A novel current differential protection for MMC-HVDC lines

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Abstract. The present current differential protection for MMC-HVDC transmission lines has absolute selectivity and powerful ability to withstand high transition resistance, while it is easily affected by distributed capacitive current and data synchronization error. To solve the problem above, this article proposes a novel current differential protection scheme. The distributed capacitive current can be calculated by integrating the linear voltage distribution in real-time. Thus, the differential value of the midpoint currents of DC line, which are calculated based on the low-pass filtered measure voltages and currents on both sides, can be adopted to identify the fault. Besides, the data synchronization error can be eliminated based on the waveform matching of the calculated midpoint currents. This novel current differential protection has excellent performance and can solve the problems of traditional current differential protection for HVDC lines.

1. Introduction
The DC transmission line protection is important to ensure the security of the entire system [1-2]. In existing MMC-HVDC transmission projects, traveling wave protection (TWP) and differential undervoltage protection are usually used as the primary protection, and current differential protection is used as backup protection for the DC lines. However, TWP and differential undervoltage protection for HVDC lines have problems of invalid and inadaptable setting criterion, the dependency on simulation and being sensitive to transient resistance. Current differential protection has absolute selectivity and powerful ability to withstand high transition resistance. However, the long transmission distance and high voltage level in HVDC lines will produce a large distributed capacitive current (DCC) during fault transient period. Thus, large time delay has to be set in the presently applied current differential protection to prevent mal-operation [3-4].

Some improved current differential protections for HVDC lines have been proposed. Refs [5-7] propose current differential protection principles based on the distributed parameter line model and frequency-dependent parameter line model, by which the DCC can be compensated. However, the complex calculation and sensitivity to noise and parameter errors make them difficult to be applied in actual engineering. Refs [8-9] propose novel differential protection schemes for HVDC lines, in which the DCC can be calculated based on the linear distributed voltage. However, they are very likely to mal-operate for the lack of capability against data synchronization error (DSE). Thus, they have high requirements for communication real-time quality between both sides [10-11].

To solve those problems mentioned above, a novel current differential protection for MMC-HVDC lines is proposed. When the voltage and current signals at both line ends are filtered by the low-pass
filter, the voltage distribution can be approximately regarded as linear distribution. The DCC can be calculated based on the linearly distributed voltage. Thus, the differential value of the midpoint currents of DC line, which are calculated with filtered measure voltages and currents, can be adopted to identify the fault. Besides, the data synchronization error can be eliminated based on the waveform matching of the calculated midpoint currents. With PSCAD/EMTDC, an MMC-HVDC transmission system is modeled and extensive simulation results demonstrate that the newly proposed protection stands out for absolute selectivity, fast response and powerful fault resistance withstand ability.

2. Compensation method of DCC

The distributed parameter model of transmission line is shown in Figure 1. According to Kirchhoff’s current law, the current along the DC transmission line satisfies equation (1).

\[ i_{M0} (t) - \int_0^1 i_{k0} (x,t) \, dx = i_{N0} (t) \tag{1} \]

Where \( i_{M0} (t) \) and \( i_{N0} (t) \) represent the measure currents on both sides of DC transmission line, \( i_{k0} (x,t) \) represents the DCC per unit length at \( x \), \( k=1 \) means 1-mode, \( k=0 \) means 0-mode, \( l \) means the DC line length. Since \( i_{k0} (x,t) \) cannot be measured, the current differential protection in practical HVDC systems usually sets a long time delay to avoid maloperation caused by DCC during transient process. In order to improve the operating speed of current differential protection in MMC-HVDC systems, it is necessary to compensate for the DCC along the DC line.

