Adaptive distance protection scheme with quadrilateral characteristic for extremely high-voltage/ultra-high-voltage transmission line

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Abstract: Traditional distance protection may mal-operate or refuse to operate in the case of non-metallic faults, endangering the safety of power system. Therefore, a new adaptive distance protection scheme based on the impedance complex plane is proposed in this study. First, by utilising the phase relationship between the negative sequence current at the relaying point and the current at the fault point, the fault supplementary impedance angle caused by the fault resistance is calculated. Then, the effective fault impedance from the fault point to the relaying point is obtained by the trigonometric function relationship of the effective fault impedance, measured impedance and fault supplementary impedance on the impedance complex plane. On this basis, the criterion of the adaptive distance protection is constructed. Finally, test results on real-time digital simulator demonstrate that the protection scheme proposed in this study is applicable to various types of faults, and has a good adaptability to different system operating conditions. Compared with traditional distance protection scheme, the proposed scheme is immune to the fault resistance, thus mal-operation or operation-rejection of distance protection caused by the fault resistance could be effectively avoided.

1 Introduction

Concerning the protection range and sensitivity, the influence of the system operation mode variation on distance protection is less than that on voltage protection and current protection. Distance protection could meet the requirement of complex network to clear the fault components fast and selectively, thus it is widely applied in high-voltage/ultra-high-voltage transmission lines [1, 2]. However, distance protection may mal-operate or refuse to operate in the case of non-metallic faults, endangering the safety of power system [3–6]. Scholars home and abroad have conducted a lot of research concerning the poor immunity of traditional distance protection to the fault resistance. Two main methodologies are as follows:

(a) Construct protection schemes by avoiding the influence of fault resistance. For example, adaptively adjust the operation boundary of protection to improve its immunity to fault resistance [7–9]; compensate for the fault supplementary impedance caused by the fault resistance, so that the measured impedance could reflect the distance between the relay location and the fault location more accurately [10]; calculate the actual fault location, and then determine if it falls in the protection setting range to discriminate between in-zone and out-of-zone faults [11–15]. These methods could to some extent prevent under-reach of the protection range, but the protection range may over-reach due to the load current. Besides, some of the methods are only applicable to single source system [11].

(b) Construct protection schemes by utilising the fault characteristics of fault resistance. For example, identify in-zone and out-of-zone faults according to the direction trend of voltage amplitude along the line after the fault [16]. However, this method uses fault components, thus it is effective only in the early stage after fault occurs and can only be used for primary protection; calculate the active power consumed by the fault resistance, and identify the high-resistance grounding faults [17], but this requires the interaction of information between two terminals.

Since the method of adaptively adjusting the operation boundary of protection could effectively improve the operation performance of distance protection, an adaptive distance protection scheme based on the impedance complex plane is proposed in this paper. First, according to the phase relationship between the negative sequence current at the relaying point and the current at the fault point, the phase angle of the fault supplementary impedance caused by fault resistance is calculated. Moreover then, according to the geometric distribution of the measured impedance, fault supplementary impedance and effective fault impedance on the impedance complex plane, the effective fault impedance from the fault point to the relaying point is calculated. On this basis, the operation equation of the adaptive impedance relay with quadrilateral characteristic is established. Finally, simulation results of the tests on real-time digital simulator (RTDS) verify the correctness and effectiveness of the proposed method.

2 Theory

Take the three-source system presented in Fig. 1, for example, to analyse the protection principles. The equivalent electromotive force (emf) of the sources at the back side of bus M, bus N and bus P are $E_M$, $E_N$ and $E_P$, respectively, and the corresponding equivalent impedances are $Z_M$, $Z_N$ and $Z_P$. The line impedances of line $L_1$, line $L_2$, line $L_3$, line $L_4$ and line $L_5$ are $Z_{m1}$, $Z_{m2}$, $Z_{m3}$, $Z_{m4}$ and $Z_{m5}$, respectively.

2.1 Analysis of the impedance complex plane

If there is a fault on $L_1$, the voltage equation at relay 1 can be described as

$$U_m = I_m \times \alpha Z_{m1} + U_f$$

where $U_m$ is the measured voltage at relay 1, $U_f$ is the voltage at the fault point, $I_m$ is the measured current at relay 1. $Z_{m1}$ is the
impedance of line $L_1$, \( \alpha \) is the ratio of the distance between the fault point and relay 1 to the whole length of line $L_1$.

