Research On The Fault Tripping Criteria Of Stability Control Device Adapting To AC-DC Hybrid Power Grid

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Abstract. The fault of AC bus in HV (high-voltage) AC-DC hybrid system can cause consequential commutation failure in converter station, and it affect the correct operation of the current stability control device. The mechanism of phase commutation failure is explained in the paper, and the variation of each electrical quantity in AC/DC system during phase commutation failure is analyzed. In addition, it puts forward the new fault tripping criteria in stability control device which adapts to the fault characteristic of AC power grid nearby converter station and based on the comparison between phase voltage and sequence voltage, and sets up the hybrid system containing three DC transmission line under PSCAD/EMTDC to verify the effectiveness of the criteria.

Introduction

As an important way of asynchronous interconnection, HVDC transmission can transmit power with high voltage, large capacity and long distance, and it has already been developed by power grid in China [1]. It is a supplement of AC transmission, which will inevitably be hybrid connected with the current large-scale AC power grid. Due to its particular electrical characteristics, HVDC transmission brings many hidden dangers to the security and stability of AC-DC hybrid power grid while bringing benefit.

Ref. [2] analyzes the malfunction of relay protection during DC system commutation failure caused by AC system fault. By using the fault recorder, Ref. [3] restores the event of the maloperation of protection element at the two sides of 220kV line caused by commutation failure in DC converter station. Ref. [4] studies the principle of multi-infeed DC system commutation failure, and analyzes the characteristics of commutation failure under different types of AC fault. Some scholars like Thio think that the main reason causing commutation failure is the voltage dip when short-circuit fault happened on the commutation bus at inverter side[5]. The analysis and research above shows that there are large differences between the post-fault electrical characteristic of HV AC-DC hybrid system and traditional pure AC power grid, especially nearby electrical quantity of DC converter station. Therefore the grid fault tripping criteria in stability control device adapting to the traditional power grid has risks of maloperation or missoperation which are serious threats to the safety of power grid.

By analyzing the continuous commutation failure in inverter station caused by short-circuit fault on the AC bus nearby converter station, and the principle of commutation failure from the conduction angle and extinction angle of the thyristors, this article concludes the change law of converter bridge's conduction & extinction angle during commutation failure and voltage & current of the thyristors, further analyzes the electrical quantity characteristic of nearby AC system, puts forward new fault tripping criteria which based on the comparison between phase voltage and sequence voltage, and finally builds simulation models to verify the new criteria by using PSCAD/EMTDC.

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Analysis On Short-Circuit Fault Characteristic Of AC System Nearby HVDC Inverter

When metal short-circuit fault happens on the AC bus at inverter side in HVDC power transmission line, the voltage in fault phase drops rapidly, causing offset of conduction angle and extinction angle, and finally causing commutation failure in the inverter station[6]. The influence of commutation failure happening once in the converter station on the power grid is not severe, but if the unsuccessful restoration process causes continuous commutation failure, the DC transmission power will be interrupted, even the whole AC-DC hybrid system will lose stability[7]. Therefore this article will study the changing situation of some electrical quantities during two or more commutation failure processes.

Principle Of Continuous Commutation Failure. The structure diagram of inverter station is shown in Fig. 1, in which V1-V6 are commutated thyristors, $Ra = Rb = Rc = R$, which are the resistances of transmission line and transformer, $La = Lb = Lc = L$, which are the inductive reactance of the transformer original side, $La' = Lb' = Lc' = L'$ are the sub-side, and a, b, c represent phase.

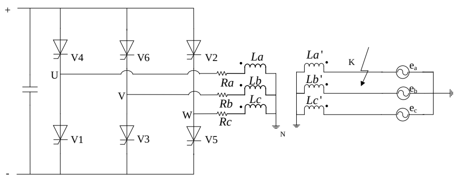

Fig. 1 Sketch diagram of inverter station

During normal operation, the conduction order of the thyristors is 123→23→234→34→345→45→456→56→561→61→612→12→123……The detailed conduction and turn-off process of thyristor V1 is shown in Fig. 2. When Uc=Ua and thyristor V1 is triggered, thyristor V5 starts to commutate to V1, after passing overlap angle μ , V5 turns off, and V1 conducts. Then at the angle γ before Ua=Ub, V1 turns off after passing overlap angle μ.

