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RESEARCH ARTICLE

A Location Method for AC Fault in LCC-HVDC System Based on Virtual Conduction Width Characteristics

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ABSTRACT When an AC fault occurs in HVDC transmission system, the transient response change in the rate of change of current and voltage, which may lead to the unexpected action behavior of converter protection. This is attributed to the electrical quantity similarities between internal and external faults, leading to difficulties in fault location identification and reducing the sensitivity in protection measure activation. To realize internal and external fault identification and quickly deal with external faults, an AC fault detection method for LCC-HVDC systems based on virtual conduction width characteristics is proposed. First, by utilizing the ratio integral of the three-phase AC current on the valve side to the reference current, the virtual conduction width flowing through each valve in the sampling window is calculated. Second, according to the size relationship among virtual conduction widths, internal and external faults are identified. Third, after determining the external faults, the difference in the virtual conduction width for each valve branch in the sampling window is calculated to locate the fault phase. Finally, the simulation results based on EMTDC/PSCAD show that the proposed method can quickly identify internal and external faults and locate fault phases and is not affected by fault moment and fault resistance.

INDEX TERMS HVDC transmission, AC fault, fault location, temporal features, virtual conduction width.

I. INTRODUCTION

An alternating current (AC) system fault on the inverter side of a line-commutated converter high voltage direct current (LCC-HVDC) system easily induces commutation failure [1], [2]. The converter valve's primary protection mechanism fails to identify the fault area, owing to the similarities in electrical quantities between internal and external faults. When commutation failures occur, the converter protection system may exhibit unexpected action behavior and is affected by many factors, resulting in a decrease in the sensitivity and speed of protection [3], [4], [5]. Commutation failure causes a three-phase valve current imbalance, resulting in certain converter valves overheating [6], [7]. To ensure converter valve safety and rapid maintenance, there is an urgent need to monitor abnormal converter valves with commutation failures.

There are two types of commutation failure protection methods: predictive and measured [8], [9], [10], [11]. In comparing the two methods, the measured method is relatively accurate in the detection and determination of commutation failures. However, since this method is based on the difference between the measured extinction angle and the set extinction angle, there is a certain blind area, resulting in commutation failure misjudgment behavior. In [12], a commutation failure evaluation method was proposed. By analyzing the discreteness of commutation failure, the extinction angle criterion of the commutation bus voltage amplitude and phase change is combined. However, the indirectly calculated commutation bus voltage cannot track the change in extinction angle in real time. Thus, this method is not suitable for commutation failure in a critical state. In [13], it was proposed that a commutation

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failure occurs when the extinction angle is less than the inherent limit extinction angle and the valve current and voltage are continuously zero. By satisfying any of the above three conditions, it is possible to determine a commutation failure from its inherent characteristics. However, this method has a large blind area. In [14], the commutation failure mechanism was analyzed and a diagnosis method for HVDC commutation failure was proposed, in which the valve voltage continues to be zero or the valve current continues to be nonzero for more than one power frequency cycle. In [15], a commutation failure criterion based on the waveform characteristics of electrical quantities was designed. To satisfy this criterion, three references must be determined: the extreme point of the valve current and its detected change rate, the maximum value of the valve current, and the continuous nonzero time of the valve current after the extreme point. In [12], [13], [14], and [15], these references are based on the variation characteristics of the valve current or valve voltage for commutation failure determination. However, in an actual project, the current detection device is not configured in the converter valve of the HVDC system due to the process problem, so the above methods cannot be applied.

Continuous commutation failure will threaten the safety of the converter valve, which requires AC/DC isolation realized by the control system. The phase of the final valve is maintained through the valve control system. The activation of a non-fault phase bypass pair will undoubtedly exacerbate an accident [16]. There has been some research on the location of the fault phase. When a valve control system receives an AC/DC isolation signal, the existing control strategy is to retain the last valve, which is located at the phase input bypass pair. If a non-fault phase is included in a bypass pair, an accident will undoubtedly be exacerbated [17], [18], [19], [20]. There have been some studies on the location of the fault phase. In [17] and [18], by considering the influence of protection and control on fault electrical quantity characteristics, the classification criteria of faults at different positions were designed by using the DC and AC electrical quantity data within 10 ms after different converter fault types. In [19], a method based on the current integral was proposed to locate the fault bridge arm by using the cross-sectional relationship of the current integral between the AC and the bridge arm branches. In [20], according to following by a detailed mathematical analysis of a conventional bipolar and the proposed four-pole systems, a method for reliability and power density increase in a novel four-pole system for line-commutated converter HVDC transmission is proposed, and phase-to-ground ac faults and pole-to-ground dc faults have been efficiently cleared. In the above literature, these location methods designed of the fault phase are based on the criterion by the amplitude characteristics of the electrical quantity after the fault. Due to the influence of many fault factors, these criterions have a blind area and cannot directly characterize the abnormal state of the converter valve in the judgment process.

