Study on the Selection of New Parallel Gap of 500kV Transmission Line at High Altitude

Hu Wen* and Zhao Chun²

¹College of Information and Communication Engineering, Hubei University of Economics, Wuhan, Hubei, 430205, China
²Wuhan NARI Limited Company of State Grid Electric Power Research Institute, Wuhan, Hubei, 430074, China
*Corresponding author’s e-mail: whuhuwen@vip.qq.com

Abstract. The current relevant power industry standards regulate the structure and size parameters of transmission line parallel gap. But practical operation experience proves that protection failure often occurs with the 500kV parallel gap recommended in the standards. A new 500kV parallel gap suitable for general areas had been developed for the purpose of improving the efficiency of protection, reducing the damage to insulator string caused by lightning flashover, and reducing the line lightning strike outage rate. However, under the condition of high altitude, the dimension parameters of general areas cannot be directly used in the new 500kV parallel gap. This paper conducts some tests on parallel gap of different size parameters with different serial lengths at UHV engineering technology (Kunming) national engineering laboratory at an altitude of 2100 m, including, U50%, lightning impulse test, volt-second characteristic test, visible corona and radio interference test. Protection effectiveness have been analyzed. The results prove that the recommended transverse extension lengths of parallel gap electrodes are 750/750mm and 800/800mm respectively, when the number of insulators is 33 and 37.

1. Introduction

The parallel clearance is a kind of lightning protection device, and it now has been widely used in 110(66)kV~500kV transmission lines in China. The core idea of the parallel clearance is to allow the circuit to have a certain lightning trip rate. The device is used for parallel connection with the lightning flash beside the insulator string, dredging power arc, to prevent insulator string from being burnt by arc. There is lightning flashover but no permanent fault, reclosing can be successful[1-6].

The type structure and size of 110kV~500kV transmission line parallel gap are normalized in the current electric power industry standard “DL/T 1293-2013 Guidelines for the use of parallel gaps between insulators on ac overhead transmission lines”[7]. But practical operation experience proves that protection failure often occurs with the 500kV parallel gap recommended in the standards. Therefore, relevant research teams have carried out a series of research work in recent years. Ref. [8] established a simulation model of 500kV parallel gap specified in the guidelines based on the finite element simulation platform, and did a electric field distribution calculation. A new typical structure of parallel gap of new 500kV transmission line is proposed, presenting as racket shape at low voltage side and half track ring at high voltage side, as shown in figure 1. Ref. [9][10] recommended that the transverse distance of parallel clearance between high and low pressure ends should be 750mm and
600mm respectively, after studying on the structural type parameter optimization with lightning impulse test.

Ref. [11] finds that the operating impact and lightning impulse characteristics of the parallel gap will decrease at high altitude, impulse breakdown characteristic linearly decreases with gap decreasing, after studying on the lightning impulse characteristic and volt-second characteristic to the 500 kV rod and annular parallel gaps at high altitude. Ref. [12] takes study on the discharge characteristic and inefficiency of the parallel gap for 200 kV long insulator series at high altitude. The result shows that the inefficiency patterns of parallel gaps are different for the long insulator series with different materials, there's a range of protection failure probability for long composite insulator series. Ref. [13] takes study on the lightning impulse flashover and volt-second characteristic of the 220 kV porcelain and composite insulator series under negative polarity standard lightning impulse voltage at high altitude. Comparing with the results at low altitude, 50% impulse spark-over voltage and volt-second characteristic of parallel gap decrease at high altitude.

At present, the transmission lines are important grids for interconnection of power systems and west-east power transmission project in the high altitude area of western China. It is of great significance to ensure the stability and reliability of transmission line operation in high altitude area. Most of the current researches on 500kV parallel clearance in high altitude area are traditional parallel clearance. There are few studies on lightning protection effect of high altitude parallel clearance. This paper obtained the structure parameters of parallel gap suitable for high altitude, based on the new 500kV parallel gap structure, after running high voltage test in the high altitude area.

2. High voltage test of parallel gap under the high altitude conditions

2.1. Test condition
The testing ground is UHV engineering technology (Kunming) national engineering laboratory at an altitude of 2100 m. The laboratory has a 7200 kV impulse voltage generator, the nominal voltage of which is 7200kV, and the capacity of which is 720 kJ. The parallel gap structure selected in the test is the new structure parallel gap shown in figure 2.
The flashover voltage of insulators at high altitudes varies with altitude, the number of overhanging insulators shall be modified as follows[14]:

\[ n_H = n_0 e^{0.1215m_1(H-1000)/1000} \]  \hspace{1cm} (1)

Where, \( n_H \) is the number of insulators each insulator string at high altitude, \( H \) is the altitude, \( m_1 \) is the characteristic index reflects the influence of air pressure on pollution flashover voltage. When the altitude \( H \) is 1000 m, the number of insulators each insulator string needed is calculated as follows[14]:

\[ n \geq \frac{\lambda U}{K_c L_{o1}} \]  \hspace{1cm} (2)

Where, \( \lambda \) is the specific creepage distance, kV/cm; \( U \) is the nominal system voltage, kV; \( L_{o1} \) is the geometric creepage distance of single suspension insulator, cm; \( K_c \) is the coefficient of efficiency of the insulator geometric creepage.