The definition of the measured impedance $Z_m$: namely, $Z_m = \frac{U_m}{I_m}$, according to (1), $Z_m$ be described as: (1) can be modified as the expression of $Z_m$

$$Z_m = \frac{aZ_m + I_i}{I_m} = aZ_m + \frac{I_i}{I_m} \tag{2}$$

where $I_i$ is the current through the fault point. $R_f$ is the fault resistance.

If there is a fault on the neighbouring line $L_3$, the voltage equation at relay 1 can be described as

$$U_m = I_m Z_{m1} + I_1 Z_{m2} + U_t \tag{3}$$

where $I_m$ is the measured current at relay 3. $Z_{m1}$ and $Z_{m2}$ are, respectively, the line impedances of lines $L_1$ and line $L_3$. Here, $\alpha_1$ is the ratio of the distance between the fault point and relay 3 to the whole length of line $L_3$.

According to (3), the measured impedance $Z_m$ is

$$Z_m = Z_{m1} + \frac{I_i}{I_m} \alpha_1 Z_{m2} + \frac{U_t}{I_m} = Z_{m1} + K_{1f} \alpha_1 Z_{m2} + \frac{I_i}{I_m} R_f \tag{4}$$

where $K_{1f}$ is the branch coefficient.

Denote the line impedance between the fault point and the relaying point uniformly as the effective fault impedance $Z_f$. When fault occurs on a certain line, in (2) $Z_i = aZ_m$; when fault occurs on the adjacent line, in (4) $Z_i = Z_m + K_{1f} \alpha_1 Z_{m2}$. Thus the measured impedance $Z_m$ becomes

$$Z_m = Z_f + \frac{I_i}{I_m} R_f \tag{5}$$

It is should be noted in (5) that, when fault occurs in the system, the measured impedance $Z_m$ consists of the effective fault impedance $Z_f$ and the fault supplementary impedance $\Delta Z = (I_i R_f) / I_m$ at the same time. When metallic fault occurs, the value of $R_f$ is 0, then $Z_m = Z_f$. When non-metallic fault occurs, the value of $R_f$ is not 0, and $\Delta Z$ is not negligible.

Shown in Fig. 2 is the geometric distribution of the measured impedance $Z_m$, the effective fault impedance $Z_f$ and fault supplementary impedance $\Delta Z$ on the impedance complex plane. In Fig. 2, $\varphi_1$ is the angle between $Z_f$ and the real axis, called the effective fault impedance angle, which is only related with the line impedance. $\varphi_m$ is the angle between $Z_m$ and the real axis, called the measured impedance angle. $\varphi_3$ is the angle between $Z_m$ and $\Delta Z$. $\varphi_3$ denotes the angle between $Z_m$ and $\Delta Z$.

According to Fig. 2, $\varphi_1$, $\varphi_2$ and $\varphi_3$ are, respectively

$$\begin{align*}
\varphi_1 &= \varphi_s - \varphi_m \\
\varphi_2 &= 180^\circ - \varphi_s + \varphi_f \\
\varphi_3 &= 180^\circ - \varphi_f - \varphi_z
\end{align*} \tag{6}$$

where $\varphi_m = \arg(Z_m)$, $\varphi_f = \arg(\Delta Z)$ and $\varphi_s = \arg(Z_s)$. Here, $\arg$ represents the phase angle. When $\Delta Z$ is resistive–capacitive, $\varphi_f < 0$ and when $\Delta Z$ is resistive–inductive, $\varphi_f > 0$. Thus in resistive–capacitive fault case, the value of $\varphi_2$ is:

$$\varphi_2 = 180^\circ - \varphi_1 - \varphi_3 = 180^\circ - \varphi_1 - \varphi_z$$

According to the Law of Sines in triangle, the following relationship exists between $Z_f$ and $Z_m$:

$$\frac{|Z_f|}{\sin \varphi_1} = \frac{|Z_m|}{\sin \varphi_2} \tag{7}$$

Since

$$|Z_f| = \frac{Z_f}{\cos \varphi_1 + j \sin \varphi_1}, \quad |Z_m| = \frac{Z_m}{\cos \varphi_m + j \sin \varphi_m}$$

(7) can also be expressed as

$$Z_f = \frac{|Z_f|}{|Z_m|} \times Z_m \cos \varphi_1 + j \sin \varphi_1 = Z_m \cos \varphi_m + j \sin \varphi_m \times (R + jX) \tag{8}$$

where $R + jX$ is denoted as the adaptive protection measured value.
2.2 Calculation of the fault supplementary impedance angle

According to [12], the fault resistance \( R_f \) is usually resistive. Therefore, the fault supplementary impedance angle \( \phi_f \) can be expressed as

\[
\phi_f = \arg\left(\frac{I_f}{I_m}\right) = \arg\left(\frac{I_a}{I_m}\right) \quad (9)
\]

For different types of faults, \( \phi_f \) can be transformed to the angle between the measured current and the negative sequence current at the fault point, which is discussed below in detail.

