Analysis of DC inter-electrode fault overvoltage in AC/DC hybrid power system

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Abstract. AC/DC hybrid power system has become an important distribution system for high-proportion distributed renewable energy consumption and multi-energy supply. Among the DC-side fault overvoltage, the inter-electrode fault overvoltage is the most harmful to the system. In order to analyze the principle of overvoltage generation, this paper establishes a mathematical model for AC/DC hybrid power system, and researches the mechanism of inter-electrode fault overvoltage generation on the DC side of the system, and builds a Matlab/Simulink simulation model so that gets the simulation analysis results of 10kV DC and ±375V DC side in the system. The research shows that the system high-frequency mathematical model relation which obtained according to the mathematical mode is belongs to the coupled nonlinear time-varying system. The DC-side overvoltage development can be divided into three stages: after happening of the fault until the converter station is locked, after the converter station is locked until the fault is removed, after removal of the fault until the converter station is unlocked. Through modeling and simulation, it is verified that the development process of overvoltage is consistent with the theoretical analysis. According to the research conclusion, the method of ‘arrester + parallel resistance + grounding device’ is proposed to protect the DC side overvoltage of the system.

1. Introduction
It has become a trend that a large amount of distributed energy access to AC/DC power systems in the process of global energy revolution [1, 2], and renewable distributed energy plays an increasingly important role in the proportion of energy in the distribution system [3, 4]. With the rapid development of generalized DC loads such as inverter air conditioners and IT loads, traditional AC power distribution systems have many power conversion links and low efficiency[5, 6], while AC/DC hybrid power systems have AC/DC hybrid power supply. It meets the advantages of AC/DC energy access, less power conversion, simple structure and high efficiency, and has gradually become the preferred power supply system for various energy-using scenarios such as data centers, industrial parks, office and living parks[7, 8, 9]. Power electronic transformers are the key equipment for commutation in AC/DC hybrid power systems. Fully-controlled power electronic devices are used to realize bidirectional flow of AC and DC power [10, 11, 12]. Due to the existence of sophisticated devices and complex control of power electronic devices, the pressure and overcurrent capability are poor, so it is of great significance to carry out the DC side fault analysis in the system, especially the interpole faults with large faults [13, 14], so as to propose effective overvoltage protection measures.

Some researches have been carried out on the overvoltage of flexible DC systems in China. The internal overvoltage generation mechanism of Zhoushan multi-terminal flexible DC transmission project is simulated and analyzed. The overvoltage mechanism of the AC/DC side of the converter
station is analyzed in detail [15]. The DC overvoltage after the short-circuit fault of the DC line of the Zhangbei flexible DC power grid and the receiving converter station is analyzed, and the dynamic process of the DC system overvoltage before and after the DC breaker action is obtained [16]. Reference [17] analyzed the single-phase ground fault of the converter valve side busbar with the most over-voltage of the converter valve station, the short-circuit fault of the converter valve, the fault of the top of the converter valve to the ground, the grounding fault of the DC bus, and the ground fault of the DC line. A ±10kV two-terminal flexible DC distribution network is taken as an example for the AC side DC distribution network AC side fault, grid side fault, converter area fault, DC line area fault, and access equipment area fault[18]. The fault voltage of the class is simulated and analyzed. The above overvoltage analysis is mainly for the flexible DC system and its converter valve device, and the voltage level is relatively high. At present, the DC side overvoltage of the AC/DC hybrid power system with the power electronic transformer as the key equipment has not been studied.

In order to solve the DC side overvoltage problem of AC/DC hybrid power system, the new AC/DC hybrid power system structure with power electronic transformer is used to analyze the fault overvoltage mechanism on the DC side, and establish a mathematical model. The simulation of the inter-electrode fault of 10kV DC and ±375V DC is carried out, and the DC-side overvoltage protection principle and protective measures of AC/DC hybrid power system are proposed.

2. AC/DC hybrid power system

The AC/DC hybrid power system uses two power electronic transformers as the key equipment, covering 10kV AC, 10kV DC, 380V AC, ±375V DC, and which is connected by four voltage grade busbars. Among them, 10kV AC and 10kV DC are distribution voltages, and 380V AC and ±375V DC are used voltages. The 10kV DC bus and ±375V DC bus are connected to the renewable energy photovoltaic system, and the 380V AC bus is connected to the wind power system and the CSP system. The 10kV AC bus, 380V AC bus and ±375V DC bus are all powered to the load and are equipped with an uninterruptible power system (UPS) to provide stable and reliable power. The system can access a variety of distributed energy sources and different voltage level loads, enabling efficient consumption of regional distributed energy and meeting the power requirements of different types of loads. The AC/DC hybrid power system is shown in Figure 1.

