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Research of Bipolar HVDC Transmission Lines based on Traveling Wave Differential Protection

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Abstract

The principle of the traveling wave based differential protection for bipolar HVDC transmission lines is proposed in the paper. Unlike the traditional current differential protection, the quantity of current is replaced by the quantity of the traveling wave for comparison. The traveling wave at the remote end is transferred to the local end for comparison to the local traveling wave. For the bipolar DC transmission lines, the polar-mode (aerial mode) traveling waves are employed to establish the discriminative criterion. The ground-mode traveling waves are utilized for faulty line detector for bipolar operation modes. The entire protection scheme is simulated in PSCAD/EMTDC associated with the standard ±500kV HVDC transmission system. The simulation results show that the new protection has the advantages of higher sensitivity, reliability and security. The fault resistance can be coverd by the traveling wave based differential protection reaches to 500Ohm.

Keywords*: traveling wave, differential protection, protection scheme, faulty line detector*

1. Introduction

With the rapidly development of power electronics and control techniques, the high voltage direct current (HVDC) transmission systems are widely established in modern power systems [1]. Currently, most of the protections for HVDC transmission system employ the ABB's or Siemens' control and protection systems. For example, in Siemens protection systems, the Wavefront Protection (WFPDL) unit functions as the main protection for HVDC transmission lines, the under voltage and the du/dt detection unit as the auxiliary discriminative criterion and the current differential protection is employed as the backup protection for high resistance faults [2-4].

However, the current differential protection actually can not accomplish the mission of backup protection. Due to the distributed capacitances of the long transmission lines, there are large amounts of unbalanced currents generated by the distributed shunt branches, especially in the case of the operation of the Voltage Dependent Current Order Control (VDCOL) system. The current differential unit must be delayed at least 500ms in order to avoid the mal-operation of the protection [5]. Moreover, in order to avoid communication failure, the current differential protection will be blocked for 600ms when the detected current changes over 210A during 65ms. It will lead to the mal-operation of the protection system, because the other backup protections, such as converter over-current and over fire angle protection, trip prior to current differential protection [6]. According to the analysis reports of the HVDC system accidents by the National Grid and South Power Grid Companies, most of the causes are due to the mal-operation of the HVDC line protection [7-8].

Recently, more traveling wave based or transient based boundary protections are proposed by employing the wavelet transform or multi-resolution methods [9-10], in which the higher frequency components are required to be obtained. However, the high frequency information actually has already been deeply attenuated by the long distance DC transmission line.

In the paper, the traveling wave based differential protection (TWDP) for HVDC transmission line is proposed as well as the complete protection scheme is presented. Based on the traveling wave propagating theories [11-13], one can find that the traveling wave at local

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terminal equals the traveling wave propagating from the remote terminal as the line is healthy or the external faults occuring. That is to say, when there is no fault or external fault on the transmission line, the traveling waves of the two terminals are balanced. However, such propagating relations are violated when an internal fault occurs [14-15].

The operating traveling wave is defined as that the traveling wave at local end minus the traveling wave propagating from the remote end. At the same time, the restraint traveling wave is defined as the traveling wave at local end plus that of remote end. The discriminative criterion of the traveling wave based differential protection is then established by comparing the operating traveling wave with the restraint traveling wave. For bipolar HVDC lines, the polar-mode (aerial mode) quantities are utilized for forming the protective criterion. The ground-mode current detector is employed to determine the faulted line.

The configuration of the protection scheme is presented as follows, the TWDP unit with the faulty line detector functions as the main protection for high resistance faults. The wave front protection and the under voltage detector as backup protection, it will play an important role to detect the fault with high speed as the communication links of TWDP are damaged. The entire protection scheme is simulated in PSCAD/EMTDC associated with the standard ±500kV HVDC transmission system supplied by Cigre [16]. The simulating results show that the new protection has the advantages of higher sensitivity, reliability and security. The fault resistance covered by the traveling wave based differential protection reaches to 500ohm.

2. Basic Principle of TWDP

2.1. Fault Analysis

Consider a single phase distributed parameter transmission line, shown in Figure 1. Suppose that there is a fault at location F, which is x kilometers from terminal M, the overall line length is L. Based on the traveling wave theories, if the line is healthy, the forward traveling wave (FTW) propagates from terminal M to N, while the backward traveling wave (BTW) from terminal N to terminal M. i.e. in the case of no fault or external fault, there are fixed propagation relations between the two terminals (in frequency domain):

$$\begin{cases} F_N(s) = F_M(s)A_L(s) \\ B_M(s) = B_N(s)A_L(s) \end{cases} \quad (1)$$

Where $F = V + Z_c I$ means FTW, $B = V - Z_c I$ means BTW, $A_L(s) = \exp[-\gamma(s)L]$ is propagation function, $\gamma(s) = \sqrt{Z(s)Y(s)}$ means the propagation coefficient, Z and Y are respectively the series impedance and shunt admittance per-length of transmission line.