2.2.1 Single-phase-to-ground fault: According to the composite sequence network, the zero sequence current, the positive sequence current and the negative sequence current at the fault point, denoted by \( I_{\bar{0}} \), \( I_a \), and \( I_c \), respectively. According to the boundary conditions of single-phase grounding fault, \( I_{\bar{0}} \), \( I_a \), and \( I_c \) are all equal, i.e. \( I_{\bar{0}} = I_a = I_c \). Thus

\[
I_i = I_{\bar{0}} + I_a + I_c = 3I_c \quad (10)
\]

Therefore, the fault supplementary impedance angle \( \phi_c \) is

\[
\phi_c = \arg\left(\frac{I_i}{I_m}\right) = \arg\left(\frac{I_c}{I_m}\right) \quad (11)
\]

2.2.2 Phase-to-phase fault: In the case of phase-to-phase fault, the fault currents of phase-A \( I_{\bar{0}} \) is 0, the fault currents of phase B \( I_b \) and phase C \( I_c \) are equal in amplitude, but have contrary phase, i.e. \( I_{\bar{0}} = -I_b \) thus

\[
I_c = \frac{1}{3}(I_{\bar{0}} + aI_b + a^2I_c) = \frac{1}{3}(a^2 - a)I_b = \frac{1}{3}(a - a^2)I_c \quad (12)
\]

where \( a = e^{j2\pi/3} \).

The relationship between \( I_i \) and \( I_{12} \) can be expressed as

\[
I_i = \frac{6I_{12}}{a-a^2} = j2\sqrt{3}I_{12} \quad (13)
\]

Therefore, the fault supplementary impedance angle \( \phi_c \) is

\[
\phi_c = \arg\left(\frac{2j\sqrt{3}I_{12}}{I_m}\right) = \arg\left(\frac{I_{12}}{I_m}\right) + 90^\circ \quad (14)
\]

2.2.3 Two-phase-to-ground fault: According to the composite sequence network, in the case of phase BC-to-ground fault, \( I_{\bar{0}} + I_a + I_c = 0 \). The fault currents of phase B and phase C can be expressed as

\[
\begin{align*}
I_{\bar{0}} &= (a - a^2)I_{12} + (1 - a^2)I_{10} \\
I_c &= (a^2 - a)I_{12} + (1 - a)I_{10}
\end{align*} \quad (15)
\]

Thus the relationship between \( I_i \) and \( I_c \) can be expressed as

\[
I_i = I_{\bar{0}} - I_c = (a - a^2)\left(2 + \frac{I_{10}}{I_{12}}\right)I_{12} = (a - a^2)\left(\frac{2Z_{2c} + 6R_g + Z_{2g}}{Z_{2c} + 3R_g}\right)I_{12} \quad (16)
\]

where \( Z_{2c} \) and \( Z_{2g} \) are, respectively, the equivalent negative sequence and zero sequence impedance of the network seen from the fault point.

Since \( Z_{2c} \ll Z_{2g} \), (16) can also be approximated as

\[
I_i \approx 2(a - a^2)I_{12} \quad (17)
\]

Therefore, the fault supplementary impedance angle \( \phi_c \) is

\[
\phi_c \approx \arg\left(\frac{I_{12}}{I_m}\right) + 90^\circ \quad (18)
\]

2.2.4 Three-phase fault: In the case of three-phase fault, since the arc voltage is very small (voltage at the fault point is lower than 0.05 pu), the influence of contribution current from the opposite power source on the arc voltage is negligible. Thus, the fault system could be approximated to a single source system for analysis, i.e. the phase angle of \( I_{\bar{0}} \) is the same as that of \( I_{12} \) which means the fault supplementary impedance angle \( \phi_c = 0 \). Since the phase angle of system equivalent negative sequence impedance on two sides of the transmission line is approximately the same as the phase angle of line negative sequence impedance [18], i.e. whether the fault occurs on this line or the neighbouring line, the negative sequence current at the relaying point and the negative sequence current at the fault point are approximately the same in phase angle (see the Appendix for proof). Therefore, the expression of \( \phi_c \) could be further transformed to (see (19)). With (19), the fault supplementary impedance angle \( \phi_c \) could be calculated though \( I_i \) is un-measurable.

