Study on overvoltage characteristics and arrester configuration strategy for ±1 100 kV HVDC transmission lines

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Abstract: Overvoltage caused by faults or switching is one of the decisive factors affecting the insulation level of equipment in UHVDC transmission systems. As for ±1 100 kV transmission projects, there has been no clear conclusion about the overvoltage distribution characteristics along transmission lines. This paper studies characteristics of the overvoltage distribution under monopolar line-to-ground fault and line-broken-down fault of transmission lines. The distribution characteristics of overvoltage along the line under different faults are obtained. The simulation results show that the arresters installed along the lines can significantly reduce the switching voltage level of DC lines. The voltage-current characteristics and the installation density of the arresters along the line have an important influence on the overvoltage suppression effect. Through the comparative analysis, a configuration scheme of arresters along the lines is proposed, which has a great effect for overvoltage suppression. The results are instructive for the design of insulation coordination in practical projects.

1 Introduction

In China, the geographical dispersion of the energy resource centers and the power load centers is very obvious [1–3]. Traditional AC systems consume large amounts of power in long-distance and large-capacity transmissions, and the stability of the system is also faced with severe challenges [4]. UHVDC transmission technology becomes an inevitable solution to such problems.

With the rapid development and widely application of UHVDC technology in China, a series of researches on overvoltage and insulation coordination have been carried out by State Grid Corporation and research institutes [5–8]. However, when voltage level increases to 1100 kV, there is no clear conclusion of the distribution characteristics of overvoltage along the line. With the increase of voltage level, the external insulation of transmission lines also bears very severe electrical field stress. The reasonable configuration of the arrester undoubtedly has better economic benefits than increasing the insulation level of transmission lines.

Here, the simulation model of Changji-Guquan ±1100 kV UHVDC transmission system is established using PSCAD software. The calculations of transmission line overvoltage distribution under monopolar line-to-ground fault and line-broken-down fault are carried out. According to overvoltage distribution, the arrester configuration is chosen reasonably and the influence of arrester configuration strategy on line overvoltage distribution is studied. The results are instructive for the design of insulation coordination in practical projects.

2 Simulation model of ±1 100 kV UHVDC transmission system

According to practical operation parameters of the Changji-Guquan ±1100 kV UHVDC transmission project [9], PSCAD simulation model is built as shown in Fig. 1, in which the points marked with letters are monitoring points of line voltage. The simulation model includes converter transformers, valves, AC and DC filters, smoothing reactors and overhead transmission lines.

Monopolar line-to-ground faults occur frequently along UHVDC transmission lines and cause severe overvoltage. Therefore, the overvoltage of monopole line-to-ground fault is the focus of the research on the overvoltage of UHVDC transmission lines. In addition, although the probability of the line-broken-down fault of the transmission line is small, once the fault occurs the overvoltage is very serious. Therefore, this paper focuses on these two kinds of faults to explore the configuration strategy of arresters.

3 Simulation results of typical faults in ±1100 kV UHVDC transmission system

3.1 Overvoltage under a monopolar line-to-ground fault

As shown in Fig. 2, the line-to-ground fault occurs at the middle point of the positive line, that is, Point C in Fig. 1. $I_k$ is the grounding current, and the $I_{k1}$ and $I_{k2}$ are the short-circuit currents on both sides of the fault point, respectively. By Kirchhoff’s current law, we have

$$I_{k1} = I_k + I_{k2}$$

Here, grounding resistance $R_g = 20 \Omega$. The current at the fault point obtained by the simulation is shown in Fig. 3. It can be seen that the waveforms of $I_{k1}$ and $I_{k2}$ are similar, and $I_{k1} > I_{k2}$, which means that only a part of the current delivered by the rectifier station flows to the tower at the fault point, while the rest part is sent to the inverter station along the transmission line. The duration of impact current is <50 ms, during which there is an obvious oscillation of the grounding current. At the same time, overvoltage
is induced by electromagnetic coupling along the non-fault line, as shown in Fig. 4.

According to the simulation results, we can obtain overvoltage distribution along the line as shown in Fig. 4, in which the highest overvoltage peak appears at the midpoint of non-fault line, reaching 1.50 p.u. The farther away from the fault point, the lower overvoltage will be.

From Fig. 5, it can be seen that the closer the distance to the fault point is along the non-fault line, the earlier the overvoltage occurs. As in Fig. 6, the overvoltage appears the earliest at the point \( c \), and the overvoltage at points \( b \) and \( d \) appears almost simultaneously, and the time of overvoltage at the \( e \) point has a delay of about 2 ms compared to the point \( d \). This conforms to the propagation characteristics of the wave on the lossy long line.

