

The overhead transmission line protection scheme for the voltage-source converter-based HVDC grids

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Abstract: The fast DC line protection technology is one of the main challenges to high-voltage direct current (HVDC) grids. Based on the Zhangbei HVDC grid project, this paper proposes a non-unit overhead transmission line protection scheme for bipolar voltage-source converter-based HVDC grids equipped with DC circuit breakers. The voltage gradient is used to detect faults rapidly and start the protection algorithm, and the voltage derivative criterion is adopted to discriminate the internal faults from the external ones. Two kinds of faulty pole identification methods are proposed based on the propagation characteristics between the line- and zero-mode voltages, ensuring the selectivity of the protection. The Zhangbei HVDC grid model is built in power systems computer-aided design/electromagnetic transients including DC and the performance of the proposed protection scheme is verified by simulation results of various fault conditions.

1 Introduction

In recent decades, the renewable energy generation has developed rapidly. However, since the renewable energies such as wind and solar power are intermittent and random, the power system accommodated capacity is limited, resulting in a large number of curtailment of wind and solar power. The voltage-source converter (VSC)-based high-voltage direct current (HVDC) technology, featuring fast dynamic response and flexible control, has the ability to improve the efficiency of renewable energy integration and has alleviated the impact of voltage fluctuation of the power system [1, 2]. On the other hand, the fast growing renewable energy generation is challenging the structure and operation of existing power transmission systems [3]. The increased penetration of renewables puts geographical restrictions on the location of the generation, increasing the demand for new electrical connections. However, presently, the vast majority of HVDC systems have been built as point-to-point connectors between AC transmission systems. To interconnect multiple locations would require many additional HVDC converter stations. The creation of HVDC grids will allow the transmission of DC power to multiple locations, only requiring converters – the interfaces between the HVDC system and the existing AC system. This brings the potential advantage of a significant reduction in the number of converter equipment and the higher reliability of power transfer [4, 5]. Therefore, VSC-HVDC grids are now being considered as effective means for the integration of renewables.

To cooperate with the concept of Green Olympics, the State Grid Corporation of China is constructing the Zhangbei VSC-HVDC grid in Beijing and Hebei Province, China. Up to now, the Zhangbei HVDC grid project has the highest voltage level and the largest transmission capacity among all the HVDC grids in the world. The Zhangbei HVDC grid is a symmetric bipolar system which transmits power through overhead transmission lines. The converters are half-bridge modular multi-level converters (MMCs), and hybrid DC breakers are installed at both ends of each DC line.

The DC line protection technology is one of the main challenges to HVDC grids. First, the HVDC systems are characterised by low series impedances, leading to a high rate of rise and large steady-state value of the DC fault current [6]. This poses strict timing requirements to the protection system to avoid damage to the power-electronic equipment and limits the fault influence on neighbouring DC lines. Second, for the maximum reliability of HVDC grid systems, only the faulty section should be

isolated. So that the faults could be cleared without interrupting the healthy part of the HVDC grid.

In the literature, several protection schemes against DC faults for VSC-HVDC grids have been proposed. In earlier works, the main purpose was to develop a protection scheme without using DC breakers [7]. After faults, all converter stations are blocked and the AC circuit breakers are utilised to clear the fault. This would cause a temporary outage of the entire DC system which has a negative impact on the reliability of the combined AC and DC power systems. This kind of protection scheme is not suitable for an HVDC grid equipped with DC circuit breakers. Several protection schemes based on the communications between converter stations have been proposed [8]. However, due to the propagation delay, it is hard to meet the fast-speed requirement of the fault detection in the HVDC grid. Therefore, non-unit protection is a good alternative for the HVDC grid protection. Up to now, most of the HVDC grids are monopolar systems, and they transmit power through cables. Present studies on the protection scheme for HVDC grids mainly focus on the cable fault conditions, and few of them relate to the faulty pole identification problem [9–11].

In the Zhangbei HVDC grid, converter stations are connected through overhead transmission lines, which suffer a high fault rate, and have different fault travelling wave propagation characteristics from cables. Moreover, unlike the monopolar system, the two poles in the symmetrical bipolar system are independent from each other; thus, the healthy pole could continue to operate under the single pole to ground fault. Accordingly, the faulty pole should be identified to make sure that only the faulty pole line is to be isolated. In all, the fault-detection method for overhead transmission lines of bipolar HVDC grids still remains a major challenge. Based on the Zhangbei VSC-HVDC grids, this paper proposed a protection scheme for overhead transmission lines of bipolar HVDC grids equipped with DC breakers. The performance of the proposed protection scheme is tested using the power systems computer-aided design (PSCAD) model of HVDC grids under various fault conditions.