2.3 Protection criterion

In real power grid, the quadrilateral operation characteristic is widely applied for distance protection. As shown in Fig. 3, \( R_{act} \) and \( X_{act} \) are, respectively, the resistive reach setting and reactive reach setting. Usually, \( \alpha_1 \) is between 15° and 30°, \( \alpha_2 \) is between 15° and 30°, \( \alpha_3 \) is between 60° and 65° and \( \alpha_4 \) is between 7° and 10°. If the fault occurs within the setting range of the protection, the effective fault impedance \( Z_f \) will inevitably fall into the operating region. Otherwise, the effective fault impedance \( Z_f \) will not fall into the operating region.

The operation equations of the quadrilateral relay in Quadrant I can be expressed as

\[
\phi_c = \begin{cases} 
\arg\left(\frac{I_{\bar{0}}}{I_m}\right), & \text{single – phase to – ground fault} \\
0, & \text{three – phase fault} \\
\arg\left(\frac{I_{\bar{0}}}{I_m}\right) + 90^\circ, & \text{phase – to – phase fault or two – phase to – ground fault} 
\end{cases} \quad (19)
\]
The operation equations of the quadrilateral impedance relay in Quadrant II are

\[
\begin{align*}
R \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) & \leq X \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) \cot \alpha_i \\
X \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) & \leq X_{set}
\end{align*}
\]  

(20)

The operation equations of the quadrilateral impedance relay in Quadrant IV are

\[
\begin{align*}
R \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) & \leq R_{set} \\
X \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) & \geq -R \left( \frac{\sin \varphi_1}{\sin \varphi_2} \right) \tan \alpha_i
\end{align*}
\]  

(22)

Define \( K_a = \left( \frac{\sin \varphi_2}{\sin \varphi_1} \right) \) as the adaptive coefficient, thus the operation equations of the adaptive quadrilateral impedance relay can be described as

\[
\begin{align*}
R - X \cot \alpha_i & \leq K_a R_{set} \\
X + R \cot \alpha_i & \leq K_a X_{set}
\end{align*}
\]  

(23)

If all the above operation equations are satisfied simultaneously, it indicates that the fault is within the protection range, and then the distance protection will operate. Since \( \varphi_2 \), \( R_{set} \) and \( X_{set} \) are constants, \( \varphi_2 \) and \( \varphi \) are measured values; these parameters have nothing to do with the source impedance. Therefore, the proposed scheme fits for various conditions with different source impedances.

In the execution of the proposed method, only two-phase angles need to be calculated, i.e. the phase angles of \( I_m \) and \( I_{set} \). On this basis, the adaptive coefficient is calculated so that the protection setting value can be gained. The computation amount of the proposed method is small. However, there are two issues that still need to be discussed:

(a) The effect of the noise: In the proposed scheme, the full-Fourier algorithm is used for filtering, which could filter most of the noises [19]. Moreover, the disturbance that remains is negligible, since compared with the power frequency components, it is very small in magnitude and will not have any influence on the identification result.

(b) Error analysis of \( \varphi_2 \): In the calculation process of \( \varphi_2 \), it is assumed that the phase angle of \( I_{set} \) is used to represent the phase angle of \( I_m \). However, the difference angle \( \theta \) between these two-phase angles equals the phase angle of the coefficient in (26) and (27). For (27), suppose (see equation below)

\[
\frac{X_{set}}{R_{set}} = \frac{Z_{set}}{Z_{set} + Z_{nm}} = \frac{Z_{T2} + Z_{nm}}{(Z_{C2} + Z_{nm}) \times (Z_{T2} + Z_{nm})} \times \left( \frac{Z_{R2} + (1 - a)Z_{nm}}{(Z_{C2} + Z_{nm}) \times (Z_{T2} + Z_{nm})} \right)
\]

Apply the data of simulation system to \( C_{in2} \), so that the variation of phase angle \( \theta \) of \( C_{in2} \) with fault distance \( l \) can be gained, shown in Fig. 4, where \( l = \alpha L \), \( L \) is the whole line length.

