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Study on Reactance Relays for Single Phase to Earth Fault on EHV Transmission Lines

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Abstract

Two questions about zero-sequence-reactance relay to overcome the disadvantages of high fault resistance for single phase to earth fault of high voltage transmission lines are discussed in this paper. The first question is about the phase difference between the measured zero-sequence current and voltage at fault position for un-balanced transmission lines. The second question is about the "in-phase" problem in reactance relays (or fault component reactance relays). This paper analyzes the two questions theoretically and the reactance relay is improved by a new discriminative principle. The capability against the fault resistance is largely enhanced by the improved schemes.

Keywords: *Zero-sequence reactance relay; High voltage transmission lines; Fault resistance; In phase*

1. Introduction

The single-phase to earth fault with high fault resistance is most common for transmission lines. Therefore, the zero-sequence-reactance relay is used for single-phase to earth faults. For single phase to earth fault, the zero-sequence current at relay location is approximately in phase with the voltage phasor at fault point, the phase difference angle between the two phasors is very important to the characteristic of reactance relay, it will lead to the over-reach or under-reach of the reactance relays [1-3]. Traditionally, under the assumption of the balanced transmission line, the phase difference is independent with the value of fault resistance, and only depends on the fault distance. Many documents studied this angle and made a conclusion that the phase difference is not more than 10^{o} [4, 5]. However, it is not the case for unbalanced lines, EMTP simulations show that the phase difference is not only dependent on fault location but also on fault resistance.

The other disadvantage that the reactance relay (or fault component reactance relay) suffers is the "in phase" problem [6, 7]. When the relay is located at receiving end, there exists value of fault resistance which makes the operation voltage in phase with the compensate voltage, as the fault resistance is larger this value, the relay will mal-operate. The former two questions are discussed in this paper, and the methods to solve the problems are proposed. Zero-sequence current is replaced by its fault component can easily solve the first problem. As the voltage phasors are just in phase, there is no way to make out correct decision for reactance relay, however, when the fault resistance is larger than the value which makes the phsors just in phase, the voltage phasor at fault location can be accurately evaluated, using a additional discriminative criterion can solve the "in phase" problem. EMTP simulation tests show that the capacitance against the fault resistance of improved reactance is much larger than traditional reactance relays.

2. Overview of Reactance Relays

Consider the single phase to earth fault with high resistance show in Figure 1. The transmission line shunt capacitance is neglected. The positive-, negative-, and zero-sequence impedance are respectively marked as Z_1, Z_2 and Z_0.

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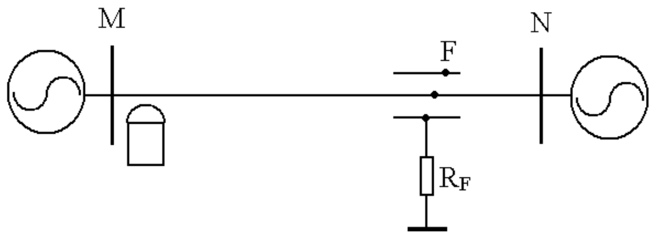


Figure 1. System Diagram

Under the assumption of $Z_1 = Z_2$, one can get the following equation:

$$\dot{U}_{M\phi} = \dot{U}_{F\phi} + Z_1(\dot{I}_{M\phi} + 3\dot{K}\dot{I}_{M0}) \quad (1)$$

Where the subscript ϕ means the fault phase, The complex constant $\dot{K} = \frac{Z_0 - Z_1}{3Z_1}$. The operating voltage phasor (marked as $\dot{U}'$) is defined as (based on the assumption that the line from relay location to the setting point is healthy):

$$\dot{U}'_{\phi} = \dot{U}_{M\phi} - Z_{set}(\dot{I}_{M\phi} + 3\dot{K}\dot{I}_{M0}) \quad (2)$$

Where Z_{set} means the setting impedance, and subscript ϕ means the fault phase. The fault phase voltage phasor diagram of single phase to earth fault is shown in Figure 2 (the resistance of transmission line is neglected in the figure).

