

Hybrid ROCOV/Waveform Similarity Coefficient Based Protection for DC Lines in HVDC Grids

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Abstract—DC line protection with high speed and strong robustness against high fault resistance is essential in high-voltage direct current (HVDC) grids. The conventional voltage-derivative-based protections for DC lines exhibit the problem of low reliability on the occurrence of high-impedance faults. In this paper, fault traveling waves at the fault point and at the line side of the DC reactor are first analyzed using phase-modal transformation. Based on the theoretical analysis of the modal fault-component voltages at the line side of the DC reactor, a novel hybrid protection scheme utilizing the single-ended rate of change of voltage (ROCOV) and waveform similarity coefficient is proposed. It utilizes the hybrid ROCOV criterion and waveform similarity coefficient to identify the faulted line and the amplitudes of the 0- and 1-mode fault-component voltages to identify fault type, and the polarities of the 0- and 1-mode fault-component voltages to identify faulted pole. Simulations under various fault conditions verify that the proposed protection scheme can achieve fast and reliable identification of faulted line, fault type, and faulted pole in 1 ms, and effectively improve the reliability against high-impedance faults up to 1200 Ω .

Index Terms—DC line protection, MMC-HVDC grid, phase-modal transformation, ROCOV, waveform similarity coefficient.

I. INTRODUCTION

HIGH-VOLTAGE direct-current (HVDC) transmission systems have been established as valuable complements to the existing AC transmission systems, especially in the collection of renewable energy [1]. Wherein, the line-commutated-converter-based HVDC (LCC-HVDC) systems are primarily applied to point-to-point connections, whereas the voltage-source-converter-based HVDC (VSC-HVDC) systems are well suited for HVDC grids [2]. Currently, HVDC grids are being built to interconnect wind, hydro, and solar resources, and to expand to a grid overlaid on a whole continent, owing to their increased flexibility and reliability at a relatively low cost by sharing resources [3], [4].

However, in the event of a DC line fault, all converters in the VSC-HVDC grids would have to be shut down to clear the fault [5], which significantly reduces the reliability of the entire grid. Therefore, a sound fault interruption objective is to quickly isolate faulted lines, and to maintain the operation of the converters connected to healthy DC lines [6], [7]. To achieve the objective, it requires fast fault detection and selective identification of the faulted lines in the VSC-HVDC grids.

Traveling-wave-based protection (TWP) meets the requirement of fast fault detection and is widely adopted in conventional HVDC projects. Developed for TWP, SIEMENS products use the DC voltage derivative (dv/dt) and DC current derivative (di/dt) whereas ABB adopts a polar wave derivative to identify the faulted line in conventional HVDC systems [8], [9]. However, both dv/dt and di/dt are determined by the fault loop impedance, and will be reduced by the high transition resistance of the fault [10]. Therefore, TWP has to tackle the problem of low reliability for the occurrence of high-impedance faults.

To improve the reliability of protection in case of high-impedance faults, double-ended methods are proposed. The transient energy [11] and transient harmonic currents [12] at both terminals have been analyzed, extracted, and used for double-ended protection design, respectively. Reference [13] utilizes the voltage polarities of DC reactors at the ends of DC lines to propose a pilot protection scheme. These methods provide active responses to high-resistance faults and can identify faults with the resistance of 300 Ω to 500 Ω . However, transmitting and synchronizing measurements at both terminals of a DC line are demanding [9].

Single-ended protection provides a high-speed and practicable way to identify a faulted line in a HVDC grid. Based on [16], the protection in [6] utilizing the change rate of the DC reactor voltage can detect the DC line fault faster, because the change rate of the DC reactor voltage is equivalent to the second derivative of the DC current. However, the interference from the adjacent bus faults is not considered. The method in [17] adopts the combination of dv/dt , di/dt , and undervoltage as a fault criterion to discriminate between internal and external faults, whereas interferences of measurement errors and noise are excluded. A high anti-noise protection in [9] using the ratio of the transient voltages (ROTV) at both sides of the DC reactor is applied to the fault identification. Reference [18] uses the single-terminal DC reactor voltage to identify the faulted line and the faulted pole within 1 ms. How-

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ever, both voltage and voltage derivative are determined by the fault loop impedance, thus the methods related to the voltage derivative or the voltage may fail in high-resistance faults, including the methods in [9], [16], [17], and [18]. To avoid the failure in high-resistance fault conditions, backup protections are complemented in [9] and [18], which utilize double-ended information and demand communication between the two ends of the DC line. Methods in [15] and [19] use the high-frequency transient voltage extracted by wavelet transform for fault identification and can identify faults with the resistance of 300 Ω and 200 Ω , respectively.

To achieve fault detection with high speed and strong robustness against high fault resistance, this paper proposes a novel hybrid protection scheme consisting of a single-ended ROCOV and waveform similarity coefficient to detect DC line faults in an HVDC grid. The remainder of this paper is organized as follows. In Section II, fault traveling waves at the fault point and at the line side of the DC reactor are analyzed based on the phase-modal transformation method, and two major conclusions are obtained: i) the waveform of the fault-component voltage at the line side of the DC reactor almost remains unchanged against various fault resistances; ii) the distortion degree of the fault traveling wave for external faults is deeper than that for internal faults due to the additional boundary distortion. Thus, the criteria for distinguishing the internal, forward external, and backward external faults can be determined. Then, the novel hybrid protection scheme utilizing the single-ended voltage on the line side of the DC reactor is proposed in Section III, including identification of faulted line, fault type, and faulted pole. In Section IV, numerous simulations under various conditions demonstrate that identification of faulted line, fault type, and faulted pole can be achieved with robustness against high fault resistance. Finally, the conclusions are drawn in Section V.

II. FAULT TRAVELING WAVE ANALYSIS IN HVDC GRIDS BASED ON PHASE-MODAL TRANSFORMATION

Recently, to alleviate corrosion caused by a ground return, a metallic return conductor is preferably adopted as the neutral conductor in bipolar HVDC grids [2]. A typical topology of a half-bridge modular-multilevel-converter-based DC grid with a metallic return conductor is shown in Fig. 1 [20], where four

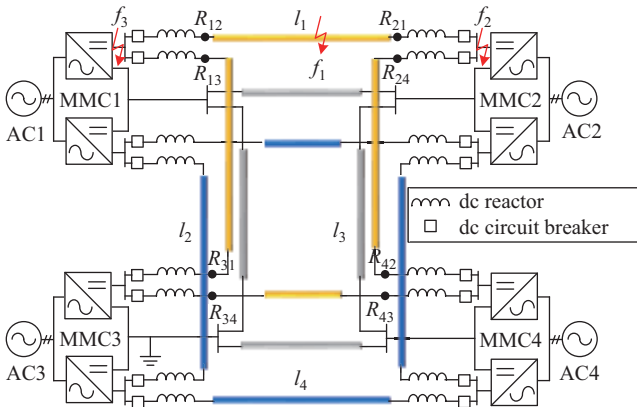


Fig. 1. Topology of a four-terminal dc grid with a metallic return conductor.

bipolar MMC stations are connected by four DC overhead transmission lines $l_1 \sim l_4$. To suppress the fast-rising fault current, a DC circuit breaker and a DC reactor are placed at the both ends of the DC lines [21]. The protective relays $R_{12} \sim R_{43}$ and the measuring points are placed at the line side of each DC reactor (Only the relays on the positive pole are shown). A fault on any DC line will be identified by the protective relay on the faulted line, and the corresponding DC circuit breaker will be tripped to isolate the fault whereas the healthy part of the grid continues to operate. Use protective relay R_{12} as an example to investigate the protection scheme. For R_{12} , faults at different locations are considered, including the internal fault f_1 , the forward external faults f_2 , and the backward external faults f_3 .