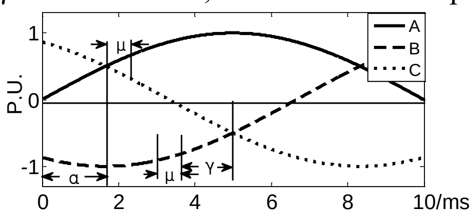

Fig. 2 Commutation process of V1

When short-circuit fault happens in phase A , its voltage drops rapidly, as shown in Fig. 3, the instantaneous voltage value decreases, causing the backward of commutation point, increase of overlap angle α and decrease of conduction area. The DC system using ABB predictive control strategy will keep the conduction area by decreasing the extinction angle γ, making the AC voltage unchanged after commutation.

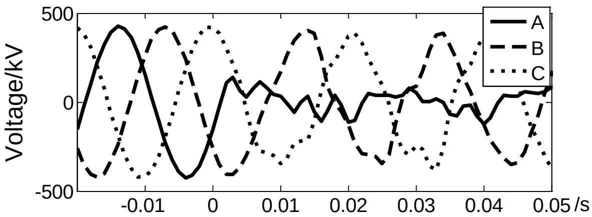

Fig. 3 Waveform of fault voltage

If γ reduces to an angle less than 7°, commutation failure will happen in the DC system; if the fault lasts a long time, it will lead to continuous commutation failure in DC system[8,9]. The conduction and extinction angle when continuous commutation failure happens are shown in Fig.4; If the extinction angle reduces to 0, the conduction angle will increases, then decreases due to the decrease of short-circuit commutation voltage, and the converter station does not stop working until the relay protection device operates.

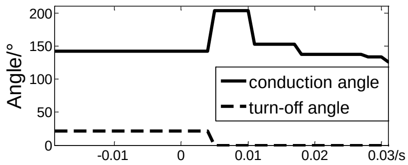

Fig.4 Changing situation of angle

The Influence Of Continuous Commutation Failure On Fault Characteristic. When continuous commutation failure happens in system, assume that V1 and V2 are conducted when fault starts, V1 begins to commutate to V3; when V3 is triggered and conducted, the reverse voltage V1 bears is Uba, at which time the commutation starts. Because the electrical potential of Ub is higher than Ua, the current through V1 decreases, and current through V3 increases. If the current through V1 does not reduce to 0 to complete turn-off before Uba changes direction, after Uba is less than zero, current through V1 will increase and current through V3 will reduce to 0 and turn off, and V1 will continue opening. Then V2 commutates to V4 , since there is no fault happening in phase B and C, V2 and V4 could commutate normally, at this time V1 and V4 will conduct simultaneously, DC transmission line is short-circuited, and the power could not be sent out, the voltage and current through thyristor are shown in Fig.5 and Fig.6.