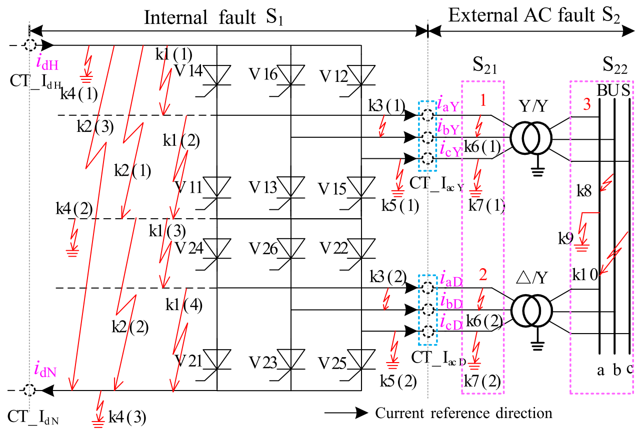


FIGURE 1. Converter fault distribution.

In the above literature, the location methods designed for the fault phase are based on the criterion of the amplitude characteristics of the electrical quantity after a fault occurs. Due to the influence of many fault factors, there is a blind area that hinders the ability to directly characterize the abnormal state of the converter valve in the judgment process.

Based on the above analysis, a fault phase method for locating AC faults that utilizes the polarity characteristics of a three-phase AC current on the valve side is proposed. This method determines a commutation failure by observing the continuous nonzero state of the current for more than one power frequency cycle. Taking the inverter side of AC system as the research object, utilizing the ratio of the valve-side three-phase AC current to the half of the valve-side three-phase AC current amplitude, the converter valve state is characterized. In the sampling window, the virtual conduction width of each valve is obtained by integrating the converter valve state. Then, according to the change characteristics of the virtual conduction width before and after the fault to determine whether the conduction state of a converter valve is abnormal, the occurrence of commutation failure is determined. Through the virtual conduction width of the converter valve after the fault and the characteristics of the fault electrical quantity, accurate fault phase location is realized. The simulation verifies the reliability of the commutation failure detection method based on the temporal features of the three-phase AC current on the valve side.

II. CHARACTERISTICS ANALYSIS OF THE CONVERTER TERMINAL CURRENT FOR AC SYSTEM FAULT

A 12-pulse bridge converter, as a basic conversion unit in LCC-HVDC projects, is used. The inverter covers all fault types on the rectifier, and commutation failure occurs in the inverter. The inverter side is the research object in this study, and the distributions of the converter internal fault and external fault are shown in Figure 1. k1-k10 are the fault numbers.

According to the converter protection scheme, converter faults can be classified into internal and external AC faults, as shown in Figure 1. Internal converter faults are distributed

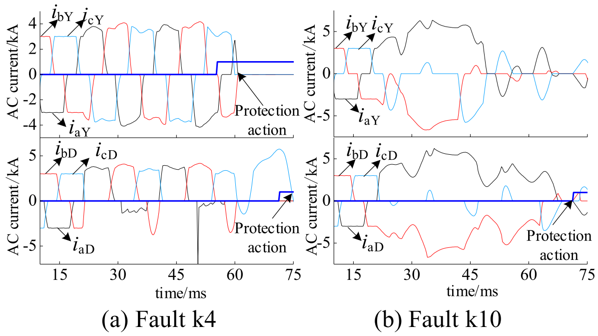


FIGURE 2. Valve-side three-phase AC current waveforms for different faults.

between DC (CT_I_{dH}, CT_I_{dN}) and AC current transformers (CT_I_{acY}, CT_I_{acD}), and the fault area is S_1. Typical faults include k1-k3 short-circuit faults and k4-k5 ground faults. External AC converter faults are distributed between the AC current transformers and inverter commutation bus, and the fault area is S_2. Typical faults include k6-k10 faults. Among them, k6-k7 faults between the AC current transformer (CT_I_{acY}, CT_I_{acD}) and converter transformer are involved in the occurrence of an external fault, i.e., AC line fault, within the converter, and the fault area is S_{21}. k8-k10 faults between the converter transformer and converter bus are a part of the same type of fault, and the fault area is S_{22}.

An external AC fault in the converter causes the converter bus voltage to decrease and indirectly changes the AC current. The converter bus voltage cannot be directly measured and cannot be used as the electrical quantity of the protection criterion. A converter protection system is constructed by the differential current of the three-phase AC current and the DC current on the valve side, and the differential current conforms to the fault response of the indirect electrical quantity change of the converter external fault.

The converter protection system cannot determine internal and external faults, and the unexpected action behavior of this system occurs after an AC fault. The valve-side three-phase AC current waveforms of a valve-side phase-to-phase fault (k4) in area S_1 and single-phase ground fault (k9) in area S_2 are shown in Figure 2.

Figure 2 shows that the three-phase current changes corresponding to the same type of faults inside and outside the region are quite different, and the fault converter valve in the S_1 region will not experience commutation failure. The commutation failure of the fault converter valve in the S_2 region occurs due to the reduction in the commutation voltage. The time of the converter protection action is different, but the time for an external fault to meet the protection criterion is longer than that for an internal fault.

