

Voltage pole-wave protection scheme for multi-terminal DC grid

 eISSN 2051-3305
 Received on 22nd August 2018
 Accepted on 19th September 2018
 E-First on 29th November 2018
 doi: 10.1049/joe.2018.8415
 www.ietdl.org

 Zhongrun Xie¹, Guibin Zou¹ ✉, Lei Gao², Jie Zhang¹, Houlei Gao¹
¹Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education, School of Electrical Engineering, Shandong University, Ji'nan, People's Republic of China

²State Grid Ji'nan Electric Power Company, Ji'nan, People's Republic of China

✉ E-mail: guibinzou@sdu.edu.cn

Abstract: With the rapid development of flexible DC transmission and multi-terminal high voltage direct current transmission (HVDC) (MTDC) grid, the protection schemes of flexible DC transmission lines are still the traditional methods, which do not achieve the properties of fast and selective operation in the DC grid. In this study, using Zhangbei MTDC grid as the research object, the fast protection of DC transmission lines of MTDC grid has been studied. First, the voltage response characteristics of fault line and non-fault line at the boundary of DC lines are analysed. On the basis of this, using wavelet transform to extract the characteristic value of voltage pole-wave, this study put forward a high-speed non-unit protection criterion to identify the internal and external faults. In addition, two auxiliary criteria are constructed to identify lightning disturbance and faulted pole, respectively. Finally, a simulation model of Zhangbei MTDC grid is constructed, and the effectiveness of the proposed protection scheme is verified by extensive simulation results.

1 Introduction

In today's electric power system, the proportion of distributed generation gradually increases year by year, and the proportion of DC loads also rises following the growing number of new energy vehicles and other DC devices. Meanwhile, with the widespread application of power electronic equipment, the flexible DC transmission and distribution systems based on a voltage source converter (VSC) are becoming one of the mainstream trends in the Global Energy Interconnection. Among them, the multi-terminal high voltage direct current transmission (HVDC) (MTDC) grid is the focus of research and application in the field of VSC-HVDC. It can achieve multiple power supply and receiving, save the operating cost in the case of multiple converter stations, and has obvious advantages in power supply reliability [1].

Generally, the topology of the MTDC grid is ring or lattice, when a short-circuit fault occurs on the DC side, the fault current will be sensed in all converters and lines. Its one-to-multiple structure increases the difficulty in the selectivity of DC line protection. In addition, there are fewer elements in the MTDC grid, which is a kind of 'low inertia and low damping' system. When a fault occurs, it instantly affects the whole grid and its fault current rises very quickly to the peak value within several microseconds. To avoid destroying the converter valves and improve the reliability of power supply, the DC line protection schemes must rapidly detect the fault within 2 ms or so. Therefore, it is essential to study fast and selective line protection in the MTDC grid [2]. At present, many experts and scholars have done substantive research in the field of DC line protection, which can be classified into two categories, namely, unit protection and non-unit protection.

Unit protection algorithms use differential current, travelling wave, or directional information to distinguish the faulted line [3–5]. These data need to be exchanged between both ends of line. Although these unit algorithms have absolute selectivity, they are not suitable as the main protection schemes for the DC line of the MTDC grid due to the low speed. To achieve ultra-high speed protection, it has to use single-end data to construct protection criterion.

Non-unit protection algorithms commonly use travelling wave signal, voltage deviation etc. [6, 7]. The current protection methods are mostly used for the HVDC system with point-to-point or radial topology [8, 9]. However, for the meshed MTDC grid, a few

protection methods have been proposed [10–12]. The aforementioned non-unit protection schemes have a fast operation speed due to using transient signals to identify faults, but they are vulnerable to high-frequency interference signals such as lightning and noises. Moreover, most of the proposed protection methods for the MTDC grid do not study the effects caused by lightning disturbance.

