Application of Fault Location Mode Based on Travelling Waves for Neutral Non-effective Grounding Systems

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Abstract—**Fault location for distribution feeders short circuit especially single-phase grounding fault is an important task in distribution system with non-effectively grounded neutral. Fault location mode for distribution feeders using fault generated current and voltage transient traveling waves was investigated. The characteristics of transient traveling waves resulted from each short circuit fault and their transmission disciplinarian in distribution feeders are analyzed. This paper proposed that double end travelling waves theory which measures arriving time of fault initiated surge at both ends of the monitored line is fit for distribution feeders but single end traveling waves theory not. According to different distribution feeders, on the basis of analyzing original traveling waves reflection rule in line terminal, Current-voltage mode, voltage-voltage mode and current-current mode for fault location based on traveling waves are proposed and aerial mode component of original traveling waves is used to realize fault location. Experimental test verify the feasibility and correctness of the proposed method.**

***Keywords*—distribution feeders; neutral non-effective grounding; traveling waves; fault locationmode**

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1 Introduction

The mode of non-effectively grounded neutral is adopted widely in medium and low-pressure distribution system of our country. Fault location rapidly and exactly for distribution feeders short circuit especially single-phase grounding fault can improve the power supply reliability, and minimize the losses for the power cut, and ensure the safe, stable and economic operation. A number of principles and methods were put forward after the study by the expert[1-7], which mostly limited to theoretical studies because of their limitations yet, and the ones which were used in reality also can not resolve the problem satisfactorily, that is because the failure current is weak, and arcing fault is unstable when single-phase grounding fault happens.

On the basis of the fault location of the travelling wave applied successfully in the distribution feeders [8, 9], the investigator have researched on the fault location mode and have different idea on how to fulfill it. In [5,6] single end fault location theory and corresponding measures were proposed, which is possible in theory, but haven't considered the difficulty and key technology in the practical application. Double end fault location theory was proposed, but fault location mode hasn’t been researched in detail according to the structural characteristics of different kinds of distribution feeders in [7].

On the basis of analyzing every fault travelling wave’s characteristic and its propagation discipline, this paper proposes double end traveling waves theory and three fault location mode according to different kinds of distribution feeders , chooses initial line mode component of travelling wave as the measuring signal ,and establishes theoretic base for the later research on fault location using transient state travelling wave in ground-fault of ungrounded systems.

2 Structural characteristics of distribution feeders

Single Supply dendriform structure or ring structure with open-loop operation are adopt for 6 ~ 35kV distribution feeders in our country. They are supplied by the single power source, and are about ten to a few tens of kilometers length. Most feeders are joint line including overhead line and subterranean cable, and supply power for the company and residents through the transformers on the numerous branch circuits. There are more than three outgoing lines, but special system only one or two such as run-through and self closing feeders in railway. Generally, there are not any other outgoing line but transformers at the end of feeders. Especially, some have other outgoing line. For example, there are several other outgoing lines for the company and residents in the switching station.

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3 The analysis of fault mode travelling wave in the distribution feeders

According to the superposition theorem, at the exact moment of short fault, it equal to attaches a equal and opposite virtual power supply which produces voltage and current travelling wave moving two ends. It is difficulty to analyze directly vector of travelling wave because of electromagnetic coupling existing among three phase line. The paper gives a feature analysis on fault location based on dividing travelling wave in three phase line into separately mode system [10].The transformation matrix is defined as follow.

$$\begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix}\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (1)$$

Where X_A ,X_B and X_C are phase voltage or phasing current of A ,B and C phase apart, and X_0 and X_1 and X_2 are zero and one and two mode component of voltage or current apart.

One and two mode component are called loop mold component spreading between the conductors of three phase ,and zero- mode component is called floor mold component spreading between the conductors of three phase and earth.

3.1 Mode travelling wave analysis of single-phase earth fault

Taking A phase current grounding fault for example, we can get the relational expression following based on vector boundary condition and (1).

$$\begin{cases} U_1 + U_2 + U_0 = U_F \\ I_1 = I_2 = I_0 = \dfrac{1}{3} I_A = \dfrac{1}{3} I_F \end{cases} \quad (2)$$

Where U_F and I_F are separately fault voltage and fault current. U_1 , U_2 ,U_0 ,I_1 , I_2 and I_0 are separately one mode component, two mode component and zero mode component of fault voltage and current.

