Study on characteristics and calculation method of VSC-HVDC short circuit current under three-phase AC short circuit

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Abstract. VSC-HVDC has been widely used at home and abroad, but there is no clear conclusion about the characteristics and calculation method of the short-circuit current contributed by VSC-HVDC during the AC Short-Circuit Fault near the converter station. The calculation methods in the field of short-circuit current engineering have not been unified, and the adaptability and error of different methods have not been analyzed in detail. Through electromagnetic transient simulation, this paper analyzes the transient characteristics of VSC-HVDC contribution short-circuit current, and comb the key influencing factors of VSC-HVDC contribution short-circuit current. Finally, taking a VSC-HVDC system in China as an example, the adaptability of the commonly used short-circuit current algorithm is analyzed. It is verified that the existing engineering algorithms have made great progress compared with the original. However, compared with the electromagnetic transient refined simulation, there is still a large error in the calculation results of individual nodes under some control modes / fixed values.

1. Introduction
VSC-HVDC (Voltage Source Converter based High Voltage Direct Current Transmission) has the advantages of flexible power control, fast regulation and power transmission for passive systems and islands [1-5], which has been widely used at home and abroad. It has been pointed out that the short-circuit current level of AC system will increase after being connected, but the analysis of its influence mechanism and related factors is not comprehensive [6-8].

With the operation and planning of VSC-HVDC project is advancing, the capacity is becoming larger. The influence of VSC-HVDC on the short-circuit current level of AC system is widely concerned by academia. At present, the analysis of transient process, method and influence factors are not comprehensive. Reference [9-10] studies the fast transient process of LCC-HVDC system in case of commutation failure, puts forward the mechanism and characteristics of its contribution to short-circuit current, but does not analyze the contribution of VSC-HVDC to short-circuit current. It is pointed out in reference [11] that the transient process of VSC-HVDC output current is related to control mode and converter station control parameters, but the influence mechanism and phase relationship are not clear. Reference [12] points out that the steady-state value of short-circuit current is closely related to the control mode, operation mode and control parameters of converter station.
controller. After fault time, the VSC-HVDC converter station acts as current source, but the influence of short-circuit current phase on the calculation results is also not clear.

In this paper, the transient characteristics and influencing factors of the contribution current of VSC-HVDC are analyzed. Based on the electromagnetic transient simulation model of the VSC-HVDC simplified system equivalent to the actual system, the key influencing factors of the short-circuit current near the converter station (control limiting, flexible and direct capacity, power, etc.) are simulated and analyzed. Taking a VSC-HVDC system as an example, this paper analyzes the adaptability of short-circuit current algorithm commonly used in engineering to the fault in the near area of VSC-HVDC. Pointed out there is still large error in the calculation results of individual nodes under some control modes / fixed values.

2. Basic structure and mathematical model of VSC-HVDC receiving system

2.1 Mathematical model of VSC-HVDC receiver system

The active power P and reactive power Q of the VSC-HVDC converter station connected to the active AC system in the ABC three-phase static coordinate system can be expressed as follows:

\[
\begin{align*}
P &= u_a i_a + u_b i_b + u_c i_c, \\
Q &= [(u_a - u_b) i_a + (u_b - u_c) i_b + (u_c - u_a) i_c]/\sqrt{3}
\end{align*}
\]

In the synchronous rotating coordinate system, the AC voltage \( U_s \) in the d-q axis voltage component \( u_{sd}, u_{sq} \), and the output P and Q are expressed as:

\[
U_s = \sqrt{u_{sd}^2 + u_{sq}^2}, \\
P = \frac{3}{2}(u_{sd}i_d + u_{sq}i_q), \\
Q = \frac{3}{2}(u_{sd}i_q - u_{sq}i_d)
\]

The output current \( I_d \) component of the VSC converter station is in phase with the AC voltage \( U_s \), so \( u_{sd} = U_s, u_{sq} = 0 \), the above formula is simplified as:

\[
\begin{align*}
P &= \frac{3}{2}u_{sd}i_d, \\
Q &= \frac{3}{2}u_{sq}i_q
\end{align*}
\]

It can be seen from formula (3) that the active power and reactive power of the output are only related to the active and reactive current \( i_d, i_q \), thus realizing the decoupling control of the active and reactive components. The control system controls \( i_d, i_q \) respectively to adjust the active and reactive power exchanged between the converter station and the AC system.