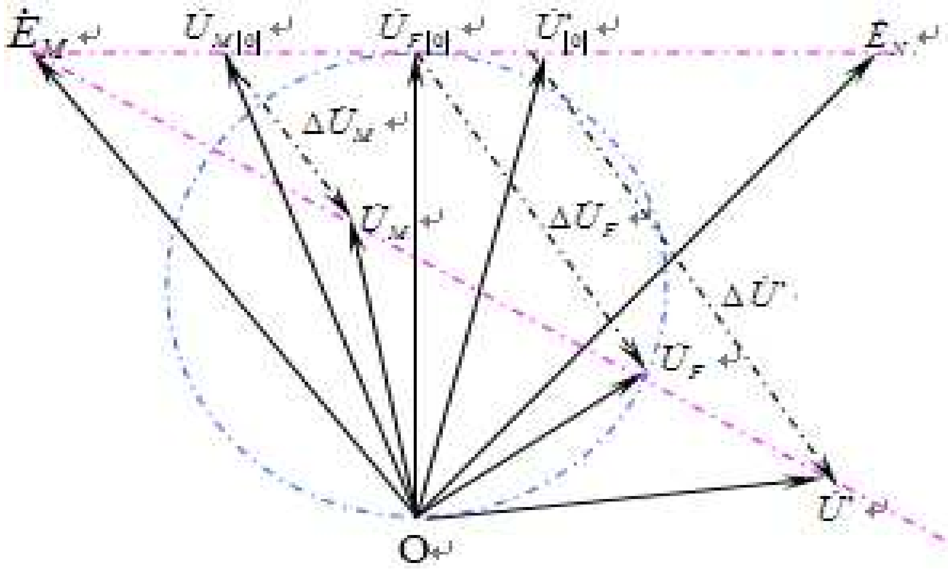


Figure 2. The Phasor Diagram of Single Phase To Earth Fault

In Figure 2, the subscript $|0|$ means the pre-fault phasor. Considering the neglect of system resistance, the trajectory of $\dot{U}_F$ moves up along the right half cycle with the increase of fault resistance, and should be in phase with $\Delta\dot{U}_F$ and $\Delta\dot{U}'$ (that is, the three phasors are parallel). The criterion of conventional Mho relay is to compare the phase of $\dot{U}_M$ (or $\dot{U}_{M|0|}$ for overcome the dead zone at close relay location) with $\dot{U}'$. If the fault resistance exceeds a certain value, the phase difference between $\dot{U}_M$ and $\dot{U}'$ will less than 90^o and therefore the Mho relay will refuse to trip.

From Figure 2, it can be seen that the key to overcome high fault resistance is to evaluate the fault point voltage phasor. As reactance relay, the measured zero-sequence current is used to replace the fault point voltage phasor. Once the phasor $\dot{U}'$ lag $\dot{U}_F$, the decision of the relay is internal fault, otherwise, the decision is external fault. Since the fault-location voltage is immeasurable, it is replaced by zero-sequence-current, based on the fact that the phase-difference between the fault-location voltage and zero-sequence current is small.

It is seen that the setting of the phase-difference is directly related to the relay over-reach or under-reach. For balanced-line, the phase-difference is independent on the value of fault-resistance, that is, it is constant when fault occurs at a fixed location. However, large amount EMTP simulations show that this is not true for the un-balanced lines, the phase-difference varies with the value of fault resistance.

3. Study on the Phase-Difference for Unbalanced Line

The phase-difference is marked as $\delta = Arg(\dot{I}_{M0}/\dot{U}_F)$. Theoretically, under the assumption of balanced three-phase system, the phase angle δ only depends on the system parameter and fault location and is independent on fault resistance [8, 9], that is, the angle is constant at a fixed fault location (see formula (3).

$$\delta = Arg\frac{\dot{I}_{M0}}{\dot{U}_F} = Arg\frac{\dot{I}_{M0}}{\dot{I}_{F0}} = ArgC_{M0} \tag{3}$$

Where C_{M0} is the zero-sequence distribution coefficient. However, due to the real transmission system is not strictly balanced, the angle is variable along with the increase of fault resistance. The angle in a typical transmission system by EMTP is shown in Figure 3. The fault resistance is from 0 to 1000 ohm, the angle is from –3^o to 120^o with the increase of resistance.