The fault in the S_2 area is prone to commutation failure, which seriously threatens the safety of the converter valve. It is necessary to protect the converter valve in real time and remove the fault. The conditions satisfied by the protection criterion of the converter area are related to the change rate and delay of the differential current. This is affected not only by the fault moment but also by the fault type, system strength, fault resistance, DC operating conditions and other factors, making the protection action uncertain. On the one hand, the uncertainty of the protection action reduces the protection of the converter valve safety through the differential flow criterion. On the other hand, the differential protection of the converter satisfies the condition action, the protection system issues an electronic shift-on-the-fly (ESOF) instruction, and the control system performs a bypass instruction. When the bypass corresponds to the fault phase of the last valve, the three-phase current of the converter valve is 0, and the AC switch of the converter transformer is switched off, playing the role of AC and DC isolation. When the bypass valve corresponds to the non-fault phase, the three-phase current of the converter valve is not 0, and the non-fault and fault phases of the bypass pair form an interphase short circuit, resulting in the expansion of an accident.

Based on the above analysis, correctly locating a fault phase is conducive to the system removing a fault point in a timely manner to ensure converter valve protection. The characteristics of electrical quantities are affected by many factors and are quite different, and the fault phase cannot be detected and located directly by using these characteristics. Therefore, the utilization of a three-phase current integration on the valve side is proposed to obtain the converter valve conduction time and monitor the converter valve state in real time. According to the virtual conduction width of a converter valve, the internal and external fault discrimination and the fault phase location of different fault types are realized.

III. FUNDAMENTAL PRINCIPLES

When a system is in a normal operation state, the three-phase AC current measured by the AC-side current transformer is equal to the current of the corresponding phase flowing through the converter valve. When an S_1 area fault occurs, due to the increase in the short-circuit branch, in addition to the current flowing through the converter valve, there is also a fault current inside the converter. Therefore, the three-phase AC current on the valve side is not equal to the current flowing through the corresponding phase. When a fault occurs in the S_2 area outside the converter, regardless of how the fault size and type of fault current change, the relationship between the three-phase AC current on the valve side and the converter valve current of the corresponding phase is not affected. Therefore, in this section, the relative relationship between the three-phase AC current amplitudes on the valve side is exploited to obtain the valve current conduction time, which can not only be used to detect the abnormal conduction state of the converter valve when the system has an external AC fault but can also be used to determine the internal and external faults.

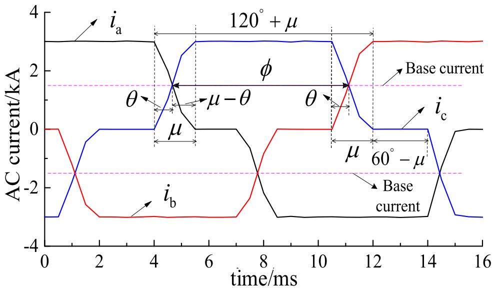


FIGURE 3. The AC current waveform during normal operation.

A. VALVE CURRENT CONDUCTION STATE DURING NORMAL OPERATION

In the normal operation mode of the system, the conduction width of the converter valve is fixed, and the current amplitude of the converter valve is unchanged. The normal operation mode of a 12-pulse dual-bridge converter in an HVDC transmission system occurs when four or five valves are turned on at the same time, and the six valve arms of a single bridge are triggered by a 60° equal phase interval. In the commutation process, the electric angle corresponding to the duration of the commutation valve is the commutation angle, which is represented by μ. The waveform of the three-phase AC current on the single-bridge valve side is shown in Figure 3. In a power frequency cycle T, the AC current waveform is formed by approximately positive and negative rectangular waves, in which the positive current or negative current continues at the $(120° + \mu)$ electrical angle and turns off at the $(60° - \mu)$ electrical angle. Therefore, the width corresponding to the normal conduction of the converter valve current is:

$$t_{\mathrm{VT}} = \frac{120° + \mu}{360°}T \tag{1}$$

where t_{VT} is the conduction width of each valve.

The amplitude of the polarity current is directly utilized to construct the width of the valve conduction state, and the conduction width is related to the commutation interval μ, resulting in an uncertain conduction width.

In this study, it was found that the proportional relationship between the current at the intersection current of the two commutation valves in the commutation process and the maximum of the three-phase AC current is consistent in time series (Figure 3). The proportional relationship can solve the problem of polarity current amplitude change. To realize the standard calculation without considering the influence of the commutation angle on the conduction width, the conduction state of the corresponding phase converter value is defined as the three-phase current of the valve side being greater than the reference current. The reference current is the current corresponding to the same phase as that of the two commutation valves, and the electric angle corresponding to the reference current is measured as θ.

As shown in Figure 3, where the commutation from a-phase to b-phase is used as an example, the electrical angle corresponding to the valve conduction and the conduction width in the corresponding power frequency cycle are:

$$\begin{cases} \phi = (120^{\circ} + \mu) - \theta - (\mu - \theta) = 120^{\circ} \\ t_{\mathrm{HVT\_normal}} = \dfrac{120°}{360°}T = \dfrac{T}{3} \end{cases} \tag{2}$$

where ϕ is the valve conduction angle and $t_{\mathrm{HVT\_normal}}$ is the width of the conduction corresponding to the conduction angle of the normal operation valve.

