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Boundary Protection Strategy for the VSC-MTDC under DC Faults

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Abstract: Multi-terminal HVDC transmission system based on voltage source converter is a promising topology for the integration of the renewable energy sources. The fault characteristics of VSC-MTDC system under DC side faults was analyzed in this paper, as well as the particular requirements for the protection strategy. On the basis of the work metioned above, a four-terminal DC connected transmission system model was built in PSCAD/EMTDC. The boundary protection algorithm was proposed and the wavelet analysis was introduced. The protection scheme for VSC-MTDC transmission lines is based on the attenuation characteristics of line boundary for high frequency transient signals, which constitutes the operation criteria of the boundary protection. The protection scheme puts forward an effective method for the protection selectivity of the VSC-MTDC transmission system.

Introduction

HVDC-Flexible has the ability to maintain the DC voltage polarity while the power flow reverses, which is conducive to constitute a flexible parallel multi-terminal HVDC system. Compared with two-terminal system, VSC-MTDC (Multi-terminal DC Transmission System based on VSC) is more flexible and reliable, which has great prospects in renewable energy generation, high voltage DC distribution system and asynchronous AC grid interconnection.

As the equipment manufacturing, control strategies and protection methods are more complicated than two-terminal HVDC, many key issues have not been resolved yet. The DC side faults are critical because the DC line and DC link capacitor discharge circuit are difficult to be blocked. Reference [1] analyzed the impact of DC line faults of the MTDC system and the corresponding control and protection method are given. Reference [2] analyzed the steady-state operation and transient fault process of four-terminal parallel HVDC systems. On the basis of the work mentioned above, a cooperation mode of the controller with the protection under fault occurred in DC transmission line was put forward. Currently, few studies have been focused on the working principle and algorithm of the protection. This paper presents a kind of DC transmission line boundary protection based on wavelet analysis. By the use of this non-unit transient based protection, the selectivity of the protection under DC faults was ensured. A four-terminal VSC-MTDC model was simulated in PSCAD/EMTDC and the data acquired from PSCAD was processed in Matlab using wavelet analysis packet.

Requirements for the Protection Strategy

The requirement for fast action of the protection equipment is extremely strict. Traditional protection methods with LCC (Line commutated converter) converters are not relevant to VSC as the operating principle is fundamentally different. The existing VSC-MTDC protection schemes are also not the best options. When a single line fault occurs, the Handshaking method disconnects the entire DC network by activating AC switchgear. Because of the temporary outage of the entire DC system, this method has a negative impact on the reliability of the combined AC and DC power systems. Most of the research on the protection strategy for VSC-MTDC focused only on a particular individual aspect, while this paper proposed combined attempts to optimize the system as a whole.

Optimization of the Converter Topology. Currently, there are three kinds of topologies being adopted by the HVDC flexible project: two-level VSC, three-level diode-clamped VSC and the modular multi-level converter. The three-phase two-level VSC topology is the most widely used topology nowadays. With the application of optimized PWM technology, the harmonic distortion is less than before, as well as the significant reduce of the switching frequency (reduced to 1150Hz). Besides, the MMC is well suitable to avoid the severe drawbacks of conventional VSC except for DC pole-to-pole fault. When DC pole-to-pole fault occurs, the anti-parallel diodes in the sub-modules keep conducting during the fault, leaving the HBMMC (Half-Bridge MMC) out of control. Considering the HBMMC cannot cut off the short circuit current by itself, Marquardt has introduced the FBMMC (Full-Bridge MMC) which has strong ability to ride through serious DC faults[3]. From an economic point of view, the FBMMC requires double the number of IGBTs and causes almost double the operating losses in normal operation, which will be a severe drawback for massive application. In spite of the fact that the HBMMC cannot limit a DC line pole-to-pole fault, it is still a promising topology, which is a trade-off option considering both economic costs and function. Hence, the availability of HVDC circuit breakers (CBs) will be critical for the reliability of DC networks.