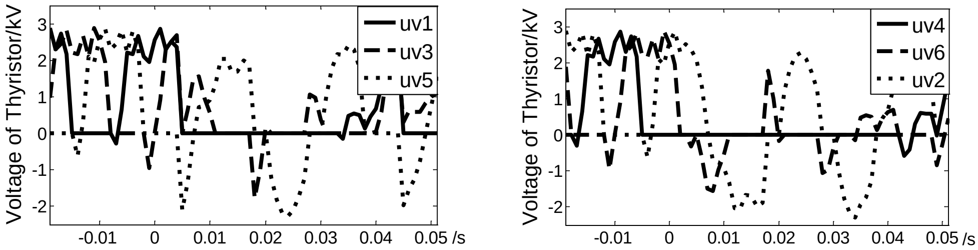

Fig. 4 Voltage at the two ends of thyristors

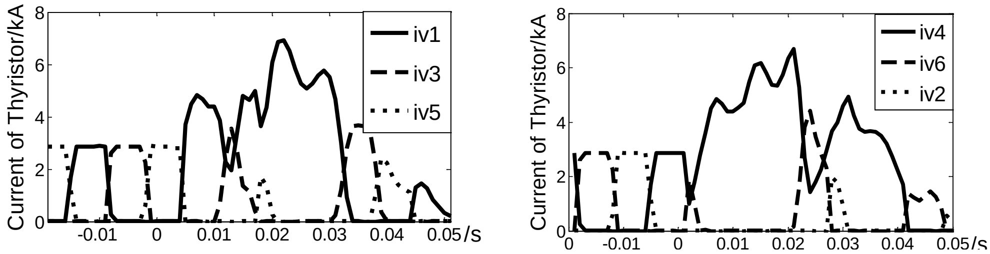

Fig. 5 Current through each thyristor

In the meantime, because grounding fault happened in phase A, and its load turns into small impedance and inductive reactance, as shown in Fig. 6, the current will continue increasing to about 2 times of rated current due to the current limitation of thyristor [10], and the short-circuited current will last for some time after commutation failure due to the ballasting of high inductance in transformer. As shown in Fig. 7. When the upper and lower bridge arms are conducted at the same time during continuous commutation failure, the DC system is short-circuited, the current through V1 and V4 continues increasing, and the AC bus current nearby converter station starts to decrease, then the AC power is introduced into DC transmission line, causing power converse[11].

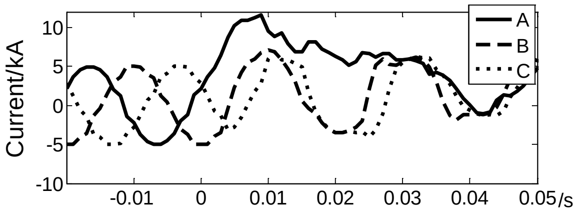

Fig. 6 Waveform of AC bus current

Further investigation on the amplitude of fault current when grounding short-circuited fault in phase A happens at different time can find: when fault happens at the time when V1 commutates to V3 and causing continuous commutation failure, V4 is conducted and there is only an electrical angle of 30°, at this time current in phase A has the time of increasing an electrical angle of 30°, the increased amplitude of short-circuit current is small, combined with the offset of overlap angle, the short-circuit current may not increase. When fault happens after the successful commutation from V1 to V3 which causes continuous commutation failure, current in phase A has the time of increasing an electrical angle of 330°, at this time the short-circuit current can reach the maximum. The simulation result is shown in Fig. 8.

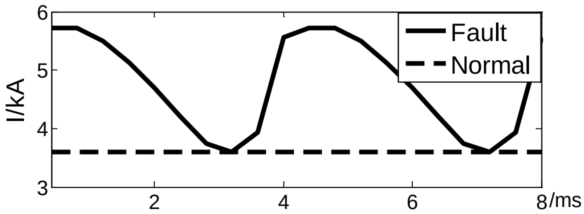

Fig. 7 Short-circuit current at different time

When Ua= Ub, V1 starts to commutate to V3, or V2 starts to commutate to V4, Which is at 5/6π and 11/12π, the short-circuit current reaches the minimum, then it increases immediately, reaching the maximum, finally it starts to decrease. Simulation result in Fig. 8 is in line with the theoretical analysis, showing that when short-circuit fault happens in the AC bus nearby converter station, the fault current may not increase obviously.

In pure AC system, when short-circuit fault happens, the voltage suddenly drops, and the current suddenly increases[12], therefore there are great differences between the electrical characteristics of AC-DC hybrid system nearby converter station and pure AC system.

