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PHASE DIFFERENTIAL PROTECTION OF VOLTAGE FAULT COMPONENT FOR HALF-WAVELENGTH TRANSMISSION LINE

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ABSTRACT

The distribution of voltage and current along the half-wavelength transmission line presents a non-linear fluctuation characteristic, which is quite different from those along the traditional ultra-high voltage (UHV) transmission line. In this paper, the influence factors of the voltage phase difference between two ends of the half-wavelength transmission line are analyzed. The characteristics of the voltage fault component phase difference between two ends of the line are studied when internal and external faults occur, a phase differential protection for half-wavelength transmission line is proposed.

Keywords: Half-wavelength AC transmission, Fault component, Phase differential protection, transmission equations of transmission line

1. INTRODUCTION

HALF-wavelength alternating current transmission (HWACT) is the ultra-long-distance AC transmission technology whose electrical distance is close to half-wavelength of the power frequency, which is 3000Km under 50Hz or 2500Km under 60Hz. Since the electrical characteristics of half-wavelength AC transmission line (HWACTL) are quite different from those of traditional UHV transmission lines, the existing protection principles cannot be applied directly, it is necessary to study new protection principles for HWACTL.

The distribution characteristics of voltage and current along HWACTL are studied from the view of time and space in reference [1], which have obvious fluctuations in aspect of space and present non-linearity and non-monotony. Further than that, this paper proved that the existing protection principles are unsuitable for HWACTL. Reference [2] proposed a calculating method for the optimal differential point based on the time-space characteristic of HWACTL, but the accuracy of calculation is affected by the sampling frequency of protection device. Based on the difference between the measured and calculated values of current, reference [3] proposed a current differential protection, when the difference is greater than the threshold value, the protection acts, but it is unable to protect the full length of the line. Reference [4] selected 1/6, 1/2 and 5/6 point of the HWACTL as the differential points to calculate three differential currents, and adding them together and dividing them by two to obtain the approximate differential current. But its accuracy is affected by the change of system parameters.

In this paper, it is proved that the voltage phase difference between two ends of HWACTL is not exactly 180° during normal operation, and the factors causing the phase deviation are analyzed. The phase characteristic of voltage fault component on HWACTL is studied when external fault and internal fault occur, and a novel voltage fault component-based phase differential protection principle is proposed.

2. PHASE DIFFERENTIAL PROTECTION OF VOLTAGE FAULT COMPONENT FOR HWACTL

2.1 Effect analysis for the attenuation factor and load current on the electrical characteristics of HWACTL

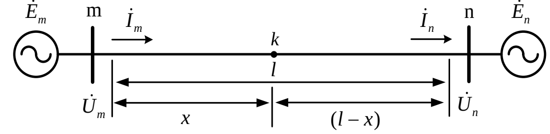


Fig. 1. A bilateral power supply system connected by HWACTL

The distributed parameter model should be adopted for HWACTL. In figure 1, two power systems are connected by HWACTL, voltage and current on the line satisfies following equations under the power frequency.

$$\begin{cases} \dot{U} = \dot{U}_m ch(\gamma x) + \dot{I}_m Z_c sh(\gamma x) \\ \dot{I} = \dot{I}_m ch(\gamma x) + \dfrac{\dot{U}_m}{Z_c} sh(\gamma x) \end{cases} \tag{1}$$

Where, $\dot{E}_m$ and $\dot{E}_n$ are the equivalent potentials of system m and system n, $\dot{U}_m$ and $\dot{I}_m$ are the voltage and current at end-m and the positive direction of $\dot{I}_m$ is from bus to line, $\dot{U}$ and $\dot{I}$ are voltage and current at point-*k* which is x km far from end-m; $\gamma = \alpha + \mathrm{j}\beta = \sqrt{Z_0 Y_0}$ is the propagation constant of transmission line, α and β are attenuation factor and phase coefficient respectively; $Z_0 = R_0 + \mathrm{j}\omega L_0$ and $Y_0 = G_0 + \mathrm{j}\omega C_0$ are the impedance and admittance of unit length of line; $Z_c = \sqrt{Z_0 / Y_0}$ and $v = 1/\sqrt{L_0 C_0}$ are respectively the characteristic impedance and wave velocity.