### 3.2 Overvoltage under a monopolar line-broken-down fault

When a line-broken-down fault occurs at Point \( C \), the midpoint of the positive line, the voltage waveform of each marked point along the positive line is shown in Figs. 7 and 8. Through comparison, it can be seen that overvoltage characteristics have significant differences, on the two sides of the breakpoint, that is, and the overvoltage on the rectifier side is much more severe.

In fact, when a line-broken-down fault occurs, two suspended endpoints are formed on the left and right of the breakpoint and the breakpoint splits the line into two parts. On the rectifier side, the voltage wave from the rectifier station is totally reflected when it reaches the breakpoint. The reflected and incoming wave voltages have the same polarity. After propagating to the rectifier station, they are refracted repeatedly, superposition of which produces a very high overvoltage.

On the inverter side of the breakpoint, the situation is different. Due to the distributed inductance and capacitance of the line, the current at this point will not change to zero after the break and will continue to flow to the inverter station for a period until the charge stored in the transmission line dissipates. As shown in Fig. 6, the current flowing through points \( C, D, E, I \) decay to zero successively, indicating that the current will still exist for some time after broken. That freewheeling process gradually consumes the charge in the line distribution capacitance, causing the part of the line voltage to drop to zero.

Under line-broken-down faults, overvoltages on the rectifier side are always more severe than those on the inverter side. Therefore, we should focus on the former ones. Simulation analysis of other fault locations gives a series of overvoltage distribution on the rectifier side of the breakpoint (Fig. 9). The maximum overvoltage appears at the rectifier side of the break point, up to 3.12 p.u. Due to the effect of the line resistance, the reflected wave
is gradually attenuated during the propagation. Therefore, from the breakpoint to the rectifier station, the overvoltage decreases along the line. However, the overvoltage at the rectifier station is also generally higher than 1.9 p.u., which poses a tremendous threat to the safety of the rectifier station equipment (see Fig. 10). Similar to line-to-ground faults, line-broken-down faults also result in overvoltage along the non-fault line due to electromagnetic induction. When line-broken-down faults occur at different locations on the negative line, the distribution curve of overvoltage induced on the positive line is shown in Fig. 11, which shows that the overvoltage on the non-fault line at the corresponding location is lower than that on the rectifier side. The overvoltage at the rectifier station is the most severe, up to 2 p.u.

### 4 Study on the arrester configuration strategy along DC lines

As an overvoltage protection device, the lightning arrester plays an important role in the safe operation of UHVDC transmission systems. According to the research results of the third section, the switching overvoltage wave will occur with the fault of the DC lines and will be transmitted along the line to converter stations, which will cause great harm to the insulation of the converter station equipment. Therefore, lightning arresters should be installed along the DC lines to reduce the line overvoltage level.

#### 4.1 Basic parameters of DC arresters

The basic performance indexes of the DC arresters mainly include the crest value of continuous operating voltage (CCOV), the DC reference voltage \( U_{\text{ref}} \) and the arrester voltage rate (AVR). This paper chooses DB arrester in Guquan converter station as DC line arrester, of which parameters are shown in Table 1.

#### 4.2 Effect of arrester on overvoltage

According to the calculation results of the third section, when a monopolar line-to-ground fault occurs at the middle point of one polar line, the overvoltage at the middle point of the other polar line, the non-fault line, is the highest. Thus, the first consideration is to install the arrester at the middle point of the line. When a line-to-ground fault occurs in the middle point C of the positive line, the amplitude of the overvoltage in the middle point of the negative pole is significantly reduced, from 1645 to 1508 kV, shown as Fig. 12.

The simulation results show that the overvoltage of other marked points in the non-fault line is also reduced after the arrester is installed in the middle of the line. In order to protect the safety of

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**Table 1 Basic parameters of DB arrester**

| Parameter                              | Value   | Description                      |
|----------------------------------------|---------|----------------------------------|
| crest value of continuous operating voltage CCOV, kV | 1120    | slightly higher than DC line voltage |
| peak value of continuous operating voltage PCOV, kV | 1120    | equal to CCOV                    |
| DC reference voltage \( U_{\text{ref}} \), kV | 1318    | generally DC 1mA corresponding voltage |
| arrester voltage rate, AVR             | 0.85    | the ratio of PCOV to \( U_{\text{ref}} \) |

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![Fig. 8 Overvoltage at the marked points on the inverter side of the breakpoint under a line-broken-down fault](image1)

![Fig. 9 Overvoltage distribution along the positive line on the rectifier side of the breakpoint under line-broken-down faults at different locations on the positive line](image2)

![Fig. 10 Overvoltage distribution along the whole positive line under line-broken-down faults at different locations on the negative line](image3)

![Fig. 11 Energy absorption of arresters at the point c, i of the negative line](image4)