![Figure 1 AC/DC hybrid power system](image-url)
The AC/DC hybrid power system is a system with high renewable energy ratio access, and the power electronic transformer is used as the key equipment. The system overvoltage characteristics are different from the traditional power system overvoltage. In order to protect the system from overvoltage and keep the system stable, it is of great significance to carry out research on overvoltage of AC/DC hybrid power system. In the overvoltage analysis, there are unipolar ground overvoltage, lightning overvoltage, operating overvoltage, and inter-electrode fault overvoltage. Among them, the most influential system is the inter-pole fault over-voltage. Therefore, this paper focuses on the formation mechanism of the system-to-pole fault over-voltage and gives protective measures.

3. Mathematical model

In order to facilitate analysis of the overvoltage, the power electronic transformer is treated as a voltage source converter (VSC) according to the AC/DC hybrid power system structure of figure 1. Thus, a structural diagram of a two-port AC/DC hybrid power system is obtained, as shown in figure 2. This process does not affect the analysis of the mechanism of system overvoltage generation.

For the convenience of analysis, the following assumptions are made for the AC/DC hybrid power system. 1) The AC system on both sides takes the same voltage amplitude, but the initial phase and frequency of the voltage can be inconsistent. The three-phase AC voltage is sinusoidal. 2) Both the converter transformer and the commutating reactor are linearly symmetrical, regardless of their saturation state, and the transformer winding near the converter side adopts the “△” connection method, so there is no zero sequence component in the system. 3) The commutation reactance and equivalent loss of each phase in the two systems are symmetric. 4) The converters on both sides of the system have symmetry, that is, they all adopt a three-phase two-level topology, and the switching devices and other corresponding passive components are completely identical.

In order to further simplify the analysis, considering that the secondary side of the transformer adopts the "△" wiring mode, which is no zero-sequence component path in the system. Figure 2 can be simplified to some of the circuits shown in Figure 3.

If not specified, the side system of the AC/DC hybrid system is used for analysis. According to Kirchhoff's law, the voltage equation of phase A in Figure 3 can be obtained.

\[
L \frac{di_a}{dt} + R_i \cdot i_a = u_{sa} - (u_{AN} + u_{SO})
\]  

(1)
Let the upper arm switching function of phase A be \( S_a \) and the lower arm switching function be \( S'_a \). The upper arm of the A phase is closed and the lower arm is opened when \( S_a = 1 \) and \( S'_a = 0 \), then there is \( u_{AN} = u_a \). The upper arm of the A phase is opened and the lower arm is closed when \( S_a = 0 \) and \( S'_a = 1 \), then there is \( u_{AN} = 0 \), there is a relationship \( S_a + S'_a = 1 \). There are \( i_a + i_b + i_c = 0 \) in the three-phase three-wire system. In addition, there is \( u_a + u_b + u_c = 0 \) when the three-phase AC system voltage is symmetrically balanced. It is now substituted into formula (1).

\[
u_{NO} = \frac{u_a \cdot (S_a + S_b + S_c)}{3}
\]  

(2)

Substituting the formula (2) into the formula (1) gives the following formula.

\[
L \frac{di_a}{dt} + R \cdot i_a = u_a - \frac{u_a \cdot (2S_a - S_b - S_c)}{3}
\]  

(3)

\[
L \frac{di_b}{dt} + R \cdot i_b = u_a - \frac{u_a \cdot (2S_b - S_a - S_c)}{3}
\]  

(4)

\[
L \frac{di_c}{dt} + R \cdot i_c = u_a - \frac{u_a \cdot (2S_c - S_a - S_b)}{3}
\]  

(5)

There is the following differential relationship on the DC side of the system.

\[
C \frac{du_a}{dt} = (S_a \cdot i_a + S_b \cdot i_b + S_c \cdot i_c)
\]  

(6)

Equations (3)–(6) constitute the high-frequency mathematical model of the system. It can be obtained that the current per phase of the system is determined by the three-phase switching function, so it is a nonlinear time-varying system coupled with each other.