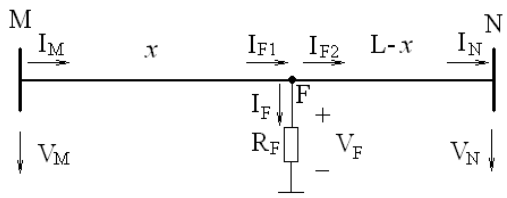


Figure 1. Single Phase Line

However, for the case of internal fault, see Figure 1, the relationship of the traveling waves can be defined as:

$$\begin{cases} F_N(s) = F_M(s)A_L(s) - I_F \exp[-\gamma(L-x)] \\ B_M(s) = B_N(s)A_L(s) - I_F \exp[-\gamma x] \end{cases} \quad (2)$$

Where I_F is the fault current of the branch of fault point to ground.

2.2. Basic Principle of TWDP

Based on the fault analysis in previous section A, the operating and restraint quantities at terminal M and N are respectively defined as follows:

i) At the terminal M, the operating traveling wave and restraint traveling wave are respectively defined as:

$$\begin{cases} D_{opM} = \|B_M - A_L B_N\| \\ D_{resM} = \|B_M + A_L B_N\| \end{cases} \quad (3)$$

ii) At terminal N, the operating traveling wave and restraint traveling wave are respectively defined as:

$$\begin{cases} D_{opN} = \|F_N - A_L F_M\| \\ D_{resN} = \|F_N + A_L F_M\| \end{cases} \quad (4)$$

Where symbol "$\| \;\|$" means the root mean square (RMS) value. At terminal M, when external fault occurs, there is:

$$\begin{cases} D_{opM} = 0 \\ D_{resM} = 2\|B_N A_L\| \approx 2\|B_N\| \end{cases} \quad (5)$$

However, when internal fault occurs, there is:

$$\begin{cases} D_{opM} \approx \|B_N\| \\ D_{resM} \approx \|B_N\| \end{cases} \quad (6)$$

The situation at terminal N is similar to terminal M, when external fault happens, there is:

$$\begin{cases} D_{opN} = 0 \\ D_{resN} = 2\|F_M A_L\| \approx 2\|F_M\| \end{cases} \quad (7)$$

However, as internal fault occurs, there is:

$$\begin{cases} D_{opN} \approx \|F_M\| \\ D_{resN} \approx \|F_M\| \end{cases} \quad (8)$$

So that the discriminative criterion of the TWDP is shown in the following formula:

$$D_{op} > K_1 D_{res} \quad (9)$$

Where $0 < K_1 \le 0.5$.

3. The Algorithm for TWDP

3.1. The Formation of Traveling Waves

Based on the basic principle of TWDP, one can find that the operating traveling wave is formed by comparison the local traveling wave with the remote traveling wave (see formula 3 and 4).

At the rectifier terminal, the quantities to be compared are backward traveling waves. Suppose that $u_{\mathrm{Re}c}$ and $i_{\mathrm{Re}c}$ are respectively voltage and current measured at the rectifier terminal, u_{Inv} and i_{Inv} are those at the inverter terminal. Then the backward traveling waves are formed by the following formula:

$$\begin{cases} b_{\mathrm{Re}\,c} = u_{\mathrm{Re}\,c} - Z_c i_{\mathrm{Re}\,c} \\ b_{Inv} = u_{Inv} - Z_c i_{Inv} \end{cases} \quad (10)$$

Where Z_c is the surge impedance of the DC line.

Similarly, at the inverter terminal, the quantities to be compared are forward traveling waves. The forward traveling waves are formed as follows.

$$\begin{cases} f_{\mathrm{Re}\,c} = u_{\mathrm{Re}\,c} + Z_c i_{\mathrm{Re}\,c} \\ f_{Inv} = u_{Inv} + Z_c i_{Inv} \end{cases} \quad (11)$$

3.2. The Algorithm of Traveling Wave Propagation

The operating traveling wave is defined as the local traveling wave minus the remote traveling wave propagating to the local end, the restraint traveling wave is defined as the local traveling wave plus the remote traveling wave propagating to the local end (see formula 3 and 4). In the time domain, the operating and restraint traveling waves can be written as follows.