The current amplitude of the normal operation valve, electric angle corresponding to the valve current conduction, and valve conduction state are constant. After a fault occurs, the conduction current and conduction time width of the converter valve are changed due to the short circuit or formation of bypass pairs, and the commutation balance is broken. Therefore, the width of the current conduction time of the converter valve can be used as the basis for determining the abnormal current conduction of the converter valve.

B. DETECTION PRINCIPLE OF VALVE CURRENT TEMPORAL FEATURES

According to the literature [21], the current of the converter valve i_{VTm} is obtained by using the three-phase current of the valve side.

To monitor the sampling information online in real time, the converter valve current in the previous power frequency cycle is sampled with the current time as the sampling cutoff time. In Figure 4, t_1 and (t_1) are the starting times of the sampling window, and t_2 and (t_2) are the termination times of the sampling window. The integral of the ratio of the converter valve current to the reference current is used to construct the conduction time width of the converter valve.

Because the constructed conduction width is not the real conduction width, it is referred to as the virtual conduction width in this paper. The integral criterion has a better anti-interference ability than the current criterion. The calculation formula of the virtual conduction width of the converter valve is as follows:

$$\begin{cases} t_{\mathrm{HVTm}} = \displaystyle\int_{t_1}^{t_2} s_{\mathrm{VTm}} dt \\ s_{\mathrm{VTm}} = \dfrac{i_{\mathrm{VTm}}}{i_{\mathrm{base}}} \qquad\qquad i_{\mathrm{VTm}} \geq i_{\mathrm{base}} \\ i_{\mathrm{base}} = \dfrac{\max(|i_{\mathrm{VTm}}|)}{2}; \end{cases} \tag{3}$$

where s_{VTm} is the converter valve conduction state, i_{VTm} is the six valve currents, $m = 1, 2, 3, 4, 5, 6$, i_{base} is the maximum value of the current amplitude when the two commutation valves are equal, and t_{HVTm} is the virtual conduction width of the commutation valve.

An asymmetric fault occurs in the system, and the DC current surges. The instantaneous value of the conduction current of the converter valve in the corresponding phase is larger than the current phasor amplitude under the normal operation state of the system, and the conduction time is longer. The virtual conduction width of the valve in one power

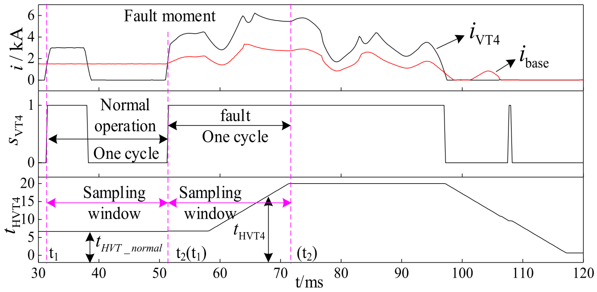


FIGURE 4. **Converter valve current and conduction width waveforms.**

frequency cycle is exceeded, that is, the conduction current of the converter valve is too long. According to formula (3), the valve virtual conduction width can be obtained. The current of the converter valve, the conduction state of the converter valve and the change in the valve virtual conduction width before and after a fault are shown in Figure 4.

IV. EXTERNAL FAULT LOCATION SCHEME

An internal converter fault causes an abnormal conducting state of the converter valve, but no commutation failure occurs. An external AC fault easily causes a commutation failure of the converter valve, and the virtual conduction width of the converter valve is too long. The influence of internal and external faults on the converter valve is different. According to the current virtual conduction width of the converter valve, the internal and external faults can be distinguished. Accurate fault phase positioning is beneficial for the control system to promptly generate a protection output signal, ensuring the rapid spread of protection actions following a fault. This facilitates the timely removal of the fault point by the system, thereby achieving the purpose of protecting the converter valve.

A. FAULT AREA DIAGNOSIS

In the operation of an HVDC system, utilizing the valve-side three-phase AC current to obtain the converter valve conduction current is divided into three situations. (1) When there is a normal operation state, and the converter valve current amplitude and virtual conduction width remain unchanged. (2) When there is an abnormal operation but no commutation failure occurs, such as a converter DC side-to-ground short circuit. There are differences in the change in valve current amplitude and virtual conduction width, but the change difference is not large. (3) When there is an abnormal operation and commutation failure occurs, the valve current amplitude and virtual conduction width vary greatly, and the longest conduction time of the converter valve current is greater than or equal to one power frequency cycle [13]. For example, single-phase to ground faults of converter buses, interphase faults of converter AC connections and short circuits of converter valves. The core idea of positioning is to determine the virtual conduction width of the commutation failure of the converter valve. However, the current virtual conduction width of the converter valve cannot be used to simply determine whether an internal or external fault occurred. Therefore, the three-phase AC current on the valve side and the virtual conduction width of the converter valve current are combined as the positioning criterion.