When there is no fault or external fault on the DC line, the sum of DCC can be calculated by

\[ \int_0^1 i_{k0} (x,t) \, dx = \int_0^l c_x \frac{\partial u_{k0} (x,t)}{\partial t} \, dx \tag{2} \]

According to [8], after voltage and current signals at both line ends are filtered by the low-pass filter, the voltage distribution can be approximately regarded as linear distribution. The cut-off frequency \( f_c \) of the low-pass filter should satisfy

\[ f_c < \frac{\arccos(1-E_{k,\text{max}})}{180l} \tag{3} \]

Where \( E_{k,\text{max}} \) is the maximum linear fitting error. Thus, the voltage along the DC line can be given by

\[ u_k (x,t) = u_{M0} (t) + \frac{u_{N0} (t) - u_{M0} (t)}{l} x \tag{4} \]

Where \( u_k (x,t) \) is the low-pass filtered voltage along the line, \( u_{M0} (t) \) and \( u_{N0} (t) \) are the low-pass filtered measure voltages on both sides. According to (2) and (4), when there is no fault or external fault on the DC line, the sum of DCC can be given by

\[ \int_0^l i_{k0} (x,t) \, dx = \int_0^l c_x \frac{\partial u_k (x,t)}{\partial t} \, dx = \frac{c_x l}{2} \left[ \frac{du_{M0} (t)}{dt} + \frac{du_{N0} (t)}{dt} \right] \tag{5} \]
Where $i_{ck}(x,t)$ represents the DCC per unit length caused by $u_{bk}(x,t)$. According to (5), when the measure voltages and currents on both sides are processed by the low-pass filter, the original distributed parameter line model can be equivalent to Figure 2.

![Figure 2. The equivalent model of DC line](image)

The expression of $i_{Mk}(t)$ and $i_{Nk}(t)$ can be given by

$$
i_{Mk}(t) = \frac{c_kl}{2} \frac{du_{Mk}(t)}{dt}$$

$$i_{Nk}(t) = \frac{c_kl}{2} \frac{du_{Nk}(t)}{dt}$$

(6)

When there is an external fault, the low-pass filtered current along the DC line can be given by

$$i_{M}(t) - i_{Mk}(t) = i_{N}(t) + i_{Nk}(t)$$

(7)

Where $i_{M}(t)$ and $i_{N}(t)$ represent the low-pass filtered measure currents on both sides.

It is obvious from (3) that $f_c$ is related to $E_{k_{max}}$ and $l$. The larger the $l$ is, the lower the $f_c$ should be set under the same $E_{k_{max}}$. However, the lower cut-off frequency will lead to longer time delay. In order to realize accurate compensation to the DCC as well as fast protection response, a sectional compensation method is proposed in this article, in which the DC line is divided into $N$ sections. Based on this, it is feasible to realize sectional compensation to DCC. For the DC line of 200km, considering calculation complexity, voltage linear fitting error and protection operating speed, $N$ can be set as 2. Thus, the length of each section of the DC line is 100km, and cut-off frequency $f_c$ can be set lower than 190Hz according to (3). The sectional compensation method is shown in Figure 3.

![Figure 3. Sectional compensation to the DCC](image)

When there is no fault or external fault on the DC line, the currents in Figure 3 satisfy

$$i_{M}(t) = i_{M}(t) - i_{M}(t) - i_{N}(t) + i_{N}(t) = i_{N}(t) + i_{N}(t) + i_{N}(t)$$

(8)
\[
\begin{aligned}
    i_{\text{ML}} (t) &= \frac{c_I}{4} \frac{du_{\text{ML}} (t)}{dt} \\
    i_{\text{ML}}' (t) &= \frac{c_I}{4} \frac{du_{\text{ML}}' (t)}{dt} \\
    i_{\text{NL}}' (t) &= \frac{c_I}{4} \frac{du_{\text{NL}}' (t)}{dt} \\
    i_{\text{NL}} (t) &= \frac{c_I}{4} \frac{du_{\text{NL}} (t)}{dt}
\end{aligned}
\]

Where \( i_{\text{ML}} (t) \) and \( i_{\text{NL}} (t) \) are the midpoint currents of DC line, which are calculated with low-pass filtered measure voltages and currents on both sides. The 1-mode values are adopted and the internal faults and external faults can be discriminated by \( i_{\text{ML1}} (t) \).

\[
i_{\text{ML1}} (t) = \lvert i_{\text{ML1}} (t) - i_{\text{NL1}} (t) \rvert > I_{\text{set}}
\]

Where \( I_{\text{set}} \) is the setting value of the differential current.

