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A travelling wave differential protection scheme for half-wavelength transmission line

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A R T I C L E I N F O

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A B S T R A C T

Half-wavelength transmission technology is getting more and more attention due to its excellent characteristics such as large transmission capacity and long transmission distance. Traditional differential protection is not applicable to half-wavelength transmission line because of the impact caused by large distributed capacitance current. Travelling wave (TW) differential protection is not affected by distributed capacitance current, so it can be applied to long EHV/UHV transmission line. However, when directly applied to half-wavelength transmission line, large unbalanced differential current will appear during external faults, since the resistance of the line and the frequency-dependent feature of the line parameters which are neglected by TW differential protection have such great impact that they cannot be neglected anymore. In order to improve the performance of TW differential protection, this paper proposes a scheme which has taken the resistance into account and uses power-frequency component of the differential current to identify fault for the purpose of avoiding the influence of the frequency-dependent feature of the line parameters. Simulation results verify that the proposed scheme is effective in reducing the unbalanced differential current, and as a result, ensures the selectivity of the protection. The scheme also has high sensitivity during internal faults with large fault resistance.

1. Introduction

The half-wavelength transmission line refers to a long AC transmission line whose equivalent electrical length is a little longer than half of the wavelength at the power frequency [1,2], that is, a little longer than 3000 km at 50 Hz or 2500 km at 60 Hz. The equivalent electrical length of the line cannot be a little shorter or exactly equal to half-wavelength because of stability problem. This means that the natural length of the transmission line should be a little greater than half the wavelength, or the tuning circuit should be used to compensate for the shortage of electrical length in those lines whose natural length is shorter than half the wavelength [3,4].

The half-wavelength AC power transmission was first proposed by Soviet scientists in 1940s [3]. Afterwards, some research of relevant problems appeared [3–7]. However, because there was little demand for this kind of technology with such large transmission capacity and such long transmission distance that it remained at the stage of very little theoretical research.

In recent years, along with the increase of demand for ultra-long transmission distance and large transmission capacity, this technology has aroused general concerns again [8–13]. Compared with traditional AC power transmission technology, the half-wavelength transmission technology has excellent characteristics such as long transmission distance, high power factor, simple configuration, and large transmission capacity when designed to have high surge impedance loading by increasing the voltage level, like the 1000 kV ultra-high-voltage in China [1,6]. However, half-wavelength transmission line has to maintain its integrity, so it has great difficulty in interconnecting with the power grid along the line, and it cannot be sectioned by switching substations [9,14]. Consequently, it is mostly used for point-to-point power transmission. In China, the energy center in the west is approximately 3000 km away from the load center in the eastern coastal areas, therefore this technology has significant potential for application.

In order to ensure the safe operation of half-wavelength transmission line, relay protection is indispensable. Differential protection is one kind of simple and reliable relay protection. Although distributed capacitance current has an impact on differential protection for ultra/extra-high-voltage (UHV/EHV) transmission lines, proper measurements, such as increasing the threshold and partly compensating the capacitance current [15,16], can still ensure the reliability and sensitivity of the protection. However, as the half-wavelength transmission line is far longer than traditional transmission line, the impact due to distributed capacitance current is so great that traditional differential protection is no longer suitable for half-wavelength transmission line.

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One way to solve this problem is to employ travelling wave (TW) differential protection. TW differential protection was first proposed in 1977 [17]. It uses distributed parameter line model and is based on the theory of uniform transmission line. Both the model and the theory are also the basis of the principle of the half-wavelength transmission line. In theory, TW differential protection has taken distributed capacitance current into account and has the ability to accurately reflect the internal fault current [18], so this protection can distinguish internal fault from external fault with high selectivity and reliability. However, in the implementation of TW differential protection, the distributed resistance of the transmission line and the frequency-dependent feature of the line parameters are neglected in order to obtain a simple time-domain formula for the calculation of differential current. This means the attenuation and distortion of TW when it travels along the line is totally neglected. This is feasible for lines which are not very long, but for half-wavelength transmission line the attenuation and distortion are so serious in some cases that the neglect of them may cause large unbalanced differential current during external fault and lead to the maloperation of the protection. In order to reduce the unbalanced differential current and maintain the high selectivity of TW differential protection when applied to half-wavelength transmission line, this paper proposes a protection scheme which has taken the distributed resistance into account and has taken measures to avoid the influence caused by frequency-dependent feature of the line parameters.

The rest of the paper is organized as follows. In Section 2, the theory of uniform transmission line, and the basic principle of half-wavelength transmission line and TW differential protection are introduced. In Section 3, the influence caused by the distributed resistance and the frequency-dependent feature of the line parameters is analysed. Detailed protection scheme is presented in Section 4. In Section 5, simulation results are presented to show the effectiveness and the performance of the proposed scheme. Finally, Section 6 is conclusion.

2. Basic principle

A single-phase uniform transmission line shown in Fig. 1 will be used to illustrate the basic principles in this paper. In Fig. 1, u_m and u_n represent the voltages at terminal M and terminal N respectively. i_m and in are the currents flowing into the line at terminal M and terminal N respectively. $\mathrm{R_m}$ and $\mathrm{R_n}$ are the relays installed at terminal M and terminal N respectively. Fig. 1(a) shows a complete transmission line without any internal fault on it. $u(x,t)$ and $i(x,t)$ are the voltage and current at the distance x from terminal M. Fig. 1(b) shows a transmission line with an internal fault on it. i_{Fm}, i_{Fn} and i_F are the currents flowing towards terminal M, terminal N and the ground at the internal fault point F. u_F is the voltage at the fault point F. l_m and l_n are the distances from the fault point F to terminal M and terminal N respectively.