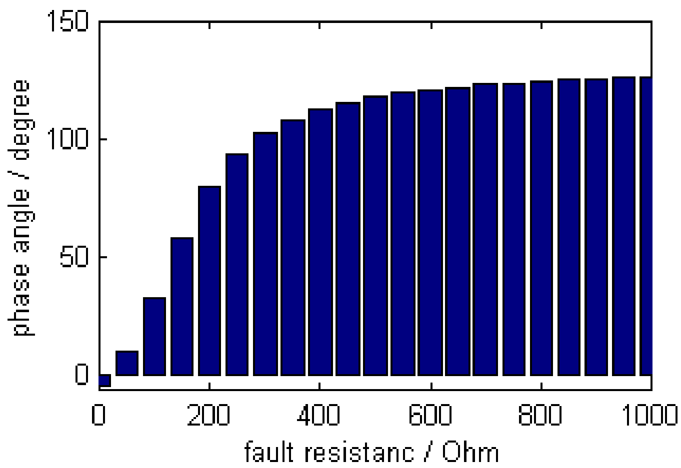


Figure 3. Phase Angle $\delta = f(R_f)$

Why does this phenomenon happen? The answer is that the transmission system is not strictly balanced; therefore, there exists zero-sequence current in the pre-fault network. The three phase equations of pre-fault can be written as following:

$$\begin{bmatrix} \dot{E}_{Ma} \\ \dot{E}_{Mb} \\ \dot{E}_{Mc} \end{bmatrix} = \begin{bmatrix} \dot{U}_{Fa|0|} \\ \dot{U}_{Fb|0|} \\ \dot{U}_{Fc|0|} \end{bmatrix} + \begin{bmatrix} Z_s & Z_m & Z_m + \Delta Z_1 \\ Z_m & Z_s & Z_m + \Delta Z_2 \\ Z_m + \Delta Z_1 & Z_m + \Delta Z_2 & Z_s \end{bmatrix} \begin{bmatrix} \dot{I}_{Ma|0|} \\ \dot{I}_{Mb|0|} \\ \dot{I}_{Mc|0|} \end{bmatrix} \tag{4}$$

Where Z_s is the self-impedance of three-phase, $Z_m = Z_{ab}$ is the mutual impedance of phase a and b, $\Delta Z_1 = Z_{ac} - Z_{ab}$, $\Delta Z_2 = Z_{bc} - Z_{ab}$.

In equation (4), the impedance matrix can be separated into two parts $\mathbf{Z} = \mathbf{Z}_1 + \Delta\mathbf{Z}$, where matrix $\mathbf{Z}_1$ is balanced and $\mathbf{Z}_2 = \begin{bmatrix} 0 & 0 & \Delta Z_1 \\ 0 & 0 & \Delta Z_2 \\ \Delta Z_1 & \Delta Z_2 & 0 \end{bmatrix}$. Transform the equation (4) to sequence mode by the symmetry component matrix:

$$\begin{bmatrix} \dot{E}_{Ma} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \dot{U}_{F1|0|} \\ \dot{U}_{F2|0|} \\ \dot{U}_{F0|0|} \end{bmatrix} + \begin{bmatrix} Z_1 & & \\ & Z_2 & \\ & & Z_0 \end{bmatrix} \begin{bmatrix} \dot{I}_{M1|0|} \\ \dot{I}_{M2|0|} \\ \dot{I}_{M0|0|} \end{bmatrix} + \begin{bmatrix} \Delta E_{1|0|} \\ \Delta E_{2|0|} \\ \Delta E_{0|0|} \end{bmatrix} \tag{5}$$

Suppose that single-phase to earth fault occurs at point F (shown in Figure 1). According to equation 5, the zero-sequence network is shown in Figure 4.