4. The overvoltage generation mechanism of DC inter-electrode fault

According to Fig. 2, the equivalent circuit of the two-port AC/DC hybrid power distribution system can be obtained, as shown in Fig. 4. In the figure, \( I \) is a DC current power supply. \( I_1 \) is a DC side photovoltaic current power supply. \( C_N \) is an overvoltage absorbing capacitor of neutral point bus. \( D \) is a single-phase conduction diode of analog VSC. \( R_1 \) and \( C_1 \) are respectively resistance and capacitance of converter stations. \( L \) is a smoothing reactor of DC system. \( C_3 \) is a storage capacitor. \( R, L, C \) are the unit impedance values of the DC side, respectively.

![Figure 4](image)

**Figure 4** Equivalent circuit of of two-port AC/DC hybrid power system

![Figure 5](image)

**Figure 5** Inter-electrode fault on the DC side of the system
The most serious fault in the AC/DC hybrid distribution network system is the two-pole short-circuit fault, so the overvoltage caused by the two-pole short-circuit fault is mainly analyzed. The AC side and the DC side will simultaneously feed the fault current to the fault point. When the fault occurs, considering that such a large fault current in the actual system will burn the insulated gate bipolar transistor (IGBT) in the converter, the IGBT in the actual engineering has a reliable self-protection function, which causes the DC fault to occur. It can be turned off immediately. However, although the self-protection function of the IGBT does not burn it in the event of a DC fault, the short-circuit current is still supplied to the AC and DC sides after the IGBT inside the VSC is turned off due to the presence of the freewheeling diode. This not only jeopardizes the freewheeling diode itself, but also causes the DC side fault to be completely isolated, affecting the safe and reliable operation of the grid.

Starting from the internal structure of the VSC, considering the self-protection function of the IGBT, an inter-electrode fault F3 as shown in Fig. 5 occurs on the DC side of the system. Since the IGBT will be turned off immediately due to the self-protection function due to the fault, which is assumed that the IGBT is immediately turned off after the fault occurs for the convenience of analysis. The development process of overvoltage on the DC side is divided into three phases. The first stage, the DC voltage \( U_{dc} \) is greater than the AC side line voltage at the beginning of the fault. At this time, the DC side fault current will be discharged mainly from the DC capacitor to the short circuit point. Among them, \( L_1 \) is the bridge arm reactance, \( C_1 \) is the VSC DC side shunt capacitor, \( L_0 \) is the DC side equivalent reactance of the discharge loop, \( R_0 \) is the DC side equivalent resistance of the discharge loop, and \( R_1 \) and \( C_1 \) are the converter station resistance and capacitance, respectively. It can be seen from Fig. 3 that the dynamic process of this stage can be expressed as differential equation (7).

\[
LC \frac{d^2u_{dc}}{dt^2} + RC \frac{du_{dc}}{dt} + u_{dc} = 0
\]  

Since the equivalent resistance on the DC side is small, the damping is generally satisfied \( R < 2L/C \), so the discharge of the capacitor \( C \) is an underdamped oscillation process. It can be obtained that the DC capacitor discharge is a second-order under-damped oscillation process, and the capacitor voltage attenuates the oscillation zero-crossing. At the same time, since the short-circuit current supplied by the AC side in this stage is only the continuous current of the AC reactor, no overcurrent occurs in the AC side and the inverter. On the DC side, an overcurrent occurs due to the discharge of a large capacitor.

The second stage, when \( U_{dc} \) drops to the AC side line voltage, the AC side power supply will begin to feed the fault current through the diode to the fault point. At this time, the conduction of the diode is based on the natural commutation principle of the uncontrolled rectifier bridge, so the process can be referred to as a diode natural commutation phase. At this stage, the AC power source and the DC capacitor are simultaneously discharged to the fault point, and the diode has a commutation process of alternatingly turning on and off. Each time this commutation process occurs, the dynamic process is re-solved once. The initial conditions are determined by the previous commutation process. Taking T1 and T2 conduction as an example, the flow path of the fault current is shown in figure 6.