Different from the second-order phase-modal transformation matrix to decouple the coupling between the positive and negative poles in HVDC systems with ground return [22], a three-order phase-modal transformation matrix introduced in [23] is applied to decouple the coupling between the positive pole, negative pole, and the neutral-metallic conductors. The three-order phase-modal transformation matrix is expressed as:

$$\begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} = \frac{1}{\sqrt{6}} \begin{bmatrix} \sqrt{2} & \sqrt{2} & \sqrt{2} \\ 1 & -2 & 1 \\ \sqrt{3} & 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} X_p \\ X_m \\ X_n \end{bmatrix} \quad (1)$$

where X_p , X_m , and X_n are the positive-, neutral-, and negative-pole components, X_0 , X_1 , and X_2 are the 0-, 1-, and 2-mode components, respectively. Additionally, X can represent voltage u or current i .

From (1), the modal components have the following physical meanings: i) X_0 is equally distributed in positive, neutral, and negative poles; ii) X_1 travels along the positive and negative poles equally and returns through the neutral metallic conductor; iii) X_2 only flows through the positive and negative poles and forms a closed loop.

A. Fault Traveling Wave Generation

According to the superposition theorem, the voltage at the fault point can be treated as an additional voltage source $-U_F$ superimposed on the pre-fault voltage U_F . Furthermore, the faulted network can be divided into two separate parts, namely, pre-fault network and fault-component network containing the additional voltage source $-U_F$ [9], as shown in Fig. 2. Since the pre-fault network is almost steady, only the fault-component network in Fig. 2(b) is analyzed. Two common faults, i.e., pole-to-ground (PTG) fault and pole-to-pole (PTP) fault, are discussed in this section.

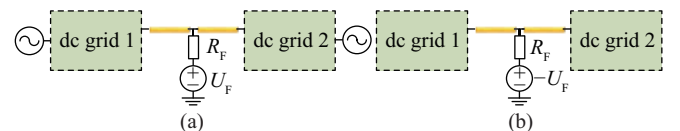


Fig. 2. Equivalent network of DC grid. (a) Pre-fault network. (b) Fault-component network.

1) Pole-to-ground (PTG) Fault:

Once a negative PTG fault occurs, according to Fig. 3(a), the instantaneous boundary conditions at the fault point are:

$$\begin{cases} \Delta u_{Fn} = -U_F - \Delta i_{Fn} R_F \\ \Delta i_{Fp} = 0 \\ \Delta i_{Fm} = 0 \end{cases} \quad (2)$$

where Δu_{Fn} represents the negative-pole-to-ground fault-component voltage at the fault point, Δi_{Fp} , Δi_{Fm} , and Δi_{Fn} are the positive-, neutral-, and negative-pole fault-component currents into the fault point. R_F is the fault resistance.

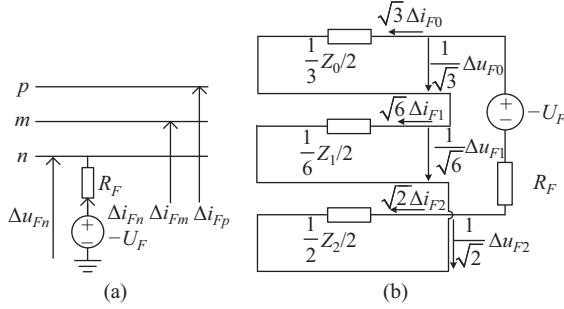


Fig. 3. Negative PTG fault. (a) Diagram in the fault-component network. (b) Modal-network connection at the fault point.

Using (1), the instantaneous boundary conditions (2) of the negative PTG fault at the fault point are obtained in modal quantities:

$$\begin{cases} \frac{\Delta i_{F0}}{\sqrt{2}} = -\frac{\Delta i_{F2}}{\sqrt{3}} = \Delta i_{F1} \\ \frac{\Delta u_{F0}}{\sqrt{3}} + \frac{\Delta u_{F1}}{\sqrt{6}} - \frac{\Delta u_{F2}}{\sqrt{2}} \\ = -U_F - \left(\frac{\Delta i_{F0}}{\sqrt{3}} + \frac{\Delta i_{F1}}{\sqrt{6}} - \frac{\Delta i_{F2}}{\sqrt{2}} \right) R_F \end{cases} \quad (3)$$

where Δu_{Fj} ($j = 0, 1, 2$) is the modal-voltage traveling wave generated at the fault point in the fault-component network, and Δi_{Fj} ($j = 0, 1, 2$) is the modal-current traveling wave.

Because Δu_{Fj} ($j = 0, 1, 2$) will equally propagate to both sides of the fault point, both sides of the fault point are in parallel, that is:

$$\Delta u_{Fj} = \Delta i_{Fj} \times Z_j / 2 \quad (4)$$

where Z_j ($j = 0, 1, 2$) is the j -mode surge impedance which are frequency-dependent. This frequency-dependent characteristic is not obvious when the frequency exceeds kilohertz [24]. The surge impedance can be treated as a constant to analyze the fault traveling wave process.

According to (3) and (4), the modal-network connection at the fault point can be obtained, as shown in Fig. 3(b).

Derived from Fig. 3(b), the 0-, 1-, and 2-mode fault traveling waves generated at the fault point can be solved as follows:

$$\begin{cases} \Delta u_{F0} = -U_F 2\sqrt{3}Z_0/Z_\Sigma \\ \Delta u_{F1} = -U_F \sqrt{6}Z_1/Z_\Sigma \\ \Delta u_{F2} = U_F 3\sqrt{2}Z_2/Z_\Sigma \end{cases} \quad (5)$$

where $Z_\Sigma = 2Z_0 + Z_1 + 3Z_2 + 12R_F$.

Similarly, for a positive PTG fault, the 0-, 1-, and 2-mode fault traveling wave generated at the fault point can be obtained:

$$\begin{cases} \Delta u_{F0} = -U_F 2\sqrt{3}Z_0/Z_\Sigma \\ \Delta u_{F1} = -U_F \sqrt{6}Z_1/Z_\Sigma \\ \Delta u_{F2} = -U_F 3\sqrt{2}Z_2/Z_\Sigma \end{cases} \quad (6)$$

2) Pole-to-pole (PTP) Fault:

Once a PTP fault occurs, according to Fig. 4(a), the instantaneous boundary conditions at the fault point are:

$$\begin{cases} \Delta u_{Fp} - \Delta u_{Fn} = -2U_F + \Delta i_{Fn} R_F \\ \Delta i_{Fp} + \Delta i_{Fn} = 0 \\ \Delta i_{Fm} = 0 \end{cases} \quad (7)$$

where Δu_{Fp} represents the positive-pole-to-ground fault-component voltage at the fault point.