Optimization of the DC Grid Topology. One possible MTDC topology for the future DC grid is shown in Fig. 1. Via the bipolar DC transmission lines, each converter is connected to the other three, which forms a meshed HVDC network. The AC system is connected by one converter station, while the converter stations are connected to the DC grid via HVDC circuit breakers. When a DC fault occurs, the circuit breakers can cut off the faulted branch in a selective manner within a few milliseconds[4].

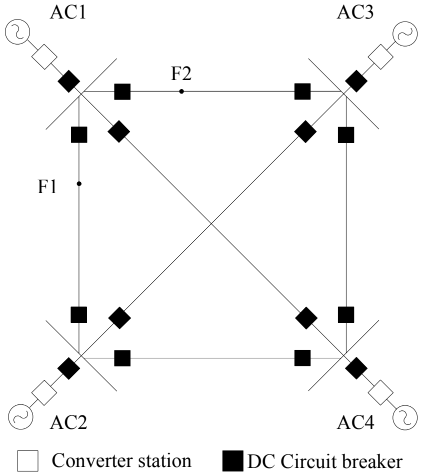


Fig. 1 A typical topology diagram of multi-terminal DC transmission system

Optimization of the HVDC CBs. With the increasing demand for DC switchgears, the practical HVDC circuit breakers have been one of the key problems for the popularization of DC grids. The most commonly used HVDC circuit breaker is divided into three categories: mechanical breaker based on separating metal contacts, solid-state DC circuit breaker (SSCB) based on power electronic devices and a hybrid combination of the above two. The significant advantage of SSCB is that the switching time can be as low as a few microseconds, while the main drawbacks are costs and on-state power losses. The forward conduction losses of SSCBs are 0.1-0.4% of the transmitted power[5,6]. Considering the fact that no other HVDC circuit breaker concept is capable of breaking circuit in 1 ms, the SSCB is the only feasible solution nowadays.

DC Fault Characteristics

Typically, each converter station adopts bipolar symmetry operation mode. Thus the DC line fault types can be divided into DC pole-to-pole fault, line-to-ground fault and open-circuit fault. Since there is no effective technology to control the DC fault current, the DC cable was adopted to improve system reliability and availability. As a consequence, the DC line faults were permanent usually, which were caused by external mechanical stress. In comparison to two-terminal VSC-HVDC systems, an addition difficulty appears in an MTDC system. The DC bus voltage will affect other two nearest converter stations, the fault might be detected in the other healthy cables connected to the same DC bus. To solve the selectivity problems existing in MTDC system, the novel non-unit main protection algorithm based on transient signals was introduced in the next chapter.

Boundary protection based on wavelet analysis

With the development of VSC-MTDC system, the traditional protection will not meet the requirements for selectivity and fast clearance. The boundary protection, which relies on the information of non-unit transients, is proposed in this paper. Because of the circuit breakers, DC-side reactors and other devices connected at line ends, the DC transmission line boundaries do exist, which lead to different characters of signals at line boundaries between internal and external faults. Considering the DC-side reactor in VSC-HVDC is much smaller than that in the conventional LCC-HVDC, it is necessary to verify that whether the boundary protection is feasible for the VSC-HVDC field[7].

Criteria of the Starting Unit. When a DC fault occurs, the abrupt change of voltage can lead to a singularity of transients. The Lipschitz exponent is a measurement of the strength of a singularity. The Lipchitz exponent of Gaussian white noise and impulse noise is negative, while the Lipschitz exponent of faulted transients values between 0 and 1. It has been proved that the Lipschitz exponent of a local singularity can be characterized by wavelet transform[8]. The wavelet transformation modulus maximum increases as the scale increases during the fault, while the wavelet transformation modulus maximum decreases as the scale increases when it comes to noise or impulse. Thus the algorithm of starting unit is shown as follows:

1) Sample the voltage and obtain the line mode voltage through phase-mode transformation.

$$U_{\mathrm{m}}(\mathrm{k})=U_{\mathrm{p}}(\mathrm{k})-U_{\mathrm{n}}(\mathrm{k}). \tag{1}$$

2) Use three level wavelet analysis on the $U_{\mathrm{m}}(\mathrm{k})$, if the wavelet transformation modulus maximum presents to be $|W1|<|W2|<|W3|$, it is a fault, otherwise determined to be disturbance or noise.