It can be seen from Fig. 4 that, for transmission lines <300 km long, \( \theta \) is close to 0°. No matter fault occurs on this line or on the neighbouring line. In this case, the error of calculating the deviation angle \( \theta \) is very small. However, for long transmission lines, the phase angle \( \theta \) is relatively big, thus the error of this approximation will be relatively big. Therefore, further study is needed for application to long transmission lines.

### 3 Simulation verification

RTDS is designed by the RTDS Company in Manitoba, Canada, which electromagnetic transient simulation is especially accurate. It could reflect the system fault condition faithfully, and the real-time simulation is flexible to operate. Therefore, this paper uses RTDS to verify the proposed scheme, in order to guarantee the accuracy and reliability of analysis.

In this paper, a 500 kV simulation system is established in RTDS, as shown in Fig. 5. The C-builder in RTDS is used to establish the protection modules, which then read the simulation data of the above system in real time and do the calculation for protection functions. After the calculation, the tripping command is issued to the circuit breaker in RTDS simulation model. The parameters have been shown in Tables 1 and 2.

In real system, the influence of the arc resistance in inter-phase fault (including grounded fault and ungrounded fault) on distance protection is smaller than the influence of the fault resistance in single-phase-to-ground fault on distance protection [10]. Therefore,
in this paper, simulation tests are conducted mainly concerning the single-phase-to-ground fault.

Taking the protection located at the sending end (bus M) of line L₁ for instance, zone I of the distance protection is set to protect 80% of the whole length of the line; zone II is set in cooperation with zone I at bus P of the neighbouring line (L₂, L₃ and L₄), and to ensure the sensitivity of the distance protection when fault occurs at the remote end of this line. In the simulation tests, parameters α₁–α₄ in the quadrilateral characteristic are 15°, 15°, 60° and 7°, respectively. The fault occurs at t = 0.5 s and the fundamental frequency component is extracted by means of the full-wave Fourier algorithm, and the sampling frequency is 1 kHz. Consider the dynamic characteristics of the full-wave Fourier algorithm, the fault impedance calculated after one post-fault cycle is the effective value. Simulation results in the 1/4 cycle after t = 0.52 s are shown below.

The difference between traditional method and the newly protection lies in that, the former is not adaptive, i.e. Kₐ = 1 in (23). For the proposed method, the adaptive coefficient Ka will vary correspondingly to the change in fault condition, thus, the traditional scheme distinguished from the claimed approach in the calculation for protection functions.

4 Results and discussion

4.1 Simulation analysis of distance protection zone I

4.1.1 Different fault resistances: Fig. 6 shows the simulation results of distance protection zone I, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L₁, where δ = 10°. For the same fault resistance, the adaptive coefficient decreases as the fault distance increases. Thus, distance protection can operate reliably in the case of internal fault, but would not operate in the case of external fault. It can be seen from Fig. 7 that, when fault locates within 95% of the protection range (i.e. 190 km from bus M), the measured impedance falls outside the operating region of adaptive distance protection and then distance protection zone I operates correctly. When fault locates at 105% of the protection range (i.e. 210 km from bus M), the measured impedance of the distance protection falls outside the operating region and then distance protection zone I does not operate. This means the setting error of the proposed scheme is within ±5% of the protection range, which could meet the demands of ground distance protection technique [18].

4.1.2 Different fault locations: Fig. 7 shows the simulation results of distance protection zone I, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L₁, where δ = 10°. Notably, the fault resistance has no effect on the correctness of the proposed scheme. Since the adaptive coefficient increases when the fault resistance increases, the measured impedance falls into the operating region of adaptive distance protection and distance protection zone I is able to operate correctly even when fault occurs with high resistance.

4.1.3 Different operating conditions: Fig. 8 shows the simulation results of distance protection zone I, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L₁, where δ = 30°. The phase angle δ increases as the load current increases. When phase angle δ increases, the equivalent fault resistance ΔZ becomes more capacitive in fault condition, thus the measured impedance decreases correspondingly. As can be seen by comparing Figs. 7 and 8, the proposed scheme is not affected by the system operating condition. When high-resistance fault occurs in different operating conditions, distance protection zone I could distinguish between in-zone and out-of-zone faults correctly, even in heavy load condition.