Based on the current research status for HVDC line protection and the fault characteristic of the MTDC grid, this paper proposes a novel non-unit ultra-high-speed protection scheme, which includes three criteria: one is to discriminate the internal line fault from the external fault, second is to distinguish between the lightning disturbance and the fault, and third is the faulted pole identification criterion. To validate the feasibility of the proposed protection scheme, a four-terminal flexible HVDC grid model is constructed according to the actual parameters of Zhanbei ± 500 -kV DC grid in China, and simulation results show the good performance of the proposed protection scheme.

2 Analysis of the MTDC grid

2.1 Boundary characteristics of DC lines

When a short-circuit fault occurs on the DC side of the MTDC grid, the short-circuit current can reach several tens of kilo-amperes within a few milliseconds. Therefore, it has to take countermeasures to limit fault current of the MTDC grid. Current limiting reactors, which are installed at both ends of the DC line, are the most commonly used fault current limiters. The reactor can make the fault voltage and current changing more smoothly. Therefore, the speed of fault current rising is restrained, and the converter station blocking is delayed. As a result, the requirement of speed for protection algorithm and DC circuit breaker (DCCB) detecting and clearing fault can be reduced. In addition, the current limiting reactors form a natural boundary between the adjacent DC lines and create a precondition for DC line non-unit protection. The following specifically analyses the reactors' blocking characteristics to high-frequency signals.

Fig. 1 shows the boundary structure between two adjacent DC lines of a MTDC grid. In Fig. 1, a ground fault at f , which is 100 km away from relay 1, is the internal fault for line 1 and the external fault for line 2, u_i is the fault additional voltage source, u_o

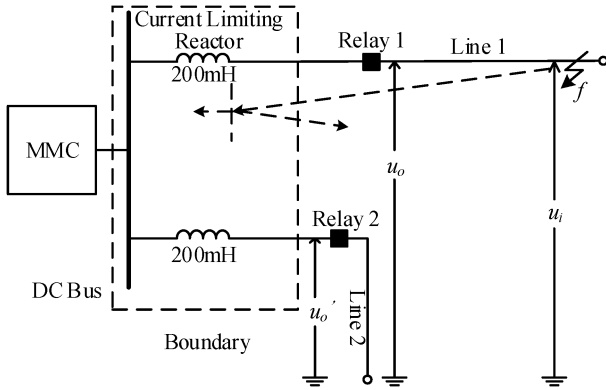


Fig. 1 Boundary of adjacent DC lines

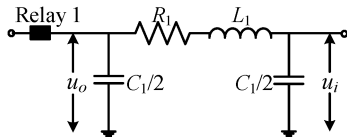


Fig. 2 Equivalent circuit for internal fault

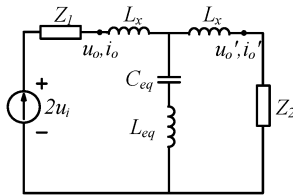


Fig. 3 Peterson equivalent circuit for external fault

is the fault caused by voltage at the relay 1, and u_o' is the fault caused by voltage at relay 2. When a fault occurs, u_i generated transient travelling wave propagates to both ends of line 1, and the refraction and reflection of travelling wave will appear at where the wave impedance changes.

For internal fault, the transient voltage travelling wave detected by relay 1 only passes through line 1, so there is little loss when it propagates within line 1. The approximate equivalent circuit is shown in Fig. 2, where R_1 , L_1 and C_1 are the lumped parameters of line 1.

For external fault, the transient voltage travelling wave passes through two reactors and an MMC station. So, Peterson's law can be used and the equivalent circuit is shown in Fig. 3, where Z_1 and Z_2 are the wave impedances of line 1 and line 2, respectively, C_{eq} and L_{eq} are the equivalent capacitor and inductor of MMC, which can be expressed as follows, respectively:

$$C_{eq} = \frac{6C}{N} \quad (1)$$

$$L_{eq} = \frac{2}{3}L_a \quad (2)$$

According to Fig. 3, the high-frequency signals will be greatly decayed after they pass through the DC line boundary. Therefore, the DC line boundary has the capability to block high-frequency signals, and its blocking effect enhances with increasing signal frequency. Also, for fault signals, it will be nearly unchangeable at the internal zone but seriously decayed at the external zone. With these high-frequency signals as characteristic quantities, the internal relays can detect significant fault signals but external relays cannot.