Criteria of the Directional Unit. By analyzing the frequency response of reflection and refraction in the DC line boundary, it was found that the different characteristics of transient components are mainly focused on $[0, 2T]$, where T is traveling time from one end to another. The ratio of wavelet spectra energy of backward traveling wave to that of forward traveling wave is larger than 1 when positive-directional fault occurs; however, the ratio is less than 1 when reverse fault occurs. Thus the algorithm of directional unit is shown as follows:

(1) Calculate the forward and backward traveling wave of the line-mode transient components.

$$f_{\mathrm{m}}(k)=u_{\mathrm{m}}(k)+z_{\mathrm{c}}i_{\mathrm{m}}(k). \tag{2}$$

$$b_{\mathrm{m}}(k)=u_{\mathrm{m}}(k)-z_{\mathrm{c}}i_{\mathrm{m}}(k). \tag{3}$$

(2) Use wavelet analysis on the forward and backward traveling wave individually, which is $W_{\mathrm{f}}(k)$ and $W_{\mathrm{b}}(k)$

(3) Calculate the wavelet spectra energy of forward and backward traveling wave in the time span $[0, 2T]$ individually. The time window width is N.

$$E_f=\frac{1}{N}\sum\left|W_f(k)\right|^2 . \tag{4}$$

$$E_b=\frac{1}{N}\sum\left|W_b(k)\right|^2 . \tag{5}$$

(4) If it could meet the requirement,

$$E_b/E_f>k_{\mathrm{dl}}. \tag{6}$$

it is judged as a positive-directional fault, otherwise determined to be a reverse fault. Take k_{dl}=0.8 to increase the operation margin.

Criteria of the Boundary Unit. The wavelet spectra energy of transient components in high frequency band caused by an internal fault is much larger than that caused by an external fault[9]. Thus the algorithm of boundary unit is shown as follows:

(1) Calculate the first and third level wavelet coefficients of the high frequency transient components, the time window width is *N*.

$$E_{i1} = \frac{1}{N}\sum_{k}\left|W_{i1}(k)\right|^{2} . \tag{7}$$

$$E_{i3} = \frac{1}{N}\sum_{k}\left|W_{i3}(k)\right|^{2} . \tag{8}$$

(2) If it could meet the requirement,

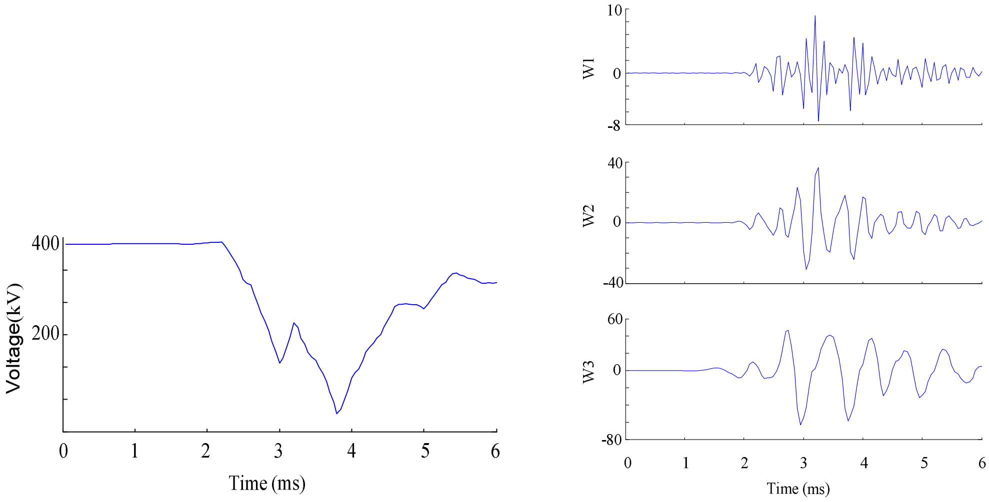
$$E_{\mathrm{i1}}/E_{\mathrm{i3}}>K_{\mathrm{k}}. \tag{9}$$

it is judged as an internal fault, otherwise determined to be an external fault. Take K_{k}=0.8 to increase the operation margin.