Let $b'_{\mathrm{Re}c} = a_L * b_{Inv}$, $f'_{Inv} = a_L * f_{\mathrm{Re}c}$, where symbol * means revolution, the operating and restraint traveling waves in the time domain can be written as follows.

$$\begin{cases} d_{op\ \mathrm{Re}\ c}(t) = b_{\mathrm{Re}\ c}(t) - b'_{\mathrm{Re}\ c}(t) \\ d_{res\ \mathrm{Re}\ c}(t) = b_{\mathrm{Re}\ c}(t) + b'_{\mathrm{Re}\ c}(t) \end{cases} \quad (12)$$

$$\begin{cases} d_{opInv}(t) = f_{Inv}(t) - f'_{Inv}(t) \\ d_{resInv}(t) = f_{Inv}(t) + f'_{Inv}(t) \end{cases} \quad (13)$$

The propagation function a_L can be selected to be simplest delta function with attenuation and time delay, i.e.

$$a_L(t) = \exp(-R_1 / Z_c)\delta(t - T_D) \quad (14)$$

Denote T_{com} as the communication time delay, T_{wave} as the propagation time delay, then $T_D = T_{wave} - T_{com}$.

Then the algorithm of the propagating traveling wave is very simple:

$$\begin{cases} b'_{\mathrm{Re}\ c}(n) = \exp(-\dfrac{R_1}{Z_c}) b_{Inv}(n - M) \\ f'_{Inv}(n) = \exp(-\dfrac{R_1}{Z_c}) f_{\mathrm{Re}\ c}(n - M) \end{cases} \quad (15)$$

Where R1 is the resistance per length; Zc is the surge impedance; M is the delay sampling points.

3.3. The Algorithm for Bipolar DC Line

For bipolar DC transmission lines, shown in Figure 2, there are mutual impedance and mutual admittance between the two polar lines.

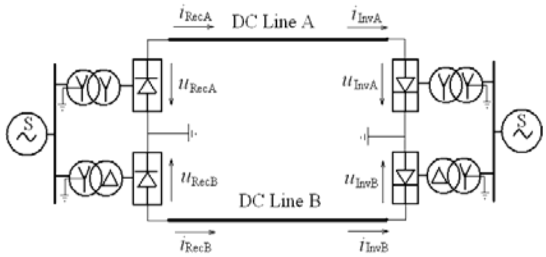


Figure 2. Bipolar HVDC Transmission System

So that the measured bipolar voltages and currents should be transformed into the mode domain, shown in following formulas.

$$\begin{bmatrix} u_1 \\ u_0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} u_A \\ u_B \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} i_1 \\ i_0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} \tag{17}$$

Where, subscript “1” and “0” respectively represent the polar-mode (aerial mode) and the ground-mode, subscript A and B indicate the positive and the negative polars.

In formulas 10 to 15, all voltages and currents are replaced by those of polar-mode quantities.

3.4. Algorithm for Discriminative Creterion

The real time RMS value of operating and restraint quantities can be realized by the following formula:

$$D(n) = \sqrt{\frac{1}{N} \sum_{k=n-N+1}^{n} |d(k)|^2} \tag{18}$$

Where, N is the length of the time window.

The discriminative criterion of traveling wave based differential protection is shown in the following formula:

$$D_{op} > K_1 D_{res} + K_2 V_{Rate} \tag{19}$$

Where V_{rate} is the rating voltage. $K_2 V_{rate}$ is the fixed threshold for higher security of the protection.

3.5. Principle of Faulty Line Detection

Suppose that there are mutual-coupled two lines A and B, shown in Figure 3.

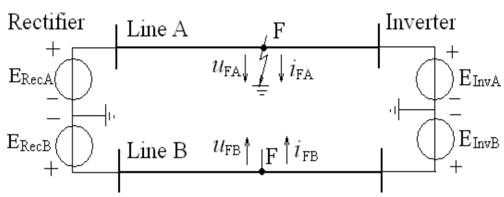


Figure 3. Fault Occurs at Line A (Positive polarity)

If the fault occurs on line A, at the fault point F, there is:

$$\begin{cases} u_{FA} = 0 \\ i_{FB} = 0 \end{cases} \quad (20)$$

Convert condition (9) to mode domain, there is:

$$\begin{cases} u_{F1} = -u_{F0} \\ i_{FA} = i_{F0} \end{cases} \quad (21)$$

The equivalent circuit is shown in Figure 3, in which it can conclude that the zero-mode current at the rectifier terminal is larger than zero, i.e.:

$$i_{\mathrm{Re}c0} = i_{\mathrm{Re}cA} + i_{\mathrm{Re}cB} > 0 \quad (22)$$

The reason for the previous conclusion is that $E_1 = E_A - (-E_B)$ is larger than $E_0 = E_A + (-E_B)$. Note that, in Figure 3, the direction of EB is reference direction, the real direction actually is negative.