2 System description

The Zhangbei HVDC grid system is a four-terminal symmetric bipolar HVDC system. It contains four power-converter stations, which are the KangBao station integrated with photovoltaic power, the FengNing station integrated with pumped storage, the Zhangbei

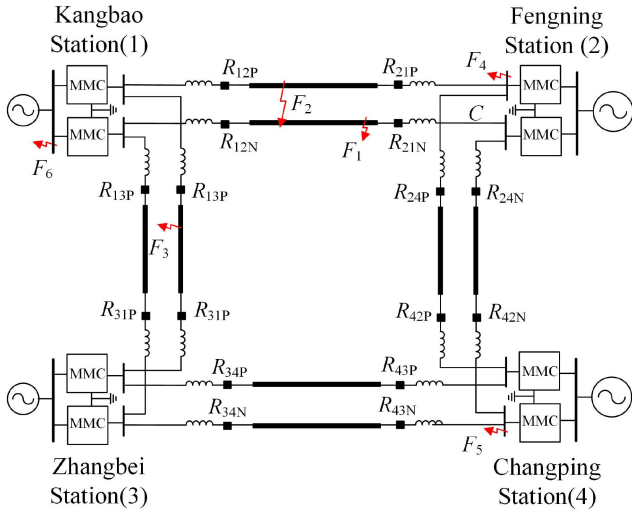


Fig. 1 Configuration of Zhangbei VSC-HVDC grid

Table 1 Main circuit parameters of converter stations in the VSC-based HVDC grid

Station	Capacitance per module, mF	Number of submodule per arm	Arm inductance, mH
Kangbao	10	625	150
Fengning	10	625	150
Zhangbei	10	625	150
Changping	15	455	80

station integrated with wind power, and the Changping station. The four stations are all connected to the local 500 kV AC grids. The nominal DC voltage is ± 500 kV, and the nominal power is 3000 MW for Changping station and 1500 MW for the rest of the three stations. Fig. 1 shows the layout of the Zhangbei HVDC grid.

Each power converter is a half-bridge MMC, and the main parameters of MMC are listed in Table 1. Converter stations are connected through overhead transmission lines. In order to interrupt the fault current, the hybrid DC breakers are installed at both ends of each transmission line. Inductive fault current limiters (FCLs) that contain the rise of fault currents within the capacity of hybrid DC breakers are installed in series with each hybrid DC breaker. The lengths of the transmission lines and the inductances of FCLs in the Zhangbei HVDC grid are shown in Table 2.

The protective relays (R) are installed at each end of the DC lines. After a fault is detected and distinguished as an internal fault on this pole by the protective relay, the trip instruction is issued to the corresponding DC breaker to isolate the faulted line.

3 Protection principle

3.1 Smoothing effect of FCL

The inductive FCLs assembled at the end of each line form the transmission line boundaries. The transfer function of the line boundary is

$$H = \frac{Z_c}{Z_c + sL} \quad (1)$$

where Z_c is the wave impedance of the transmission line and L is the inductance of the FCL.

Generally, it is considered that the fault travelling wave generated at the fault point is a step wave, whose amplitude is the pre-fault voltage E at the fault point. After it passes through the line boundary, the step wave becomes

$$u_{\text{after}} = -(1 - e^{-(Z_c/L)t})E\varepsilon(t) \quad (2)$$

Table 2 Length of DC lines and inductance of FCLs

Line	Length, km	Inductance of FCL, mH
Line 12	227	200
Line 24	126	200
Line 34	219	200
Line 13	66	300

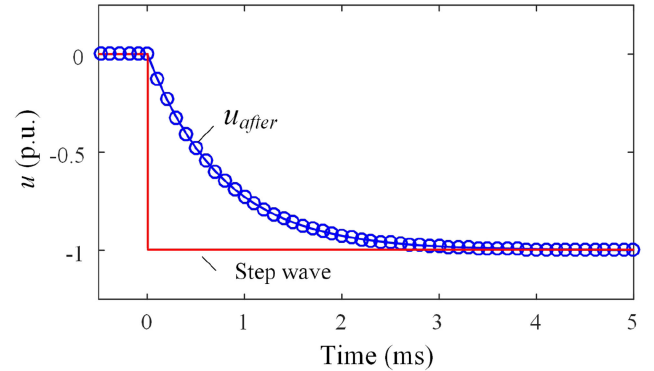


Fig. 2 Waveforms of the step wave before and after it passes through the line FCL

Fig. 2 shows the waveform of (2), with $L = 200$ mH, $Z_c = 260 \Omega$, compared with the original step wave. It can be seen that the voltage step change becomes smooth after passing through the inductive FCL. In other words, the voltage change rates have obvious differences between the internal fault and external fault conditions.