Fault Simulations

The VSC-MTDC model in Fig. 1 was adopted and the DC line pole-to-pole fault was simulated. The DC line was chosen to be frequency dependent (Phase) cable. The length of cable_{12} is 100km and the cable_{14} is 150km. In consideration of the balance of suppressing noise and accuracy of detection, the cubic B-spline wavelet was adopted. The sampling rate is 20 kHz and the time window width is 6ms.

Criteria of the Starting Unit. The voltage waveform and wavelet transformation modulus maximum of DC pole-to-pole fault at F_1 are illustrated in Fig. 2.

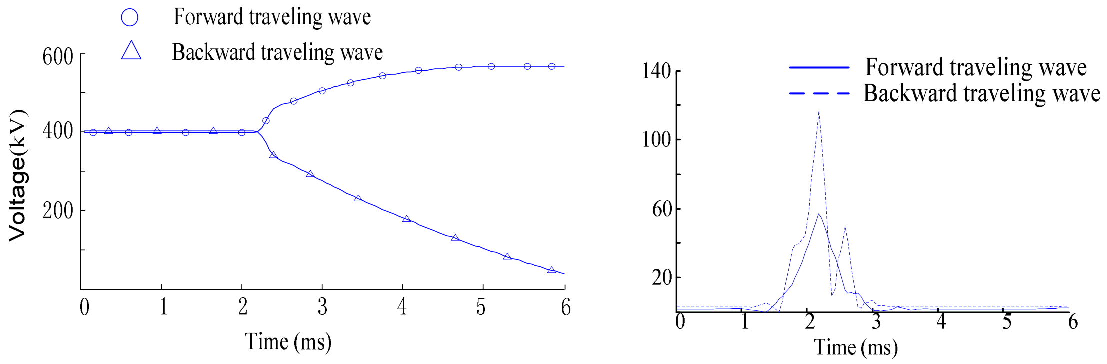


(a) (b)

Fig. 2 Voltage waveform and wavelet transformation modulus maximum of DC pole-to-pole fault

Fig.2(b) shows the wavelet transformation modulus maximum |W1|=8.934; |W2|=36.46; |W3|=62.91. |W1|<|W2|<|W3|, so the starting unit activates.

Criteria of the Directional Unit. The traveling wave waveform and wavelet spectra energy of the fault at F_1 are illustrated in Fig. 3.

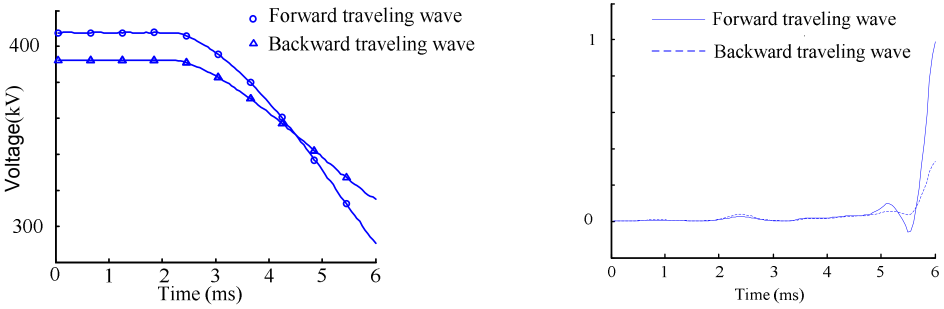


(a) (b)

Fig. 3 Traveling wave waveform and wavelet spectra energy of the fault at F_1

Fig. 3(b) shows E_b=10.4195, E_f=9.8141, E_b/E_f=1.06>0.8, it is a positive-directional fault.

The traveling wave waveform and wavelet spectra energy of the fault at F_2 are illustrated in Fig. 4.