Improved Scheme Of Fault Tripping Criteria Based On Phase/Sequence Voltage

The fault of power transmission line in stability control device is mainly divided into single-phase fault and two-phase fault. Most of the fault tripping criteria used presently mainly contain break variable start-up, the voltage decreasing while the current in the same phase increasing, and protection tripping signal appearing. If there is one phase voltage decreases while the current in the same phase increases, meanwhile there is one tripping signal within 15 seconds, then it can be considered as single phase transient fault; If there are at least two phases voltage decrease while the current in the same phase increases, meanwhile there is two-phase tripping signal, then it can be considered as phase-to-phase fault; if the phase-to-phase fault condition is not satisfied, but there is at least one phase voltage decreases while the current in the same phase increases, meanwhile there is two-phase tripping signal, it can be considered as permanent single-phase fault[13].

Combined with the fault tripping criteria in the stability control device above and analysis on the electrical quantity characteristic of continuous commutation failure when short-circuit fault happens nearby converter station, the amplitude of fault phase current has relation with the occurrence time. When short-circuit fault happens at the time of 5/6kπ(K is integer), the short-circuit current does not increase obviously, and the criteria may refuse tripping, therefore the break variable start-up and current increasing criteria in traditional stability control device need to be improved.

The AC transmission line nearby converter station is shown in Fig. 9, because the spatial scale of AC outgoing line nearby converter station is relatively small, its resistance could be ignored, and the phase angle of voltage and current at point M can be considered approximately equal to N (M and N are at the position where the protection is installed). Based on the conditions above the voltage amplitude of metal short-circuit fault phase and sequence can be analyzed, therefore the fault type can be discriminated[14], and it also can serve as the judging condition of fault tripping criteria nearby converter station of AC-DC hybrid system.

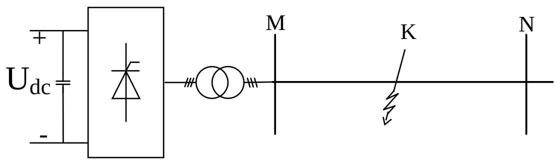

Fig. 9 Diagram of AC line nearby converter station

Single-Phase Fault. When short-circuit fault of A happens between M and N , it can be known from the fault boundary condition and sequence network structure that the sequence voltage of mounting point M satisfies $\arg(\dot{V}_{A1}/\dot{V}_{A2}) \approx 180°$ and $\arg(\dot{V}_{A2}/\dot{V}_{A0}) \approx 0°$. According to the distribution law, the further away from short-circuited point, the higher the positive-sequence voltage is, the lower the negative-sequence and zero-sequence voltage are. The phase relations between each sequence voltage are shown in Fig. 10, and at this time each phase voltage and sequence voltage at M satisfy the equation (1).

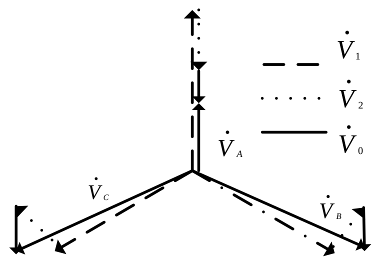

Fig. 10 Phasor diagram of sequence voltage

Note: V_1=V_{A1} is positive sequence, V_2=V_{A2} is negative sequence, and V_0=V_{A0} is zero sequence, the same below.

$$\begin{cases} \left|\dot{V}_A\right| = \left|\dot{V}_{A1}+\dot{V}_{A2}+\dot{V}_{A0}\right| < \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_B\right| = \left|a^2\dot{V}_{A1}+a\dot{V}_{A2}+\dot{V}_{A0}\right| > \left|a^2\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_C\right| = \left|a\dot{V}_{A1}+a^2\dot{V}_{A2}+\dot{V}_{A0}\right| > \left|a\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \end{cases} \quad (1)$$

It can be known by analyzing the equations above that in the single-phase grounding fault, the criteria that the fault phase voltage is lower than positive-sequence voltage and non-fault phase voltages are higher than positive-sequence voltage can be adopted, and the complete criteria scheme is shown in Fig. 11.