For the lossless HWACTL, $R_0 = 0$, $G_0 = 0$, $Z_0 = \mathrm{j}\omega L_0$, $Y_0 = \mathrm{j}\omega C_0$ and $\gamma = \alpha + \mathrm{j}\beta = \sqrt{Z_0 Y_0} = \mathrm{j}\omega\sqrt{L_0 C_0}$, thus $\alpha = 0$, $\beta = \omega\sqrt{L_0 C_0} = 2\pi f / v$, $\gamma = \mathrm{j}\beta = \mathrm{j}2\pi f / v$. The length of HWACTL is selected by the formula $l = v / 2f$. So $ch(\gamma l) = ch(\mathrm{j}\pi) = -1$, $sh(\gamma l) = sh(\mathrm{j}\pi) = 0$, substituting them into formula (1) and letting $x = l$, obtain

$$\begin{cases} \dot{U}_n = -\dot{U}_m \\ \dot{I}_n = -\dot{I}_m \end{cases} \tag{2}$$

It can be seen from formula (2) that the amplitudes of voltages and currents at two ends of lossless HWACTL are equal and their phase difference is 180° during normal operation.

For actual HWACTL, $R_0 \neq 0$ and $G_0 \neq 0$, thus, $\alpha \neq 0$, $ch(\gamma l) \neq -1$, $sh(\gamma l) \neq 0$. According to formula (1),The voltage phase difference and the current phase difference between two ends aren't 180° during normal operation, and $\dot{U}_m$, Z_c, $ch(\gamma l)$, $sh(\gamma l)$ and $\dot{I}_m$ all affect the phase differences. Because $\dot{U}_m$ and Z_c are constant during normal operation, the influence factors are $ch(\gamma l)$, $sh(\gamma l)$ and $\dot{I}_m$.

When $l = v / 2f$, $\beta = \pi$, and $\gamma l = \alpha l + \mathrm{j}\pi$, the influence of β can be ignored. Thus, the influence factors of $ch(\gamma l)$ and $sh(\gamma l)$ is only α. Considering that there isn't corona under normal operation, $G_0 = 0$. Substituting $G_0 = 0$ into $\gamma = \sqrt{(R_0 + \mathrm{j}\omega L_0)(G_0 + \mathrm{j}\omega C_0)}$, the following formula can be obtained.

$$\alpha = \sqrt{2\sqrt{\omega^4 L_0^2 C_0^2 + \omega^2 R_0^2 C_0^2} - 2\omega^2 L_0 C_0} \tag{3}$$

Obviously, the bigger R_0 is, the bigger α is, the more $ch(\gamma l)$ deviates from -1, the more $sh(\gamma l)$ deviates from 0, and the more phase differences deviate from 180°. Figure 2 is the voltage phase differences varying with $\dot{I}_m$ and α, which is based on the parameters in Table 1 and calculated with MATLAB. The following conclusions can be drawn from Figure 2: (1) the phase voltage difference between two ends of HWACTL isn't exactly 180° during normal operation of power system. (2) The main influence factors of phase deviation are α and $\dot{I}_m$, the larger α or $\dot{I}_m$ is, the more the voltage phase difference deviates from 180°.

Table 1. parameters of the 1000kV UHVAC Power Transmission

sequence component	resistance per unit length/($\Omega \cdot \mathrm{km}^{-1}$)	inductive impedance per unit length/($\Omega \cdot \mathrm{km}^{-1}$)	Capacitance per unit length/($\mu\mathrm{F} \cdot \mathrm{km}^{-1}$)
positive sequence	0.009 4	0.270 2	0.013 97
zero sequence	0.175 7	0.780 4	0.008 96

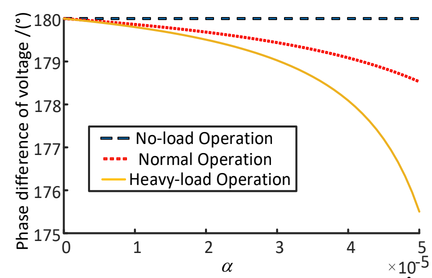
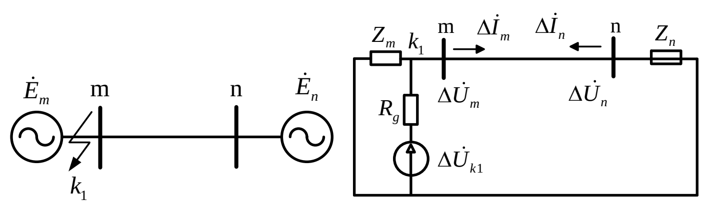