After calculation according to these provisions, the number of insulator pieces each insulator string needed is at least 33, at an altitude of 2100 m. The numbers of insulators are selected as 33 and 37 respectively, according to theoretical calculation results and practical operation experience. Combined with the research results of the new 500kV parallel gap, electrode size parameters are selected shown in table 1. Each insulator string of different insulator number takes 3 groups of parameters, to study the optimal parameter of parallel gap.

| Number of insulators | 33 | 37 |
|----------------------|----|----|
| Transverse extension length of electrode/mm | \( X_c \) | \( X_p \) | \( X_c \) | \( X_p \) |
| 600 | 750 | 700 | 700 |
| 700 | 700 | 750 | 750 |
| 750 | 750 | 800 | 800 |
| \( Z/Z_0 \) | 0.85 | 0.85 |

2.2. Test method

The high-voltage test mainly includes \( U_{50\%} \) lightning impulse test, volt-second characteristic test, visual corona and radio interference test.

In the natural lightning statistics of Yunnan Province, the frequency of negative polarity lightning accounts for more than 80% of the total number of lightning. So the negative polarity standard full lightning impulse is used in this paper, front time \( t_1 \) is about 1.88 \( \mu \)s, half-wave peak time \( t_2 \) is about 42.75 \( \mu \)s, as shown in figure 3. Up-down method is used in the \( U_{50\%} \) lightning impulse test[15], which is calculated as follows:
Where, $U_i$ is the amplitude of lightning impulse voltage in the $i$th efficiency test, $n$ is the number of efficiency tests. Each test item is conducted 20 lightning impulse tests.

In the volt-second characteristic test, the waveform of the impulse voltage is kept unchanged, the voltage keeps increasing until the gap breakdown. The breakdown voltage $U$ and the breakdown time $t$ are recorded according to the oscillogram. As the voltage amplitude increases, the breakdown will occur in the wave tail, wave peak and wave front. When the breakdown occurs in the wave peak or wave front, $U$ and $t$ take the value of them when breakdown occurs. When the breakdown occurs in the wave tail, $t$ takes the value of it when breakdown occurs, but $U$ takes the value of the peek of the impulse-voltage instead. As, $U$ takes the maximum voltage applied during breakdown. The voltage-time curve is drawn out by connecting each point.

The visual corona is the phenomenon of gas discharge caused by partial breakdown of air insulation near the surface of electric appliance, under power frequency voltage operating conditions. In the visual corona test, the voltage applied to the test item is kept increasing until a corona is observed, then the voltage is maintained for 5 min. The voltage is the corona inception voltage. After that, the voltage applied to the test item is kept decreasing until the corona disappears, then the voltage is maintained for 5 min. The radio interference voltage (μV) is used to measure the strength of the interference signal effect to the surrounding radio receiver when there is corona. The voltage effective value in the visual corona and radio interference test is calculated as follows:

$$U_0 = \frac{1}{1.1-0.1H} \times 1.1 \times k_1 \times k_2 \times k_3 \times \frac{U_m}{\sqrt{3}}$$

(4)

Where, $H$ is the altitude, km; $k_1$ is the correction factor of test position which takes 1.05 for the fittings near tower; $k_2$ is the meteorological correction factor calculated in (5); $k_3$ is the suspension height factor of the test item; $U_m$ is the maximum operating voltage, kV.

$$k_2 = \frac{p_0 \times 273 + t_0}{p_1 \times 273 + t_1}$$

(5)

Where, $p_0$ and $p_1$ are standard and test atmosphere respectively; $t_0$ and $t_1$ are standard and test temperature respectively, °C.

EUVI is used to observe visible corona of parallel gap. Qualified criterion is that when there is no visible corona for the test item, the radio interference voltage is less than 1000 μV.

3. High-voltage test result

3.1. $U_{50\%}$ lightning impulse test

The lightning impulse tests are conducted to the 6 test items shown in table 1, the charging voltage lifting and lowering curve of parallel gap is shown in figure 4. The values of $U_{50\%}$ of each parallel gap are shown in table 2, different electrode size parameters have no significant influence to the values of $U_{50\%}$ of parallel gaps, when the number of insulator strings are same.
Figure 4. The charging voltage lifting and lowering curve of parallel gap

Table 2. The values of $U_{50\%}$ of parallel gap with different electrode size parameters

| Number of insulators | Parallel gap size/mm | $U_{50\%}$/kV |
|----------------------|-----------------------|--------------|
| 33                   | 600/750               | 2616.6       |
|                      | 700/700               | 2614.5       |
|                      | 750/750               | 2619.5       |
| 37                   | 750/750               | 2961.4       |
|                      | 800/800               | 2958.3       |

3.2. Volt-second characteristic test

According to the test method above, the volt-second characteristic tests are conducted to the 6 test items shown in Table. 1. The test results are shown in figure 5 and figure 6. The curve goes down with the transverse extension length of parallel gaps increasing for the parallel gap with same string length, but the the range of change is not obvious. All the volt-second characteristic curves of parallel gaps located beneath the volt-second characteristic curves of insulator strings, which meets the requirements of parallel gap’s protection to insulator strings.