3. The method to estimate DSE

The proposed protection above still requires strict synchronization. The current differential protection may mal-operate under DSE. To solve the problem mentioned above, a method to estimate DSE is proposed. The waveforms of \( i_{\text{ML1}} (t) \) and \( i_{\text{NL1}} (t) \) will be matched under external faults. Accurate DSE can be obtained by matching the waveforms of \( i_{\text{ML1}} (t) \) and \( i_{\text{NL1}} (t) \) under external faults. Thus, the differential current \( i_{\text{ML1X}} (t) \), in which the DCC is compensated and DSE is eliminated, can be obtained based on \( i_{\text{ML1}} (t) \). The differential current \( i_{\text{ML1X}} (t) \), which is greater than the threshold under internal faults and lower under internal faults, can be employed to establish the protection criterion. To describe the waveform similarity between \( i_{\text{MLk}} (t) \) and \( i_{\text{NL1}} (t) \), the Pearson correlation coefficient (PCC) is adopted. For any two sets of discrete signal sequences \( x = \{x_1, x_2, \ldots, x_n\} \) and \( y = \{y_1, y_2, \ldots, y_n\} \), the PCC \( p_{x,y} \) of \( x, y \) can be given by

\[
p_{x,y} = \frac{\sum_{i=1}^{N_d} \left( x_i - \frac{1}{N_d} \sum_{i=1}^{N_d} x_i \right) \left( y_i - \frac{1}{N_d} \sum_{i=1}^{N_d} y_i \right)}{\sqrt{\sum_{i=1}^{N_d} \left( x_i - \frac{1}{N_d} \sum_{i=1}^{N_d} x_i \right)^2} \sqrt{\sum_{i=1}^{N_d} \left( y_i - \frac{1}{N_d} \sum_{i=1}^{N_d} y_i \right)^2}}
\]

Where \( N_d \) denotes the sampling number. The greater \( p_{x,y} \) indicates the stronger correlation between \( x \) and \( y \). When \( x \) and \( y \) are exactly matched, \( p_{x,y} = 1 \); When \( x \) and \( y \) have opposite trends, \( p_{x,y} = -1 \); When \( x \) and \( y \) are unrelated, \( p_{x,y} = 0 \).

After the fault occurs, the midpoint currents of the DC line \( i_{\text{ML1}} (t) \) and \( i_{\text{NL1}} (t) \), which are calculated based on (8)-(9), have obvious waveform characteristics. The waveforms of \( i_{\text{ML1}} (t) \) and \( i_{\text{NL1}} (t) \) are exactly the same regardless of the DSE, and can be completely matched at a certain moment during the data window sliding process. Through waveform matching, an accurate DSE can be calculated and the differential current, in which the DCC is compensated and DSE is eliminated, can be obtained.

4. Current differential protection scheme of DC line

A novel current differential protection for MMC-HVDC lines which can solve the problems of DCC and DSE is proposed. The protection scheme is composed of four parts.

1) Protection start-up element

The maximum value of the modulus of positive, negative and 1-mode measure voltage change rate is adopted as the protection start-up element, which can be given by

\[
\left| \frac{du_{\text{ML}} (t)}{dt} \right| = \max \left| \frac{du_{\text{ML}} (t)}{dt} \right|, \left| \frac{du_{\text{NL}} (t)}{dt} \right|, \left| \frac{du_{\text{ML}} (t)}{dt} \right| > D_{\text{set}}
\]

Where \( u_{\text{ML}} (t) \), \( u_{\text{NL}} (t) \) and \( u_{\text{ML1}} (t) \) are measure voltages of the positive pole, negative pole and 1-mode respectively. \( D_{\text{set}} \) is setting threshold setting value.
When the start-up element is tripped, the measure voltage and current signals will be sent to the opposite side, and calculate start time of opposite side by opposite side measured voltage. \( t_{Mq} \) is start time of side M, \( t_{Nq} \) is start time of side N.