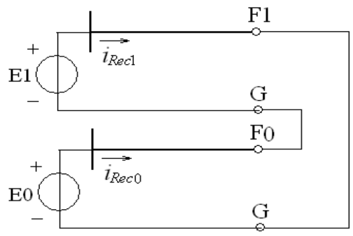


Figure 4. The Equivalent Circuit for Line A fault

If the fault is occurring at Line B, the situation is opposite, that is:

$$\begin{cases} u_{F1} = u_{F0} \\ i_{FA} = -i_{F0} \end{cases} \quad (23)$$

Based on its equivalent circuit it can conclude that the zero-mode current is less than zero, i.e.

$$i_{\mathrm{Re}c0} = i_{\mathrm{Re}cA} + i_{\mathrm{Re}cB} < 0 \quad (24)$$

Therefore, the faulty line detector can be designed by utilizing the previous conclusions, that is: If $I_{\mathrm{Re}c0} > I_{set}$, then fault at Line A (Positive Polarity); If $|I_{\mathrm{Re}c0}| < I_{set}$, then fault at both Line A and B; If $I_{\mathrm{Re}c0} < -I_{set}$, then fault at Line B (Negative Polarity).

Where $I_{\mathrm{Re}c0}$ is defined as the following (N is the window length of integral):

$$I_{\mathrm{Re}c0}(n) = \frac{1}{N} \sum_{k=n-N+1}^{n} [i_{\mathrm{Re}cA}(k) + i_{\mathrm{Re}cB}(k)] \quad (25)$$

4. Protection Scheme

The complete protection scheme for bipolar HVDC transmission lines is shown in Figure 5.

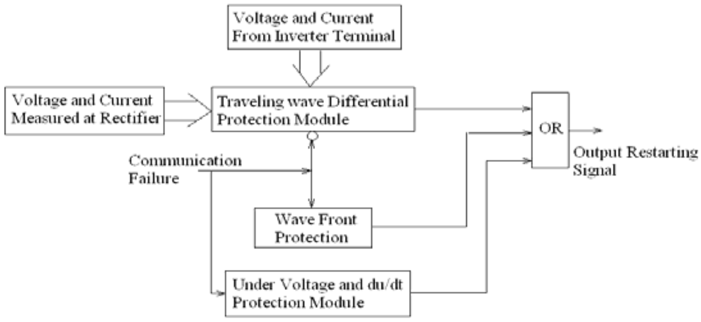


Figure 5. The Entire Protection Scheme for HVDC Lines

The traveling wave based differential protection (TWDP) functions as the main protection, while the wave front protection and the under voltage protection are the backup protection in the case of communication failure.

4.1. The Scheme of TWDP Module

The scheme for traveling wave based differential protection at rectifier terminal is shown in Figure 6 (the TWDP at inverter terminal is similar to that at rectifier terminal).

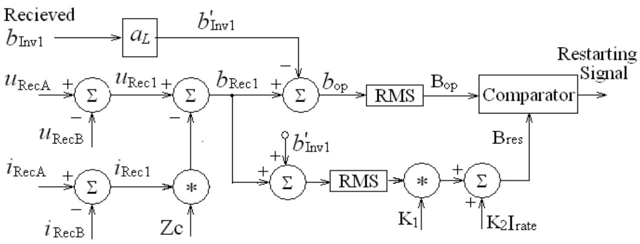


Figure 6. The Scheme of TWDP at Rectifier Terminal

The backward traveling wave in mode 1 at rectifier terminal $b_{\mathrm{Re}c1}$ is formed by employing the measured voltage and current data. Subsequently, the backward traveling wave propagating from inverter terminal b'_{Inv1} is calculated by means of propagation function using the data received from inverter station. Accordingly the operating and restraint traveling waves are obtained. The output signal is generated by comparing the RMS values respectively of the operating and restraint traveling waves.

4.2. The Faulty Line Selector

The scheme of faulty line selector is shown in Figure 7.