Figure 5. Volt-second characteristic of parallel gap with 33 insulators

Figure 6. Volt-second characteristic of parallel gap with 37 insulators

3.3. Protection effectiveness analysis

Most of the traditional 500 kV parallel gaps are annular, electrode horizontal extension elongation $X_e$ and $X_p$ are generally between 300 mm and 400 mm[7]. Actual operation experience shows that
lightning protection failures occur frequently with the parallel gaps are of this structure. The parallel gap lightning protection device on the transmission lines cannot prevent insulators from being burned by power by lightning stroke. In order to ensure the parallel gap can effectively guide the lightning strike frequency arc to the electrode end, to protect the insulators from being burned, the protection effectiveness analysis are necessary. Protection efficiency, characterizing the protection effectiveness of parallel gap, is introduced in this paper. The protection efficiency is calculated as follows:

\[ \eta = \frac{N_t}{N_s} \times 100\% \]  

Where, \( \eta \) is the protection efficiency of parallel gap; \( N_t \) is the number of effective protection; \( N_s \) is the total number of flashover, which should be 10 at least to get stable value of \( \eta \). Digital cameras are used to still capture the arc form of lightning discharge moment. The typical effective protection and protection failure are shown in figure 7 during the \( U_{50\%} \) lightning impulse test and volt-second characteristic test.

The protection efficiency of parallel gap with different parameters is calculated, the results are shown in table 3. When the electrode horizontal extension elongation of parallel gap reaches 750/750 for 33 insulators, or it reaches 800/800 for 37 insulators, the protection efficiency can be 100%. As the electrode horizontal extension elongation getting bigger, the protection efficiency increases. Because along with elongation getting bigger, the the length of the current element is larger, the total gap magnetic force increases, but the arc itself will be stretched further apart, the magnetic force towards the insulator applied to the arc element will be much weaker[10].

| Number of insulators | Parallel gap size/mm | Protection efficiency |
|----------------------|----------------------|-----------------------|
| 33                   | 600/750              | 92.4%                 |
|                      | 700/700              | 96.2%                 |
|                      | 750/750              | 100%                  |
| 37                   | 700/700              | 92.9%                 |
|                      | 750/750              | 96.4%                 |
|                      | 800/800              | 100%                  |

3.4. Visual corona and radio interference test

The voltage effective \( U_0 \) value in the visual corona and radio interference test can be calculated as 395 kV based on (4). The test result shows that when the power frequency voltage increases to the specified test voltage, no visible corona was found by observing the parallel gap with EUVI. When the voltage reaches the value shown in Table. 4, the corona was visible in the test item, the corona discharge points are located at the end of the lower electrode.
When the power frequency voltage increases to the specified test voltage $U_0$, the radio interference value can be measured by radio interferometer, shown in table 4. The radio interference values are less than 1000 μV, which meet the standard requirements.

### Table 4. Corona inception voltage and radio interference value with the specified test voltage $U_0$

| Number of insulators | Parallel gap size/mm | Corona inception voltage/kV | Radio interference value with the specified test voltage $U_0$/ μV |
|----------------------|-----------------------|-----------------------------|---------------------------------------------------------------|
| 33                   | 600/750               | 453                         | 789                                                           |
|                      | 700/700               | 467                         | 774                                                           |
|                      | 750/750               | 479                         | 768                                                           |
| 37                   | 700/700               | 493                         | 742                                                           |
|                      | 750/750               | 501                         | 729                                                           |
|                      | 800/800               | 510                         | 720                                                           |

3.5. Summary

The lightning impulse tests, volt-second characteristic test, protection effectiveness analysis, visual corona and radio interference tests have been conducted to the 6 test items with different dimension parameters. The test results show that the 6 test items can meet the requirements of relevant standards in those tests. When the electrode horizontal extension elongation of parallel gap reaches 750/750 for 33 insulators, or it reaches 800/800 for 37 insulators, the protection efficiency can be 100%. From above, parallel gaps of these two size can be chosen as the typical parallel gap at high altitude.

4. Conclusion

The high-voltage test have been conducted to the new 500 kV parallel gap at high altitude, including $U_{50\%}$ lightning impulse test, volt-second characteristic test, visual corona and radio interference test. The recommended sizes of parallel gap suitable for high altitude have been obtained. The results prove that:

1. At the altitude of 2100 m, the new structure parallel gap can meet the requirements of relevant standards in volt-second characteristic test, visual corona and radio interference test.
2. There’s no significant differences among the new parallel clearance with different size parameters in $U_{50\%}$ lightning impulse test, volt-second characteristic test, visual corona and radio interference test.
3. The effectiveness of lightning impulse protection is positively correlated with the transverse extension length of electrode for the parallel gaps with same insulator number. When the electrode horizontal extension elongation of parallel gap reaches 750/750 for 33 insulators, or it reaches 800/800 for 37 insulators, the protection efficiency can be 100%.

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