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Non-unit transient based boundary protection for UHV transmission lines

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ABSTRACT

Different from EHV transmission lines, the boundary of UHV transmission lines naturally consists of busbar stray capacitance, shunt reactor and/or series capacitor. The frequency characteristics of the UHV line boundaries with different structures are analyzed deeply, which have significant attenuation on both high frequency signal and low frequency signal. The attenuation is the inherent characteristic of UHV line boundary. Based on the UHV boundary characteristic, a novel boundary protection principle utilizing backward traveling wave is proposed. The fault direction is identified by means of the time-domain energy of the backward traveling wave. The high frequency energy and the low frequency energy of the backward traveling wave are extracted by wavelet transform, and then the forward internal and external faults are discriminated by the product of high frequency energy and low frequency energy. An adaptive setting calculation method in terms of fault type is presented, which is able to improve effectively the right discriminating rate for internal faults. The simulation model of Jindongnan-Nanyang-Jingmen UHV transmission project is established in ATP/EMTP. The simulation results show that the boundary protection possesses stable performance under various fault situations, and the operation time is less than 2 ms, which is appropriate as the non-unit ultra-high-speed protection element for UHV transmission lines.

1. Introduction

With the development of tightly interconnected large power grid, EHV/UHV transmission plays an important role in modern power system. In order to reduce the hazard to electrical equipments caused by fault and improve the transient stability, the fast fault clearance of EHV/UHV transmission lines is indispensable. Thus, considerable effort has been devoted to research on the high-speed even ultra-high-speed protection [1].

Due to the inherent delay for estimating fundamental frequency phasors, it is difficult to improve the operation speed of conventional line protection based on fundamental component. In order to speed up the protection operation and improve the performance of transmission line protection, the novel protection principles utilizing fault transients directly were proposed in the past four decades [2–6]. The unit transient based protection schemes need an expensive and complicated communication system [2,3,5,6], so the reliability and operation speed of unit protection are affected by the used communication systems. Thus the advanced non-unit transient based boundary protection is presented [7], which completely depends on locally measured fault transients and accomplishes ultra-high-speed operation without any communication system. Boundary protection distinguishes the internal faults and external faults in terms of the fault characteristic differences caused by the change of the surge impedance at the line boundary.

It is well to be reminded that the performance of boundary protection is directly determined by both the existence of line boundary in primary system and the boundary characteristics. In the primary system of high voltage direct current (HVDC) transmission, DC filters and smoothing reactors at each line terminal constitute HVDC line boundary. This line boundary imposes a significant attenuating or smoothing effect on transient signals, and makes the characteristics differences between internal and external faults remarkable. Therefore, compared with the alternating current (AC) boundary protection, the research on the HVDC boundary protection has made great progress [8–12]. However, for UHV AC transmission lines, the study on the composition and characteristics of UHV line boundary is still in the blank.

The previous research on AC boundary protection all focused on the 400 kV or 500 kV EHV transmission lines [13–21]. The researchers have tried their best to find the available line boundary in the primary side of EHV transmission systems. A line trap as the line boundary and a specially designed stack tuner aimed at capturing high-frequency voltage signal are discussed in [13,14]. However, adjusting line trap and installing stack tuner are difficult in practice. Bo ZQ regards busbar stray capacitance as the line boundary [15], which has severely attenuation on high-frequency transient current. But the performance of this

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scheme directly depends on the magnitude of busbar stray capacitance, i.e. the sum of the stray capacitances of the apparatuses connected to a busbar. In order to improve the performance of boundary protection, some researchers consider both line trap and busbar stray capacitance as line boundary [16,17]. Nevertheless, optical fiber communication has extensively replaced power line carrier now, and line traps are rarely employed. Thus, the application of this protection principle is strictly limited.

In order to make full use of the fault characteristics differences cased by line boundary, besides the digital filters [14,15], wavelet transform, neural network and mathematical morphology are applied in boundary protection algorithms [18–21]. But they still rely on the line boundary composed by busbar stray capacitance [18–21].

Still some issues remain in these boundary protections above: (1) The setting method of thresholds is not clear [13–15,17–20]; (2) The fault direction cannot be distinguished [13–18,20,21]; (3) A typical value of 0.1 μF for the busbar stray capacitance is usually assumed [15,18–20]. In the practical system, the value of the busbar stray capacitance may be less than 0.1 μF [21,22], which affects the performance of boundary protection; (4) The complex algorithms delay the protection operation time, for instance, neural networks take a half-cycle data window [19].

This paper aims at a novel non-unit transient based boundary protection applicable to UHV transmission lines and its efficient setting calculation method. First, the composition and frequency characteristics of UHV line boundary are analyzed. Second, based on the UHV boundary characteristics, a novel boundary protection principle utilizing backward traveling wave is proposed. In order to ensure the validity of the protection principle, the post-fault time range is quantitatively given. Subsequently, a wavelet transform based protection algorithm is established, and the operation time is less than 2 ms. For the purpose of improving the right discriminating rate, an adaptive setting method in terms of fault type is presented. Finally, the effectiveness of the proposed protection is validated by the simulation tests of the 1000 kV UHV transmission system in China.

The remainder of this paper is organized as follows. In Section 2, the frequency characteristics of the UHV line boundaries with different structures are analyzed. In Section 3, the boundary protection principle and algorithm are introduced, followed by a description of the adaptive setting calculation method. In Section 4, simulation model is established, and the test results and related analysis are given. Finally, conclusions are drawn in Section 5.