2.2 Control and protection system

According to the system level control signals and different target control quantities set according to different system requirements, the converter station can realize the separate control of active and reactive target quantities. The control mode mainly includes constant active power control, constant DC voltage control, constant AC voltage control and constant reactive power control.

According to the national standard "performance transient of VSC-HVDC transmission system", in case of system failure, VSC-HVDC should have certain fault crossing ability. At the same time, the protection device limits the operation mode of the VSC-HVDC during the fault period. The fault crossing strategy of the VSC-HVDC has an important impact on the system safety and the short-
circuit current level during the fault period. VSC-HVDC will trigger different protection strategies according to different fault duration and impact severity. It includes blocking exit of converter station, locking of phase-locked loop, limiting current, etc.

3. Mechanism analysis of factors influencing short-circuit current contribution of VSC-HVDC system

3.1 VSC-HVDC capacity and pre fault power

In order to prevent IGBT equipment from being damaged by over-current in case of fault or interference, current limiting measures are usually added to the control link to limit the current output amplitude of converter station. The limiter setting \( k_{\text{lim}} \) is usually 1-1.2. The output current of VSC-HVDC before fault \( I_{dc0} \) and the steady-state current after fault \( I_{dc\text{max}} \) are as follows.

\[
\begin{align*}
I_{dc0} &= \frac{\sqrt{P_0^2 + Q_0^2}}{\sqrt{3}U_s} \\
I_{dc\text{max}} &= k_{\text{lim}} \frac{S_{\text{QG}}}{{\sqrt{3}}U_s}
\end{align*}
\]

It can be seen from the above formula that: (1) the transmission power before the fault directly affects the transient starting value of the output current after the fault. (2) in the steady-state phase after fault, the output current of VSC-HVDC reaches the limiter limit. The larger the limiter value is, the larger the output current of VSC-HVDC is.

3.2 Limiting link

The VSC-HVDC operation control standard requires that the VSC-HVDC transmission system should have strong grid fault response capability [13-14]. However, due to the limited overload capacity of the device itself, the current limiting link is usually set in the design process of the outer and inner loop controllers to control the current flowing through the converter valve at a safe level, so as to improve the system's ability to resist fault disturbance. The flow of limiting link of control system is shown in Figure 1.

![Fig.1 Limiting Link Flow structure diagram](image)

Reference current amplitude \( i_{\text{ref}} = \sqrt{i_{\text{dref}}^2 + i_{\text{qref}}^2} \), where \( i_{\text{dref}}, i_{\text{qref}} \) are the reference values of current active and reactive components respectively. When \( i_{\text{ref}} > i_{\text{max}} \), the active and reactive components of current shall be limited. The matching limiting modes of different application scenarios are different, and the proportion of the middle and component of the output current \( i_d, i_q \) is also different, which will directly affect the phase difference between the VSC-HVDC output current \( i_{\text{max}} \) and the AC system. Common limiting strategies are as follows:

1) equal proportion limiting mode
2) priority to ensure active power output mode
3) priority to ensure reactive power output mode
3.3 **Control mode and control setting**

The VSC-HVDC control system, which is controlled by active and reactive decoupling, controls active current $i_d$ and reactive current $i_q$ respectively.

Under the constant AC voltage control mode, the voltage drops and the VSC-HVDC converter station increases the reactive output, reactive current reaches the limiting amplitude 21 ms after fault. The waveform of reactive current control quantity and output quantity is shown in the figure below.

![Fig.3 Constant AC voltage control flow chart of Iq/Iqref response process](image)

When the fixed reactive power is output 50Mvar, the reactive current 130 ms after the fault is limited to the limiter amplitude, and the waveform is as shown in the figure below.

![Fig.4 Constant Reactive power control flow chart of Iq/Iqref response process](image)

The selection of VSC-HVDC control mode will directly affect the growth rate of output current during the period of VSC-HVDC transient regulation after short circuit fault. Generally, the growth rate of reactive current under constant AC voltage control is faster than that under constant reactive power control mode. In terms of active power, the regulating speed of active current is faster than that of fixed active power under constant DC voltage control.