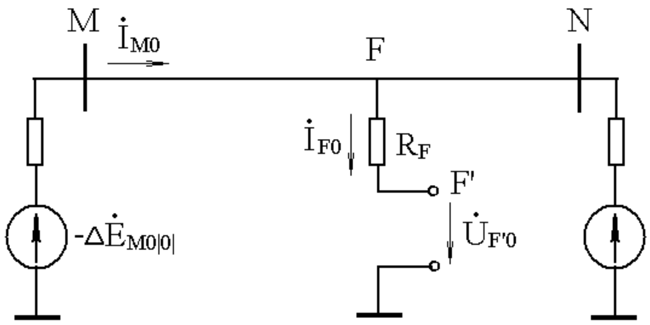


Figure 4. Zero-sequence Network

Using the superposition principle, $\dot{I}_{M0} = \dot{I}_{M0|0|} + C_{M0}\dot{I}_{F0}$, Let $\dot{I}_{F0} = A\angle 0^\circ$, $\dot{I}_{M0|0|} = B\angle\alpha_0$, the phase difference between the $\dot{I}_{M0}$ and $\dot{I}_{F0}$ can be written as:

$$\delta = Arg\frac{\dot{I}_{M0}}{\dot{I}_{F0}} = arctg\frac{K_0 R_f \sin\alpha_0}{1 + K_0 R_f \cos\alpha_0} + ArgC_{M0} \tag{6}$$

Where $K_0 = B/A$. From equation 6, it can be seen that, when $R_f = 0$, $\delta = ArgC_{M0}$; on the other hand, if $R_f \to \infty$, $\delta = \alpha_0$, that is, when the fault resistance is significantly high, the phase difference is controlled by phase angle of pre-fault zero-sequence current.

If the zero-sequence current $\dot{I}_{M0}$ is replaced by its fault component $\Delta\dot{I}_{M0}$, then, $\Delta\dot{I}_{M0}$ is approximately in phase with $\dot{I}_{F0}$. That is, the discriminative criterion of reactance relay is improved by the following:

$$-180^\circ < Arg\frac{\dot{U}'}{\Delta\dot{I}_{M0}\angle -\beta} < 0^\circ \tag{7}$$

where β is setting phase angle which value is selected the maximum value of $ArgC_{M0}$.

4. Analysis of “In Phase” Problem

As the relay is located at receiving end, the “in phase” problem can be described as the following phasor diagram (shown in Figure 5).

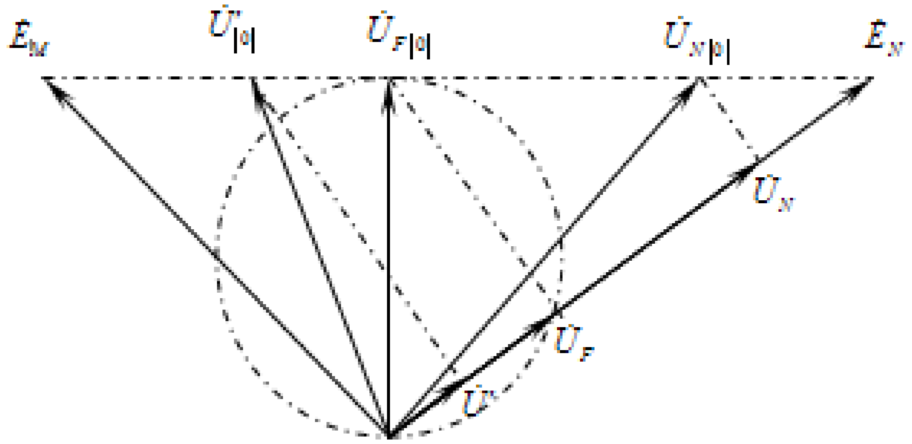


Figure 5. The ‘in phase’ Problem of Distance Relay

Considering that the relay is located at the receiving end (point N in Figure 1), one can easily see from Figure 7 that there must exist a fault resistance R_{fit} which makes $\dot{U}_N$ in phase with $\dot{U}_F$ and $\dot{U}'$. Once the fault resistance $R_f > R_{fit}$, the traditional relays, such as Mho, reactance, fault component reactance and other adaptive relays, will mal-operate at the receiving end.