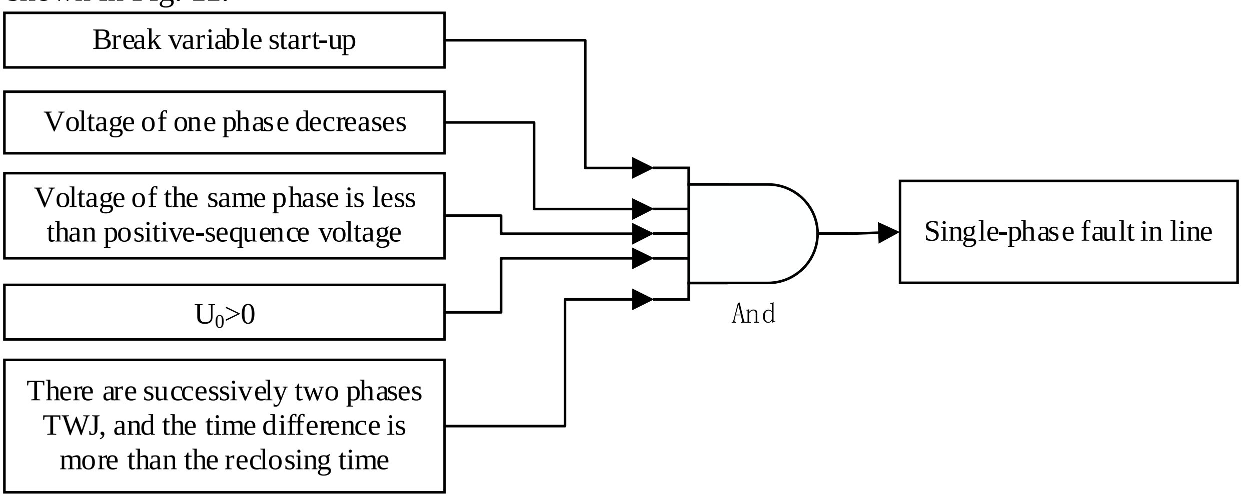

Fig. 11 Logic block diagram of single-phase fault tripping criteria

When in single-phase fault, transmission line of high voltage grade will directly trip three-phase switch, and the stability control device monitors that the two phases tripping signals almost come simultaneously. In order to prevent the single-phase fault from being misjudged as phase-to-phase fault, the zero-sequence component should be added to constitute integrated blocking auxiliary criteria by referencing to the behavior of relay protection, adding the reliability of stability control device.

Two-Phase Fault. In stability control device, two-phase grounding fault, phase-to-phase fault and three-phase grounding fault are all belong to two-phase fault, but with a little difference in phase and sequence voltage characteristic, which will be introduced separately here.

When a BC two-phase grounding fault happens, $\arg(\dot{V}_{A1}/\dot{V}_{A2}) \approx 0°$ and $\arg(\dot{V}_{A2}/\dot{V}_{A0}) \approx 0°$ can be obtained from fault boundary condition and sequence network structure. The amplitude of positive-sequence voltage is larger than negative-sequence and zero-sequence voltage at M. The phasor diagram of each sequence voltage is shown in Fig. 12, therefore each phase voltage and sequence voltage satisfy the equation (2):

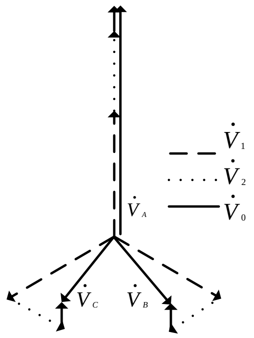

Fig. 12 Phasor diagram of sequence voltage

It can be known by analyzing the Eq. 2 that when a BC two-phase grounding fault happened, the amplitude of fault phase voltages are smaller than positive-sequence voltage, while the non-fault phase voltage amplitude is larger than positive-sequence voltage.