(2) Low-pass filter
Butterworth low-pass filter is applied to filter the measure voltages and currents, the cut-off frequency of which can be set based on (3).

(3) DSE estimation
Taking the relay M for an example, the process of DSE estimation include the following steps.

a. Select the sampling data of \( i_{NL1}(t) \) during \([t_{Nq}-\Delta t/2, t_{Nq}+\Delta t/2]\) as the scanning sample.

b. Set \( t_{Mq}-\Delta t/2-\Delta t_H \) as the match start point and \( t_{Mq}+\Delta t/2+\Delta t_H \) as the match terminal point.

c. Set the match start point as the calculation start point, select the sampling data of \( i_{ML1}(t) \), the data window of which is equal to \( \Delta t_L \), and calculate the PCC \( p_{ML1, i_{NL1}}(t) \) between it and the scanning sample.

d. If \( t < t_{Mq}-\Delta t + \Delta t_H \), the match start point will move to next sampling point, and turn back to step c. Otherwise, move to next step.

e. Calculate the maximum \( p_{ML1, i_{NL1}}(t_{\text{max}}) \) of PCC, in which \( t_{\text{max}} \) is time of the greatest PCC. If \( p_{ML1, i_{NL1}}(t_{\text{max}}) \) is less than \( p_{\text{set}} \), which is the threshold, the synchronization error \( \Delta t_d=0 \). If \( p_{ML1, i_{NL1}}(t_{\text{max}}) \) is greater than \( p_{\text{set}} \), the synchronization error \( \Delta t_d=t_{\text{max}}-(t_{Nq}+\Delta t_H/2) \).

(4) Current differential protection criterion
The current differential protection criterion can be expressed as

\[
i_{i_{11X}}(t) = |i_{ML1}(t) - i_{NL1}(t - \Delta t_d)| > I_{\text{est}}
\]  

Where \( i_{ML1} \) and \( i_{NL1}(t-\Delta t_d) \) can be obtained based on (8)-(10). If there are \( K \) values satisfying (13) continuously, an internal fault is detected.

5. Simulation Analysis
For a further study and verification of the novel differential current protection scheme, a ±500kV four-terminals MMC-HVDC transmission system model is established in the transient simulation software PSCAD/EMTDC. \( U_{S1} \sim U_{S4} \) denote the AC power sources, MMC1~MMC4 denote the converters, Line1~Line4 denote the DC lines, \( U_{dc1} \sim U_{dc4} \) denote the DC bus voltages, and \( L_T \) is the DC reactor. \( D_{ij} \) \((i,j=1,2,3,4)\) represents the DC circuit breaker and \( R_{ij} \) \((i,j=1,2,3,4)\) represents the relay.

![Figure 4 Structure of MMC-HVDC system](image-url)
Table 1 Parameters of converters

| Converter | C_m/µF | R_m/Ω | L_m/mH | N_m |
|-----------|--------|-------|--------|-----|
| MMC1      | 8000   | 0.005 | 100    | 244 |
| MMC2      | 8000   | 0.005 | 100    | 244 |
| MMC3      | 15000  | 0.005 | 50     | 244 |
| MMC4      | 15000  | 0.005 | 50     | 244 |

Table 2 Parameters of DC transmission lines

| Projects | Parameters | Projects | Parameters |
|----------|------------|----------|------------|
| Line12   | Length 200 km | Unit resistance | 0.03984 Ω/km |
| Line23   | Length 157 km | External radius | 0.03623 m |
| Line34   | Length 205 km | SAG | 16.5 m |
| Line41   | Length 50 km | Bundle spacing | 0.5 m |