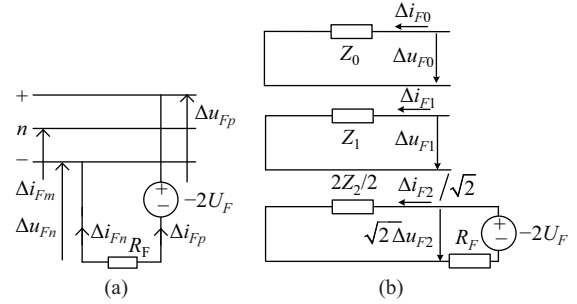


Fig. 4. PTP fault. (a) Diagram in the fault-component network. (b) Modal-network connection at the fault point.

Using (1), the instantaneous boundary conditions (7) of the PTP fault at the fault point are obtained in modal quantities:

$$\begin{cases} \Delta i_{F0} = \Delta i_{F1} = 0 \\ \sqrt{2}\Delta u_{F2} = -2U_F - \frac{\Delta i_{F2} R_F}{\sqrt{2}} \end{cases} \quad (8)$$

According to (4) and (8), the modal-network connection at the fault point can be obtained, as shown in Fig. 4(b).

Derived from Fig. 4(b), the 0-, 1-, and 2-mode fault traveling wave generated at the fault point can be solved as follows:

$$\begin{cases} \Delta u_{F0} = 0 \\ \Delta u_{F1} = 0 \\ \Delta u_{F2} = -\sqrt{2}U_F Z_2/(Z_2 + R_F) \end{cases} \quad (9)$$

From (5), (6), and (9), the comparison of the modal fault-traveling wave between the negative PTG fault, the positive PTG fault, and the PTP fault are shown in Table I.

TABLE I
COMPARISON OF THE MODAL FAULT-TRAVELING WAVES BETWEEN THREE TYPICAL FAULTS

Fault traveling wave	Negative PTG fault			Positive PTG fault			PTP fault		
Mode	0	1	2	0	1	2	0	1	2
Polarity	+	+	-	-	-	-	0	0	-

Note: Polarity "0" represents that the corresponding amplitude is ideally zero.

From Table I, three conclusions are obtained: i) the 2-mode fault-traveling waves contained in three typical faults are all negative; ii) the difference between the two PTG faults and the PTP fault lies in the amplitudes of the 0- and 1-mode fault-traveling waves; iii) the difference between the negative and positive PTG fault lies in the polarity of the 0- and 1-mode fault-traveling waves.

B. 2-mode Fault-component Voltage at R_{12} at various fault locations

The 2-mode fault-traveling-wave Δu_{F2} propagating to R_{12} becomes $e^{-\gamma_2(s)x} \Delta u_{F2}$ [25] and produces a 2-mode fault-component voltage at R_{12} , where $e^{-\gamma_2(s)x}$ is used to describe the propagation characteristics of the 2-mode traveling wave through the DC line in the frequency domain. At various fault locations, a traveling wave propagating through different surge impedances is typically analyzed by the *Peterson's Law*.

To achieve a simplified calculation, the propagation function $e^{-\gamma_2(s)x}$ of the DC line is approximated as [25]:

$$e^{-\gamma_2(s)x} \approx \frac{1 - k_{a2}x}{1 + s\tau_{d2}x} e^{-sT} \quad (10)$$

where e^{-sT} is used to describe the time delay caused by the distance between the fault point and R_{12} ; k_{a2} is the 2-mode attenuation coefficient of the DC line per unit length; τ_{d2} is the 2-mode dispersion time constant of the DC transmission line per unit length; x is the distance from the fault point to R_{12} .

1) When Internal Fault f_1 occurs:

When the internal fault f_1 occurs at the distance of x km from R_{12} as shown in Fig. 1, assuming that the reflected wave from the fault point does not arrive at R_{12} , the Peterson equivalent circuit is shown in Fig. 5(a).

Derived from Fig. 5(a), the 2-mode fault-component voltage $U_{R_{12}-f_1}(s)$ at R_{12} is:

$$U_{R_{12}-f_1}(s) = 2 \frac{(1 - k_{a2}x) \Delta u_{F2} e^{-sT}}{s(1 + s\tau_{a2}x)} \frac{sL_{dc} + Z_{2eq}}{sL_{dc} + Z_2 + Z_{2eq}} \quad (11)$$

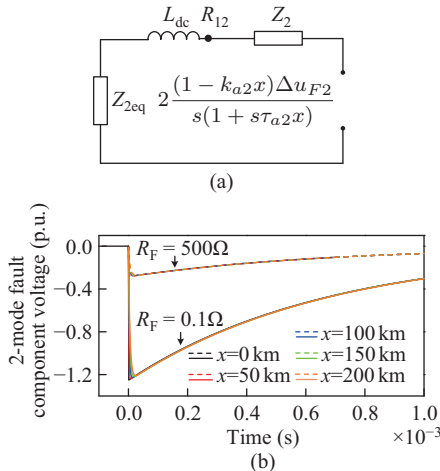


Fig. 5. Internal fault f_1 . (a) Peterson equivalent circuit. (b) 2-mode fault component voltage $u_{R_{12}-f_1}(t)$ at R_{12} .

where L_{dc} is the inductance of the DC reactor and Z_{2eq} is the equivalent impedance on the unfaulted side of the DC reactor.

Using the *Inverse Laplace Transform* of (11), the 2-mode fault-component voltage at R_{12} in the time domain is expressed as:

$$u_{R_{12}-f_1}(t) = A_1 e^{-(t-T)} + A_2 e^{-(t-T)/T_d} + A_3 e^{-(t-T)/(L_{dc}/(Z_2 + Z_{2eq}))} \quad (12)$$

where

$$A_1 = \frac{2K_a \Delta u_{F2} Z_{2eq}}{Z_2 + Z_{2eq}}, \quad A_2 = -\frac{2K_a \Delta u_{F2} (L_{dc} - T_d Z_{2eq})}{L_{dc} - T_d (Z_2 + Z_{2eq})}$$

$$T_d = \tau_{d2}x, \quad A_3 = \frac{2K_a \Delta u_{F2} Z_2 L_{dc}}{(Z_2 + Z_{2eq})(L_{dc} - T_d (Z_2 + Z_{2eq}))}$$

$$K_a = 1 - k_{a2}x, \quad t \geq T$$

In (12), Z_{2eq} is the parallel impedance of MMC1 and the adjacent DC line l_2 , and the equivalent impedance of MMC1 relates to the sub-module capacitance C_{SM} , on-resistance R_{on} , the arm inductance L_{arm} , and the number of the sub-module per arm N_{SM} . Additionally, the 2-mode surge impedance Z_2 is hundreds of ohms and the 2-mode dispersion time constant τ_{d2} is of 10^{-8} s/km [26]. In this paper, these parameters adopt: $\tau_{d2} = 2.5 \times 10^{-8}$ s/km, $k_{a2} = 0$, $Z_0 = 360 \Omega$, $Z_1 = Z_2 = 260 \Omega$, $L_{dc} = 150$ mH, $C_{SM} = 15$ mF, $L_{arm} = 50$ mH, $R_{on} = 0.005 \Omega$, and $N_{SM} = 244$. When negative PTG faults with different fault resistances occur, the 2-mode fault-component voltage $u_{R_{12}-f_1}(t)$ at R_{12} is shown in Fig. 5(b), where the base voltage is the system voltage.

As shown in Fig. 5(b), $u_{R_{12}-f_1}(t)$ under different fault distances obeys the pattern of dropping to its first peak instantly and then rises. With R_F increased from 0.1Ω (solid line) to 500Ω (dashed line), although the magnitudes of $u_{R_{12}-f_1}(t)$ are scaled down, the shapes of $u_{R_{12}-f_1}(t)$ remain unchanged. Therefore, when internal faults f_1 occur, the waveform similarity between $u_{R_{12}-f_1}(t)$ at different fault locations is quite high (positive) and is resistant to the high fault resistance.