3.2 Propagation characteristics of fault traveling waves in bipolar system

Due to the electromagnetic coupling effect between the parallel transmission lines of the bipolar HVDC system, single line to ground fault would induce changes of voltage on the healthy pole line. Therefore, the healthy pole cannot be discriminated from the faulty pole by the voltage derivative criterion. In order to isolate the line of the faulty pole only, the accurate identification of the faulty pole is necessary.

For the symmetrical bipolar system, the phase-mode transformation method can be used to decouple the bipolar component into zero- and line-mode components. The transformation matrix $\mathbf{Q}$ is

$$\mathbf{Q} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (3)$$

Suppose that the pole to ground voltages of the positive pole and negative pole under the normal condition are $+E$ and $-E$, respectively. Under the single pole to ground fault (take positive pole to ground fault as an example), the zero- and line-mode voltage changes, Δu_0 and Δu_1 , generated at the fault point are

$$\begin{cases} \Delta u_0 = -\sqrt{2} \frac{Z_0 E}{Z_0 + Z_1 + 2R_g} \\ \Delta u_1 = -\sqrt{2} \frac{Z_1 E}{Z_0 + Z_1 + 2R_g} \end{cases} \quad (4)$$

where Z_0 and Z_1 are the zero-mode wave impedance and line-mode wave impedance, respectively. R_g is the grounding resistance.

Transforming (4) into positive and negative pole expressions, we obtain

$$\begin{cases} \Delta u_P = \frac{1}{\sqrt{2}} (\Delta u_0 + \Delta u_1) = -\frac{Z_0 + Z_1}{Z_0 + Z_1 + 2R_g} E \\ \Delta u_N = \frac{1}{\sqrt{2}} (\Delta u_0 - \Delta u_1) = -\frac{Z_0 - Z_1}{Z_0 + Z_1 + 2R_g} E \end{cases} \quad (5)$$

where Δu_p and Δu_N are the voltage change of the positive and negative pole expressions at the fault point, respectively.

From (11), we can obtain $|\Delta u_p| > |\Delta u_N|$, indicating that the magnitude of the voltage change of the faulty pole is larger than the magnitude of the voltage change of the non-faulty pole. Therefore, the faulty pole could be identified by comparing the voltage change magnitude on both poles.

On the other hand, as for the faulty pole (positive pole), both the zero- and line-mode voltage changes are negative, opposite to the faulty pole voltage. Therefore, the voltage magnitude of the faulty pole decreases. As for the healthy pole (negative pole), the line-mode voltage change has opposite polarity to the pole voltage, which decreases the voltage magnitude, but the zero-mode voltage change has the same polarity with the pole voltage, which increases the voltage magnitude. Since Z_0 is greater than Z_1 , we have $|\Delta u_0| > |\Delta u_1|$. Therefore, the voltage of the healthy pole increases after fault, namely the single pole to ground fault will induce overvoltage on the healthy pole.

Zero- and line-mode voltage changes propagate from the fault point to both ends of the line in the form of step voltage wave, at zero-mode wave velocity and line-mode wave velocity separately. Consequently, voltages measured at each end of the line vary after fault. Since line-mode wave velocity is greater than zero-mode wave velocity, the line-mode wave propagates to the protective relay first, causing the decrease in voltages of both faulty and healthy poles. The zero-mode wave arrives subsequently, bringing out the increase of healthy pole voltage, but continues to decrease in the faulty pole voltage, namely the variation trends of the faulty pole voltage and healthy pole voltage are the same until the zero-mode wave arrives.

Fig. 3 shows the voltage waveforms of both positive pole and negative poles at each end of Line12 when the positive line to ground fault occurs at the start of the line. Since the Kangbao end is close to the fault, the line-mode voltage wave and zero-mode voltage wave arrive at the same time. As a result, the voltage of the faulty pole u_p decreases and the voltage of the non-faulty pole increases. As for the Fengning end, the line-mode fault-generated wave arrives first, voltages of both the positive and negative poles decrease; after the zero-mode fault-generated wave arrives, the voltage of the faulty pole decreases continuously, but the voltage of the non-faulty pole increases and the overvoltage appears. The faulty pole can also be identified based on the different voltage variation trends after fault.