![Figure 6](image)

**Figure 6** the flow path of fault current

The \( i_{sa}, \ i, \ u_{dc} \) are the state variables in the figure. Solving the multivariate state equation (8) can obtain the transient solution of AC and DC current and DC voltage under this condition.
Given the following matrix equation:

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
    u_a \\
    u_b \\
    u_c
\end{bmatrix} =
\begin{bmatrix}
    \frac{R}{L} & 0 & -\frac{1}{2L} \\
    0 & \frac{R}{L} & -\frac{1}{L} \\
    1 & 0 & -\frac{1}{C} \\
    1 & 0 & -\frac{1}{C} \\
    0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
    u_a \\
    u_b \\
    u_c
\end{bmatrix}
+ \begin{bmatrix}
    \frac{1}{2L} \\
    \frac{1}{L} \\
    0 \\
    0
\end{bmatrix} u_{nc}
\] (8)

The capacitor is in a charging state and the voltage is raised when the input and output power of the converter station is unbalanced. The following formula can be obtained when the A phase and the C phase are turned on according to Fig. 6,

\[u_a(t)+u_{nc}(t)+u_{sa}(t)+u_{sc}(t)-u_c(t) = 0\] (9)

Where, \(u_a(t)\) is the instantaneous phase A voltage of the converter station outlet. \(u_{nc}(t)\) is the instantaneous phase voltage of the C-phase of the converter station. \(u_{sa}(t)\) is the instantaneous phase voltage between phase A and phase C. \(u_{sd}(t)\) is the instantaneous voltage of the phase A diode. \(u_{sc}(t)\) is the instantaneous voltage of the C-phase diode. The capacitor starts to charge When the A phase and the C phase are turned on. Therefore, it is known from the formula (9), DC overvoltage will occur during the charging process of the capacitor. The waveform of the overvoltage will pulsate because the diodes of each phase are alternately turned on.

The third stage, the back EMF of the DC side short-circuit reactance will cause the six diodes in the VSC to be turned on when the DC capacitor voltage \(U_{dc}\) decays and oscillates through zero. Thereby a first-order discharge loop is formed on the DC side. The DC capacitor voltage is clamped to 0 by the diode. Therefore, the \(N_p\) and \(N_n\) potentials of Figure 6 are equipotential, and the AC power supply circuit can be equivalent to Figure 7(a).

\[
\begin{cases}
U_{ws}=U_w+U_u+U_l \approx 0 \\
U_{ds}=U_w+U_u+U_u \approx 0 \\
U_l=U_u+U_u \approx 0
\end{cases}
\] (10)

Where, \(U_{ds}\) is the DC side positive voltage of the converter station. \(U_{ds}\) is the negative voltage of the converter station. \(U_i(i=a, b, c)\) is the outlet phase voltage of the AC side of the converter station. Therefore, the circuit shown in Figure 7(b) is completely symmetrical. The AC side is equivalent to a three-phase short circuit. Therefore, this stage can be decomposed into two parts of the AC side three-phase short circuit and the DC side side discharge, as shown in figure 7. Set the DC voltage zero crossing time to zero time. The A phase voltage on the AC side is expressed as \(u_a=t_s U_w \sin(\omega t + \phi)\). The instantaneous value of phase A current is \(I_{a0}\). The instantaneous value on the DC side is \(I_{a0}'\). The fault current flowing through the diode during this process can be obtained according to Figure 7.

\[
\begin{aligned}
    i_{t1} &= \frac{1}{3} i_a - \frac{1}{2} i_u \\
    i_{sa} &= \frac{1}{3} i_a - \frac{1}{2} i_u
\end{aligned}
\] (11)

The above analysis shows that the current \(i_t\) of the DC link in this phase is an attenuation. The current \(i_{sa}\) supplied by the AC side consists of an attenuation component and a sinusoidal steady-state component. Therefore, the attenuation component decreases with \(i_t\) and \(i_{sa}\). The sinusoidal steady-state component has the potential to cause a zero-crossing of the current flowing through the diode. Once the current of any of the six diodes crosses zero, the three-phase symmetrical short-circuit state of the AC side at this stage is destroyed. This phase ends and enters the natural commutation phase of the diode.

5. Simulation analysis
In the Matlab/Simulink environment, a two-phase AC/DC hybrid power system was built. The topology wiring diagram of system is shown in Figure 2. There are two VSC converter stations, and station 1 and station 2 are both fixed DC voltage control. The distributed power supply that is connected is exemplified by a photovoltaic power supply. The DC load is replaced by a DC resistor. According to the foregoing analysis, the two-pole short-circuit fault overvoltage of the 10kV and ±375V DC busbars is analyzed.
5.1 The inter-electrode fault overvoltage simulation of 10kV DC side
Two-pole short-circuit fault is introduced on the 10kV DC side when the system runs stably to 1s. The corresponding simulation curve is shown in Figure 8.