Suppose impedance of zero-mode component and line- mode component are partly Z_0 , Z_1 and Z_2 , their distribution diagram of original traveling waves is shown in figure 1 considering transition resistor R_F.

According to the figure 1, we can derive original traveling waves' zero-mode component and line-mode component as shown in (3) and (4).

$$U_1 = U_2 = \frac{Z_1}{Z_1 + Z_2 + Z_0 + 6R_F} U_F \quad (3)$$

$$U_0 = \frac{Z_0}{Z_1 + Z_2 + Z_0 + 6R_F} U_F \quad (4)$$

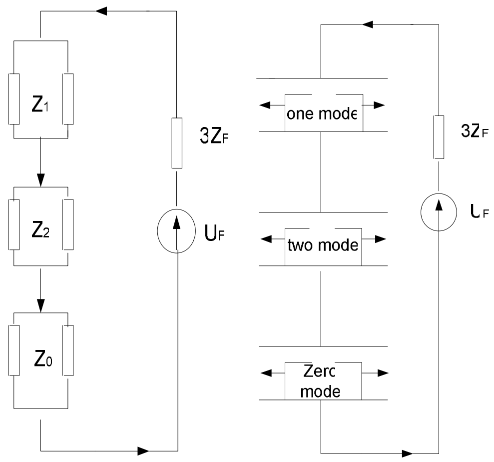

Fig1 The mode components and it's transmission of traveling waves produced by single phase earth fault

We can see that traveling waves in three phase line divide into line mode component and zero mode component and mode component is related to wave impedance,but not to length of line.Influenced by earth resistivity and so on ,zero-mode signal will be weaken and out of shape seriously with great transmission length, while line-mode component's attenuation among three phase conductor is much less .

3.2 Mode travelling wave analysis of multiphase earth fault

Multiphase earth fault include two and three phase short circuit fault and two-phase grounding fault. Take BC phase short circuit fault for example, we can get the (5) according to the phasor boundary conditions in fault point and (1).

$$\begin{cases} U_0 = 0 \\ U_\alpha = -U_\beta = \dfrac{1}{6} U_{BC} \end{cases} \quad (5)$$

Where U_{BC} is line voltage of B and C phase before fault happening.

The analysis above indicated that line mode component exist in the two phase short circuit fault, but zero-mode component not. We can **a**nalyze the other two fault travelling wave signature according to the same method.

Based on the analysis above, we can sum up a conclusion following :for single and two phase grounding fault, line mode and earth mode component in both way exit, while for two and three phase short circuit fault, only line mode component exit, but earth mode component not.

4 Travelling wave's propagation characteristic in the distribution feeders

4.1 Travelling wave's propagation characteristic in the mixed line

Overhead line's impedance which is about between 300 and 500 Ohm is different from underground cable's which is about between 10 and 100 Ohm. The joint of mixed lines is wave impedance's discontinuous point where refraction and reflection happen. Suppose overhead cable's wave impedance is Z1, underground cable's is Z2.As show in the figure 2,the refraction and reflection happen in the discontinuous point when the traveling wave whose incidence voltage magnitude is U is in spreading process from A point to B point. Suppose incidence direction as forward direction, and the time reaching A point as starting time, the expression in B point is defined as follow without regarding the influence of reflected wave and refractive wave.

$$U_{B+} = \gamma_A \gamma_B U(t-\tau) + \sum_{n=1}^{+\infty} \gamma_A \gamma_B (\rho_B \rho_A^{'})^n U(t-(2n+1)\tau) \quad (6)$$

Where τ is the time from A to B; γ_A、γ_B are separately forward voltage travelling wave's refractivity at A and B point; $\rho_A^{'}$ is opposite voltage travelling wave's reflectance at A point; ρ_B is forward voltage travelling wave's reflectance at B point.