2) When Forward External Fault f_2 occurs:

When the forward external fault f_2 occurs as shown in Fig. 1, assuming that the reflected wave from the fault point does not arrive at R_{12} , the Peterson equivalent circuit is shown in Fig. 6(a).

Derived from Fig. 6(a), the 2-mode fault-component voltage $U_{R_{12}-f_2}(s)$ at R_{12} is:

$$U_{R_{12}-f_2}(s) = \frac{4\Delta u_{F2}}{s} \frac{Z_2 e^{-sT}}{sL_{dc} + 2Z_2} \frac{(1 - k_{a2}L_{12})}{(1 + s\tau_{a2}L_{12})} \frac{sL_{dc} + Z_{2eq}}{sL_{dc} + Z_2 + Z_{2eq}} \quad (13)$$

where L_{12} is the length of dc line l_1 .

The waveform of $u_{R_{12}-f_2}(t)$ in the time domain is obtained using the *Inverse Laplace Transform* of (13). As shown in Fig. 6(b), $u_{R_{12}-f_2}(t)$ obeys the pattern of dropping to its first peak gently and then rises. Compared to Fig. 5(b), the waveform similarity between $u_{R_{12}-f_2}(t)$ and $u_{R_{12}-f_1}(t)$ is quite low.

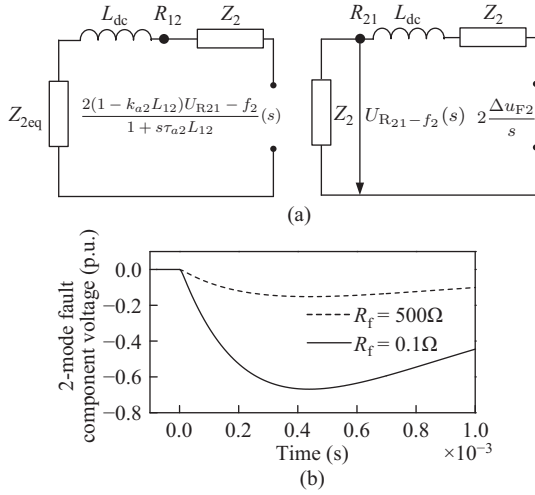


Fig. 6. Forward external fault f_2 . (a) Peterson equivalent circuit. (b) 2-mode fault component voltage $u_{R12-f_2}(t)$ at R_{12} .

3) When Backward External Fault f_3 occurs:

When the backward external fault f_3 occurs as shown in Fig. 1, the Peterson equivalent circuit is shown in Fig. 7(a).

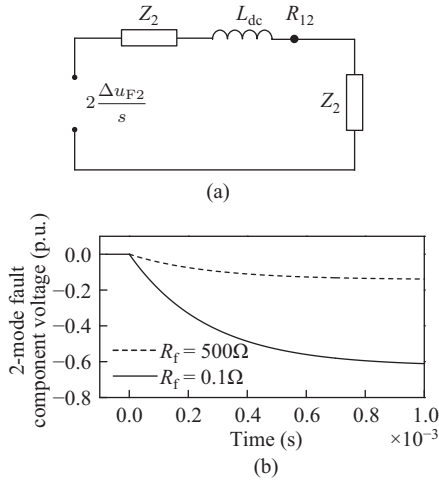


Fig. 7. Backward external fault f_3 . (a) Peterson equivalent circuit. (b) 2-mode fault component voltage $u_{R12-f_3}(t)$ at R_{12} .

Derived from Fig. 7(a), the 2-mode fault-component voltage $U_{R12-f_3}(s)$ at R_{12} is:

$$U_{R12-f_3}(s) = \frac{2\Delta u_{F2}}{s} \frac{Z_2}{sL_{dc} + 2Z_2} e^{-sT} \quad (14)$$

Using the *Inverse Laplace Transform* of (14), the $u_{R12-f_3}(t)$ in the time domain is obtained:

$$u_{R12-f_3}(t) = \Delta u_{F2} (e^{-(t-T)} - e^{-(t-T)/(L_{dc}/2Z_2)}) \varepsilon(t-T) \quad (15)$$

As shown in Fig. 7(b), $u_{R12-f_3}(t)$ keeps declining in the given time window. Compared to Fig. 5(b), the waveform similarity between $u_{R12-f_3}(t)$ and $u_{R12-f_1}(t)$ is quite low.

Selecting $u_{R12-f_1}(t)$ at $x = 100$ km as the reference U_{ref} for similarity calculation, Table II compares the waveform similarity of three situations: i) $u_{R12-f_1}(t)$ and U_{ref} , ii) $u_{R12-f_2}(t)$ and U_{ref} , iii) $u_{R12-f_3}(t)$ and U_{ref} .

TABLE II
COMPARISON OF THE WAVEFORM SIMILARITY OF THREE SITUATIONS

Description	$u_{R12-f_1}(t)$ & U_{ref}			$u_{R12-f_2}(t)$ & U_{ref}	$u_{R12-f_3}(t)$ & U_{ref}	
x km	50	150	200			
Similarity	0.9978	0.9986	0.9955	-0.4921	-0.9394	

From Table II, the waveform similarities between U_{ref} and $u_{R12-f_1}(t)$ at different fault locations within line l_1 are quite positive-high whereas the waveform similarity between $u_{R12-f_2}(t)$ and U_{ref} or $u_{R12-f_3}(t)$ and U_{ref} is rather low or quite negative-high. This is because the distortion degree of the fault traveling waves for faults f_2 and f_3 is deeper than that for fault f_1 due to the additional boundary distortion. Therefore, the waveform similarity between U_{ref} and the 2-mode fault-component voltage at the line side of the DC reactor can be utilized to distinguish internal faults from external faults. Note that the distortion degree of the fault traveling wave for external faults becomes lower with smaller L_{dc} due to the decreased boundary distortion, as shown in Table III. Therefore, the waveform difference between the internal faults and external faults is narrowed down when L_{dc} decreases to a low level, which may cause the failure of distinguishing internal faults from external faults. Although using the waveform similarity to identify the faulted line has the limitations of low reliability on small inductance of the DC reactor, the inductances of the DC reactors are typically several tens of a millihenry and even up to hundreds of a millihenry in practical DC grids [15]. Therefore, the low reliability of the waveform similarity on small inductance of the DC reactor can be alleviated in practical DC grids.

TABLE III
COMPARISON OF THE WAVEFORM SIMILARITY OF THREE SITUATIONS WITH DIFFERENT L_{dc}

L_{dc}		$u_{R12-f_1}(t)$ & U_{ref}			$u_{R12-f_2}(t)$ & U_{ref}	$u_{R12-f_3}(t)$ & U_{ref}
150 mH	x km	50	150	200	—	—
	S	0.9978	0.9986	0.9955	-0.4921	-0.9394
100 mH	x km	50	150	200	—	—
	S	0.9982	0.9989	0.9963	0.0937	-0.9143
50 mH	x km	50	150	200	—	—
	S	0.9982	0.9989	0.9965	0.6238	-0.8465
10 mH	x km	50	150	200	—	—
	S	0.9969	0.9982	0.9941	0.8695	-0.5760

Note: Similarity is abbreviated as "S" due to the limited space.