Therefore, the non-unit DC line protection scheme can discriminate internal line faults from external faults by comparing the magnitude of high-frequency components of fault transient signals.

In the initial phase of internal fault of a DC line, the first fault transient voltage signal arriving at relay is the backward travelling

wave, whose propagation path is from the fault point to both ends of the line. In order to make the fault signature more clearly, this paper adopts the voltage pole-wave, which represents voltage backward travelling wave in essence, as the fault characteristic signal. Voltage pole-wave can be written as $p(k)$, which is defined as follows:

$$p(k) = Z\Delta i(k) - \Delta u(k) \quad (3)$$

where k denotes the sampling point, Z is the wave impedance of the DC line, and $\Delta i(t)$ and $\Delta u(t)$ are the fault components of current and voltage, respectively.

2.2 Analysis of lightning strokes

The long overhead lines are subject to lightning strokes. If the lightning stroke does not cause any fault, it will still generate the transient high-frequency signals, which adversely influences the protection of lines. The lightning wave is a kind of unipolar pulse wave, its high-frequency components are abundant but low-frequency components are weak. So, when a lightning stroke, whether it causes disturbance or fault, occurs on the DC line, the generated transient signal $p(k)$ on the line contains a large number of high-frequency components. Also, when a lightning fault or short-circuit fault occurs on the DC line, $p(k)$ has a large number of low-frequency components as well.

Take the lightning disturbance, general short-circuit fault, and lightning fault as examples, the generated signals $p(k)$ for three cases and their frequency spectrum maps of different frequency bands are calculated, which are shown in Fig. 4. The amplitudes of the lightning current are 15 and 50 kA, respectively, for lightning disturbance and lightning fault.

According to Fig. 4, the waveform of lightning disturbance is very sharp, and its components above 200 Hz are large. As for lightning fault and short-circuit fault, their high-frequency components are lower than low-frequency components below 100 Hz.

3 Transient voltage pole-wave protection based on wavelet transform

3.1 Protection start-up criterion

In order to prevent protection frequently starting up caused from the noise interference and voltage fluctuation, a quick start-up criterion of protection scheme is established:

$$|\Delta P| > \Delta_{set} \quad (4)$$

where $\Delta P = p(k) - p(k-1)$, ΔP is the difference between two consecutive sampling points, Δ_{set} is the threshold value set as $0.01U_e$, and U_e is the rated voltage of the DC line. If ΔP meets (4), the DC line protection algorithm starts up, records the sudden change moment of $p(k)$, and takes the sudden change point and subsequent sampling data within 0.5 ms as data window for the next steps of fault identification.

3.2 Identification criterion for internal and external faults

This paper selects the high-frequency component of $p(k)$ to identify the internal and external faults and adopts the Mallat algorithm to extract the component. The Mallat algorithm is a kind of the discrete wavelet transform, which has fast running speed and requires less computing capability. The Mallat algorithm consists of a series of high-pass filters and low-pass filters, so it can decompose signals in multiple scales of frequency domain. The original signal will be decompose into $d_j(k)$ and $a_j(k)$; $d_j(k)$ denotes the j th-level high-frequency coefficient, and $a_j(k)$ represents the j th-level low-frequency coefficient. According to the frequency band of the original signal, each coefficient has a specific frequency band.