4 Protection scheme

4.1 Starting unit

The starting unit is to detect the abnormal conditions rapidly and start the protection algorithm. The voltage gradient is adopted to detect the voltage changes and determine whether the HVDC grid has faults or not. The criterion and the calculation expression of the starting unit are as follows:

$$|\nabla u(k)| > \nabla_{\text{set}} \quad (6)$$

$$\nabla u(k) = \sum_{j=0}^2 u(k-j) - \sum_{j=3}^5 u(k-j) \quad (7)$$

where $u(k-j)$ is the j th voltage value sampled prior to the present moment. $\nabla u(k)$ is the calculated voltage gradient. ∇_{set} is the threshold value of the starting unit. The threshold value should be greater than the maximum voltage gradient under the normal conditions and should guarantee fast and reliable starts for faults within the HVDC grid, and it is set as 0.01 pu. The sampling point that the starting unit criterion first satisfied is denoted as k_s , which is the starting time of protection algorithm.

4.2 Fault section discrimination unit

The aforementioned analysis shows that the FCL inductors assembled at the ends of the line have a significant smoothing

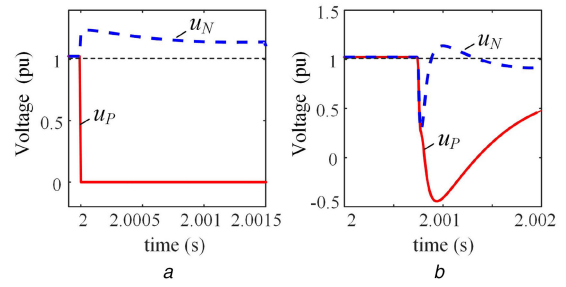


Fig. 3 Voltage waveforms under single line to ground fault: (a) Kangbao end; (b) Fengning end

effect on the voltage signals, leading to a comparatively small voltage change rate under the external fault conditions. The difference in the voltage change rate could be used to differentiate the internal faults from the external ones. If the maximum of the negative value of the voltage change rates in the continuous five sampling points after k_s is greater than the threshold value, the fault is determined to be internal fault; otherwise, the fault is outside the protection zone. The criterion and calculation expressions of the fault section discrimination unit are as follows:

$$-du/dt_m > \Delta_1 \quad (8)$$

$$-du/dt_m = \max(-du/dt(k)) \quad k \in [k_s, k_s + 4] \quad (9)$$

$$du/dt(k) = (u(k) - u(k-1))/\Delta T \quad (10)$$

where u is the measured DC voltage, ΔT is the sampling step length, $-du/dt$ is the voltage change rate. Δ_1 is the threshold of the voltage change rate criterion. It should be set greater than the maximum of the negative value of the voltage change rate under external fault conditions, which is noted as ρ . Therefore, the threshold Δ_1 is set as ρ multiplying a reliable coefficient $k_{\text{rel}1}$:

$$\Delta_1 = k_{\text{rel}1} \times \rho \quad (11)$$

4.3 Faulty pole identification unit

After the protection starts, integrate the voltage change in a certain data window:

$$\Delta U = \sum_{k=k_s}^{k_s+N-1} \Delta u(k) \Delta T \quad (12)$$

where Δu is the voltage fault component, ΔT is the sampling step, and N is the sampling point number in the data window.

If the signals of both the poles are available for the protection, the faulty pole could be identified by comparing the voltage change integral values of two poles. The criterion is as follows:

$$R_{\Delta u} = \frac{|\Delta U|}{|\Delta U_{\text{op}}|} > R_{\text{set}} \quad (13)$$

where ΔU is the voltage change integral value of the pole that the relay locates, ΔU_{op} is the voltage change integral value of the opposite pole, $R_{\Delta u}$ is the ratio of the voltage change integral values, R_{set} is the threshold value. If the ratio $R_{\Delta u}$ is greater than the threshold value, the pole that the relay locates is identified as the faulty pole.

In the condition that the protections of the two poles are independent from each other, the protection should discriminate the faulty pole using signals of the local pole only.