III. PROPOSED PROTECTION SCHEME

This section proposes a single-ended protection scheme for fast fault detection of a DC line. It contains a triggering criterion, and a fault identification criterion. The overall flowchart of the proposed protection scheme is presented in Fig. 8.

A. Triggering Criterion

The triggering criterion to initiate the protection scheme is:

$$|u_{Rp}(t)| > U_{Thre1} \text{ or } |u_{Rm}(t)| > U_{Thre1} \\ \text{or } |u_{Rn}(t)| > U_{Thre1} \quad (16)$$

where $|\cdot|$ is to calculate the absolute value; $u_{Rp}(t)$, $u_{Rm}(t)$,

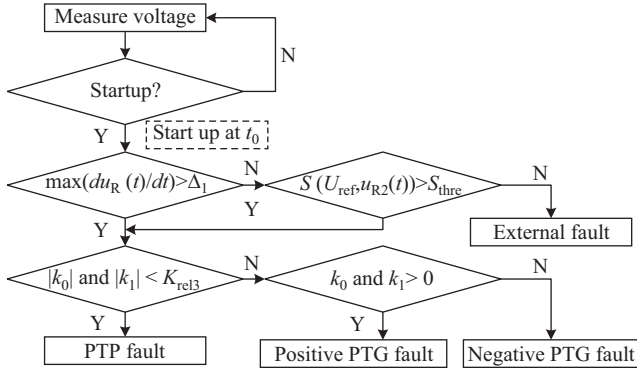


Fig. 8. Flowchart of the proposed protection scheme.

$u_{Rn}(t)$ and are the positive-, neutral-, and negative-pole fault-component voltages at the line side of the DC reactor, respectively, which can be collected by subtracting the pre-fault components from the post-fault components. U_{Thre1} is the threshold value of the pole voltage for protection initiation. To guarantee that the remote internal faults with high resistance can also trigger the protection, U_{Thre1} is selected to be smaller than the corresponding pole-voltage value on the line side of the DC reactor. When an internal fault with a fault resistance of 500Ω occurring at the remote end is considered, the pole fault-component voltage at the protective relay on the faulted line is estimated to be 0.2268 pu based on (1) and (5) while no attenuation and dispersion are considered. To achieve fast and reliable protection triggering, U_{Thre1} is selected as 0.1 pu whose base is the rated DC pole voltage.

According to (1) and (5), the generated fault component voltage $u_{Rn}(t)$ for negative PTG faults versus fault resistance R_F are shown in Fig. 9. The results show that the absolute values of $u_{Rn}(t)$ gradually decrease below 0.1 p.u. (threshold for protection initiation) after R_F reaches 1200Ω , which indicates that faults with fault resistance above 1200Ω cannot trigger the protection scheme.

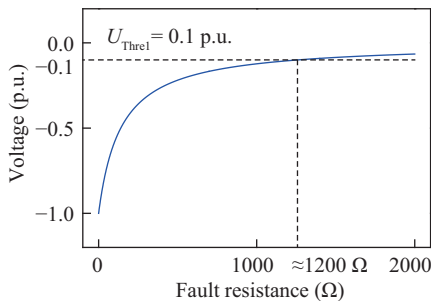


Fig. 9. Generated fault component voltage $u_{Rn}(t)$ in phase domain versus fault resistance R_F .

B. Fault Identification Criterion

Fault identification criterion follows the protection triggering, including the identification of faulted line, fault type, and faulted pole.

1) faulted Line Identification

The waveform similarity between U_{ref} and the 2-mode fault-component voltage at the line side of the DC reactor can be

utilized in the fault line identification. When the protection scheme starts up at t_0 , it indicates that the fault voltage traveling wave has arrived at the protective relay. Then the 2-mode fault-component voltage $u_{R2}(t)$ at the protective relay is obtained using (17):

$$u_{R2}(t) = \frac{1}{\sqrt{6}} \begin{bmatrix} \sqrt{3} & 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} u_{Rp}(t) \\ u_{Rm}(t) \\ u_{Rn}(t) \end{bmatrix} \quad (17)$$

In case of a metallic fault occurring at the midpoint of the DC line, the 2-mode fault-component voltage measured at the protective relay is selected as the reference U_{ref} for similarity calculation. Then the criterion of the faulted line identification is:

$$S(U_{ref}, u_{R2}(t)) > S_{thre} = K_{rel1} S(U_{ref}, u_{R2_ex}(t)) \quad (18)$$

where $S(x, y)$ calculates the similarity between x and y using the Pearson correlation coefficient; $u_{R2_ex}(t)$ is the 2-mode fault-component voltage measured at the protective relay when the most serious external fault occurs, which is considered as the forward external metallic fault occurring at the converter side of the remote DC reactor; S_{thre} is the threshold value which is set to be greater than the calculated similarity coefficient when the most serious external fault occurs; K_{rel1} is the reliable coefficient and is set as 1.2 .

The similarity-based faulted line identification is valid before the reflected wave from the fault point arrives at the protective relay. Therefore, the data window for the similarity calculation starts at $t_0 - T_s$ (T_s is the time interval between two sampling points) and ends with the arrival of the subsequent reflections. The arrival time of the reflected traveling wave is calibrated at t_1 by the wavelet transform modulus maxima (WTMM) [25]. However, when a close-in fault occurs, the reflected waves frequently travel back and forth between the fault point and the protective relay, and thus the number of the data points used for the similarity calculation is decreased. Consequently, the effectiveness of the similarity-based faulted line identification will be reduced.

To address the shortcoming of the similarity-based faulted line identification in case of a close-in fault, the rate of change of voltage (ROCOV) at the line side of the DC reactor is introduced prior to the similarity calculation, because the ROCOV-based protection is sensitive to close-in faults. The ROCOV criterion has become mature in a practical HVDC project and is easy to implement as no additional data is measured. The ROCOV criterion for close-in fault is:

$$\max \left(\frac{du_R(t)}{dt} \right) > \Delta_1 = \left(\frac{du_R(t)}{dt} \right)_{close} / K_{rel2} \quad (19)$$

where $u_R(t)$ presents $u_{Rp}(t)$ or $u_{Rm}(t)$ or $u_{Rn}(t)$; Δ_1 is the threshold value of the ROCOV criterion, which is set to be smaller than the ROCOV measured at the protective relay $(du_R(t)/dt)_{close}$ when a close-in fault occurs; K_{rel2} is the reliable coefficient and is set as 1.1 . It can be seen that the threshold value Δ_1 of the ROCOV criterion is different from that in the traditional ROCOV criterion, where the threshold is set to be higher than the ROCOV measured at the protective relay when the most serious external fault occurs.

Therefore, the fault line identification contains two steps: i) first, using ROCOV criterion to screen out the close-in fault; ii) second, using the waveform similarity coefficient to identify these high-resistance faults which failed to trigger the ROCOV criterion. Therefore, the combination of the single-ended ROCOV and waveform similarity coefficient can achieve the fast and full-length faulted line identification

2) Fault Type and Faulted Pole Identification

According to Section II-A, the amplitudes of the 0- and 1-mode fault-traveling waves can be used as a criterion to identify fault type, whereas the polarities of the 0- and 1-mode fault-traveling waves can be used as a criterion to identify faulted pole.

