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A novel differential protection scheme for HVDC transmission lines ☆

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ABSTRACT

Based on the compensation of the distributed capacitive current, a novel differential protection scheme for HVDC transmission lines was proposed in this study. According to the analysis, after voltage and current signals at both sides of the line are processed by the same low-pass filter the cut-off frequency of which is low enough, then the voltage distribution along the line can be regarded as linear distribution. The distributed capacitive current can be calculated by integrating the linear distributed voltage. After removing this current, the new differential criterion can be implemented. A ±800 kV HVDC transmission system was built in EMTDC to test the performance of the new protection. Comprehensive test studies show that the proposed method not only can detect internal faults correctly and quickly, but also can respond to internal faults with high ground resistance.

1. Introduction

Compared with high-voltage alternating current (HVAC) system, high-voltage direct current (HVDC) transmission system is more competitive for long-distance bulk power transmission, asynchronous interconnections and long submarine cable crossings on account of large power transmission capacity and flexible power control [1–3].

Most HVDC lines are applied to transferring power over long distance, inevitably passing through rough terrain and operating under bad weather condition, which causes that faults frequently occur on the line. Thus the dc transmission line protection is important to ensure the security of the entire HVDC transmission system [3,4]. Currently, traveling-wave protection and voltage derivative protection are used as the primary protection, and differential protection is used as the back-up protection [5]. The traveling-wave and voltage derivative protection have been successfully implemented in the HVDC system. However, there still are some problems limiting their application, such as being sensitive to transition impedance and requiring high accuracy on sampling rate [6,7]. The differential protection cannot detect internal faults in the fault transient period due to the existence of the distributed capacitive current. As a result, a delay time of 500 ms and a block time of 600 ms are applied to prevent mal-operation. When an internal fault occurs, if the protection is blocked firstly, the total delay will reach 1.1 s. Before the protection operates, the pole control protection has blocked the line. So the protection unable to play its function as it is designed, and this phenomenon is common in practice [8,9]. In short, the presently used protection system for the dc line still has series of problems. Thus, researches on improved protection schemes to enhance safety and stability of the system are essential.

Several improved protections have been presented in [7,10–15] to overcome the shortcomings of the conventional back-up protection for dc lines. Ref. [10] offers a new differential protection scheme based on compensating for charging current. However, the method is based on the lumped parameter model of the transmission line, which isn't applicable to long dc lines. A boundary protection scheme based on traveling-wave is proposed and successfully applied in [7], and Ref. [11] proposes a traveling-wave based pilot protection scheme. However, as proposed in [12], traveling-wave based protections have inherent problems, such as having difficulty in detecting wave-front when fault with high resistance occurs and requiring high sampling rate. Presently, boundary protection schemes are proposed in [13–15] based on the boundary characteristic of dc filter and smoothing reactor. Boundary protection, as a transient based protection, can detect the fault quickly, but requires powerful computing ability and high sampling frequency.

The differential protection is applied as main protection in conventional ac systems [3]. However, when external faults occur on the HVDC system, the distributed capacitive current along the line leads to a large differential current, which prevents the conventional differential protection from detecting internal faults correctly in the fault transient period. So the key to improving the

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performance of the protection is to compensate for the distributed capacitive current.

After voltage and current signals at both line ends are filtered by the low-pass filter the cut-off frequency of which is low enough, the voltage distribution can be approximately regarded as linear distribution. Then the distributed capacitive current can be calculated by the integrating the linear distributed voltage. Based on the compensation for the distributed capacitive current, a new differential protection scheme for HVDC transmission lines is proposed.

2. Basic principle and algorithm

2.1. Solution of distributed voltage

The distributed parameters model of the lossless HVDC uniform transmission line is shown in Fig. 1. According to the theory of equal transfer process of transmission lines (ETPTL), the voltage and current signals on the uniform transmission line transformed by the same linear transferring link still satisfy the distributed parameter model [16,17]. That is, if the voltage and current signals at both line ends pass the same linear transforming links, it can be considered that the distributed voltage and current at any point of the line have passed the same linear transforming link. Therefore, when no faults or external faults occur on the HVDC transmission line, after differential- mode voltage and current signals at both line ends are filtered by the filter, voltages and currents along the uniform transmission line still satisfy partial differential equation given by

$$\begin{cases} \frac{\partial u(x,t)}{\partial x} = -L_0 \frac{\partial i(x,t)}{\partial t} \\ \frac{\partial i(x,t)}{\partial x} = -C_0 \frac{\partial u(x,t)}{\partial t} \end{cases} \tag{1}$$

where $u(x,t)$ and $i(x,t)$ represent filtered differential-mode voltage and current signals on the line, x is the distance from the measuring point to the initial end of the line, t is measuring time, L_0 represents inductance per unit length, and C_0 represents capacitance per unit length. The general solutions of (1) should be

$$\begin{cases} u(x,t) = f_+(x/v-t) + f_-(x/v+t) \\ i(x,t) = \frac{f_+(x/v-t)}{Z_c} - \frac{f_-(x/v+t)}{Z_c} \end{cases} \tag{2}$$

In (2), $f_+(x/v - t)$ and $f_-(x/v + t)$ represents forward and backward traveling-wave respectively, v is the speed of the traveling-wave, and Z_c is wave impedance.