From the aforementioned analysis, we know that, for the faulty pole, the integral value of the voltage change is negative and large in magnitude. As for the non-faulty pole, the voltage change is positive at several sampling points after fault due to the overvoltage effect; thus, the positive and negative poles cancel out each other after integration. Consequently, the integral value of the

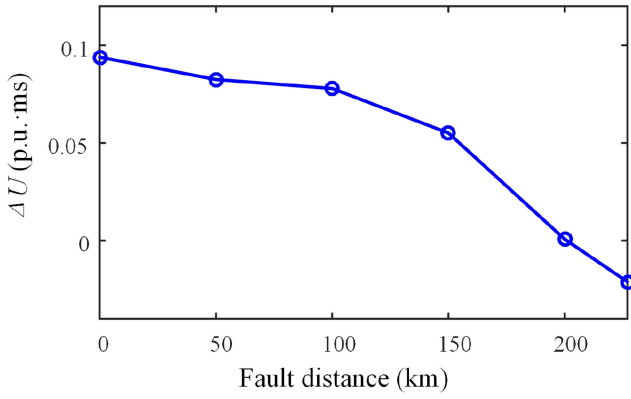


Fig. 4 Voltage change integral value of the non-faulty pole

voltage change could be positive or negative but small in magnitude. To sum up, if the integral value is smaller than the threshold value, then the pole can be judged as the faulty pole. The criterion is as follows:

$$\Delta U < \Delta_2 \quad (14)$$

4.3.1 Selection of data window: In order to fully reflect the variation trend differences between the faulty pole and non-faulty pole, the data window should be greater than the time difference between the arrival times of the line-mode and zero-mode fault travelling wave when fault occurs at the end of the transmission line and retains the sufficient margin. On the other hand, considering the speed requirement of the fault detection, the data window should be < 1 ms. In this paper, the data window is chose as 0.5 ms.

4.3.2 Threshold setting principle: For the criterion (13), the threshold value can be set according to (5):

$$\frac{|Z_0 - Z_1|}{|Z_0 + Z_1|} < R_{\text{set}} < \frac{|Z_0 + Z_1|}{|Z_0 - Z_1|} \quad (15)$$

However, for the pole-to-pole fault conditions, the voltage changes of both poles are the same; thus, the ratio $R_{\Delta u}$ is close to the unity. In this case, both poles should be judged as the faulty poles. Therefore, the threshold vale should be set < 1 . In all, R_{set} should satisfy the following inequality:

$$\frac{|Z_0 - Z_1|}{|Z_0 + Z_1|} < R_{\text{set}} < 1 \quad (16)$$

In this paper, R_{set} is set as 0.8.

It is worth noting that, if the protection is started by the interference, though the voltage integral values of both the poles are very small, the ratio of them might satisfy the criterion, causing maloperation of the faulty pole identification unit. In order to enhance the reliability of the protection, an auxiliary criterion is needed:

$$|\Delta U| > \xi \quad (17)$$

where the threshold ξ is set as the integration of 0.1 times of the rated voltage in the data window.

As for the second criterion (14), Δ_2 should be set smaller than the minimum of ΔU of the healthy pole under the single pole to ground fault conditions.

For the non-faulty pole, the line-mode wave reduces the integral value, whereas the zero-mode increases the integral value. The difference between the faulty pole and non-faulty pole relies on the zero-mode wave. The longer the fault distance, the larger the time difference between the line-mode wave arrival and zero-mode wave arrival, thus the smaller the integral value.

Fig. 4 shows the voltage change integral value of the positive pole protection R_{12P} when the solid fault occurs on the negative pole of Line 12 at different distances.

Under the fault condition, at the end of the line, the voltage change integral value is the smallest, noted as δ and consistent with the previous analysis results. Therefore, the threshold value is set as δ , multiplying a reliable coefficient $k_{\text{rel}2}$:

$$\Delta_2 = k_{\text{rel}2} \times \delta \quad (18)$$

For the short transmission lines, δ of the non-faulty pole might be close to zero or even positive. Thus, the calculated Δ_2 is too small. Similarly, in order to avoid the maloperation of the criterion under the disturbance, the threshold value of the faulty pole identification criterion (14) is set as

$$\Delta_2 = \min(k_{\text{rel}2} \times \delta, -\xi) \quad (19)$$

5 Simulation studies

5.1 Test system and protection conditions

The test system is the aforementioned Zhangbei HVDC grid system, which is modelled in PSCAD/electromagnetic transients including DC. The half-bridge MMCs are modelled by a detailed equivalent model [12]. Transmission lines are modelled using the frequency-dependent phase model.