To achieve reliability of the protection scheme, the 0- and 1-mode fault-component voltages, i.e., $u_{R0}(t)$ and $u_{R1}(t)$, are integrated from $t_0 - T_s$ to $t_0 - T_s + \Delta T$. The criterion for identifying the fault type is:

$$|k_0| < K_{rel3} \text{ and } |k_1| < K_{rel3} \quad (20)$$

where K_{rel3} is the threshold for identifying the fault type and is set as 0.01; $k_0 = \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R0}(t) / \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R2}(t)$ and $k_1 = \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R1}(t) / \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R2}(t)$; ΔT is the integral window and set as 1 ms. When (20) is satisfied, a PTP fault occurs; otherwise, it is a PTG fault.

Following the fault type identification, the criterion for identifying the faulted pole is defined as:

$$k_0 < 0 \text{ and } k_1 < 0 \quad (21)$$

When (21) is satisfied, the PTG fault occurs on the negative pole; otherwise, the PTG fault occurs on the positive pole.

IV. SIMULATION VERIFICATION

The test system built in PSCAD/EMTDC aims to emulate a four-terminal MMC-HVDC grid, whose diagram and parameters are shown in Fig. 1 and Table IV, respectively. The overhead lines (OHLs) adopt the frequency-dependent model. All faults for analysis occur at 4.5 s and the sampling frequency is 40 kHz. Use the protective relay R_{12} as an example to investigate the protection scheme.

TABLE IV
PARAMETERS OF THE FOUR-TERMINAL MMC-HVDC GRID

Parameter	Symbol	Value
DC voltage	V_{dc}	500 kV
DC reactor	L_{dc}	150 mH
Bridge arm reactor	L_{arm}	50 mH
Submodule capacitance	C_{SM}	15 mF
Number of submodule	N_{SM}	244
DC line length ($l_1 \sim l_4$)	Length	200 km

A. Selective Fault Identification

If the distance from the fault point to R_{12} is within 10 km, it is considered to be a close-in fault. The threshold value Δ_1 is set as 0.3304 p.u./50 μ s, because the ROCOV measured at the $R_{12}(du_R(t)/dt)_{close}$ equals 0.3634 p.u./50 μ s when a fault with fault resistance of 500 Ω occurs at $x = 10$ km. Fig. 10 shows the maximum ROCOV versus fault distance for negative PTG faults with different fault resistances.

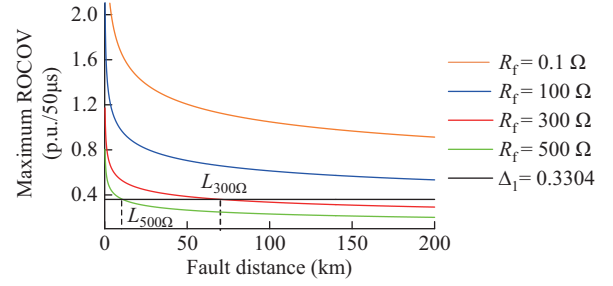


Fig. 10. Maximum ROCOV versus fault distance for negative PTG faults with different fault resistances.

negative PTG faults with different fault resistances. For the fault resistance of 0.1 to 100 Ω , using the ROCOV criterion alone can protect the full length of l_1 . However, with the fault resistance increasing to 300 and 500 Ω , the protected area of the DC line will decrease to (0, $L_{300\Omega}$) and even to several km, leading to the failure of the ROCOV criterion in high-resistance fault conditions.

For the high-resistance PTG faults or external PTG faults which failed to trigger the ROCOV criterion, the corresponding waveform similarity coefficients between $u_{R2}(t)$ and U_{ref} are calculated and the results are shown in Table V. The threshold value S_{thre} for waveform similarity criterion is set as 0.4192, because the calculated $S(U_{ref}, u_{R2_ex}(t))$ equals 0.3493 which will be presented in the results for PTP faults.

The waveforms of U_{ref} and $u_{R2}(t)$ measured at R_{12} when negative PTG faults occur at different fault locations are shown in Fig. 11. Different values of t_0 clearly show different arriving

TABLE V
SIMILARITY WAVEFORM COEFFICIENTS FOR NEGATIVE PTG FAULTS

x km	50	100	150	200	f_2	f_3
$R_F = 300 \Omega$	0.9442	0.9655	0.9735	0.8591	—	—
$R_F = 500 \Omega$	0.8828	0.9301	0.9726	0.8439	—	—
$R_F = 0.1 \Omega$	—	—	—	—	0.2525	-0.3330

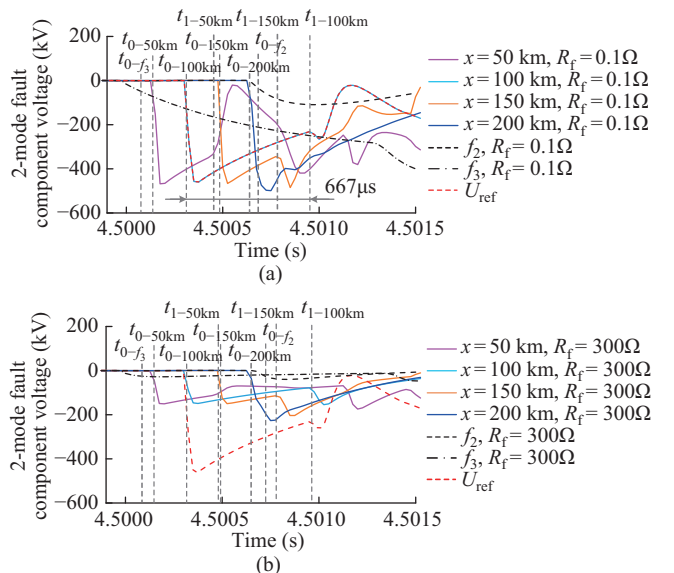


Fig. 11. Waveforms of U_{ref} and $u_{R2}(t)$ measured at R_{12} when negative PTG faults occur. (a) $R_F = 0.1 \Omega$. (b) $R_F = 300 \Omega$.

times of the fault traveling waves with different fault locations. The results show that $u_{R2}(t)$ for internal faults under different fault distances obeys the pattern of dropping to its first peak instantly and then rises. With R_F increased from 0.1Ω to 300Ω , although the magnitudes of $u_{R2}(t)$ are scaled down, the shapes of $u_{R2}(t)$ for internal faults remain unchanged.

The results for the negative PTG faults in Table V show that using the waveform similarity between $u_{R2}(t)$ and U_{ref} can reliably discriminate between the internal faults with extremely high fault resistances and external faults with a low fault resistance.

The similar results can also be obtained from the PTP faults at different fault locations, as shown in Table VI.

TABLE VI
WAVEFORM SIMILARITY COEFFICIENTS FOR PTP FAULTS

x km	50	100	150	200	f_2	f_3
$R_F = 300 \Omega$	0.9560	0.9975	0.9735	0.8750	—	—
$R_F = 500 \Omega$	0.9559	0.9974	0.9746	0.8548	—	—
$R_F = 0.1 \Omega$	—	—	—	—	0.3493	-0.2018

Once the faulted line is identified, the ratios k_0 and k_1 are used to identify fault type and faulted pole. k_0 and k_1 at R_{12} when negative PTG faults and PTP faults occur at different fault locations are shown in Table VII.