![Simulation waveform of 10kV DC inter-pole short circuit fault](image)

Figure 8 Simulation waveform of 10kV DC inter-pole short circuit fault

It can be seen from the simulation curve of figure 8 that the development process of the overvoltage on the DC side is divided into three stages. The first stage, time is from 1s to 1.00119s. A fault current controller (FCC) is connected to the 10kV DC side. 10~19 μs after the fault occurs, the short-circuit current will trigger the overcurrent protection of the FCC. The FCC is put into its current limiting reactance unit to suppress the rising speed of the short circuit current. At the same time, a breaking command is issued to isolate the entire 10kV area to match the actions of other DC fault isolation devices. Therefore, the short-circuit current at the exit of the 10kV line rises at the moment of failure,
and the fault current controller is input to limit its rising speed at 10 μs. The short circuit current drops, and the short-circuit current rises slowly and reaches a maximum value of 3680A. The second stage, time is from 1.00119s to 1.003s. The AC side current quickly changes to a three-phase short-circuit current when the DC voltage drops to zero. Since the fault is not removed, the DC voltage will remain at zero and the DC current will remain at its maximum. The third stage, 1.003s and beyond. 3 seconds after the failure, the FCC completes the breaking. The voltage at the FCC is again sharply increased to a value of nearly 10 kV, and immediately drops to zero immediately after the action is completed. The overvoltage that appears here is an operating overvoltage.

5.2 The inter-electrode fault overvoltage simulation of ±375V DC side
After the ±375V DC system enters the steady state, an inter-electrode short-circuit fault is introduced at time 1.5s. After the fault occurs, the current-limiting reactance of all fault current controllers is applied to suppress the rise of the short-circuit current. After 1ms, the differential protection is activated and the circuit breaker is instantly disconnected. Thereby the fault area is isolated.

![Waveform diagram after ±375V DC side inter-pole short circuit fault](image)

**Figure 9** Waveform diagram after ±375V DC side inter-pole short circuit fault
After the ±375V DC-side inter-pole short-circuit fault occurs, the port current, voltage, and breaker port voltage waveforms are as follows. As can be seen from Figure 9(a), the current rise speed and peak value of the ±375V DC port are suppressed due to the presence of the current limiting reactance.
of the fault current controller. As can be seen from Figure 9(b), the AC power source and the DC capacitor are discharged together to the fault point. The ±375V DC port voltage continues to drop to around zero. After the circuit breaker is activated, the fault line is cleared, the capacitor is in a charging state, and the input and output power are unbalanced. This leads to an increase in voltage with an extreme value of 588.72V. As can be seen from Figure 9(c), the circuit breaker action causes a high overvoltage at its port, with a maximum amplitude of 12000V.

5.3 Overvoltage protection measures
Modern power systems often use a gapless metal oxide surge arrester (MOA) as a critical device for overvoltage protection. Under normal conditions, the arrester has a high impedance characteristic and exhibits a low impedance characteristic when an overvoltage is applied. Due to the nonlinear nature of the arrester, it can only pass the current caused by the overvoltage without generating the power frequency follow-up current. A reasonable lightning arrester configuration can not only effectively protect the equipment in the converter station, but also improve the reliability of the system. It also reduces the cost of equipment and is optimal in terms of technology and economy.

According to the characteristics of the over-voltage across the DC side, a lightning arrester can be installed to protect against the hazard caused by the DC side overvoltage. The resistor can be connected in parallel with the arrester to limit the overvoltage amplitude. The lightning arrester is connected to the grounding device to effectively introduce a large current into the earth, which is called the ‘arrester + parallel resistance + grounding device’ method.

6. Conclusion
The overvoltage research is carried out on AC/DC hybrid power system in the paper. According to the above research, the following conclusions can be obtained. The AC/DC hybrid power system with power electronic transformer has many advantages for power supply in various parks. It can access a variety of distributed energy sources and different voltage level loads. Achieve efficient consumption of regional distributed energy and meet the power supply requirements of different types of loads. When an inter-pole short circuit fault occurs on a 10kV DC line, the voltage drops to zero and the current reaches 3680A. When an inter-pole short circuit fault occurs on a ±375V DC line, the circuit breaker port voltage reaches 12000V and the current reaches 3000A. The problem of fault overvoltage between the DC side of the system can be solved by the method of ‘arrester + parallel resistance + grounding device’. That is, the lightning arrester and the resistor are connected in parallel, and the lightning arrester and the grounding device are reliably grounded to protect against the danger of overvoltage.

7. References
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