_w$, $k$ is determined by both the $h/\delta$ function which based on the ratio of absolute humidity $h$ (unit g/cm$^3$) to the relative air density $\delta$ and the voltage type.

3. Calculation Method of Minimum Air Clearance Based on Improved Gap Shape Factor

3.1. Analysis of Factors Affecting the Shape Factor of the Gap

The influence of the specific electrode size, the gap length and the adjacent wall are not taken into account in the calculated of the traditional air gap shape coefficient.

The type of gap such as ball-plate, valve tower-plate, pipe type bus bar-plate type bus bar; pipe type bus bar (end is ring)-plate (parallel), electrode size such as ball diameter, ring diameter, gap length, and the combination gap in the valve hall section (such as adjacent to a wall) should be considered into air gap shape coefficient.

As the gap length increases, the $k$ value decreases; the ball diameter decreases and the $k$ value decreases [10].

For the gap shape coefficient when adjacent wall exists, it is calculated by the model: when there is a wall and the distance between the ball-ground and the ball-wall is equal, the $U_{50}$ reduction ratio can be up to 4.4%, which is close to the experiment result of 4%-5%.

When the gap structure is adjacent to an equidistant grounding wall, the discharge voltage is reduced, and the influence is included in the shape factor, that is, a new shape factor value is given.

When the gap is adjacent to a wall, the original gap shape factor needs to be divided by a ratio greater than 1. According to the above table analysis, consider the ratio to be 1.06, so as to obtain a new gap coefficient value when the gap is approaching a wall.

3.2. Calculation Process

Since the minimum discharge path $L$ and the minimum air clearance $d$ are the same value, it requires an iterative calculation to converge the final minimum air distance $d$. The iterative process is as follows:

1) It is assumed that the initial values of the factors $m$ and $w$ are 0, so that the correction coefficients $k_1$ and $k_2$ are 1, and the atmospheric correction coefficient $K_t$ is also 1. And we define $U_{50,\text{corr}}$, which is corrected to the 50% shock discharge voltage under standard atmospheric conditions.

2) The minimum air clearance $d$ value is calculated by $U_{50,\text{corr}}$ and operation shock and lightning impulse formula.

3) The parameter g value is calculated from the expression of $d$ value and $g$.

4) The new factors $m$ and $w$ are determined by the $g$ values and the functional relationships shown in Table 43.

5) Take the new factors $m$ and $w$ values to $k_1$, $k_2$ and $U_{50,\text{corr}}$ calculation formulas, and recalculate the discharge voltage $U_{50,\text{corr}}$, and then obtain a new minimum air clearance $d$ value by operation shock and lightning impulse formula.

6) Repeat steps 3 through 5.

| $g$       | $m$     | $w$     |
|-----------|---------|---------|
| <0.2      | 0       | 0       |
| 0.2~1.0   | $g(g-0.2)/0.8$ | $g(g-0.2)/0.8$ |
| 1.0~1.2   | 1.0     | 1.0     |
| 1.2~2.0   | 1.0     | ($2.2-g)(2-g)/0.8$ |
| >2.0      | 1.0     | 0       |

Table 1. Function relationship of $g$, $m$, $w$

Considering the Influencing factor such as atmospheric density, temperature and humidity, the $g$-parameter correction method is used for correcting the discharge characteristics of the air gap under non-standard meteorological conditions. The air clearance is calculated after a number of iterations. When the difference between the minimum air clearance $d$ values calculated twice is small enough, we can consider the final $d$ value as the minimum air clearance after considering the atmospheric correction.
4. Zhangbei Flexible DC Grid Demonstration Project System Plan

The demonstration project of ±500kV Zhangbei flexible DC power grid is composed of Zhangbei, Kangbao, Fengning, Beijing four converter stations and Zhangbei ~ Kangbao, Kangbao ~ Fengning, Fengning ~ Beijing, Beijing ~ Zhangbei four ± 500kV The DC overhead transmission line constitutes a four-terminal flexible DC grid.

4.1. Calculation Condition Determination Method

The largest value at the lowest relative humidity (10%) at different temperatures, and the maximum air clearance from curve and the table are obtained at a temperature of 40 °C.

In the calculation of the air clearance, the analysis above can be used to draw conclusions about humidity and temperature.

(1) At the same temperature, the maximum value of the air clearance is under the condition of minimum relative humidity, that is, on the curve of minimum relative humidity.

(2) Under the same relative humidity conditions, the absolute humidity changes monotonically as the temperature increases.

(3) Under the same relative humidity conditions, the air clearance increases first and then decreases with increasing temperature.

(4) The calculation for the minimum value of the minimum air clearance needs to be considering about both temperature and absolute humidity. The maximum does not necessarily occur at the highest temperature and the lowest relative humidity.

The above data shows that the maximum air clearance is obtained at a temperature of 40 °C and a relative humidity of 10% (absolute humidity of 5.09 g/m$^3$).

4.2. Input Conditions of Zhangbei Converter Station

Taking Zhangbei converter station of Zhangbei four-terminal flexible DC project as an example, the engineering calculation is as follows.