2. Frequency characteristics of UHV line boundary

The line boundary is the discontinuous point of the surge impedance of the transmission line, which is usually at both ends of the protected line. UHV busbar and its connecting apparatuses have distributed capacitance, i.e. the busbar stray capacitance. High voltage shunt reactors are usually installed at both ends of UHV transmission lines, mainly for limiting power frequency overvoltage, compensating the capacitive reactive power and restricting secondary arc current. In order to enhance the stability and security of synchronous interconnected power grid, and make full use of the advantages of large capacity and long distance transmission of UHV transmission lines, series capacitor compensation technology has been applied to 1000 kV Jindongnan-Nanyang-Jingmen UHV transmission project in State Grid of China. The fixed series compensation capacitor is installed at one end or two ends of the line. Thus the boundary of UHV transmission lines naturally consists of busbar stray capacitance, shunt reactor and/or series capacitor.

The 1000 kV Jindongnan-Nanyang-Jingmen UHV transmission system is shown in Fig. 1, where C_s represents busbar stray capacitance, L_1, L_2, L_3 and L_4 are shunt reactors, C_1, C_2, C_3 and C_4 denote series capacitors. The parameters of shunt reactors and series capacitors are given in Appendix A.

2.1. Line boundary consisting of busbar stray capacitance only

The case of the line boundary consisting of busbar stray capacitance only is shown in Fig. 2(a). Because the surge impedance is discontinuous at the line boundary of a transmission line (its surge impedance is Z_1), fault generated traveling wave u_{1b} as the incident wave is reflected to form the reflected wave u_{1f}, and is refracted to form the refracted wave u_{2f}, which enters into the other transmission line (its surge impedance is Z_2). Assuming that the both lines are infinite long, based on Peterson principle, the lumped parameter equivalent circuit in Laplace domain is depicted in Fig. 2 (b). $U_{2f}(s)$ is derived.

$$U_{2f}(s) = H(s)\ U_{1b}(s) = \frac{2(Z_2//Z_{cs})}{Z_1 + Z_2//Z_{cs}} U_{1b}(s) \tag{1}$$

where sign // represents parallel relation; $H(s)$ denotes the transfer characteristic of the line boundary, i.e. the refractive coefficient, which is related to the parameters of the line boundary and the line surge impedances Z_1 and Z_2. Replacing s with $j\omega$ in $H(s)$, the transfer characteristic of the line boundary in frequency domain $H(\omega)$ is obtained.

Considering the busbar stray capacitance in the range of 2000 pF ~ 0.1 μF [22], take the typical values 2000 pF, 10,000 pF, 20,000 pF, 50,000 pF and 0.1 μF, and suppose $Z_1 = Z_2 = 250\ \Omega$, the amplitude-frequency characteristic of line boundary $|H(\omega)|$ is shown in Fig. 3.

From Fig. 3, it is known that the line boundary consisting of busbar stray capacitance only has no effect on the low-frequency components, and imposes a significant attenuating effect on the high-frequency components (larger than 10 kHz). Higher signal frequency and greater stray capacitance will result in more significant attenuation.

2.2. Line boundary consisting of shunt reactor only

In the same way, the transfer characteristic of the line boundary consisting of shunt reactor only is as follows.

$$H(\omega) = \frac{2(Z_2//Z_L)}{Z_1 + Z_2//Z_L} \tag{2}$$

The shunt reactors with capacity of 960, 720 and 600 Mvar are denoted by L_1, L_2 and L_3 respectively, and their parameters are listed in Table A1 in Appendix A. Suppose $Z_1 = Z_2 = 250\ \Omega$, the amplitude-frequency characteristic of line boundary $|H(\omega)|$ is depicted in Fig. 4.

From Fig. 4, it can be seen clearly that the line boundary consisting of shunt reactor only has no effect on the high-frequency components, and imposes a remarkable attenuating effect on the low-frequency components (less than 10 Hz). Lower signal frequency and greater shunt reactor capacity (namely smaller rated reactance) will lead to more remarkable attenuation.

2.3. Line boundary consisting of series capacitor only

The refraction and reflection of traveling wave at the line boundary consisting of series capacitor only are shown in Fig. 5. Thus the transfer characteristic of the line boundary is

$$H(\omega) = \frac{2Z_2}{Z_1 + Z_{SC1} + Z_{SC2} + Z_2} \tag{3}$$

In practical system, the series capacitors C_{sc1} and C_{sc2} may exist only one (such as the substation M in Fig. 1), and may also be both (e.g. the substation N in Fig. 1). Suppose C_{sc1} = 107.755 μF (which is the capacitance of C_3 and C_4 in series in Fig. 1), C_{sc2} = 164.25 μF, when C_{sc1} and C_{sc2} both exist, the total capacitance C_{sc0} = 65.07 μF. Therefore, three different situations are studied: C_{sc1} and C_{sc2} both exist, and the total capacitance is C_{sc0}; only C_{sc1}; only C_{sc2}. The amplitude-frequency characteristic of line boundary $|H(\omega)|$ is illustrated in Fig. 6.

As can be seen from Fig. 6, similar to the shunt reactors in Fig. 4, the line boundary consisting of series capacitor only has no influence on the high-frequency components, and imposes a significant attenuating