When a fault occurs in areas S_1 and S_{22}, the distance between the current transformer and the converter transformer is very short, and the grounding capacitance is very small. The three-phase current on the valve side measured by the current transformer is equal to the secondary side current of the converter transformer, and the sum of the secondary side current of the converter transformer is equal to 0. When a fault occurs in the S_{21} area, due to the existence of ground current or short-circuit current, the three-phase current on the valve side measured by the current transformer is no longer equal to the current on the secondary side of the converter transformer. Thus, the sum of the three-phase current on the valve side measured by the current transformer is no longer 0. It is given as follows:

$$\begin{cases} \text{YY bridge: } i_{aY} + i_{bY} + i_{cY} \neq 0 \\ \text{YD bridge: } i_{aD} + i_{bD} + i_{cD} \neq 0 \end{cases} \tag{4}$$

where i_{aY}, i_{bY}, and i_{cY} are the three-phase AC currents on the valve side of the YY bridge and i_{aD}, i_{bD}, and i_{cD} are the three-phase AC currents on the valve side of the YD bridge.

If one bridge of the converter satisfies the condition that the sum of the three-phase current on the valve side is not 0, a fault occurs between the current transformer and the converter transformer. Otherwise, the fault is determined to be an AC fault in the S_{21} area.

In the S_2 area fault, the converter valve is prone to commutation failure, and the virtual conduction width of the converter valve with commutation failure will be greater than one cycle. Because there will be inversion in the commutation process, but the virtual conduction state of the converter valve is obtained above the intersection of the two commutation valves, the time width of the valve conduction current obtained by the current ratio integral in the sampling window is smaller than the power frequency cycle. Under normal circumstances, the value of the commutation angle μ is less than 20°, and the current ratio integral is used to obtain the continuous virtual conduction width of the commutation failure valve current under the sampling window as $t_i = [5T/6, T]$.

$$\begin{cases} \text{YY bridge: } i_{aY} + i_{bY} + i_{cY} \approx 0 \\ \text{YD bridge: } i_{aD} + i_{bD} + i_{cD} \approx 0 \\ t_{\text{HVTm}} \geq t_i \end{cases} \tag{5}$$

If the sum of the three-phase current on the valve side is zero and there is a valve with t_i continuous virtual conduction width of the converter valve current, a fault occurs between the converter transformer and the AC power supply, and the fault is determined to be an AC fault in the S_{22} area. Therefore, the fault range is determined by the three-phase AC current on the valve side and the width of the valve current conduction time in a cycle after the fault.