Fig. 2. Voltage phase difference varying with $\dot{I}_m$ and α

2.2 Analysis of phase difference of voltage fault component between two ends of HWACTL



(a) half-wavelength line (b) the fault additional network

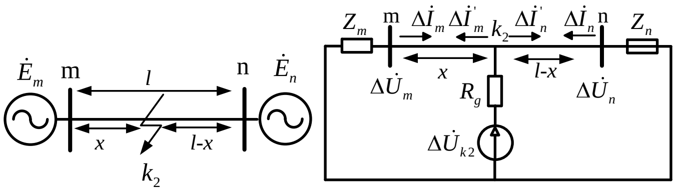
Fig. 3. Schematic diagram of fault component system

The fault system can be decomposed into normal network and fault additional network. When an external fault occurs at point-k_1, the fault additional network is shown in Figure 3. Z_m and Z_n are the equivalent impedances of system m and system n. $\Delta\dot{U}_{m1}$, $\Delta\dot{U}_{n1}$ and $\Delta\dot{I}_{m1}$, $\Delta\dot{I}_{n1}$ are voltage fault components and current fault components of two ends of HWACTL. R_g is transition resistance. $\Delta\dot{U}_{k1}$ is the voltage fault component at point-k_1, which equals to the negative value of the voltage at this point during normal operation. In this case, the line is not destroyed by the fault point and the voltage and current of each point on the line satisfy the transmission equations of transmission line.

$$\begin{cases}\Delta\dot{U}_n = \Delta\dot{U}_m ch(\gamma l) - \Delta\dot{I}_m Z_c sh(\gamma l) \\ \Delta\dot{I}_n = \Delta\dot{I}_m ch(\gamma l) - \dfrac{\Delta\dot{U}_m}{Z_c} sh(\gamma l)\end{cases} \tag{4}$$

The above formula is similar to formula (1), so the analysis result is the same, the voltage fault component phase difference between two ends is about 180°, that

$$\Delta\theta_{k1} = \left|\arg\frac{\Delta\dot{U}_m}{\Delta\dot{U}_n}\right| \approx 180^\circ \tag{5}$$



(a) half-wavelength line (b) the fault additional network

Fig. 4. Schematic diagram of fault component system

The fault additional network is shown in Figure 4 when an internal fault occurs at point-k_2. x is the distance from point-k_2 to end-m. The m-k_2 and k_2-n segments of HWACTL satisfy the following equations respectively

$$\begin{cases}\Delta\dot{U}_m = \Delta\dot{U}_{k2} ch(\gamma x) - \Delta\dot{I}'_m Z_c sh(\gamma x) \\ -\Delta\dot{I}_m = \Delta\dot{I}'_m ch(\gamma x) - \dfrac{\Delta\dot{U}_{k2}}{Z_c} sh(\gamma x) \\ \Delta\dot{U}_m = -\Delta\dot{I}_m Z_m\end{cases} \tag{6}$$

$$\begin{cases}\Delta\dot{U}_n = \Delta\dot{U}_{k2} ch[\gamma(l-x)] - \Delta\dot{I}'_n Z_c sh[\gamma(l-x)] \\ -\Delta\dot{I}_n = \Delta\dot{I}'_n ch[\gamma(l-x)] - \dfrac{\Delta\dot{U}_{k2}}{Z_c} sh[\gamma(l-x)] \\ \Delta\dot{U}_n = -\Delta\dot{I}_n Z_n\end{cases} \tag{7}$$

Solving formula (6) and (7), obtain

$$\begin{cases}\Delta\dot{U}_m = \dfrac{\Delta\dot{U}_{k2} Z_m}{Z_c sh(\gamma x) + Z_m ch(\gamma x)} \\ \Delta\dot{U}_n = \dfrac{\Delta\dot{U}_{k2} Z_n}{Z_c sh[\gamma(l-x)] + Z_n ch[\gamma(l-x)]}\end{cases} \tag{8}$$

The voltage fault component phase difference between two ends of HWACTL is

$$\begin{aligned}\Delta\theta_{k2} &= \left|\arg\frac{\Delta\dot{U}_m}{\Delta\dot{U}_n}\right| \\ &= \left|\arg\frac{Z_m\{Z_c sh[\gamma(l-x)] + Z_n ch[\gamma(l-x)]\}}{Z_n[Z_c sh(\gamma x) + Z_m ch(\gamma x)]}\right|\end{aligned} \tag{9}$$

Because Z_c and γ are constants, the magnitude of $\Delta\theta_{k2}$ is only affected by x, Z_m and Z_n. Let

$$f(x) = \arg\frac{Z_m\{Z_c sh[\gamma(l-x)] + Z_n ch[\gamma(l-x)]\}}{Z_n[Z_c sh(\gamma x) + Z_m ch(\gamma x)]} = \arg\frac{\vec{a}}{\vec{b}} \tag{10}$$