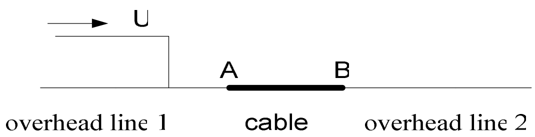

Fig 2 Sketch map of travelling waves pass through mixed lines

In (6),the first item is the travelling waves voltage component which passes though the cable to the overhead line 2.And the second item is the positive direction component which reflex several time in the cable then refract to the overhead line 2.For the first item, according to the cable's and overhead line's wave impedance and travelling wave's refraction coefficient, we can get the expression 7 below.

$$U_{B1+} = \frac{4Z_2 Z_1}{(Z_1 + Z_2)^2} U \le U \quad (7)$$

For (7), we know original traveling wave's amplitude will weaken after passing though mixed lines because cable's impedance make a great difference from underground cable's.

The opposite direction voltage expression at the A point is defined as follow.

$$U_{A-} = \rho_A U + \sum_{n=1}^{+\infty} \gamma_A \rho_B \gamma_A^{'} (\rho_A \rho_B)^{n-1} U(t - 2n\tau) \quad (8)$$

Where ρ_A is original forward voltage traveling wave's reflectance at A point ; $\gamma_A^{'}$ is opposite voltage traveling wave's reflectance at A point in the underground cable.

In (8),the first item is the voltage incident wave's reflected wave at the point A, and the second item is the opposite direction travelling wave component which reflexes firstly for several times and then refracts to the overhead line.

Travelling waves' speed is different in overhead cable and underground cable, because the impedance in two medium is different. The reference [7] put forward a speed simplification method based on equivalent circuit to solve the question of speed not unified.

4.2 Travelling wave's propagation characteristic at the point of line's branch

As shown in figure 3, refraction and reflection happen when travelling wave spreads to the point M of branching via line 1.Suppose line's wave impedance are all Z, we know branch circuit equals to two parallel circuit, and its equivalent wave impedance is Z/2, then original travelling wave's reflected wave and refracted wave in M point are defined as follows.

$$U_1 = \frac{Z/2 - Z}{Z/2 + Z} U = -\frac{1}{3} U \quad (9)$$

$$U_2 = U_3 = \frac{2 \times Z/2}{Z/2 + Z} U = \frac{2}{3} U \quad (10)$$

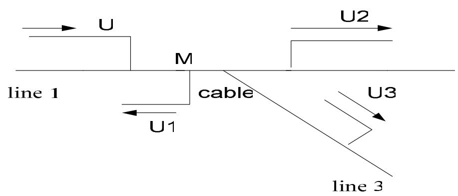

Fig 3 Sketch map of travelling waves pass through excessive branch lines

5 Study of travelling wave fault location mode

5.1 Principle of fault location

Through the previous propagation characteristic analysis, we know that refraction and reflection happen complexly in the travelling wave propagation process, and it is hard to identify fault point in one end of line. So we can't use fault location theory in single end. Figure 4 which records the single phase earth fault waveform in single end on one 10KV line gives a good proof for the conclusion.

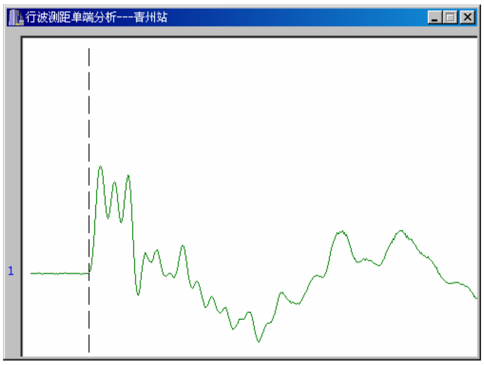

Fig 4 Single phase earth fault waveform in single end

Double end fault location method only tests the exact time from the original surge to double end. What's more, it doesn't need to consider the follow-up travelling wave's reflection and transmission .So the method is suitable for fault location in the distribution feeders because of its simple principle and reliable result.

5.2 Travelling wave's roule of reflex in the end of line

For the single bus and N outgoing system in distribution feeders, suppose all the outgoing lines' wave impedance are the same, that is to say in the other words.

$$Z_{l1x} = Z_{l2x} = \cdots Z_{lNx} = Z_x \tag{11}$$

When shorted fault happens in the point F of the Nth line, including single-phase earth fault and other fault, the wave impedance through the observation from the line N to bus can be seen as parallel impedance of non-fault line and transformer line. For the x mode (x stands for α、β or zero mode component), that is to say, the equivalent wave impedance can be expressed as following.

$$Z_{Mx} = 1/(\frac{1}{Z_{Tx}} + \sum_{k=1}^{N-1}\frac{1}{Z_{lkx}}) \tag{12}$$

Where Z_{Tx} is the transformer 's equivalent wave impedance, and Z_{lkx} is the Kth line's equivalent wave impedance.