$$\begin{cases} \left|\dot{V}_A\right| = \left|\dot{V}_{A1} + \dot{V}_{A2} + \dot{V}_{A0}\right| > \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_B\right| = \left|a^2\dot{V}_{A1} + a\dot{V}_{A2} + \dot{V}_{A0}\right| < \left|a^2\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_C\right| = \left|a\dot{V}_{A1} + a^2\dot{V}_{A2} + \dot{V}_{A0}\right| < \left|a\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \end{cases} \tag{2}$$

When a BC phase-to-phase fault happens, its fault characteristic is a little different from grounding fault. The boundary condition of fault point satisfies $\dot{V}_b' = \dot{V}_c'$ and $\dot{i}_b' = -\dot{i}_c'$, therefore the voltages in phase B and C at M satisfy the equation (3).

$$\begin{cases} \dot{V}_b = \dot{V}_b' + j\omega L \dot{i}_b' \\ \dot{V}_c = \dot{V}_c' + j\omega L \dot{i}_c' \end{cases} \tag{3}$$

At this time $\dot{i}_b' = -\dot{i}_c'$, given $\dot{i}_c' > 0$, so $\dot{i}_b' < 0$, and also $\dot{V}_b' = \dot{V}_c'$, so $\left|\dot{V}_b\right| < \left|\dot{V}_c\right|$. The phasor diagram of three-phase voltage at point M is shown in Fig. 13, therefore each phase voltage and sequence voltage at M satisfy the equation (4).

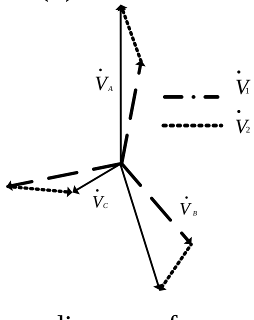

Fig. 13 Phasor diagram of sequence voltage

$$\begin{cases} \left|\dot{V}_A\right| = \left|\dot{V}_{A1} + \dot{V}_{A2}\right| > \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_B\right| = \left|a^2\dot{V}_{A1} + a\dot{V}_{A2}\right| < \left|a^2\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \\ \left|\dot{V}_C\right| = \left|a\dot{V}_{A1} + a^2\dot{V}_{A2}\right| > \left|a\dot{V}_{A1}\right| = \left|\dot{V}_{A1}\right| \end{cases} \tag{4}$$

According to the analysis, if $\dot{i}_c' < 0$ while $\dot{i}_b' > 0$, the Ub is larger than positive-sequence voltage at M, Uc is smaller than positive-sequence voltage. Therefore when in a BC phase-to-phase fault the voltage amplitude in one fault phase is smaller than positive-sequence voltage, the voltage amplitude in the other is larger than positive-sequence voltage, and the voltage amplitude in non-fault phase is also larger than positive-sequence voltage, without zero-sequence voltage.

When in a ABC three-phase grounding short-circuit fault, there are no zero-sequence and negative-sequence voltage in system, the three phases voltages decrease continuously and are equal to the positive-sequence voltage. Based on the characteristic of phase-to-phase fault above, the fault tripping criteria can be improved as shown in Fig. 14:

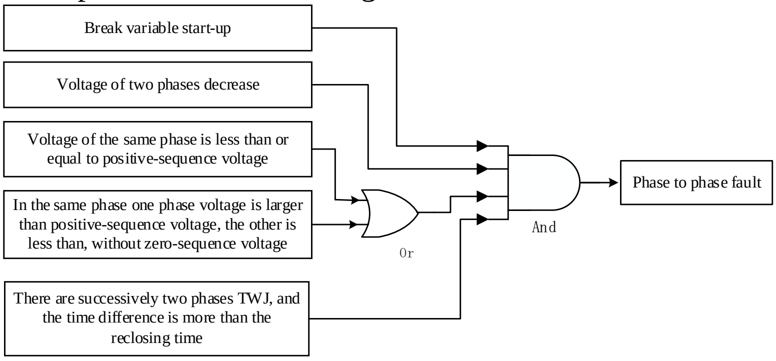

Fig. 14 Logic diagram of two phase fault

In each type of short-circuit fault, the variation of positive-sequence voltage amplitude is large, therefore the positive-sequence voltage break variable element can be used to replace the current break variable element, serving as the starting criteria condition of stability control system.