The faults occurring time is set at 0.8s, sampling rate is set as 10kHz, $D_{set}$ is set as 100kV/ms, $I_{set}$ is set as 0.1$/I_{N}$, and $K$ is set as 3. $\Delta t_L$ is set as 4ms and $\Delta t_H$ is set as 2ms. $E_{k_{max}}$ is set as 2%, and $f_c$ of the low-pass filter should satisfy

$$f_c = \frac{\pi \arccos(1 - E_{k_{max}})}{180/2} = \frac{3 \times 10^5 \arccos(1 - 2\%)}{180 \times 100} = 191Hz$$

Thus, $f_c$ can be set as 150Hz. To verify the performance of the novel protection scheme, the test system is simulated with numerous cases under different fault conditions. The simulation results under a synchronization error of 1ms are shown in Table 3 and Table 4.

Table 3 Simulation results under internal faults

| Fault Conditions | Position | $R_f$/Ω | Fault Area | Time | Action |
|------------------|----------|---------|-----------|------|--------|
| Positive pole to ground fault | 0% | 0Ω | Internal | 4.2ms | YES |
| | | 500Ω | Internal | 4.2ms | YES |
| | | 1000Ω | Internal | 4.2ms | YES |
| | 50% | 0Ω | Internal | 4.5ms | YES |
| | | 500Ω | Internal | 4.5ms | YES |
| | | 1000Ω | Internal | 4.5ms | YES |
| | 100% | 0Ω | Internal | 4.8ms | YES |
| | | 500Ω | Internal | 4.8ms | YES |
| | | 1000Ω | Internal | 4.8ms | YES |

Table 4 Simulation results under external faults

| Fault Conditions | Position | $R_f$/Ω | Fault Area | Time | Action |
|------------------|----------|---------|-----------|------|--------|
| Negative pole to ground fault | 0% | 0Ω | Internal | 4.2ms | YES |
| | | 500Ω | Internal | 4.2ms | YES |
| | | 1000Ω | Internal | 4.2ms | YES |
| | 50% | 0Ω | Internal | 4.5ms | YES |
| | | 500Ω | Internal | 4.5ms | YES |
| | | 1000Ω | Internal | 4.5ms | YES |
| | 100% | 0Ω | Internal | 4.8ms | YES |
| | | 500Ω | Internal | 4.8ms | YES |
| | | 1000Ω | Internal | 4.8ms | YES |
Table 4 Simulation results under external faults

| Fault Type   | Position | R/Ω | Protection Results |
|--------------|----------|-----|--------------------|
| DC Bus Fault | f₁       | 0Ω  | External NO        |
| DC Bus Fault | f₂       | 0Ω  | External NO        |
| DC Line2 Fault | f₃      | 0Ω  | External NO        |
| DC Line3 Fault | f₄      | 0Ω  | External NO        |
| DC Line4 Fault | f₅      | 0Ω  | External NO        |

Table 3 shows the performance of the novel current differential protection under the internal fault. From the table, when the internal fault location points from 0% to 100% and the fault resistance varies from 0Ω to 1000Ω, the internal faults can all be correctly identified and the protection has fast response. From Table 4, with different fault locations, types and resistances, the proposed protection will not operate reliably. Consequently, after changing the fault conditions, including the fault location, fault type, and fault resistance, the proposed protection method can discriminate internal faults from external faults accurately and quickly.

6. Conclusions

A novel current differential protection scheme for MMC-HVDC lines is proposed in this paper. The distributed capacitive current can be calculated by integrating the linear voltage distribution in real-time. Thus, the differential value of the midpoint currents of DC line calculated with low-pass filtered measure voltages and currents on both sides can be adopted to identify the fault. Besides, the data synchronization error can be eliminated based on the waveform matching of the calculated midpoint currents. Numerous simulations have proved that the novel current differential protection has fast response under all test conditions and does not require strict data synchronization on both sides.

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