![Fig. 12 Comparison of overvoltage waveforms before and after installing a lightning arrester in a negative middle point](image5)
4.3 Optimisation of arrester configuration

The general equation of the volt-ampere characteristic of a lightning arrester:

\[ I = AU^\alpha \]

According to the 1 mA reference voltage of the lightning arrester \( U_{500A} \) and the residual voltage \( U_{500A} \) under the current of the 500 A discharge current, \( A \) and \( \alpha \) can be solved, and then the volt-ampere characteristic curves are obtained. Therefore, the volt-ampere characteristic curve can be determined by \( U_{500A} \). The ratio of the residual voltage \( U_{500A} \) to the DC reference voltage \( U_{ref} \) under the 500 A discharge current is called the voltage ratio, that is to say

Voltage Ratio = \( \frac{U_{500A}}{U_{ref}} \)

The voltage ratio of UHVDC arresters is generally between 1.28 and 1.39 [10]. Here, three values of 1.28, 1.33, and 1.38 are studied, and the corresponding volt-ampere characteristic curve is obtained, as shown in Fig. 16.

In the simulation platform, the three arrester models above with different voltage ratios are allocated, respectively, and the simulation results of the overvoltage along negative line within monopolar line-to-ground fault are shown in Fig. 17. It can be seen that the smaller the voltage ratio is, the lower the overvoltage amplitude is, but the change is not significant. Of course, due to the limitation of manufacturing process, the voltage ratio of the arrester always has a lower limit.

Under the monopolar line-to-ground fault, the parallel scheme of different column number of lightning arresters is simulated, and Fig. 18 is obtained. With the increase of the number of arrester parallel column, overvoltage decreases, but the difference is small, especially for distribution curves of the 5 and 6 columns paralleled, which are almost the same. However, with the increase of the number of parallel column, the dispersion of arresters become more prominent, and after long-term operation, one out of the paralleled arresters accelerates aging, resulting in insulation threat. Therefore, four arresters paralleled as one group is reasonable.

There are similar conclusions for monopolar line-broken-down faults. As shown in Fig. 19, when the number of paralleled arresters of each group increases to a certain extent, the reduction of overvoltage is no longer obvious. At this time, the number of parallel columns is no longer the main factor that affects the effect of arresters to suppress overvoltages. In terms of economy, the manufacturing cost and installation and maintenance cost of the UHVDC arrester are high, and a large number of arresters will increase the cost of the project. Therefore, after comprehensive consideration, the number of paralleled arresters of each group recommended here is 4.

According to the calculation results of the third section, the line-broken-down fault occurring close to the inverter station is the most serious condition. At this time, the overvoltage at the inverter station is up to the highest. Shown in Fig. 14, the arrester has a very significant suppression effect on the overvoltage caused by monopolar line-broken-down fault. The most severe overvoltage of the incoming terminal of the inverter station has decreased from 2.76 to 1.5 p.u.

As of the high overvoltage level on the inverter side, the energy absorption of the arrester at point \( I \) in the inverter side is higher than that of the arrester at point \( R \) in the rectifier side, and the operation current is larger, as shown in Fig. 11 and 15.
decreased after doubling the density of arresters installed, but the decreased amplitude is not significant. Similarly, for monopolar line-broken-down fault, the overvoltage distribution along the line is as shown in Fig. 21, which indicates that the overvoltage at middle point of lines is further suppressed.

The results above show that the installation density of the arrester is too large to significantly increase the suppression effect of overvoltage. Considering the economic benefits, this paper recommends that the installation density of the arrester is one group every 500 km and 6–7 groups along each polar line.

5 Conclusion

Here, based on the operation parameters in Changji-Guquan ±1100 kV UHVDC transmission project, we build a simulation model within PSCAD software. According to the results of simulation, conclusions are obtained as follows:

(i) When a monopolar line-to-ground fault occurs, the overvoltage is induced in the non-fault pole line. The switching overvoltage first appears close to the fault point and spreads to both ends with the decrease of amplitude. The overvoltage distribution along the line shows a high part central and a significant decreasing tendency toward both endpoints.

(ii) When a monopolar line-broken-down fault occurs, the overvoltage on the rectifier side is much more severe than the inverter side. At a certain disconnected point of the DC line, the overvoltage at the breakpoint is the highest, and gradually decreasing along the line toward the rectifier station.

(iii) Arresters are able to play a significant role in restraining the overvoltage along transmission lines. Arresters with lower voltage ratio can have a better suppression effect on overvoltage. Considering both technical qualification and economic benefits, an optimised arrester configuration scheme is put forward: One group of arresters are installed at every 500 km of each polar line, and each group is made up of four arresters paralleled.

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7 References

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