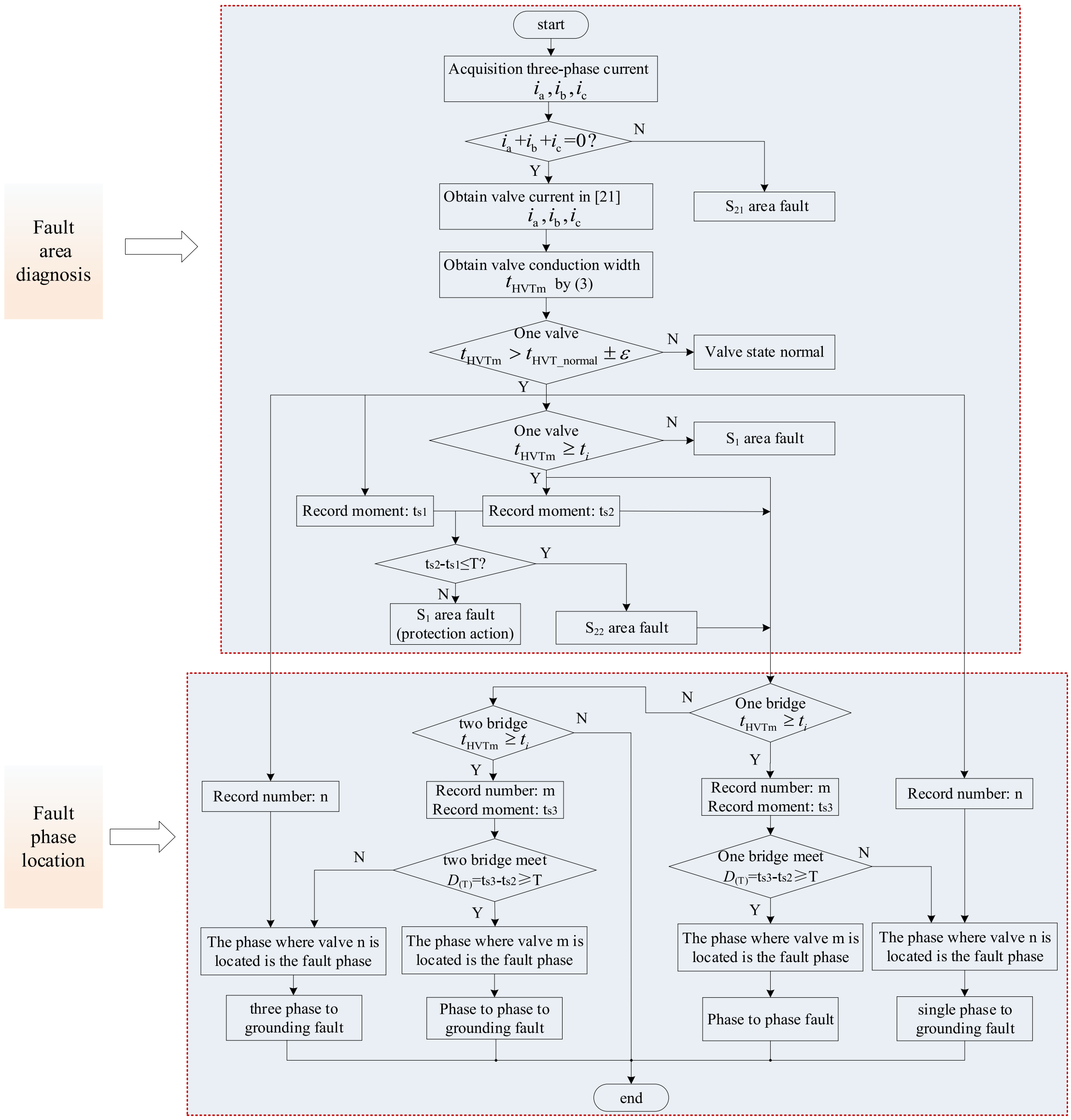


FIGURE 5. The flow chart of fault phase location.

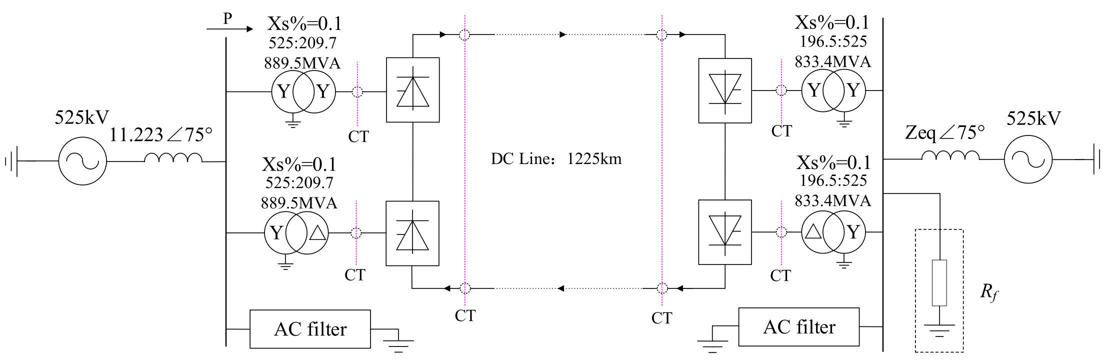
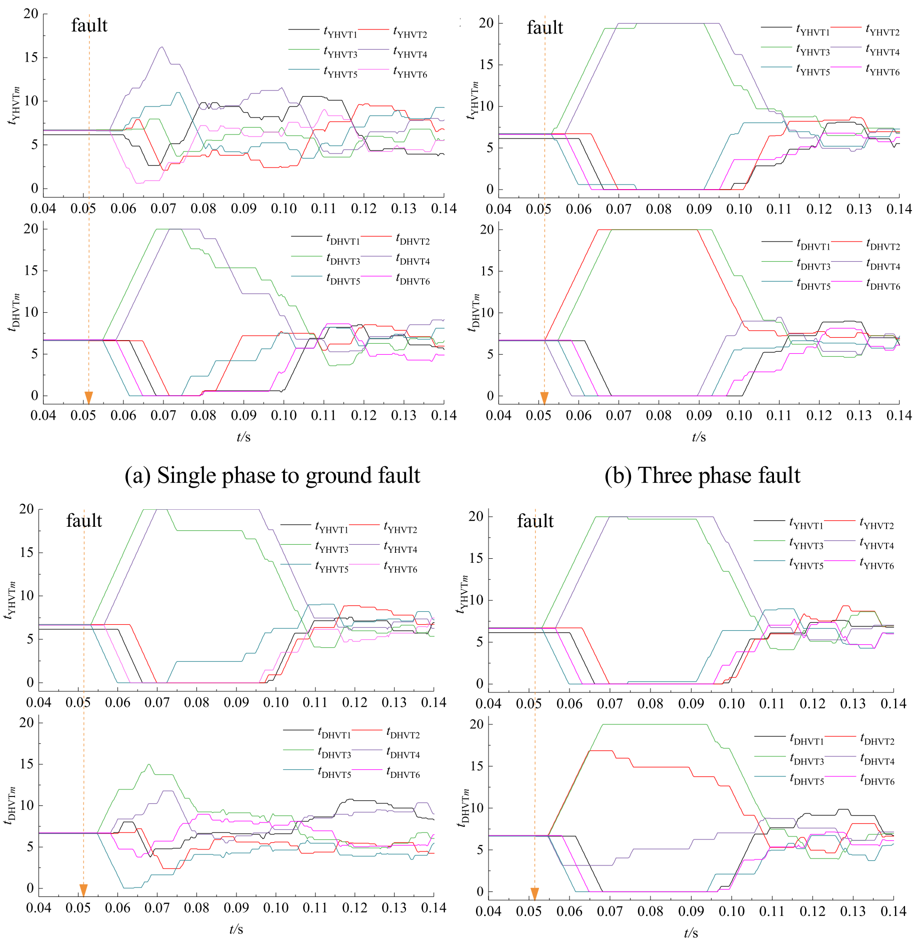


FIGURE 6. LCC-HVDC system model.