Using the wavelet modulus maximum of $p(k)$ to identify the internal and external faults, this paper proposes a voltage pole-

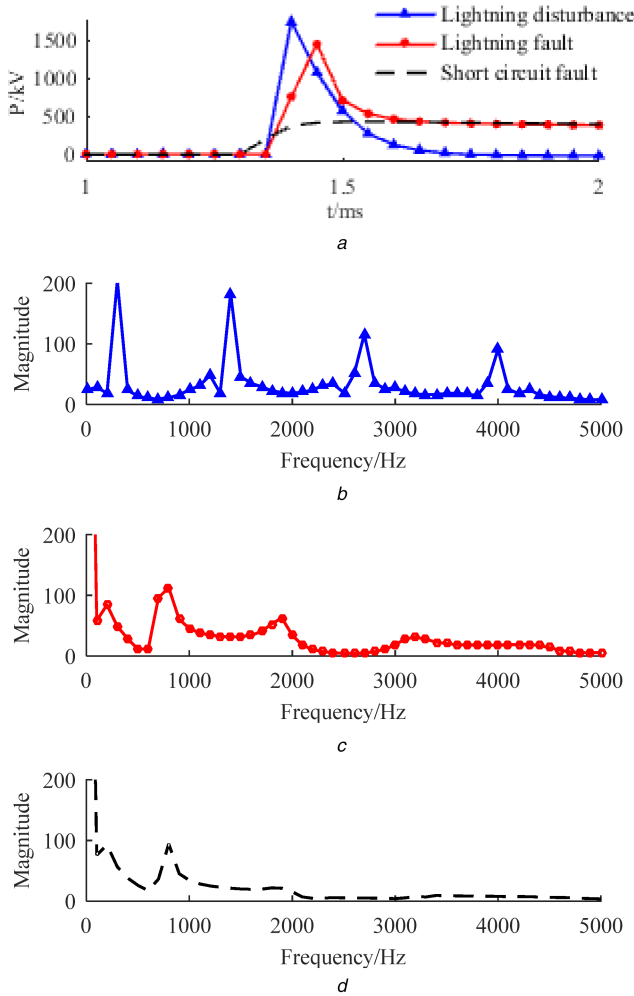


Fig. 4 Pole-wave waveforms of DC lines under lightning situations and their frequency spectrum maps

(a) Pole-wave waveforms of DC lines under lightning situations, (b) Frequency spectrum map of lightning disturbance, (c) Frequency spectrum map of lightning fault, (d) Frequency spectrum map of short-circuit fault

wave based protection criterion. When a fault occurs on the DC line, the wavelet modulus maximum of the high-frequency transient component detected on the faulted line is much larger than that detected on the non-faulted line. So, the identification criterion for internal and external faults can be constructed as follows:

$$\begin{cases} D_j > D_{\text{set}} & \text{internal fault} \\ D_j \leq D_{\text{set}} & \text{external fault} \end{cases} \quad (5)$$

where D_{set} is the threshold set by the worst external fault case that DC line protection may detect. D_j is the maximal absolute value of modulus maximum of $d_j(k)$.

Based on the above analysis, in order to meet the speed requirement of protection without giving up the reliability and selectivity, the length of wavelet data window is set as 0.5 ms. In the constructed simulation model, the sampling rate is adopted as 20 kHz. So, this algorithm chooses D_3 , which is calculated by the third-level high-frequency wavelet coefficient $d_3(k)$, as the criterion for higher reliability; the corresponding frequency band of $d_3(k)$ is 625–1250 Hz.

3.3 Lightning disturbance identification criterion

For the identification criterion of lightning, it should be ensured that the protection algorithm does not maloperate in the condition of lightning disturbance, and it will proceed to the next step in the case of lightning fault and short-circuit fault. This paper uses the

energy ratio of high-to-low frequency voltage pole-wave as the identification criterion for avoiding the impact of lightning disturbance:

$$\begin{cases} \eta_a = \frac{E_H}{E_L} \geq k_{\text{Th}} & \text{lightning disturbance} \\ \eta_a < k_{\text{Th}} & \text{internal fault} \end{cases} \quad (6)$$