The simulation data and protection operation results of zone I are presented in Table 1. It is easy to find that using the adaptive coefficient is effective in eliminating the influence of fault resistance. The protection could still operate correctly, even when high-resistance grounding fault occurs. In addition, since the adaptive coefficient used in this paper is hardly affected by the

<table>
<thead>
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<th>Side</th>
<th>Z₁, Ω</th>
<th>Z₀, Ω</th>
<th>Voltage, kV</th>
<th>S, MVA</th>
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</tr>
<tr>
<td>N</td>
<td>8.0 + j59.65</td>
<td>2.0 + j37.47</td>
<td>500 ± 0</td>
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</tr>
<tr>
<td>Q</td>
<td>1.05 + j3.14</td>
<td>0.6 + j2.79</td>
<td>500 ± 5</td>
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</table>

<table>
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<tr>
<th>Line</th>
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<th>C₁, μF/km</th>
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<th>Length, km</th>
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<tr>
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<td>0.0040</td>
<td>250</td>
</tr>
<tr>
<td>L₂</td>
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<td>0.0139</td>
<td>0.0098</td>
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<tr>
<td>L₃</td>
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<td>0.1148 + j0.7186</td>
<td>0.0129</td>
<td>0.0052</td>
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<td>L₄</td>
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<td>0.0051</td>
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when high-resistance fault occurs, the proposed distance protection results of distance protection zone II, when phase-A-to-ground fault type and location, as well as the load current, the proposed adaptive scheme could operate reliably and correctly in different fault resistances. It is demonstrated that the proposed scheme is immune to fault resistance.

4.2 Simulation analysis of distance protection zone II

4.2.1 Different fault resistances: Fig. 9 shows the simulation results of distance protection zone II, when phase-A-to-ground fault with different fault resistances occur in the system at 245 km from bus M on line L1, where δ = 10°. As can be seen from Fig. 9 and Table 4, distance protection zone II could operate reliably, whether the fault resistance is big or small. It is demonstrated that the proposed scheme is immune to fault resistance.

4.2.2 Different fault locations: Table 5 shows the simulation results of distance protection zone II, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L1 and line L3, where δ = 10°. As can be seen from Table 5, when high-resistance fault occurs, the proposed distance protection zone II could not only protect the full-length of the line, but also provide backup protection for the neighbouring line.

5 Conclusion

An adaptive distance protection scheme based on the impedance complex plane is proposed in this paper. Simulation results demonstrate that the proposed scheme has the following advantages:

(a) Immune to the fault resistance, thus mal-operation or operation-rejection of distance protection caused by the fault resistance could be effectively avoided.
(b) Unaffected by the fault type and applicable to various types of faults.
(c) Has a good adaptability to different system operating conditions.
(d) Small computation amount and easy implementation, since the proposed method could be implemented with the existing hardware conditions of protection system, with no requirement for extra communication devices.

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Fig. 6 Simulation results of zone I when phase-A-to-ground fault occurs at 125 km from bus M on line L1 via different transition resistances (a) 10 Ω, (b) 150 Ω, (c) 300 Ω fault type and location, as well as the load current, the proposed adaptive scheme could operate reliably and correctly in different fault conditions.

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4.2.1 Different fault resistances: Fig. 9 shows the simulation results of distance protection zone II, when phase-A-to-ground fault with different fault resistances occur in the system at 245 km from bus M on line L1, where δ = 10°. As can be seen from Fig. 9 and Table 4, distance protection zone II could operate reliably, whether the fault resistance is big or small. It is demonstrated that the proposed scheme is immune to fault resistance.

4.2.2 Different fault locations: Table 5 shows the simulation results of distance protection zone II, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L1 and line L3, where δ = 10°. As can be seen from Table 5, when high-resistance fault occurs, the proposed distance protection zone II could not only protect the full-length of the line, but also provide backup protection for the neighbouring line.

4.2.3 Different operating conditions: Table 6 shows the simulation results of distance protection zone II, when phase-A-to-ground fault with 300 Ω fault resistance occurs at different locations on line L3, where δ = 30°. As can be seen from Table 6, the proposed scheme is not affected by the system operating condition. When high-resistance fault occurs in different operating conditions, distance protection zone II could distinguish between in-zone and out-of-zone faults correctly.