2.1. Theory of uniform transmission line

The theory of uniform transmission line is the basis of half-wavelength transmission line and TW differential protection, and it is based on distributed parameter line model. For the single-phase uniform transmission line MN shown in Fig. 1(a), the voltage $u(x,t)$ and current $i(x,t)$ on the transmission line are the function of both the distance x and the time t.

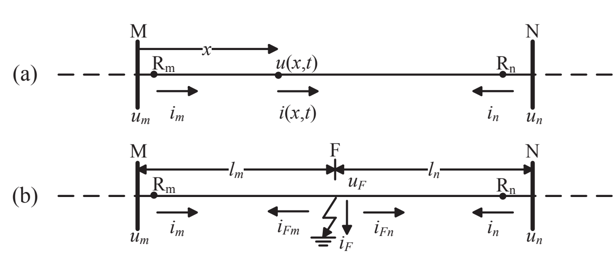

Fig. 1. A single-phase uniform transmission line. (a) Normal operation or external fault. (b) Internal fault.

Let $U(x, \omega)$ and $I(x, \omega)$ be the Fourier transform of the voltage $u(x,t)$ and current $i(x,t)$ respectively, where ω is the angular frequency, then the general solution of voltage and current are

$$\begin{cases} U(x,\omega) = B_1(\omega)\mathrm{e}^{-\gamma x} + B_2(\omega)\mathrm{e}^{\gamma x} \\ I(x,\omega) = [B_1(\omega)\mathrm{e}^{-\gamma x} - B_2(\omega)\mathrm{e}^{\gamma x}]/Z_c \end{cases} \tag{1}$$

where $\gamma = \sqrt{\mathrm{j}\omega C(R + \mathrm{j}\omega L)}$ is the propagation coefficient of the line, and $Z_c = \sqrt{(R + \mathrm{j}\omega L)/(\mathrm{j}\omega C)}$ is the surge impedance of the line. $B_1(\omega)$ and $B_2(\omega)$ can be arbitrary functions, which are determined by the boundary conditions. L, R and C are the inductance, resistance and capacitance per unit length of the line respectively.

2.2. Principle of Half-wavelength transmission line

Considering the reference direction shown in Fig. 1(a) and designating the total length of the line as l, the boundary conditions of (1) can be written as

$$\begin{cases} U(0,\omega) = U_m(\omega), \quad U(l,\omega) = U_n(\omega) \\ I(0,\omega) = I_m(\omega), \quad I(l,\omega) = -I_n(\omega) \end{cases} \tag{2}$$

where $U_m(\omega)$, $U_n(\omega)$, $I_m(\omega)$ and $I_n(\omega)$ are the Fourier transform of the voltage and current at terminal M and N respectively. Using (2) to eliminate $B_1(\omega)$ and $B_2(\omega)$ in (1), the following equations can be obtained:

$$\begin{cases} U_m(\omega) = U_n(\omega)\cosh(\gamma l) - I_n(\omega)Z_c\sinh(\gamma l) \\ I_m(\omega) = -I_n(\omega)\cosh(\gamma l) + U_n(\omega)\sinh(\gamma l)/Z_c \end{cases} \tag{3}$$

where cosh() and sinh() are the hyperbolic cosine and hyperbolic sine function respectively. If the resistance of the line is neglected and the parameters of the line are frequency-independent, the propagation coefficient γ can be written as

$$\gamma = \mathrm{j}\omega\sqrt{LC} = \mathrm{j}\omega/v = 2\pi \mathrm{j}\lambda(\omega) \tag{4}$$

where $v = 1/\sqrt{LC}$ is the velocity of the TW on the transmission line and ideally equals to the velocity of the light for overhead transmission lines. $\lambda(\omega) = 2\pi v/\omega$ is the wavelength of electromagnetic wave whose frequency is $f = \omega/2\pi$. During normal operation, there is no other frequency component except for the power-frequency component, so $U_m(\omega)$, $U_n(\omega)$, $I_m(\omega)$ and $I_n(\omega)$ can be substituted by corresponding phasor, that is, $\dot{U}_m$, $\dot{U}_n$, $\dot{I}_m$ and $\dot{I}_n$. If the length of the line l equals to half of the wavelength at power frequency, then $\gamma l = \mathrm{j}\pi$ and (5) can be obtained from (3):

$$\begin{cases} \dot{U}_m = -\dot{U}_n \\ \dot{I}_m = \dot{I}_n \end{cases} \tag{5}$$

It can be seen from (5) that a lossless transmission line whose length is exactly equal to half the wavelength at power frequency looks like an ideal transformer whose transformation ratio is −1. Because the reactive power provided by the distributed capacitance is just completely absorbed by the distributed inductance, the half-wavelength transmission line can transmit power over long distance with high efficiency. Also, as half-wavelength part of the line looks like an ideal transformer, the line whose length is a little longer than half the wavelength looks as if it is as short as the part longer than half the wavelength, or to put it in another way, half-wavelength transmission line seems to reduce the length of the line by half the wavelength.

However, it can also be inferred from (5) that traditional differential protection is not suitable for half-wavelength transmission lines. For a healthy transmission line whose distributed capacitance current can be neglected, the current flowing into the line at one end is equal to the current flowing out of the line at the other end, and this is the basic