Simulation Results And Criteria Verification

This article builds a ±400kV AC-DC hybrid simulation model containing three DC transmission line based on the electromagnetic transient simulation software PSCAD/EMTDC. The topological structure is shown in Fig.15.

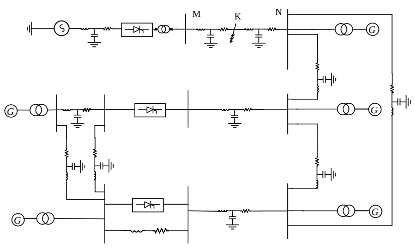

Fig. 15 AC-DC hybrid system

When verifying the reliability of fault tripping criteria proposed by this article, only the first half of cycle needs to be verified because the electrical quantity in the first half of cycle is equal to the second with direction opposite to each other. The Fig. 16 shows the changing situation of each electrical quantity when grounding fault in phase A happens in the first half of cycle, and gives analysis on the adaptation of old and new criteria.

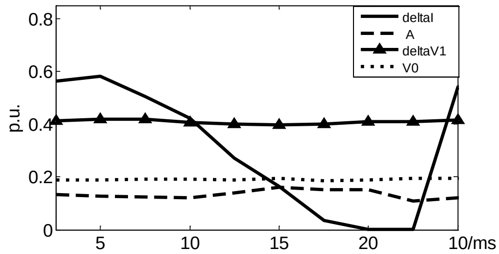

Fig. 16 Electrical quantity when short-circuit fault happens at different time in phase A

Fig. 16 shows that the delta I (the variable quantity of short-circuit current) is about 0 during the period of 8-9ms at the beginning of fundamental period, making the break variable element of traditional stability control device missoperation. However, the delta V1 chose by this article remains at about 0.4 times of rated value at any time, which could meet the starting requirements of break variable element. Meanwhile, U_A remains at about 0.15 times of rated value, and V_0 could remain at about 0.2 times of rated value during fault, therefore the new criteria could operate correctly at any time.

Further investigation on two phase fault could summarize the adaptation of old and new criteria at different time in table 1.

Table 1 adaptability of criteria

Fault type		0	2	4	6	8
AG	T	1	1	1	1	0
	N	1	1	1	1	1
BCG	T	0	0	1	0	1
	N	1	1	1	1	1
BC	T	0	0	1	1	1
	N	1	1	1	1	1
ABC	T	0	0	1	0	1
G	N	1	1	1	1	1

Note: T represents traditional criteria; N represents the new criteria; 1 represents that the criteria can operate correctly; 0 represents incorrectly.

Furthermore, the adaptation of the new fault tripping criteria in different position of line can find: the new criteria could operate correctly when different types of short-circuit fault happen in the head-end (5%), middle (50%) and end (95%) of the AC bus in converter station.

It can be known from the analysis of results above that because the amplitude of short-circuit fault current is affected by time, the traditional criteria will missoperation under some fault conditions, but the new criteria based on the comparison between phase voltage and sequence voltage could operate correctly under the fault conditions above, proving the effectiveness of new criteria.

Conclusion

In the AC-DC hybrid system, due to the nonlinearity of converter station and the conduction and turn-off characteristic of the thyristors, the changing characteristics of electrical quantity at the mounting position of fault protection in system, which is caused by commutation failure due to the AC line fault nearby converter station, is quite different from the traditional pure AC fault characteristic. The traditional fault tripping criteria of stability control device based on current condition may missoperation, while the criteria based on the comparison between phase and sequence voltage proposed by this article have the advantages of high stability, obvious fault distinguish and so on, and its reliability could be proved by PSCAD digital simulation. The analysis and results above provide theoretical foundation for the next step of RTDS.25(2013) 29-33.

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