B. FAULT PHASE LOCATION

When a fault in the S_{22} area occurs, the converter valve of the fault phase always conducts during the power frequency cycle, and the minimum width of the valve current conduction time is t_i, which is different from the valve current conduction characteristics of other faults. When the current of the



(a) Single phase to ground fault (b) Three phase fault

(c) Phase-to-phase fault (d) Phase-to-phase-to-ground fault

FIGURE 7. Simulation results.

converter valve is fully conducted in a power frequency cycle after a fault, that is, the current virtual conduction width of the converter valve is t_i (hereinafter referred to as the periodic converter valve), the system fault is determined to be an external fault. According to the phase current fault characteristics of the four fault types after the fault and the periodic converter valve and the duration of the periodic converter valve (hereinafter referred to as widening, represented by $D_{(T)}$), the fault phase is identified. The flow chart is shown in Figure 5.

In Figure 5, the fault phase location process in the S_{22} area fault outside the 12-pulse converter region is as follows:

(1) Acquire the three-phase current of the converter double bridges: i_{aY}, i_{bY}, i_{cY}, i_{aD}, i_{bD}, and i_{cD}.

(2) Calculate whether the sum of three-phase AC current is 0. If the sum is 0, proceed to Step 3; otherwise, the fault is in the S_{21} area.

(3) According to literature [21], utilize the three-phase current to obtain the valve current.

(4) Test the converter valve in real time according to the valve state detection method, and obtain the virtual conduction width of each valve by using formula (3).

(5) Compare the virtual conduction width of each valve t_{HVTm} with the conduction width of the normal operating valve t_{HVT_normal}. If there is a converter valve $t_{HVTm} > t_{HVT\_normal} \pm \varepsilon$ (ε is measurement error, reference [22]), the state of the valve is abnormal. Record the number of the converter valve n and the abnormal time of the converter valve at this time t_{s1}, Then, proceed to step (6). Otherwise, the valve running state is normal.

(6) Continue to detect whether there is a converter valve virtual conduction width is $t_{HVTm} \geq t_i$. If no such width is detected, the system is faulty in S_1 area. Otherwise, proceed to step (8), and record the number of converter valves m. The recording moment is t_{s2}.

(7) Compare the moment of two converter valves with the same number, and count the difference as t_s. If there is a relationship $t_s = t_{s2} - t_{s1} \leq T$, the fault is an external AC fault. Then, proceed to step (8). Otherwise, the fault in area S_1 is caused by the converter protection action.

(8) In step (6), if the converter valve of only one bridge of the two bridges has relation $t_{HVTm} \geq t_i$, the fault is a single-phase to ground fault or a two-phase fault. Proceed to step (9). If the relation $t_{HVTm} \geq t_i$ exists in both converter

TABLE 1. Simulation results.

Fault type		t_{s1} /s	$t_{HVTm(max)}$ /ms	t_{s2} /s	t_s /ms	$t_{HVTm(max)}$ VT	$t_s \le T$ VT	t_{s3} /s	$D_{(T)} \geqslant T$ /ms	VT of $D_{(T)} \geqslant T$	VT and Fault phase
AG	YY	0.0565	15.95	-	-	4	-	-	-	-	VT4
	YD	0.0550	20	0.06825	13.25	3	3	0.0745	6.25	-	a phase to
		0.05825	20	0.0715	13.25	4	4	0.079	7.50	-	ground
AB	YY	0.05325	20	0.0665	13.25	3	3	0.091	24.5	3	VT3, VT4
		0.05650	20	0.07	13.5	4	4	0.09525	25.25	4	a phase to
	YD	0.05175	16.55	-	-	2	2	-	-	-	b phase
		0.0550	20	0.06825	13.25	3	3	0.0775	9.25	-	
ABG	YY	0.05325	20	0.0665	13.25	3	3	0.09125	24.75	3	VT3, VT4
		0.0565	20	0.07	13.5	4	4	0.0955	25.50	4	a phase to
	YD	0.0515	17.225		-	2	-	-	-	-	b phase
		0.0550	20	0.06825	13.25	3	3	0.094	25.75	3	ground
ABC	YY	0.05075	20	0.06325	12.5	1	1	0.08775	24.5	1	VT1, VT2,
		0.05325	20	0.0665	13.25	3	3	0.09125	24.75	3	VT3
											a phase
	YD	0.05175	20	0.06725	15.5	2	2	0.08925	22.00	2	b phase
		0.0550	20	0.06825	13.25	3	3	0.09325	25.00	3	c phase

valves of the two bridges, the fault is a three-phase fault or two-phase to ground fault. Proceed to step (10).