Let $t_1 = x/v - t$, and the Fourier transform $F_+(\omega)$ of $f_+(t_1)$ can be defined as

$$F_+(\omega) = \int_{-\infty}^{+\infty} f_+(t_1) e^{-j\omega t_1} \mathrm{d}t_1 \tag{3}$$

where ω is the angular frequency variable. $f_+(x/v - t)$ can be recomputed from $F_+(\omega)$ by applying the inverse Fourier transform given by

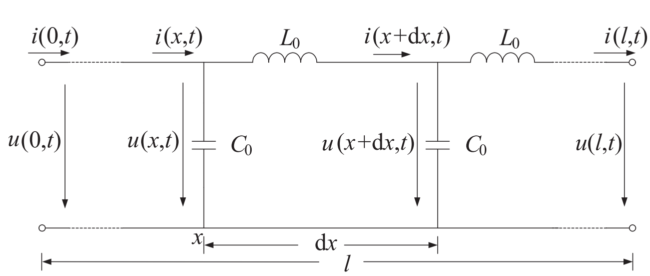

Fig. 1. Distributed parameters model of lossless HVDC transmission line.

$$\begin{aligned} f_+(x/v-t) = f_+(t_1) &= \frac{1}{2\pi}\int_{-\infty}^{+\infty} F_+(\omega)e^{j\omega t_1}\mathrm{d}\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{+\infty} F_+(\omega)e^{j\omega(x/v-t)}\mathrm{d}\omega \\ &= \frac{1}{\pi}\int_0^{+\infty} |F_+(\omega)|\cos[2\pi x/\lambda - \omega t + \varphi_+(\omega)]\mathrm{d}\omega \end{aligned} \tag{4}$$

where the wave-length $\lambda = \omega/2\pi v$, $|F_+(\omega)|$ is magnitude function of $F_+(\omega)$, $\varphi_+(\omega)$ is phase function of $F_+(\omega)$. Similarly, $f_-(x/v + t)$ can be obtained by

$$f_-(x/v+t) = \frac{1}{\pi}\int_0^{+\infty} |F_-(\omega)|\cos[2\pi x/\lambda + \omega t + \varphi_-(\omega)]\mathrm{d}\omega \tag{5}$$

where $F_-(\omega)$ is the spectrum of $f_-(x/v + t)$, $|F_-(\omega)|$ is magnitude function of $F_-(\omega)$, and $\varphi_-(\omega)$ is phase function of $F_-(\omega)$. Combing (2), (4) and (5) yields

$$\begin{aligned} u(x,t) = \frac{1}{\pi}\int_0^{+\infty} &\{|F_+(\omega)|\cos[2\pi x/\lambda - \omega t + \varphi_+(\omega)] \\ &+ |F_-(\omega)|\cos[2\pi x/\lambda + \omega t + \varphi_-(\omega)]\}\mathrm{d}\omega \end{aligned} \tag{6}$$

A low-pass filter is considered to pass frequencies lower than the cut-off frequency ω_c. Therefore, $|F_+(\omega)|$ and $|F_-(\omega)|$ are both approximately equal to zero when $\omega > \omega_c$ is satisfied. Hence the expression (6) can be described as

$$\begin{aligned} u(x,t) = \frac{1}{\pi}\int_0^{\omega_c} &\{|F_+(\omega)|\cos[2\pi x/\lambda - \omega t + \varphi_+(\omega)] \\ &+ |F_-(\omega)|\cos[2\pi x/\lambda + \omega t + \varphi_-(\omega)]\}\mathrm{d}\omega \end{aligned} \tag{7}$$

Let

$$F'_+(x,t,\omega) = |F_+(\omega)|\cos[2\pi x/\lambda - \omega t + \varphi_+(\omega)](0 \leqslant \omega \leqslant \omega_c) \tag{8}$$

If ω_c is selected low enough to ensure that $\lambda_c \gg l$, then $\lambda \gg l$ will also be satisfied, where the shortest wave-length $\lambda_c = 2\pi v/\omega_c$ and l is the length of the dc line. According to (8), if x changes from 0 to l, t and ω are kept unchanged, the $F'_+(x,t,\omega)$'s phase variation $2\pi l/\lambda \ll 2\pi$. In this case, $F'_+(x,t,\omega)$ can be regarded as a linear function of x which is given by

$$F'_+(x,t,\omega) = F'_+(0,t,\omega) + \frac{F'_+(l,t,\omega) - F'_+(0,t,\omega)}{l}x(0 \leqslant \omega \leqslant \omega_c) \tag{9}$$

where $F'_+(0,t,\omega)$ and $F'_+(l,t,\omega)$ represent the value of $F'_+(x,t,\omega)$ on the both ends of line. The integration of both sides of the equation (9) should be

$$\begin{aligned} &\frac{1}{\pi}\int_0^{\omega_c} F'_+(x,t,\omega)\mathrm{d}\omega \\ &= \frac{1}{\pi}\int_0^{\omega_c}\left[F'_+(0,t,\omega) + \frac{F'_+(l,t,\omega) - F'_+(0,t,\omega)}{l}x\right]\mathrm{d}\omega \end{aligned} \tag{10}$$

Combined with (7) and (8), it can be simplified as

$$f_+(x/v-t) = f_+(0/v-t) + \frac{f_+(l/v-t) - f_+(0/v-t)}{l}x \tag{11}$$

Similarly,

$$f_-(x/v+t) = f_-(0/v+t) + \frac{f_-(l/v+t) - f_-(0/v+t)}{l}x \tag{12}$$

Combining (2), (11) and (12) yields

$$u(x,t) = u(0,t) + \frac{u(l,t) - u(0,t)}{l}x \tag{13}$$

In (13), $u(0,t)$ and $u(l,t)$ are differential-mode voltage signals at two terminals of the dc line. According to (13), when external faults or no faults occur on the HVDC transmission line, after volt-