where k_{Th} is the present threshold, E_H is the energy sum of $d_2(k)$ to $d_5(k)$, E_L is the energy of $a_6(k)$. With the sampling rate adopted as 20 kHz in the constructed simulation model, E_H and E_L can be adopted as (7) and (8), so the frequency band of E_H is 156–2500 Hz and the frequency band of E_L is 0–78 Hz:

$$E_H = \sum_{j=2}^5 E_{Hj} = \sum_{j=2}^5 \sum_{k=1}^n |d_j(k)|^2 \quad (7)$$

$$E_L = \sum_{k=1}^n |a_6(k)|^2 \quad (8)$$

3.4 Faulted pole identification criterion

Due to the coupling effect of bipolar transmission lines, the fault signals of pole-to-ground fault will appear on the line of normal pole. Considering the criterion in Section 3.2, when a pole-to-ground fault occurs, the relay of faulted line will detect different D_3 on positive and negative lines, and the D_3 of faulted pole is much larger than that of normal pole.

Considering both unipolar and bipolar faults, the D_3 ratio of positive line to negative line can be used as the faulted pole identification criterion. Assume that D_{3p} represents D_3 of the positive line, D_{3n} denotes D_3 of the negative line, and the ratio η_b can be defined as follows:

$$\eta_b = \frac{D_{3p}}{D_{3n}} \quad (9)$$

Therefore, the faulted pole identification criterion is written as follows:

$$\begin{cases} \eta_b \geq \eta_1 & \text{positive line fault} \\ \eta_b \leq \eta_2 & \text{negative line fault} \\ \eta_2 < \eta_b < \eta_1 & \text{pole-to-pole fault} \end{cases} \quad (10)$$

where η_1 and η_2 are thresholds, and these thresholds can be set as $\eta_1 = 1.15$ and $\eta_2 = 0.85$ for considering both sensitivity and reliability.

3.5 Flowchart of the protection scheme

According to Sections 3.1–3.4, this paper designed a transient voltage pole-wave protection scheme for the DC line of the MTDC grid, and its flowchart is shown in Fig. 5. The steps are as follows. First, the start-up criterion detect any sudden change of voltage pole-wave. If the start-up criterion is satisfied, the DC line protection uses the internal and external fault identification criteria to determine the faulted line. Once an internal fault or disturbance is determines, it uses the lightning identification criterion to avoid the impact of lightning. If it determines that there is no lightning disturbance, it uses the faulted pole identification criterion to judge the fault type. Finally, according to the specific fault, the protection will send a trip command to DCCB.

4 Simulation and analysis

4.1 Simulation model and protection threshold setting

According to the topology and parameters of Zhangbei MTDC grid, a simulation model of ± 500 -kV four-terminal MMC-MTDC