The environment condition control of the valve hall is shown in the table below.

|                   | Zhangbei converter station | Kangbao converter station | Fengning converter station | Beijing converter station |
|-------------------|---------------------------|----------------------------|----------------------------|---------------------------|
| general conditions| totally enclosed, indoor, micro-positive pressure, With ventilation and air conditioning |
| long-term minimum operating temperature - long-term maximum operation temperature | 10-45°C |
| extreme minimum operating temperature - extreme maximum operating temperature | 10~50°C |
| Long-term minimum operating humidity - Long-term maximum operating humidity | 10%~50% |
| extreme minimum operating humidity - extreme maximum operating humidity | 10%~60% |
| specific distance of creepage | According to conventional DC 14mm/kV |

Take Zhangbei and Fengning converter stations as examples.
Annual average pressure at Zhangbei Converter Station: 859.8(hPa)
Annual average pressure at Fengning Converter Station: 935.5(hPa)

According to the analysis of the preceding section, it is necessary to use the maximum air clearance as the reference atmospheric condition to calculate:

Temperature: t=50°C
Absolute humidity: $h_0 =5.09g/m^3$. 
According to the preliminary results of insulation coordination of complete design, the end-to-ground insulation level of each point of flexible DC converter station is shown in the table below.

**Table 3.** The end-to-ground insulation level of each point of flexible DC converter station

| item                                    | SIWL (kV) | Other equipment | Recommended value |
|-----------------------------------------|-----------|-----------------|-------------------|
| Converter valve and neutral line equipment | -         | -               | -                 |
| 220kV AC bus                            | -         | -               | -                 |
| 550kV AC bus                            | -         | -               | 1175              |
| valve side of connecting transformer    | -         | 1125            | 1175              |
| valve side of bridge arm reactance      | 1080      | 1125            | 1175              |
| valve side of DC reactance              | 1040      | 1085            | 1175              |
| DC polar line                           | -         | 1085            | 1175              |
| neutral line equipment – valve side of smoothing reactor Max(CBN1,CBN2,E) | 650      | -               | 650               |
| neutral line equipment – line side of smoothing reactor Max(EM) | 445      | -               | 500               |

4.3. **Air Clearance Calculation Results of Different Gap Shape Coefficients Of Zhangbei Converter Station**

According to the aforementioned air clearance calculation method, considering the influence of the gap shape factor, the minimum air gap distance in the valve hall and the DC field can be calculated, and the calculation results are shown in the following table. According to the calculated minimum air clearance, multiply the appropriate safety factor as the actual air clearance of the project to design the valve hall and DC field.

**Table 4.** The calculation result of the valve side of bridge arm reactance, valve side of DC reactance, and DC polar line

| gap coefficient | switching impulse (kV) | air clearance (mm) |
|-----------------|------------------------|--------------------|
| 1               | 1175                   | 5254               |
| 1.05            | 1175                   | 4997               |
| 1.1             | 1175                   | 4782               |
| 1.15            | 1175                   | 4603               |
| 1.2             | 1175                   | 4453               |
| 1.25            | 1175                   | 4328               |
| 1.3             | 1175                   | 4225               |
| 1.35            | 1175                   | 4141               |
| 1.4             | 1175                   | 3914               |
| 1.45            | 1175                   | 3692               |
| 1.5             | 1175                   | 3489               |

4.4. **Project Value**

According to the previous analysis, combined with the margin requirements of the specification, the air clearance of the valve hall and DC field of Zhangbei Converter Station is as follows.

**Table 5.** Air clearance in the valve hall
| description                     | type                     | gap type | switching impulse withstand voltage (kV) | gap factor K | advised value of air clearance (mm) |
|---------------------------------|--------------------------|----------|-----------------------------------------|--------------|-------------------------------------|
| bridge arm AC side to ground    | phase to ground          | wire-plate | 1175                                    | 1.15         | 5000                                |
| DC pole bus to ground           | phase to ground          | wire-plate | 1175                                    | 1.15         | 5000                                |
| DC neutral bus to ground        | phase to ground          | wire-plate | 650                                     | 1.15         | 2000                                |
| DC pole bus to human            | ——                       | ——        | 1175                                    | 1            | 7800                                |

Table 6. Air clearance in the outdoor DC field

| description                     | type                     | gap type | switching impulse withstand voltage (kV) | gap factor K | advised value of air clearance (mm) |
|---------------------------------|--------------------------|----------|-----------------------------------------|--------------|-------------------------------------|
| DC pole bus to ground           | phase to ground          | wire-plate | 1175                                    | 1.15         | 5000                                |
| DC neutral bus to ground        | phase to ground          | wire-plate | 650                                     | 1.15         | 1900                                |

5. Zhangbei Flexible DC Grid Demonstration Project System Plan
In this paper, the calculation method of minimum air clearance based on improved clearance shape coefficient is proposed, and the g-parameter method is used to correct the discharge characteristics of air gap under non-standard meteorological conditions. The method is based on the atmospheric density correction coefficient $k_1$ and the humidity correction coefficient $k_2$, and the air gap distance $d$ is calculated through multiple iterations. The calculation flow is given in this paper. The method is applied to the valve hall and DC field air clearance design of Zhangbei ±500 kV flexible DC converter station. The Zhangbei converter station is used as a typical representative to empirically analyze the influence of temperature and humidity changes on the air gap, and we can get the temperature and humidity value when air clearance are at the maximum value, and we calculate the air clearance of different gap shape coefficients. This paper can provide method guidance and data for the selection of air clearance for other similar projects.

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