If the three phasors are just in phase, there is no way to make a decision that the fault is internal or external. This is described as follows:

Since $\dot{U}_N = \dot{U}_F + Z_1(\dot{I}_N + 3K\dot{I}_{N0})$

That is, $\dot{U}_N = R_F'\dot{I}_{M0}e^{-j\beta} + Z_1(\dot{I}_N + 3K\dot{I}_{N0})$ (8)

If the $\dot{U}_N$ and $\dot{U}_F$ are in phase, the equation (8) is no certain solution (two variables in one equation). Once phasor $\dot{U}_F$ is exceed $\dot{U}_N$, the traditional reactance relay (or fault component reactance relay) will make a wrong decision.

5. The Improved Principle

From the phasor diagrams, we can see that the phasor $\dot{U}_F$ can be precisely evaluated by the following formula:

$$\dot{U}_F = \left|\frac{\dot{U}_M \sin(\theta-\alpha)}{\dot{I}_{M0}\sin(\theta+\beta+\delta)}\right|\dot{I}_{M0}\angle-\delta \quad (9)$$

Where $\alpha = Arg\frac{\dot{U}_M}{\dot{I}_M + 3K\dot{I}_{M0}}$, $\beta = Arg\frac{\dot{I}_M + 3K\dot{I}_{M0}}{\dot{I}_{M0}}$, $\delta = ArgC_{M0}$, $\theta = ArgZ_1$.

Using the following improved discriminative criterion can partly solve the “in phase” problem:

$$90^\circ < Arg\frac{\dot{U}_M - \dot{U}_F}{\dot{U}' - \dot{U}_F} < 270^\circ \quad (10)$$

Note the fact that when the phasors are just in phase, the former improved principle is failed either.

6. Digital Simulation Result

The numerical simulation is given by Electromagnetic Program (EMTP) associated with the typical transmission system that is shown in Figure 1. The algorithm of proposed adaptive relay is based on the Fourier method. The transmission line parameters are listed in the following: (the transmission line is considered to be unbalanced, and using the distributed parameter line model), $z_{L1} = z_{L2} = 0.0575 + j0.3882$; $z_{L0} = 0.0955 + j1.1846$, where z_{L1}, z_{L2}, z_{L0} are respectively the positive, negative, and zero sequence impedance per-length. The length of the transmission line is considered as 180km. The setting distance is 150km.

6.1. Test 1: The Phase Difference Between ΔI_{M0} and $\dot{U}_F$

The result of $\delta(R_F) = \arg\frac{\Delta I_{M0}}{\dot{U}_F}$ at a certain fault position (130km away from point M) is given in Figure 6. One can easily see that the angle nearly does not vary with increasing of fault resistance.