(9) If the converter valve in relation to $t_{HVTm} \geq t_i$ remains open until time t_{s3}, record the number of converter valves as m. If there is a broadening $D_{(T)} = t_{s3} - t_{s2} \geq$ T for a continuous on-going process, the phase where converter valve m is located is the fault phase, and the system has a phase-phase fault. Otherwise, it has a single-phase to ground fault, and the fault phase is the common phase of the phase where the n converter valve of the two bridges is located.

(10) If the converter valve in relation to $t_{HVTm} \geq t_i$ remains open until time t_{s3}, record the number of converter valves as m. When the expansion of the continuous conduction meets $D_{(T)} = t_{s3} - t_{s2} \geq$ T, the phase where the converter valve is located is the fault phase, and the system has a three-phase fault. Otherwise, the system has a phase-phase to ground fault, and the fault phase is the common phase of the phase where the m converter valve of the two bridges is located.

The purpose of fault phase determination is to protect the control system after the operation of the fault phase bypass pair to provide a low-resistance path for the DC current that does not flow through the converter transformer. Thus, the DC current no longer flows through the transformer. However, it plays a role in the isolation of AC and DC systems, preventing non-fault phase expansion system accidents.

V. SCHEME VERIFICATION

An HVDC engineering model is used as an example. The virtual conduction width of the converter valve is monitored online to realize fault determination and fault phase location. Its operating parameters are as follows: the rated power bipolar configuration is 3200 MW, the rated voltage is 525 kV, the transformer ratio is 196.5/525, the rated current is 3 kA, the system impedance angle is 75°, the resistance of the rectifier side is 2.912 Ω, the inductance is 0.0345 H, the resistance of the inverter side is 2.373 Ω, the inductance is 0.0282 H, the sampling rate is set as 0.05 ms, ε is 1.3 ms. The fault moment is set to 0.051 s (in the YY bridge, valve 2 of the c phase starts to commutate to valve 4 of the a phase). Different fault types of AC systems are applied at point F, as shown in Figure 6.

Typical case analysis: Four converter bus fault types are used to verify the locating scheme. The simulation results of different fault types are shown in Figure 7, and the data of the simulation results are shown in Table 1. The table header in Table 1 shows the variables involved in the flow chart, whose meanings are as follows: t_{s1} is the abnormal start time of the converter valve, $t_{HVTm(max)}$ is the maximum opening time width of the converter valve within the power frequency cycle, t_{s2} is the moment of the periodic converter valve, t_s is the time used from when the valve current opening is too long to the periodic converter valve, valve VT of $t_{HVTm(max)}$ is the number of the longest opening time width of the valve, valve VT of $t_s \leq T$ is the number of the periodic converter valve, t_{s3} is the widening of the periodic converter valve, valve VT of $D_{(T)} \geq T$ is the number of periodic converter valves with a spread greater than T, and fault phase valve VT is the fault phase converter valve and fault phase.

It can be seen from Figure 7 that when an AG fault occurs, the YY bridge valve is abnormal at 0.0565 s, and the maximum virtual conduction width of converter valve VT4 is 15.95 ms. At 0.055 ms, the state of the YD bridge valve is abnormal. The longest virtual conduction width of converter valves VT3 and VT4 is T, and the whole cycle is a conduction state. Along with state detection, the spread of periodic converter valve VT3 is 6.25 ms, and the spread of periodic converter valve VT4 is 7.5 ms. The spread of the periodic converter valve is less than T, and there is no valve of $D_{(T)} \geq T$ in the double bridge. According to the flow chart, the common valve whose virtual conduction width meets the requirements of the valve in the double bridge is VT4, so the fault phase is a phase. Therefore, a single-phase fault occurs in the system.

Similarly, the simulation results of the other three fault types can be analyzed in Figure 7.

According to the discrimination, the fault phase determined by the simulation results of the above four fault types is the same as that of the fault type set, which verifies the feasibility of the proposed scheme.

VI. CONCLUSION

In this paper, a location method for ac fault in LCC-HVDC system based on virtual conduction width characteristics is proposed. Through many theoretical analyses and simulation verifications, the following conclusions are drawn:

(1) Utilizing integrating of relative relationship of three-phase AC current on the valve-side, the valve virtual conduction width is obtained and the abnormal conduction state of valve is judged.

(2) Combined with the sum of the three-phase current on the valve-side and the valve virtual conduction width in a cycle used to judge the internal and external faults. When the virtual conduction width of the converter valve is less than one cycle, the system is an external fault. When the external fault occurs, based on the relationship between the broadening of the periodic converter valve and the power frequency period, the fault type is judged, so as to locate the fault phase.

(3) The simulation results show that the proposed location method can effectively identify the fault areas of the converter internal area and external area, and accurately locate different fault phase in the external area. The proposed fault location method is not affected by the fault occurrence moment and has strong applicability. This study provides a phase selection basis for the bypass pair strategy of the converter protection scheme.

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