We know that the loop number of the bus outgoing line is the principal factor for the travelling wave's reflection and transmission [11].Because the transformer's AC impedance is very large, the line can be seen as open circuit for the high frequency signal. In order to analyze conveniently, ignoring the transformer equivalent impedance, the (12) changes to the (13) as follow.

$$Z_{Mx} = 1/(\sum_{k=1}^{N-1}\frac{1}{Z_{lkx}}) \tag{13}$$

According to the theory of travelling wave, when fault travelling wave 's incident wave spreads to bus from the fault point, because of refraction and reflection for its discontinuous wave impedance incident current wave's reflectance is defined as follow.

$$\rho_i = (Z_{lNx} - Z_{Mx})/(Z_{Mx} + Z_{lNx}) \tag{14}$$

And incident current wave's reflectance is defined as follow.

$$\rho_u = u_{Fx}(Z_{Mx} - Z_{lNx})/(Z_{Mx} + Z_{lNx}) \tag{15}$$

In the fault line's endpoint N, superposition of incident and reflected waves is original mode x travelling wave, and the expressions of original current and voltage wave are defined as follow.

$$i_{Nx} = i_{Fx} + i_{Fx}\rho_i \tag{16}$$

$$u_{Nx} = u_{Fx} + u_{Fx}\rho_u \tag{17}$$

When there are not any other outgoing lines besides the fault line N, $Z_{Mx} \to \infty$,and according to (14) and (16), $i_{Nx} \to 0$; according to (14) and (16), $u_{Nx} \approx 2u_{Fx}$。

When there are other outgoing line besides the fault line N, we can prove that Z_{Mx} reduce gradually with the increase of the number of outgoing line for (13), and satisfy the expression following.

$$Z_{Mx} \le Z_x \tag{18}$$

By knowing the (14),(15) and (18),we can get the conclusion following.

$$\begin{cases} \rho_i \ge 0 \\ \rho_u \le 0 \end{cases} \tag{19}$$

From the above analysis, we can get the discipline as follow.

1)For the fault line of single outgoing line system, the original current travelling wave in the bus measuring endpoint and the extremity of fault line is zero nearly, but the original voltage is two time than the incidence wave.

2)For fault line of less outgoing line system, the original current and voltage travelling wave can be measured at the same time in the bus measuring endpoint, and their amplitude are low relatively.

3) For fault line of more outgoing line system, the original current travelling wave's amplitude is higher, but the original voltage is lower.

5.3 Three kinds of fault location mode

In the transmission line the current travelling wave generated for fault can be used to realize fault location. Because all run modes in different distribution feeders is different, and the structure of line is complex, we need choose different fault location mode for the different distribution feeders, and make use of voltage and current travelling wave by synthesis to realize the fault location according to the different structural features.

1) Current-voltage fault location mode

For the fault bus terminal, the number of outgoing line is much generally.The original current travelling wave's amplitude is larger, and the original voltage travelling wave's amplitude is lower, so we choose the original current travelling wave as the location signal.

For the transformer load in the end of line for the user and factory, it is similar to open circuit because of its large impedance for high frequency signal. The original current travelling wave's amplitude is nearly zero, and the original voltage's amplitude is twice than incident wave's amplitude. So we choose the original voltage wave as the location signal.

After above analysis, current-voltage fault location mode is made of the original current travelling wave in the bus and the original voltage travelling wave in the end. Because their speed are same, we can use them to measure the fault distance.

2) Voltage-voltage fault location mode

For some special distribution feeders, such as run-through and self-imposed system in the railway, the number of outgoing line is little(There are only one or two),and there is the voltage regulator on the bus. There are not any loads in the end, which equals to open circuit, so we should choose the original voltage wave as the location signal. So do the bus terminal, because the line is open for high frequency signal in the single outgoing line system; In the double outgoing line system, the original voltage travelling wave can be also detected because it almost don't reflex ,but its amplitude is smaller. Therefore, whether single or double outgoing line system, the original voltage travelling wave are all detected in the bus and the end of line. we can all use voltage-voltage fault location mode to measure the fault distance.