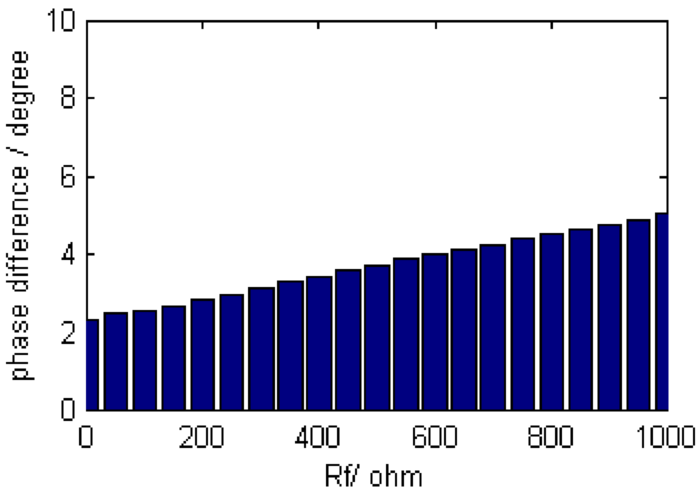
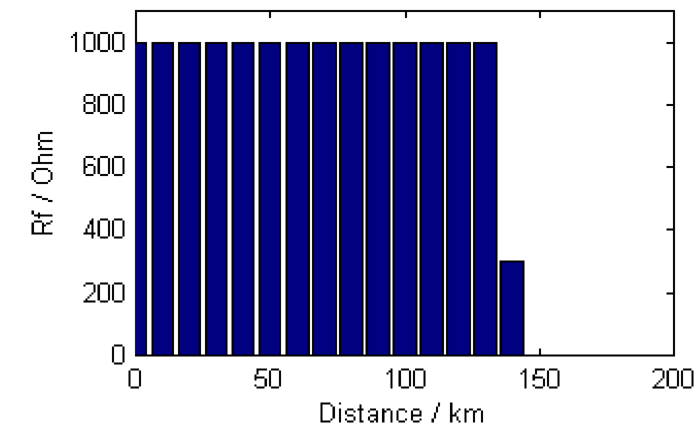


Figure 6. The Phase Difference Vary With Fault Rresistance

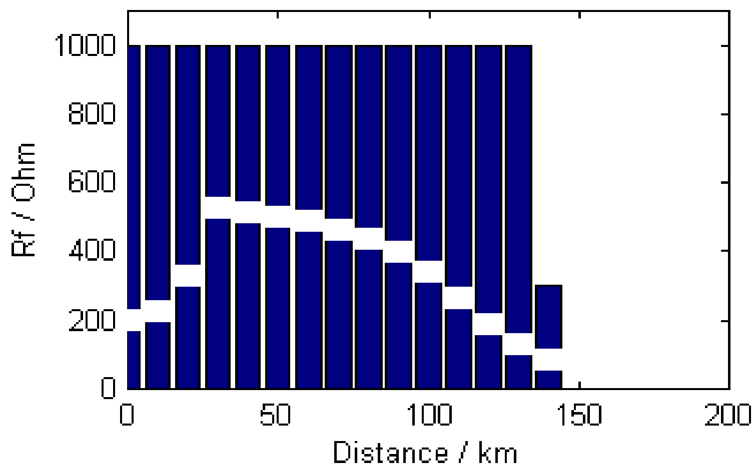
Comparing with Figure 3, which is under the same condition as Figure 6, one can conclude that $\Delta\dot{I}_{M0}$ gives more accuracy evaluation of phase angle of $\dot{U}_F$ than that of $\dot{I}_{M0}$.

6.2. Test 2: Capability Against Fault Resistance of Improved Principle

Figure 7(1) shows the capability against fault resistance of the improved relay located at sending end and Figure 7(2) shows that of relay located at receiving end. Compared with the capability against fault resistance figure of traditional reactance and adaptive relay in document [10], it is easily seen that the proposed new relay has capability against higher fault resistance, especially when the relay is located at receiving end.



(a) relay located at sending end



(b) relay located at receiving end

Figure 7. The capability against fault resistance of the improved relay.

7. Conclusion

i) The key of adaptive distance relay for overcoming fault resistance is to precisely evaluate fault point voltage, based on the boundary conditions of single-phase to earth fault, the phase of measured zero sequence current is nearly in phase with fault point voltage (traditionally, the phase difference is not more than 10^o) under the assumption that the transmission system is balanced. However, the phase difference is controlled by the pre-fault zero sequence current with the increase of fault resistance for a real unbalanced transmission system. It is concluded that the fault component of zero-sequence current is approximately in phase with fault point voltage.

ii) Replacing zero sequence current by its fault component gives more accuracy evaluation of fault point voltage (see equation (4), and the new adaptive relay have capability against higher fault resistance.

iii) If the phasors are just in phase, there is no way to make a correct decision for any relays. However, once there is an angle between the phasors, the fault point voltage can be precisely evaluated, which the additional criterion is based on.

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