The sampling rate of the protection is 50 kHz. According to the threshold setting principles, the thresholds of protections on each line are set as listed in Table 3. $k_{\text{rel}1}$ and $k_{\text{rel}2}$ are set as 1.5 and 2, respectively.

5.2 DC line faults

Various transmission line faults have been simulated, including faults located in different protection zones, at different distances, in different fault types (single-pole-to-ground fault and pole-to-pole fault), through different fault resistances. Several typical fault test results are given below. The fault locations are shown in Fig. 1. Take the protective relays on Line12 R_{12P} , R_{12N} , R_{21P} , R_{21N} as examples to demonstrate the validity of the proposed fault-detection scheme. The calculation results of each criterion of the protection are listed in Table 4. The voltage waveforms measured at each protection are presented in Fig. 5.

Fault F_1 is a negative line to ground fault through the 500 Ω fault resistance, and it occurs at Line12, 10 km from the Fengning station. For the relays at the ends of the faulty lines R_{12N} and R_{21N} , the fault section and faulty pole criteria are all satisfied; therefore, the protections operate correctly. Due to the coupling effect between the parallel lines, the voltage change rate calculated by the relay of the healthy pole, R_{12P} , is also large enough to satisfy the fault section criterion. However, the faulty pole identification criteria are not satisfied; therefore, the relay does not operate reliably. Fault F_2 is a pole-to-pole fault through the 200 Ω fault resistance located on Line12, 10 km from the Kangbao station. In this case, all the protection criteria are satisfied for protections R_{12P} , R_{12N} , R_{21P} , and R_{21N} ; thus, they operate correctly. Both faults F_1 and F_2 are through high fault resistance; thus, the results show that the protection maintains adequate sensitivity to high resistance fault. Fault F_3 is a solid positive line to ground fault occurs at Line13, 10 km from the Kangbao station, which is outside of the protection zone of R_{12P} , R_{12N} , R_{21P} , R_{21N} . The fault section criteria of R_{12P} , R_{12N} , R_{21P} , and R_{21N} are not satisfied; hence, the protections do not operate reliably.

5.3 DC bus faults

In order to test the performance of the protection scheme under the external faults, solid grounding fault on the positive DC bus of the converter station 2 (F_4) and solid grounding fault on the negative DC bus of the converter station 4 (F_5) are simulated. The faults on the DC bus are not included in the transmission line protection

zones; therefore, the DC line protective relays should not operate. The protection calculation results are listed in Table 4. The voltage waveforms measured at each protection are presented in Fig. 5.

The DC bus fault induces voltage drops of the DC lines connected to the faulty bus where the calculated voltage change integral values might be large enough to satisfy the faulty pole identification criterion (14). However, the voltage change rate is smaller than its threshold; thus, the criterion (8) is not satisfied, which inhibits the maloperation of the relays on the non-faulty pole.

5.4 AC faults

In the case of the AC system fault, the DC line protective relays should not operate. A three-phase short-circuit fault at the AC bus of the converter station 1 (F_6) is simulated in the PSCAD model.

The voltage waveforms measured at each protection are presented in Fig. 5. The starting criterion of the protections is not satisfied, showing that the proposed fault-detection method is not affected by the AC fault.

6 Conclusions

Based on the Zhangbei VSC-HVDC grids, this paper proposed a non-unit protection scheme for overhead transmission lines of bipolar HVDC grids which are equipped with DC breakers. The protection is based on the local measurements and has short data window; thus, it features fast response speed. The performance of the proposed protection scheme is tested using the PSCAD model of the Zhangbei HVDC grid. Simulation results show that the protection is able to distinguish internal faults from external ones accurately, identify the faulty pole correctly, hold adequate

Table 3 Thresholds of protections

	ρ , pu/ms	Δ_1 , pu/ms	ξ , pu ms	δ , pu ms	Δ_2 , pu ms
R_{12P}	-2.04	3	0.05	-0.021	-0.05
R_{12N}	-2.04	3	0.05	-0.021	-0.05
R_{21P}	-2.04	3	0.05	-0.023	-0.05
R_{21N}	-2.03	3	0.05	-0.023	-0.05
R_{13P}	-1.37	2	0.05	0.071	-0.05
R_{13N}	-1.37	2	0.05	0.071	-0.05
R_{31P}	-1.37	2	0.05	0.071	-0.05
R_{31N}	-1.37	2	0.05	0.071	-0.05
R_{24P}	-2.04	3	0.05	0.026	-0.05
R_{24N}	-2.04	3	0.05	0.026	-0.05
R_{42P}	-2.03	3	0.05	0.025	-0.05
R_{42N}	-2.03	3	0.05	0.025	-0.05
R_{34P}	-2.03	3	0.05	-0.023	-0.05
R_{34N}	-2.03	3	0.05	-0.023	-0.05
R_{43P}	-2.03	3	0.05	-0.024	-0.05
R_{43N}	-2.03	3	0.05	-0.023	-0.05