Where, $\vec{a} = Z_m\{Z_c sh[\gamma(l-x)] + Z_n ch[\gamma(l-x)]\}$, $\vec{b} = Z_n[Z_c sh(\gamma x) + Z_m ch(\gamma x)]$. Under the same operation mode of the equivalent systems of both ends, $Z_m = Z_n$, formula (10) can be simplified as

$$f(x) = \arg\frac{Z_c sh[\gamma(l-x)] + Z_m ch[\gamma(l-x)]}{Z_c sh(\gamma x) + Z_m ch(\gamma x)} \tag{11}$$

When fault occurs at the midpoint of the line, $x = l/2$ and $\vec{a} = \vec{b}$, $f(l/2) = \arg(\vec{a}/\vec{b}) = \arg 1 = 0^\circ$. Because $\arg sh(\gamma x)$ and $\arg ch(\gamma x)$ are monotonic increasing functions in $[0, l]$, $\arg\vec{a}$ decreases monotonously and $\arg\vec{b}$ increases monotonously in $[0, l]$. When x changes from $l/2$ to l, $\arg\vec{a}$ decreases and $\arg\vec{b}$ increases, so $f(x) = \arg(\vec{a}/\vec{b})$ decreases. When x changes from $l/2$ to 0, $\arg\vec{a}$ increases and $\arg\vec{b}$ decreases, so $f(x) = \arg(\vec{a}/\vec{b})$ increases. The change trends of $\vec{a}$ and $\vec{b}$ in above three cases and the qualitative curve of $\Delta\theta_{k2}$ are shown in Figure 5. Thus, when x changes from 0 to l, $\Delta\theta_{k2}$ is a U-shaped curve and its maximum values appear at $x = 0$ and $x = l$.

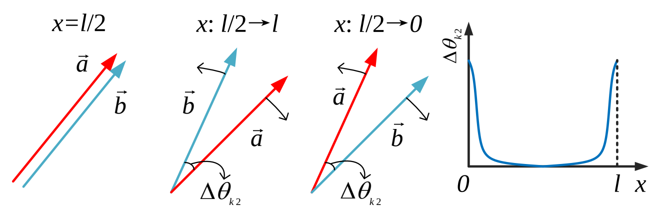


Fig. 5. the qualitative curve of $\Delta\theta_{k2}$ and the phase relation between $\vec{a}$ and $\vec{b}$

Under the different operation mode of the equivalent systems of both ends, $Z_m \neq Z_n$. the trends of $\vec{a}$ and $\vec{b}$ are the same as above. But $\vec{a}$ and $\vec{b}$ no longer coincide at $l/2$, the U-shaped curve is somewhat deformed.

In order to find the maximum value of $\Delta\theta_{k2}$, substituting $x = 0$ into formula (9)

$$\Delta\theta_{k2} = \left|\arg(-0.0567\frac{Z_c}{Z_n} - 1.0016)\right| \tag{12}$$

Z_c is constant, thus $\Delta\theta_{k2}$ is only related to Z_n. The smaller the operation mode of the equivalent system n is, the larger Z_n and $\Delta\theta_{k2}$ are. Reference [5] studied the impedance of equivalent system and drawn the conclusion that the maximum impedance of equivalent system of 1000 kV UHV system is 180 Ω. Figure 6 shows the curve of $\Delta\theta_{k2}$ when $|Z_n|$ varies from 0 Ω to 180 Ω and its phase varies from 70° to 90°, the maximum value of $\Delta\theta_{k2}$ is 154°.

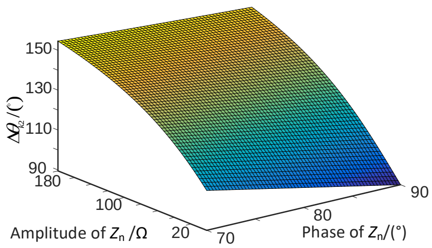


Fig. 6. $\Delta\theta_{k2}$ varying with Z_n

Similarly, substituting $x = l$ into formula (9)

$$\Delta\theta_{k2} = \left|\arg\frac{Z_m}{-0.0567Z_c - 1.0016Z_m}\right| \quad (13)$$

Z_c is constant, $\Delta\theta_{k2}$ is only related to Z_m, $|Z_m|$ varies from 0 Ω to 180 Ω and its phase varies from 70° to 90°, the maximum value of $\Delta\theta_{k2}$ is 154° too.