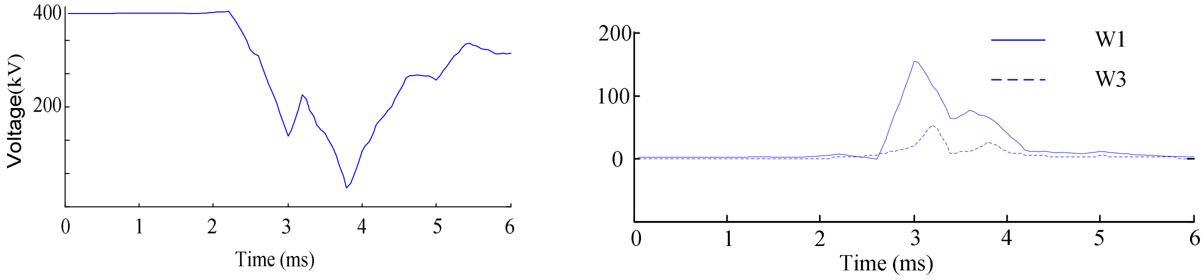


(a) (b)

Fig. 4 Traveling wave waveform and wavelet spectra energy of the fault at F_2

Fig.4(b) shows E_b=1.9486, E_f=26.4553, E_b/E_f=0.074<0.8, it is a reverse fault.

Criteria of the Boundary Unit. The waveform of transient voltage and its wavelet spectra energy of the fault at F_1 are illustrated in Fig. 5.



(a) (b)

Fig. 5 Waveform of transient voltage and its wavelet spectra energy of the fault at F_1

Fig. 5(b) shows E_{i1}=95.58, E_{i3}=46.27, E_{i1}/E_{i3}=2.07>0.8, it is an internal fault, the boundary unit operates.

The waveform of transient voltage and its wavelet spectra energy of the fault at F2 are illustrated in Fig. 6.

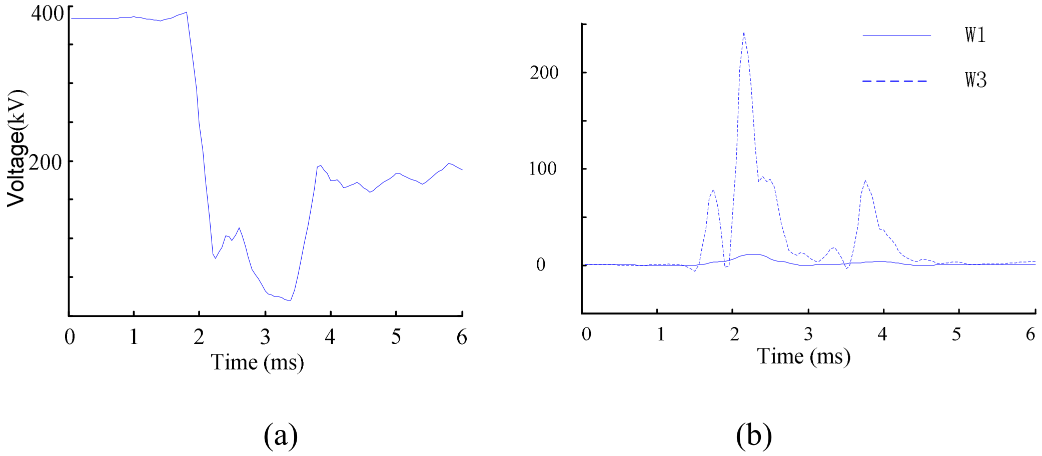


Fig. 6 Waveform of transient voltage and its wavelet energy of the fault at F_2

Fig. 6(b) shows E_{i1}=1.618, E_{i3}=23.62, $E_{i1}/E_{i3}=0.07<0.8$, it is an external fault, the boundary unit will be blocked.

Conclusions

The fast and reliable detection of DC faults in meshed DC system is a prerequisite for the protection strategy. Throughout the previous sections of the text, several aspects of the protection strategy for VSC-MTDC system were analyzed.

1) The DC fault characteristics in VSC-MTDC system were analyzed and the selectivity problem was revealed.
2) To solve the selectivity problem, the boundary protection was proposed in this paper. The wavelet analysis was used to select the faulted cable in a four-terminal DC network.
3) The proposed protection algorithms were simulated in a four-terminal VSC-MTDC model, the simulation results were post-processed by Matlab. The simulation results have proven the effectiveness of the proposed protection algorithms and the selectivity of protection strategy can be ensured.

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