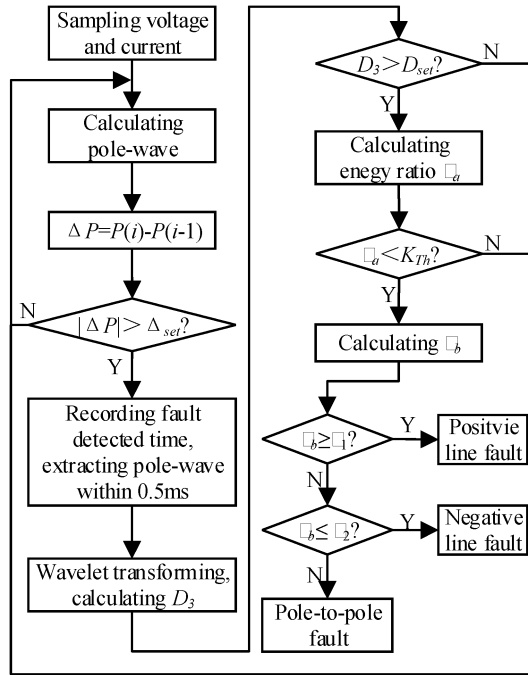


Fig. 5 Schematic diagram of the Mallat algorithm

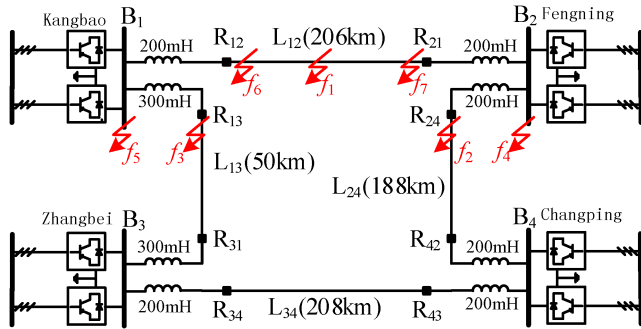


Fig. 6 Simulation model of Zhangbei MTDC grid

grid is built by PSCAD/EMTDC software, as shown in Fig. 6. The main wiring mode of the DC system is symmetrical bipolar wiring, whose positive and negative lines can operate independently. The half-bridge sub-module is adopted in MMC. The sampling rate of simulation model is adopted as 20 kHz. The DC line model is overhead line frequency-dependent model, and the parameters of each line are labelled in Fig. 6. In following sections, the relay R_{12} on DC line L_{12} is taken as a discussing object to verify the feasibility of the proposed protection scheme by simulating all kinds of faults.

The protection zone of R_{12} is DC line L_{12} , and the protection threshold of R_{12} should be preset as follows:

- D_{set} : In order to realise both high level in selectivity and sensitivity of protection, threshold D_{set} needs to avoid the maximum D_j , which is adopted as D_3 , of the worst external fault case. According to the simulation results for external faults, $D_3(f_4) = 83$ is the largest value. With the reliability factor picked as 1.2, D_{set} is set as 100 here.
- k_{Th} : Setting lightning disturbance, lightning fault, and short circuit fault on L_{12} with the most unfavourable conditions, the curve of η_a is shown in Fig. 7, where the x -axis is the distance between interference points and relay R_{12} . According to Fig. 7, k_{Th} can be set as 70. If η_a is >70 , then the result of lightning identification criterion is lightning disturbance; if η_a is <70 , then there is a true internal fault.