Table 4 Test results

	Fault section discrimination unit		Faulty pole identification unit		Operation results
	Criterion	$-du/dt_m$	$R_{\Delta U}$	ΔU	
	Threshold	3	0.8	-0.05	
F_1	R_{12P}	8.68	0.01	-0.003	not operate
	R_{12N}	8.68	81.36	-0.209	operate
	R_{21P}	0.71	0.18	0.031	not operate
	R_{21N}	13.04	5.57	-0.171	operate
F_2	R_{12P}	37.11	1.00	-0.347	operate
	R_{12N}	37.11	1.00	-0.347	operate
	R_{21P}	50.09	1.00	-0.535	operate
	R_{21N}	50.09	1.00	-0.535	operate
F_3	R_{12P}	0.43	2.92	-0.028	not operate
	R_{12N}	-0.003	0.33	0.010	not operate
	R_{21P}	0.31	11.74	-0.035	not operate
	R_{21N}	0.22	0.09	0.003	not operate
F_4	R_{12P}	1.92	12.85	-2.097	not operate
	R_{12N}	1.36	0.08	-0.016	not operate
	R_{21P}	2.04	4.68	-0.176	not operate
	R_{21N}	-0.31	0.21	0.040	not operate
F_5	R_{12P}	0.05	0.06	-0.002	not operate
	R_{12N}	0.19	12.03	-0.033	not operate
	R_{21P}	-0.06	0.25	0.013	not operate
	R_{21N}	0.17	4.29	-0.028	not operate