TABLE VII
VALUES OF k_0 AND k_1 FOR NEGATIVE PTG AND PTP FAULTS

	x km	0	50	100	150	200	
PTG	k_0	$R_F = 0.1 \Omega$	-1.06	-1.03	-0.86	-0.93	-0.90
		$R_F = 100 \Omega$	-1.05	-1.02	-0.89	-0.93	-0.91
		$R_F = 300 \Omega$	-1.04	-1.02	-0.90	-0.93	-0.92
		$R_F = 500 \Omega$	-1.05	-1.01	-0.91	-0.94	-0.92
	k_1	$R_F = 0.1 \Omega$	-0.75	-0.73	-0.61	-0.66	-0.64
		$R_F = 100 \Omega$	-0.74	-0.72	-0.63	-0.66	-0.64
		$R_F = 300 \Omega$	-0.74	-0.72	-0.64	-0.66	-0.65
		$R_F = 500 \Omega$	-0.74	-0.71	-0.65	-0.67	-0.65
PTP	$k_0 \times 10^4$	$R_F = 0.1 \Omega$	1.73	-2.30	-6.63	-4.28	-16
		$R_F = 100 \Omega$	3.84	-3.63	-10	-12	-13
		$R_F = 300 \Omega$	1.12	-2.65	-7.20	-12	-6.39
		$R_F = 500 \Omega$	-4.11	-4.30	-8.15	-8.44	-7.17
	$k_1 \times 10^4$	$R_F = 0.1 \Omega$	1.23	-1.63	-4.69	-3.03	-11
		$R_F = 100 \Omega$	2.72	-2.56	-7.14	-8.41	-8.91
		$R_F = 300 \Omega$	7.89	-1.88	-5.09	-8.82	-4.52
		$R_F = 500 \Omega$	-2.90	-3.04	-5.76	-5.97	-5.07

As shown in Table VII, no matter how large the fault resistance is, using the absolute values of k_0 and k_1 can correctly and reliably discriminate between PTG faults and PTP faults, whereas using the polarities of k_0 and k_1 can correctly and reliably identify the faulted pole.

According to the process of fault detection, the fault detection time for the proposed protection scheme contains three parts, i.e., triggering time Δt_0 , the time interval Δt_1 to identify faulted line, the time interval Δt_2 to identify fault type and faulted pole. As shown in Fig. 12, the fault detection time depends on the maximum of $\Delta t_0 + \Delta t_1$ and $\Delta t_0 + \Delta t_2$ without calculation and signal transmission delays taken into account. In this paper, Δt_0 equals a sampling time interval, i.e., $\Delta t_0 = 25 \mu s$. Δt_1 indicates the time for a traveling wave to finish a round trip between the midpoint to the protective relay, i.e., $\Delta t_1 = length/v = 667 \mu s$, where $length$ is 200 km and the

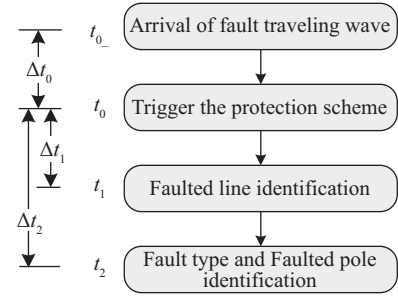


Fig. 12. Time flow chart of the proposed protection scheme.

velocity v of the traveling wave is about 300 km/ms [27]. Δt_2 equals $\Delta T - T_s$, i.e., $\Delta t_2 = 975 \mu s$. Therefore, the typical fault detection time for the proposed protection scheme is 1 ms in this paper.

B. Effect of Noise

The measuring noise is inevitable, especially when the sampling frequency is up to tens of kHz. The effect of signal noise on the proposed protection scheme is investigated by corrupting the transient voltages with white Gaussian noise (signal-to-noise ratio of 30 dB). Fig. 13 shows the corrupted $u_{R2}(t)$ for different negative PTG faults. The ROCOVs and the waveform similarity coefficients versus fault distance in negative PTG faults with measuring noise are shown in Tables VIII and IX, respectively.

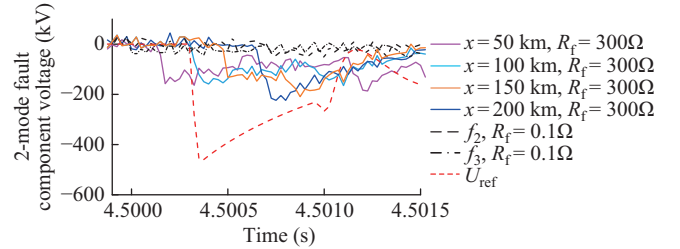


Fig. 13. Waveforms of U_{ref} and $u_{R2}(t)$ measured at R_{12} with measuring noise when negative PTG faults occur.

TABLE VIII
THE ROCOV FOR NEGATIVE PTG FAULTS WITH NOISE
(THRESHOLD $\Delta_1 = 0.3304$ p.u./50 μs)

x km	R_F	0.1 Ω	100 Ω	300 Ω	500 Ω
0		2.0	1.50	0.79	0.77
50		1.16	0.74	0.43	0.29
100		1.06	0.60	0.40	0.16
150		1.04	0.59	0.29	0.19
200		0.85	0.41	0.20	0.22
f_2		0.3136	0.15	0.12	0.08
f_3		0.18	0.07	0.10	0.08

For all the internal faults on line l_1 in Table VIII, they all can be identified by: i) the ROCOVs of $u_{R2}(t)$ are above the threshold value Δ_1 of 0.3304 p.u./50 μs when the faults with low fault resistances or close-up faults occur; ii) the waveform similarity coefficients between $u_{R2}(t)$ and U_{ref} are above the threshold value S_{thre} of 0.4192 when the faults with high fault resistances occur. For the external faults in Table IX, i.e., f_2

TABLE IX
WAVEFORM SIMILARITY COEFFICIENTS FOR NEGATIVE PTG FAULTS
WITH NOISE (THRESHOLD $S_{\text{thre}} = 0.4192$)

x km	R_F	0.1 Ω	100 Ω	300 Ω	500 Ω
0		—	—	—	—
50		—	—	—	0.6941
100		—	—	—	0.6928
150	Similarity	—	—	0.8353	0.8890
200		—	—	0.8853	0.8630
f_2		0.3211	0.1879	-0.0933	0.1299
f_3		-0.2776	-0.1880	-0.1045	-0.4628

and f_3 , the corresponding waveform similarity coefficients are below the threshold value S_{thre} of 0.4192. Once the internal fault is identified, the corresponding k_0 and k_1 at R_{12} shown in Table X can correctly and reliably identify the fault type and faulted pole under the influence of 30 dB noise.

TABLE X
VALUES OF k_0 AND k_1 FOR NEGATIVE PTG FAULTS WITH NOISE

	x km	0	50	100	150	200
k_0	$R_F = 0.1 \ \Omega$	-1.07	-1.04	-0.85	-0.93	-0.94
	$R_F = 100 \ \Omega$	-1.03	-1.02	-0.93	-0.95	-1.07
	$R_F = 300 \ \Omega$	-1.05	-1.03	-0.88	-0.91	-0.90
	$R_F = 500 \ \Omega$	-1.04	-0.97	-0.94	-0.91	-0.97
k_1	$R_F = 0.1 \ \Omega$	-0.76	-0.74	-0.60	-0.66	-0.69
	$R_F = 100 \ \Omega$	-0.73	-0.72	-0.66	-0.67	-0.73
	$R_F = 300 \ \Omega$	-0.75	-0.73	-0.63	-0.65	-0.64
	$R_F = 500 \ \Omega$	-0.74	-0.69	-0.67	-0.65	-0.69

Although the effect of the noise cannot be ignored, the general shape of the wave is dominated by the original $u_{R2}(t)$ (without the measuring noise). Therefore, the proposed method is relatively robust to the measuring noise of 30 dB.