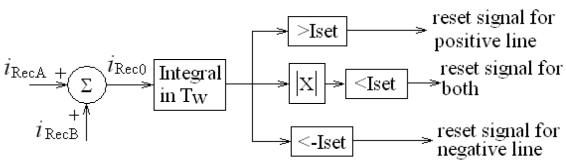


Figure 7. The Scheme of Faulty Line Selector

After the zero-mode current is formed, it is integrated in a time window Tw. The algorithm of integral block is shown in formula (14). The setting threshold is selected to be 0.1p.u.

5. Simulations

In this section, the simulation tests are performed on the typical ±500kV bipolar HVDC transmission system supplied by Cigre, see Figure 2. The transmission line is using the frequency dependant model, the structure of which is shown in Figure 8. The line length is 800km, the sampling period is 0.25ms. The communication time delay is considered as 4ms.

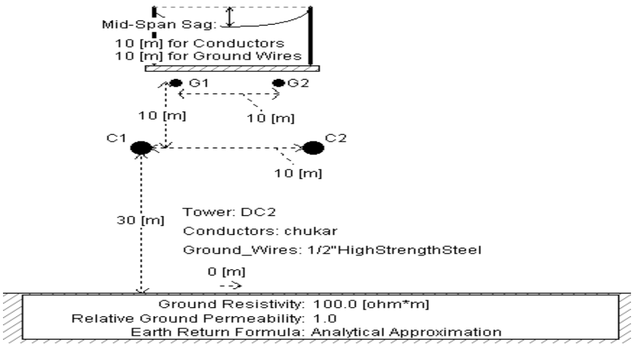
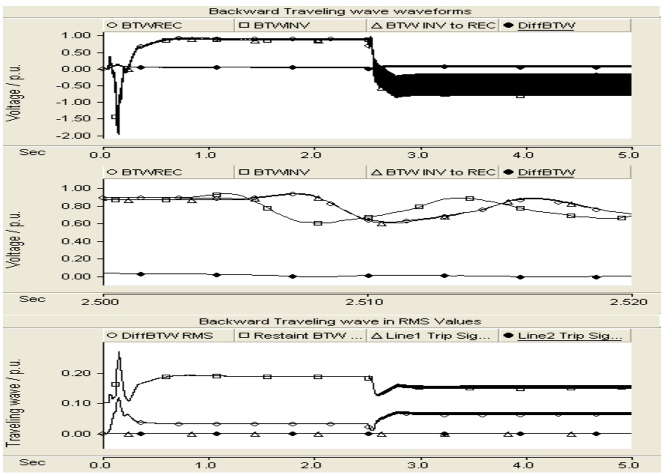


Figure 8. The Structure of HVDC Transmission Line

5.1. External Faults

Suppose that phase BC to ground fault without fault resistance occurring at the AC bus of Rectifier side. The fault takes place at 2.5s. Under such condition, the waveforms of the backward traveling waves (BTW) measured at the rectifier terminal, those received from the inverter terminal and the differential backward traveling waves are shown in Figure 9. The middle figure is the zoom-in of the upper figure.



BTWREC: the BTW at Rectifier terminal
BTWINV: the BTW at inverter terminal
BTW INV to REC: the BTW propagation from Rec to Inv
DiffBTW: the differential BTW
DiffBTW RMS: the operating BTW in RMS
Restraint BTW RMS: the restraint BTW in RMS
Line1 Trip Sig: the output tripping signal of positive polar line A, "=0" equals "No", "=1" equals "Yes"
Line2 Trip Sig: the output tripping signal of negative polar line B, "=0" equals "No", "=1" equals "Yes"

Figure 9. Waveforms of External Fault (at rectifier side AC Bus)

From Figure 9 one can find that the trip signal of line A and line B are all zero, that is, their outputs are both “No faults on DC line”.The TWDP outputs are shown in Table 1 as external faults happen in different position.

Table 1. Outputs of TWDP at the Case of External Faults

FAULT POSITION	AC BUS		DC BUS OF RECTIFIER		DC BUS OF INVERTER	
	Rec	Inv	Pos	Neg	Pos	Neg
Output LA	0	0	0	0	0	0
Output LB	0	0	0	0	0	0

From Table 1, it is clear that the new traveling wave based protection has the advantage of higher security, that is, no matter where the external faults take place, the output of the TWDP are all zeros.