Based on the above analysis, the following conclusions are drawn: (1) When internal fault occurs in most areas of the line, $\Delta\theta_{k2}$ approaches 0. (2) When internal fault occurs near two ends of the line, $\Delta\theta_{k2}$ increases and the maximum value appears at two ends and will not exceed 154°.

2.3 Voltage fault component-based phase differential protection

The voltage fault component phase difference between two ends of the line can be used to constitute the phase differential protection, and the operating criterion is as

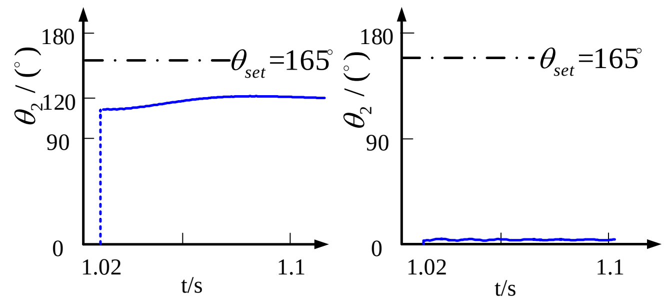
$$\Delta\theta_1 < \theta_{set} \text{ or } \theta_2 < \theta_{set} \quad (14)$$

Where, $\Delta\theta_1$ is the fault component phase difference of the positive sequence voltage, which is used to react to symmetrical faults; θ_2 is the fault component phase difference of the negative sequence voltage, which is used to react to asymmetrical faults. To ensure the selectivity of external faults and consider the measurement error and calculation error of the protection device, this paper sets θ_{set} as 165°. When $\Delta\theta_1 < \theta_{set}$ or $\theta_2 < \theta_{set}$, protection acts.

3. SIMULATION

The simulation model of 1000 kV half-wavelength transmission system is built based on PSCAD/EMTDC. The capacities of system m and system n are 30000 MVA and 28000 MVA, respectively. The line adopts the parameters given in table 1. The fault time is set as 1s and full-wave Fourier algorithm is applied for phase calculation. When external faults occur, $\Delta\theta_1 \approx 180^\circ$, $\theta_2 \approx 180^\circ$, the protection does not act. The simulation result of external faults with R_g=500 Ω at the same location is the same.

Figure 7 gives the simulation results of internal BC phase to phase grounding fault at 20 km and 1500 km from end-m, the protection acts reliably.



(a) Internal fault at 20 km (b) Internal fault at 1500 km

Fig. 7 Simulation result of BC phase to phase grounding fault

Figure 8 gives the simulation result of internal three-phase fault at 5 km from the end-m, $\Delta\theta_1 \approx 120^\circ$ and the protection acts reliably.

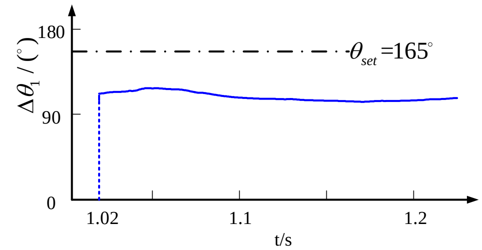


Fig. 8. Simulation result of three-phase fault

The full simulation results of internal faults are given in Table 2, and the protection acts correctly.

Table. 2 Phase difference of voltage fault component for internal fault

Fault location/km	Grounding resistance/Ω	fault type			
		AG/θ_2	CA/θ_2	CAG/θ_2	ABC/$\Delta\theta_1$
3	0	122.9°	113.8°	121.7°	113.1°
	500	120.1°	114.6°	113.7°	123.8°
500	0	6.8°	6.5°	6.3°	6.9°
	500	6.7°	6.8°	6.4°	6.2°
1000	0	1.3°	1.4°	1.6°	1.5°
	500	1.4°	1.5°	1.6°	1.5°
1500	0	0.2°	0.4°	0.2°	0.2°
	500	0.3°	0.4°	0.2°	0.2°
2000	0	1.3°	1.4°	1.7°	1.6°
	500	1.2°	1.3°	1.6°	1.5°
2500	0	6.9°	6.3°	6.2°	6.8°
	500	6.9°	6.3°	6.3°	6.8°
2997	0	121.3°	123.7°	121.8°	123.3°
	500	121.5°	123.5°	121.9°	123.4°

4. CONCLUSIONS

(1) When the system is in normal operation, the voltage phase difference between two ends of HWACTL is affected by the attenuation factor of the line and load current. The larger the attenuation factor is, the more the phase difference deviates from 180°, the larger the load current is, the more the phase difference deviates from 180°. (2) The voltage fault component-based phase differential protection can correctly distinguish between internal fault and external fault and is not affected by the transition resistance R_g.

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