3)Current-current fault location mode

For these distribution feeders where there are many outgoing lines in the bus terminal and the end of line, After above analysis, we should choose the original current travelling wave as the location signal which is the Current-current fault location mode.

5.4 The selection of mode measure signal

We need to consider which mode component should be chosen as the measure signal after fixing the location mode. Because for the zero mode component there are serious loss and varying wave speed with the frequency, and it doesn't exit when interphase short circuit happens [12] ,we should choose the line mode component whose loss is low and parameter is stable .

The regulation of choosing line mode component is like this. When two-phase short-circuit of AB, two-phase short circuit grounding of AB and single-phase grounding of any phase happen, we choose line mode component of AB; For BC and CA, we adopt the same regulation like AB above. When three-phase fault happens, we can choose anyone of line mode components above.

6 Field test

In November and December of 2004,the test of single phase grounding and interphase short circuit was performed one after another in the 10 KV run-through railway line from Zibo to Qingzhou. The total line length is 47.2km, including 1.6km cable lines. The test waveform are shown in the figure 5 and 6, the earth point is 34.9km away from Zibo transformer substation .In the test of single phase grounding fault, we can see that fault point is 35.2km away from Zibo transformer substation, and the range error is about 0.3km. .In the test of interphase short circuit fault, we can see that fault point is 35.3km away from Zibo transformer substation, and the range error is about 0.4km.

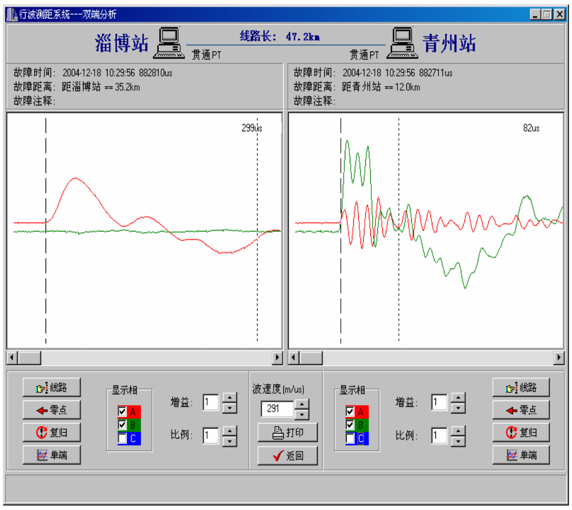

Fig 5 Fault location waveform of single phase grounding fault

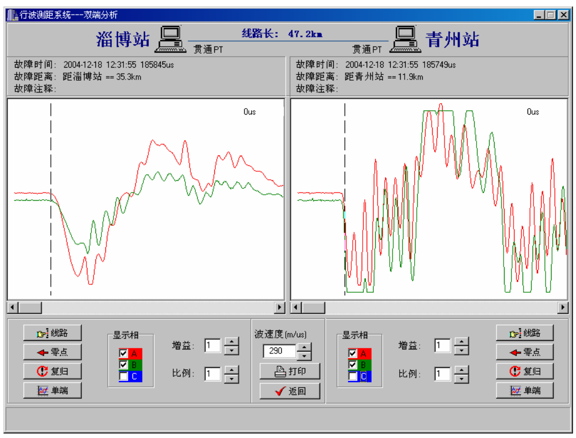

Fig 6 Fault location waveform of short circuit fault

7 Conclusion

In the paper for the difficulty of single-phase grounding fault location in the distribution in distribution system with non-effectively grounded neutral, we research all kinds of original fault travelling wave's propagation discipline, characteristic and the mode of realize the fault location, and then get the following conclusion.

1)The transient travelling wave produced by kinds of short-circuit fault contains a great deal of information, and it isn't affected by the run mode .So the study of transient travelling wave applied to fault location in ground-fault of ungrounded system is significant.

2) Intricate refraction and reflection happen in the spreading process of travelling wave. So we only make use of the principle of two terminal fault locations by measuring the original travelling wave head, not the principle of single terminal fault location

3) Depending the structure of different distribution feeders, we adopt different fault location mode and make use of the original line mode component to realize fault location.

4) Many key technologies in practical applications are still to be established with further studies, such as how to gain the signal and how to resolve the influence of overhead cable mixed lines, multi-branch line and high resistance earth fault.

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