5.2. Internal Faults

Suppose that line A to ground fault happens at 2.5s, where the fault is 100km away from rectifier terminal. The waveforms of the BTW and the output signals are shown in Figure 10. From Figure 9, it can be seen that the output tripping signal is correct, the tripping time is less than 4ms.

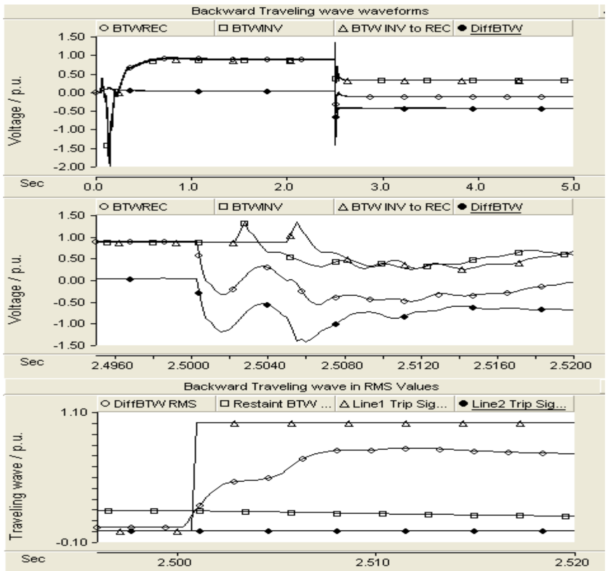


Figure 10. Waveforms of Internal Fault on Line A

5.3. Internal Fault at Various Positions

The outputs of TWDP under the condition internal fault at various fault location are shown in Table 2. Note: the communication time delay is considered as 4ms.

Table 2. Results of TWDP under Various Fault Location

FAULT POSITION	0		400		800	
	LineA	Line B	LineA	Line B	LineA	Line B
Output LA	1	0	1	0	1	0
Time(m)	1.4	/	19.5	/	38.7	/
Output LB	0	1	0	1	0	1
Time(m)	/	1.3	/	20.6	/	38.5

5.4. Fault Resistance

Suppose that line A to ground fault, with the fault resistance of 300Ohm, happens at 2.5s, where the fault is located at 100km away from rectifier terminal.

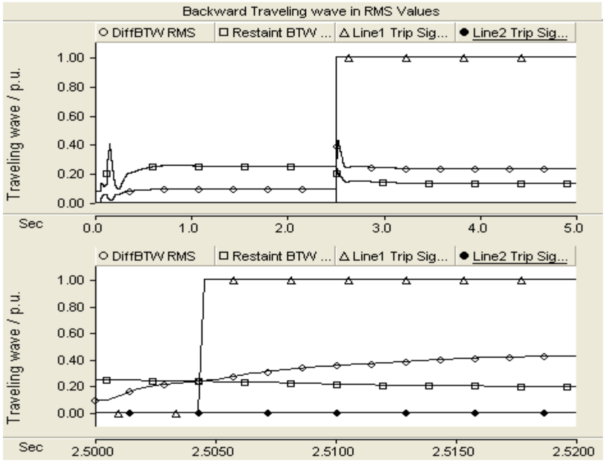


Figure 10. Waveforms of Internal Fault on line A with 300 Ohm Fault Resistance

The waveforms and the output signals are shown in Figure 11. One can see that the tripping signal is correct, however, the tripping time is delayed to 48.2ms. The discrimination results of the TWDP under the condition of various fault resistance are shown in Table 3.

Table 3. Results of TWDP under Various Fault Resisstance

FAULT RESISTANCE(□)	50		200		500	
	LineA	Line B	LineA	Line B	LineA	Line B
Output LA	1	0	1	0	1	0
Time(m)	11.1	/	16.9	/	53.1	/
Output LB	0	1	0	1	0	1
Time(m)	/	12.6	/	15.1	/	51.5

According to Table 3, it conclude that the larger value of the fault resistance, the longer the tripping time. The fault resistance can be covered by the traveling wave based differential protection reaches to 500 ohm, however the tripping time is 51.5ms.

6. Conclusion

In the paper, the traveling wave based differential protection (TWDP) for HVDC transmission line is proposed as well as the complete protection scheme is presented. The waves are employed to form the operating and restraint waves, which are not affected by the operation of the control systems. The TWDP can function as the main protection for bipolar HVDC transmission lines. The zero-mode current can be employed to detect which line is the faulty line. PSCAD simulations show that the new protection scheme has the advantage of higher security and reliability. The minimum tripping time is not more than 2ms, at the same time the maximum value for overcoming fault resistance can be enlarged to 500Ohms.

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