C. Comparison Study

The comparison between the conventional ROCOV-based protection and the proposed protection scheme is conducted in negative PTG faults, as shown in Fig. 14, wherein the threshold Δ_2 for the conventional ROCOV is set to be higher than the ROCOV measured at the protective relay when the most serious external fault occurs, that is $\Delta_2 = 1.2 \times 0.3$ p.u./50 μs = 0.36 p.u./50 μs .

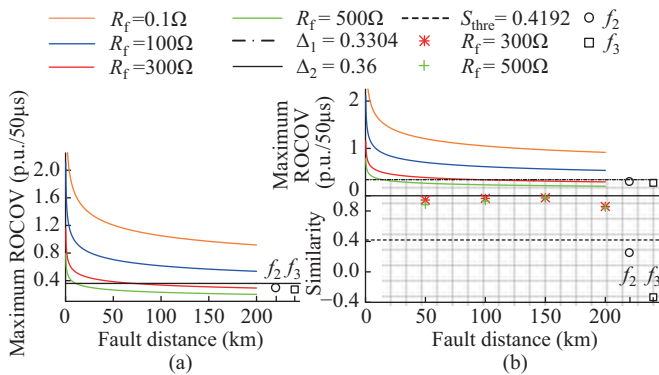


Fig. 14. Comparison results. (a) Conventional ROCOV-based protection method. (b) The proposed method.

As shown in Fig. 14(a), for the fault resistance of 0.1 to 100 Ω , using the threshold Δ_2 of the conventional ROCOV

criterion can protect the full length of l_1 . However, with the fault resistance increasing to 300 and 500 Ω , the protected area of the DC line has to decrease to tens of km and even to several km, because ROCOV is heavily determined by the fault loop impedance and will be reduced by the high transition resistance of the fault.

As shown in Fig. 14(b), the ROCOV criterion in the proposed protection scheme can screen out the close-in faults or faults with low fault resistances. For the high-resistance faults or external PTG faults which failed to trigger the ROCOV criterion (shadow area), they can be correctly identified by the waveform similarity coefficients between $u_{R2}(t)$ and U_{ref} .

D. Application to Symmetrical Mono-pole DC Systems

Different from symmetrical bipolar DC grids, symmetrical mono-pole DC systems have no metallic returns. Therefore, the second-order phase-modal transformation matrix [22] should be used to decouple the coupling between the positive and negative poles in symmetrical mono-pole DC systems without ground return. A four-terminal symmetrical mono-pole DC system, identified as the CIGRE B4 DC grid test system [28], is adopted as the test system, where the inductance of the DC reactor equals 50 mH. Because the pole-to-pole (PTP) fault is more critical than the pole-to-ground fault in the symmetrical mono-pole DC systems [29], use the PTP fault as an example to investigate the protection scheme.

The ROCOVs and the waveform similarity coefficients for PTP faults with different fault distances and different fault resistances are shown in Tables XI and XII, respectively. The threshold value Δ_1 for ROCOV is set as 0.575 p.u./50 μs , the threshold value S_{thre} for the waveform similarity criterion is set as 0.8576, and the threshold K_{rel3} for identifying the fault type is set as 0.001.

For all the internal faults in Tables XI and XII, they all can be identified by: i) the ROCOVs of $u_{R2}(t)$ are above the threshold value Δ_1 of 0.575 p.u./50 μs when the faults

TABLE XI
THE ROCOV FOR PTP FAULTS (THRESHOLD $\Delta_1 = 0.575$ p.u./50 μs)

x km	R_F	0.1 Ω	500 Ω	1000 Ω
0	ROCOV	1.99	0.95	0.63
50	(p.u./50 μs)	1.70	0.60	0.37
100		1.64	0.58	0.354
150		1.61	0.57	0.347
200		1.54	0.49	0.328
f_2		0.48	0.27	0.205
f_3		0.37	—	—

Note: “—” represents that the protection scheme is not triggered according to the trigger criterion.

TABLE XII
WAVEFORM SIMILARITY COEFFICIENTS FOR PTP FAULTS (THRESHOLD $S_{\text{thre}} = 0.8576$)

x km	R_F	0.1 Ω	500 Ω	1000 Ω
0		—	—	—
50		—	—	0.9554
100		—	—	1.0000
150	Similarity	—	0.9538	0.9537
200		—	0.9784	0.9774
f_2		0.3084	0.7147	0.6934
f_3		-0.6445	—	—

with low fault resistances or close-up faults occur; ii) the waveform similarity coefficients between $u_{R2}(t)$ and U_{ref} are above the threshold value S_{thre} of 0.8576 when the faults with high fault resistances occur. For the external faults in Table XII, i.e., f_2 and f_3 , the corresponding waveform similarity coefficients are below the threshold value S_{thre} of 0.8576. Once the internal fault is identified, the corresponding k_0 ($k_0 = \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R0}(t) / \sum_{t_0-T_s}^{t_0-T_s+\Delta T} u_{R1}(t)$) shown in Table XIII can correctly and reliably identify that a PTP fault occurred.

TABLE XIII
VALUES OF k_0 FOR PTP FAULTS (THRESHOLD $K_{rel3} = 0.001$)

x km	0	50	100	150	200
$R_F = 0.1 \Omega$	0.452	5.96	-1.49	-2.12	6.29
$k_0 \times 10^5$ $R_F = 500 \Omega$	0.22	6.14	-0.73	-3.1	-7.13
$R_F = 1000 \Omega$	-0.42	-6.35	-0.359	-3.13	8.08

The results for PTP faults in the symmetrical mono-pole DC system show that using the waveform similarity between $u_{R2}(t)$ and U_{ref} can reliably discriminate between the internal faults with extremely high fault resistances and external faults with a low fault resistance whereas using ROCOV criterion can detect the faults with low fault resistances. Therefore, the proposed protection scheme can be applied to the symmetrical mono-pole DC systems except that the thresholds and the phase-modal transformation matrix with reduced order needs to be adjusted.

V. CONCLUSION

Fault identification with high speed and strong robustness against high fault resistance is a necessity in HVDC grids. Based on the theoretical analysis of the modal fault-component voltages at the line side of the DC reactor, a novel hybrid protection scheme is proposed, including the identification of faulted line, fault type, and faulted pole. It uses the hybrid ROCOV criterion and waveform similarity coefficient to achieve fast and full-length faulted line identification under different fault resistances, and uses the amplitudes of the 0- and 1-mode fault-component voltages to identify fault types whereas the polarities of the 0- and 1-mode fault-component voltages can be used as a criterion to identify faulted poles. Simulations under various fault conditions verify that the proposed protection scheme can achieve selective fault identification under high fault resistance up to 1200 Ω , and is robust to the measuring noise of 30 dB. It is shown that the proposed protection scheme can identify the faulted line, the fault type, and the faulted pole in 1 ms. Although the proposed protection scheme is designed for DC grids with metallic return, it can be applied to the symmetrical mono-pole DC systems except that the thresholds and the phase-modal transformation matrix with reduced order need to be adjusted.

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