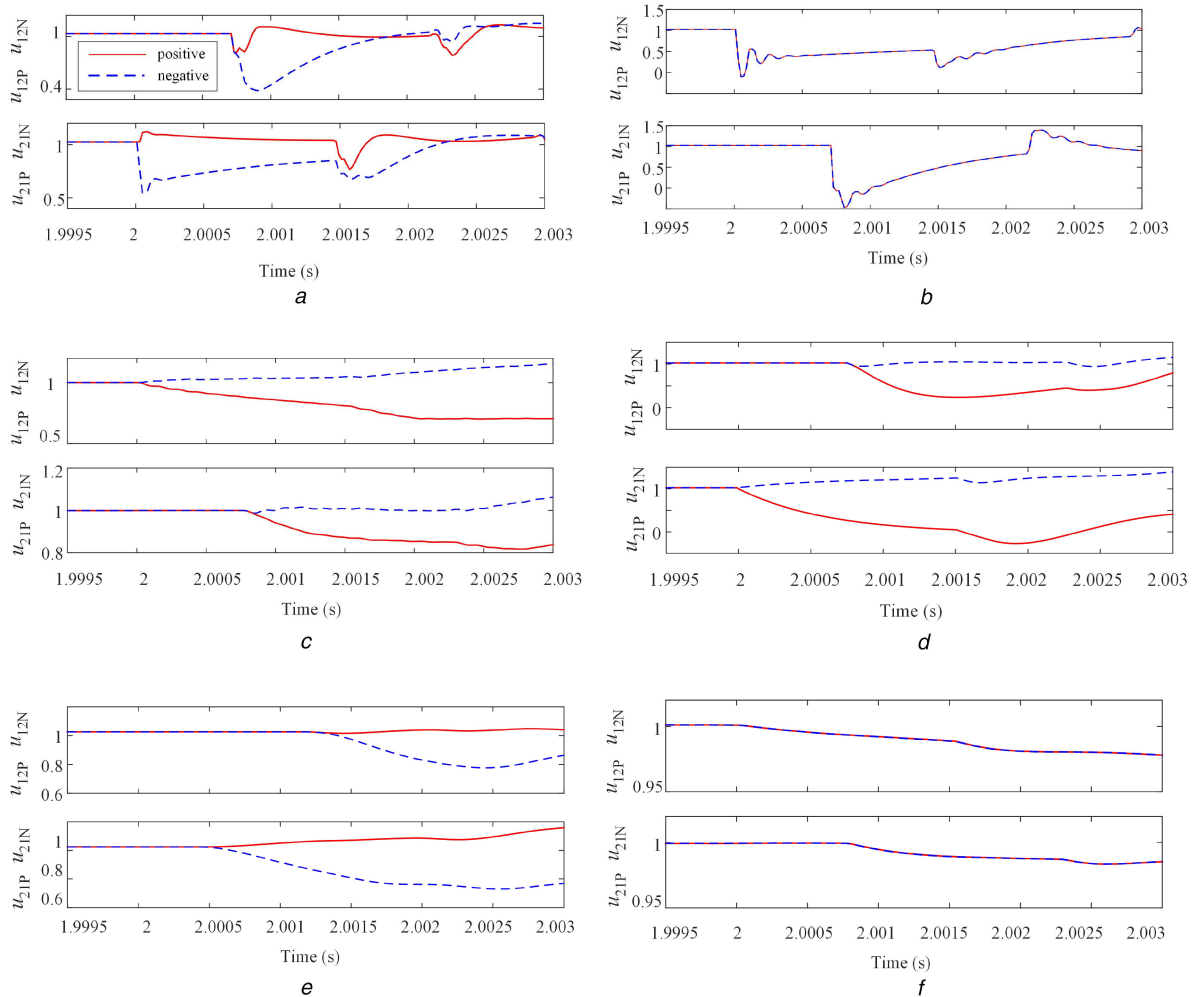


Fig. 5 Voltage waveforms measured at protections R_{12P} , R_{12N} , R_{21P} , R_{21N} under different fault conditions

(a) F1, (b) F2, (c) F3, (d) F4, (e) F5, (f) F6

sensitivity to high resistance fault, and it is not affected by AC fault disturbance.

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8 References

- [1] Nikolas, F., Vassilios, G., Georgios, D.: 'VSC-based HVDC power transmission systems: an overview', *IEEE Trans. Power Electron.*, 2009, **24**, (3), pp. 592–602
- [2] Van Hertem, D., Ghandhari, M.: 'Multi-terminal VSC HVDC for the European supergrid: obstacles', *Renew. Sustain. Energy Rev.*, 2010, **14**, (9), pp. 3156–3163
- [3] Johannesson, N., Norrga, S., Wikstrom, C.: 'Selective wave-front based protection algorithm for MTDC systems'. 13th Int. Conf. Development in Power System Protection, Edinburgh, UK, March 2016, pp. 1–6
- [4] Gupta, R., Barker, C.D., Adamczyk, A., *et al.*: 'Protection coordination in multi-terminal HVDC networks for DC fault clearance'. 13th Int. Conf. Development in Power System Protection, Edinburgh, UK, March 2016, pp. 1–6
- [5] Buigues, G., Valverde, V., Zamora, I., *et al.*: 'DC fault detection in VSC-based HVDC grids used for the integration of renewable energies'. Int. Conf. Clean Electrical Power, Taormina, Italy, June 2015, pp. 666–673
- [6] Bucher, M.K., Franck, C.M.: 'Contribution of fault current sources in multiterminal HVDC cable networks', *IEEE Trans. Power Deliv.*, 2013, **28**, (3), pp. 1796–1803
- [7] Tang, L., Ooi, B. T.: 'Locating and isolating DC faults in multi-terminal DC systems', *IEEE Trans. Power Deliv.*, 2007, **22**, (3), pp. 1877–1884
- [8] Adamczyk, A., Barker, C. D., Ha, H.: 'Fault detection and branch identification for HVDC grids'. Proc. Int. Conf. Development in Power System Protection (DPSP), Copenhagen, Denmark, March 2014, pp. 1–6
- [9] De Kerf, K., Srivastava, K., Reza, M.: 'Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems', *IET Gener. Transm. Distrib.*, 2011, **5**, (4), pp. 496–503
- [10] Leterme, W., Beerten, J., Van Hertem, D.: 'Nonunit protection of HVDC grids with inductive DC cable termination', *IEEE Trans. Power Deliv.*, 2016, **31**, (2), pp. 820–828
- [11] 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
- [12] Fan, X., Wang, Y., Zhang, B.: 'Fast electromagnetic transient simulation for flexible DC power grid', *Autom. Electr. Power Syst.*, 2017, **41**, (4), pp. 92–97 (in Chinese)