According to the simulation result of zone II, when the fault resistance is relatively big, using fixed impedance setting value will cause the protection to mal-operate. However, if the adaptive coefficient is used, the protection could operate correctly even in the case of high-resistance grounding fault.

4.3 Comparative analysis of the proposed scheme and traditional distance protection scheme

To further verify the immunity of the proposed scheme to fault resistance, comparative analysis is conducted between the proposed scheme and traditional distance protection scheme. The setting principles of the traditional distance protection scheme [10] are the same as those for the quadrilateral characteristic of the proposed scheme, i.e. parameters α1=α4 in the quadrilateral characteristic are 15°, 15°, 60° and 7°, respectively. The protection range of relay-I covers 80% of the line, and the protection zone II is set to cover 125% of L1. The difference lies in that, traditional method is not adaptive, i.e. Kα = 1. Suppose that the phase angle of the system voltage on M side δ = 10°. As shown in Fig. 10a is the simulation results of traditional distance protection zone I when fault with different fault resistances occurs at 125 km from bus M on line L1. When fault with different fault resistances occurs at 245 km from bus M on line L1, the simulation results of traditional distance protection zone II are presented in Fig. 10b. For distance protection zone I, compare simulation result of the proposed method in Fig. 6 with the result of traditional method in Fig. 10a; for distance protection zone II, compare simulation result of the proposed method in Fig. 9 with the result of traditional method in Fig. 10b. It is easy to note that the traditional distance protection is strongly affected by the fault resistance. When the fault resistance reaches 150 Ω or bigger, the traditional distance protection refuses to operate. Meanwhile, the proposed distance protection could operate correctly in the same situation. Therefore, compared with traditional method, the proposed method could solve the problem of distance protection refusing to operate caused by fault resistance more effectively.
Fig. 7 Simulation results of zone I when phase-A-to-ground fault occurs via 300 Ω fault resistance at different locations on line L1 (δ = 10°)
(a) 100 km from bus M, (b) 190 km from bus M, (c) 210 km from bus M

Fig. 8 Simulation results of zone I when phase-A-to-ground fault occurs via 300 Ω transition resistance at different locations on line L1 (δ = 30°)
(a) 190 km from bus M, (b) 210 km from bus M

Table 3 Simulation data and results of Figs. 5–7

<table>
<thead>
<tr>
<th>Figure number</th>
<th>( K_a )</th>
<th>( R, \Omega )</th>
<th>( X, \Omega )</th>
<th>( R_{set}, \Omega )</th>
<th>( X_{set}, \Omega )</th>
<th>Protection operation status</th>
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7 References


8 Appendix

As shown in Fig. 11 is the negative sequence fault network of the system when asymmetrical fault occurs. \( I_{m} \) is the negative sequence current at relay 1. \( I_{fs} \) is the negative sequence current at the fault point. \( Z_{G2}, Z_{T2} \) and \( Z_{R2} \) represent the equivalent negative sequence impedance of the sources at the back side of bus \( M \), bus \( T \) and bus \( R \), respectively. \( Z_{mn2}, Z_{m2} \) and \( Z_{nr2} \) represent the negative sequence impedance of line MN, TN and NR. \( \alpha \) is the ratio of the distance between the fault point and relay 1 to the whole length of the line.

According to Fig. 11, when fault occurs on line MN and on the neighbouring line NR, the relationship between \( I_{m} \) and \( I_{fs} \) is shown as (26) and (27), respectively: (see (26) and (27)) (see (27))

It can be seen that, the phase angle difference between \( I_{m} \) and \( I_{fs} \) depends on the phase angle of the coefficient on the right-hand side of (26) and (27). According to [16], the impedance angle of the system is approximately equals to that of the line in EHV/UHV system, thus the coefficient on the right-hand side of (26) and (27) can be approximated to real number, which means the angular difference between \( I_{m} \) and \( I_{fs} \) is \( 0^\circ \). Whether fault occurs on this line or on the neighbouring line, the negative sequence impedance angles at two sides of the fault point can be taken as the same, and the following approximation is true (Table 7):

\[
\arg(I_{m}) \approx \arg(I_{fs})
\]  
(28)
<table>
<thead>
<tr>
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<tr>
<td>$I_f$</td>
<td>the current at the fault point</td>
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<tr>
<td>$U_i$</td>
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<td>$\varphi_z$</td>
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<tr>
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<tr>
<td>$\Delta Z$</td>
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<td>$\varphi_3$</td>
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