(4) **electrical distance between short circuit point and converter station**

The distance between the short circuit point of AC system and the VSC-HVDC directly affects the voltage drop depth of the VSC-HVDC PCC point after the fault, which will trigger different fault crossing protection strategies of the VSC-HVDC. When three-phase short-circuit fault occurs in AC system, VSC-HVDC will adopt corresponding fault crossing protection strategy according to the area where the point is located. Area division is shown in the figure below:
Different fault distance reflects characteristics of VSC-HVDC

1) output locking zone, VSC-HVDC low voltage locking out of operation

2) phase locked protection zone, VSC-HVDC locked phase-locked loop after fault

When it is low voltage, to ensure the control strategy of VSC-HVDC can be realized normally, it is necessary to lock the D-axis reference phase of VSC-HVDC output current to the pre fault state.

3) zone 3, VSC-HVDC operation in equivalent current source state

When the voltage is higher than the locking threshold of the phase-locked loop of the VSC-HVDC, the phase-locked loop works normally, and the reference phase of the VSC-HVDC output is the voltage phase of the PCC point.

4. Adaptability analysis of common methods for short circuit current calculation

The common short-circuit current calculation methods of VSC-HVDC access system are as follows:

Method A. ignore the effect of VSC-HVDC

Method B. superimpose the current limiting amplitude of ignore the effect of VSC-HVDC converter with the value of AC Short-Circuit Current

Method C. common simplified vector processing methods in Engineering

At present, the commonly used short-circuit current calculation method has certain calculation ability for the short-circuit current level of AC power grid after VSC-HVDC connection. It can take into account the influence of flexible and direct fault crossing limiting strategy, and simplify the phase relationship between flexible and direct short-circuit current components and AC short-circuit current components. In practical systems, the AC short-circuit current is often much greater than the VSC-HVDC contribution short-circuit current. Therefore, the active current component (ID) provided by the VSC-HVDC with the angle close to 90 degrees with the AC short-circuit current component (ikac) can be ignored, and the reactive current component (IQ) and the AC short-circuit current are superposed as amplitude. The phase relationship is shown in the figure below.

Fig. 5: Different fault distance reflects characteristics of VSC-HVDC

Fig. 6: Short circuit current calculation flow chart and phase map

In this paper, the calculation scenario of AC short-circuit current of near area bus in a domestic VSC-HVDC project is taken as an example. The structure of the VSC-HVDC near area grid structure is shown in the figure below, in which node 18 is the VSC-HVDC transmission end, and the converter station adopts the constant DC voltage and the constant AC voltage control; node 19 is the receiving end, and the converter station adopts the constant active power and the constant AC voltage control.
By comparison, neglecting the contribution of VSC-HVDC to short-circuit current in Table 2 will make the evaluation result too optimistic. It has been shown that the effect of VSC-HVDC on short-circuit current is helpful, but the effect of VSC-HVDC on short-circuit current is not a simple numerical superposition. In the past, the phase difference between the VSC-HVDC short-circuit current component and the AC system short-circuit current component is ignored in the direct superposition algorithm, which makes the calculation results conservative. At present, compared with the amplitude superposition method, the common engineering algorithm has made great progress, which can take the VSC-HVDC short-circuit current into account, and has a certain phase processing ability of short-circuit current vector sum.

5. Conclusion
In this paper, the key factors influencing the short-circuit current contribution of the VSC-HVDC system are analyzed, and the transient process of the short-circuit current contribution of the VSC-HVDC system and the influence of different factors are verified by simulation. The results show that the transient characteristics and steady-state amplitude of VSC-HVDC output current are related to VSC-HVDC capacity, limiting link, control mode / setting value and other factors. When evaluating the short-circuit current level of the receiving AC system, the analysis should be based on the specific operation control and limiting parameter settings of the VSC-HVDC transmission project. Based on a domestic VSC-HVDC project, the adaptability of several common short-circuit current algorithms is analyzed. It is verified that the current common engineering algorithms have made great progress compared with the previous evaluation methods, which can simplify the calculation of the phase relationship between the VSC-HVDC contribution short-circuit current and the AC short-circuit current.

Acknowledgments
This work was supported by Science-Technology Project of State Grid Fujian Electric Power Research Institute (XTB11201902065)
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