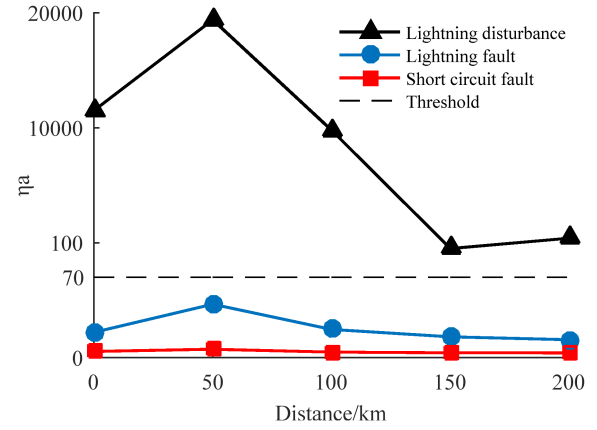


Fig. 7 Varying curve of η_a vs. distance

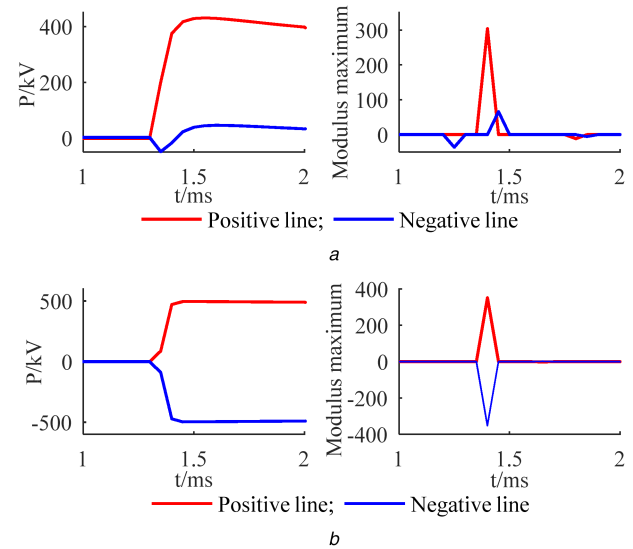


Fig. 8 Waveforms of pole-wave and modulus maximum for internal faults (a) Waveform of pole-wave and modulus maximum for internal positive pole-to-ground fault, (b) Pole-wave and modulus maximum of internal pole-to-pole fault

4.2 Simulation results

Set internal faults on L_{12} , at 1 ms, with different fault types, different fault resistances, and different distances from R_{12} . The typical waveform of $p(k)$ and their third-level modulus maximum detected by R_{12} are shown in Fig. 8. The simulation results are shown in Table 1, where x denotes the distance from R_{12} to the fault point and R_f represents the fault transition resistance.

Set external faults of R_{12} on DC lines and DC busbars adjacent to L_{12} , at 1 ms. The fault positions are f_2, f_3, f_4 , and f_5 on L_{24}, L_{13}, B_2 , and B_3 respectively. f_2 and f_3 are at the nearest close to L_{12} on L_{24} and L_{13} , respectively. Table 2 shows the simulation data detected by R_{12} .

According to the simulation results in Tables 1 and 2, all three criteria of the proposed protection algorithm can make correct decisions in any situation; the proposed protection method has good performance in selectivity and reliability. Also, the proposed scheme shows a strong anti-interference capability.

5 Conclusion

A novel MTDC line main protection scheme based on voltage pole-wave is proposed. The conclusions are as follows.

- The proposed scheme achieves high speed and excellent selectivity. The protection algorithm only requires single end voltage and current data within 0.5 ms after detecting a fault.

Table 1 Simulation results for internal fault with different distances, resistances, and fault types

Fault type	x, km	R_f, Ω	D_{3p}	D_{3n}	η_a	η_b	Identification result
positive pole-to-ground fault	10	0	339.5	55.17	5.54	6.15	positive line fault
		300	121.2	20.11	5.38	6.03	
	100	0	304.0	65.85	4.93	4.62	
		300	109.4	23.16	4.84	4.72	
	200	0	263.5	68.22	4.18	3.86	
		300	130.7	28.53	4.39	4.58	
negative pole-to-ground fault	10	0	50.01	336.4	5.55	0.15	negative line fault
		300	17.59	120.0	5.53	0.15	
	100	0	72.40	299.3	4.71	0.24	
		300	25.63	107.2	4.60	0.24	
	200	0	68.49	263.5	4.19	0.26	
		300	28.08	129.8	4.53	0.22	
pole-to-pole fault	10	0	228.5	228.5	4.12	1.00	pole-to-pole fault
		300	135.2	135.2	4.65	1.00	
	100	0	351.5	351.5	5.11	1.00	
		300	167.3	167.3	5.17	1.00	
	200	0	349.9	349.9	4.77	1.00	
		300	209.4	209.4	5.85	1.00	
lightning disturbance	10	0	1001	134.8	1.2×10^4	–	lightning distur-bance
	100	0	1230	814.4	9.8×10^3	–	
	200	0	600.0	286.2	144	–	
lightning fault	10	0	2014	262.0	22.2	7.69	positive line fault
	100	0	1024	218.5	24.6	4.67	
	200	0	788.2	340.3	15.7	2.32	

Table 2 Simulation results for external faults

Fault type	Fault point	D_{3p}	D_{3n}	Identification result
positive pole-to-ground fault	f_2	6.73	2.38	external
	f_3	4.51	1.94	
	f_4	73.05	16.50	
	f_5	35.60	18.93	
negative pole-to-ground fault	f_2	2.46	7.98	external
	f_3	1.90	4.40	
	f_4	19.15	73.08	
	f_5	23.61	39.46	
pole-to-pole fault	f_2	9.30	9.29	external
	f_3	6.32	6.31	
	f_4	82.68	82.65	
	f_5	56.95	56.87	
lightning disturbance	f_2	–	–	no response
	f_3	–	–	
lightning fault	f_2	27.25	18.14	external
	f_3	19.59	6.45	

- ii. By using wavelet transform, the protection algorithm has great robustness, and its capability against noise and ground resistance is outstanding.
- iii. With the lightning disturbance criterion, the protection algorithm has great reliability against lightning disturbance.
- iv. This is verified by a large number of simulation results that the proposed protection scheme can be successfully used as main protection for DC lines in MTDC systems.

6 Acknowledgments

This work was supported in part by the National Key Research and Development Program of China (2016FYB0900603) and in part by the National Natural Science Foundation of China (51677109).

7 References

- [1] Tang, G., Luo, X., Wei, X.: 'Multi-terminal HVDC and DC-grid technology', *Proc. CSEE*, 2013, **33**, (10), pp. 8–17
- [2] Kontos, E., Pinto, R.T., Rodrigues, S., *et al.*: 'Impact of HVDC transmission system topology on multiterminal DC network faults', *IEEE Trans. Power Deliv.*, 2015, **30**, (2), pp. 844–852
- [3] Azizi, S., Sanaye-Pasand, M.P., Abedini, M., *et al.*: 'A travelling-wave-based methodology for wide-area fault location in multiterminal DC systems', *IEEE Trans. Power Deliv.*, 2014, **29**, (6), pp. 2552–2560
- [4] Mokherdoran, A., Silva, N., Leite, H.: 'A directional protection strategy for multi-terminal VSC-HVDC grids', *Proc. IEEE 16th Int. Conf. Environment and Electrical Engineering*, June 2016, pp. 1–6
- [5] Auran, G., Raison, B., Descloux, J.: 'A novel pole-to-ground fault detection algorithm for meshed HVDC grids with half-bridge MMC converters and full recourse to DC circuit breakers', *Proc. 13th Int. Conf. Development in Power System*, 2016, pp. 1–6
- [6] Leterme, W., Beerten, J., Hertem, V.D.: 'Non-unit protection of HVDC grids with inductive DC cables termination', *IEEE Trans. Power Deliv.*, 2016, **31**, (2), pp. 820–828

- [7] Pirooz, A.S., Hertem, V.D.: 'A fast local bus current-based primary relaying algorithm for HVDC grids', *IEEE Trans. Power Deliv.*, 2017, **32**, (1), pp. 193–202
- [8] Liu, X., Osman, A.H.: 'Hybrid traveling wave/boundary protection for monopolar HVDC line', *IEEE Trans. Power Deliv.*, 2009, **24**, (2), pp. 569–578
- [9] Kerf, D.K., Srivastava, K., Reza, M., *et al.*: 'Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems', *IET Gener. Transm. Distrib.*, 2011, **5**, (4), pp. 496–503
- [10] Sneath, J., Rajapakse, A.D.: 'Fault detection and interruption in an earthed HVDC grid using ROCOV and hybrid DC breakers', *IEEE Trans. Power Deliv.*, 2016, **31**, (3), pp. 973–981
- [11] Wang, Y., Zhang, B., Fan, X.: 'Fast protection scheme for overhead transmission lines of VSC-based HVDC grid', *Autom. Electr. Power Syst.*, 2016, **40**, (21), pp. 13–19
- [12] Li, R., Xu, L., Yao, L.: 'DC fault detection and location in meshed multi-terminal HVDC systems based on DC reactor voltage change rate', *IEEE Trans. Power Deliv.*, 2017, **32**, (3), pp. 1516–1525