Study on Fault Line Selection of Single Phase-to-Ground in a Distribution Network

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Abstract

The single phase-to-ground fault is the most frequent accident in a distribution network. Due to the small fault currents, unobvious fault signatures, unstable fault arcs and stochastic factors of the single phase-to-ground fault, the problem of fault line selection has been studied for years, but it is still not solved perfectly, which has seriously blocked the development of reliable power supply and automation level of a distribution network. To solve the problem, based on single phase-to-ground fault transient process analysis in a distribution network, we presented a new method where a wavelet packet was decomposed by using transient grounding capacitive current, the maximum energy band was extracted by energy method and the feature band of each line was based on the theory of modulus maximum and signal singularity to judge the fault line. The principle of the line selection are introduced. Finally, the simulation results of MATLAB show that the method has high reliability, strong anti-interference ability and so on. The line selection has an important theoretical significance and practical value.

Keywords: energy method; distribution network; feature band; phase-to-ground fault; wavelet packet analysis

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1. Introduction

The fault line selection in a distribution network is difficult; especially, for the neutral point via the arc suppression coil grounding of the distribution network, fault line selection is more difficult. Method of small current grounding are popular in a middle-low voltage distribution network in China[1~2]. The incidence rate of single phase-to-ground fault is the highest among all the other faults in a distribution network, which shares about 80% of the total faults. When the single phase-to-ground fault happens, the current of the fault point is weak and the three-phase line voltage keeps symmetric so that the power supply of the load won’t be impacted. Therefore, normally, it is allowed to continue for 1~2 hours after the fault has happened in the distribution network. However, when the single phase- to-ground fault happens, the ground voltage of the other two phases is $\sqrt{3}$ times higher. If the intermittency electric arc's earthing happens, it might cause arc grounding overvoltage, which would impair insulation or cause trip accidents due to an interphase short circuit[3]. Thus, selecting the fault line quickly and accurately has a significant point to the safe and reliable operation in a distribution network.

Many countries have done considerable researches on fault line selection so far. Many approaches and corresponding equipment have been carried out so far, such as First semi-wave method, Signal-injection method, and Correlation analysis. However, these approaches and equipment have certain limitations. Many problems need to be solved[4,5]. Therefore, in order to improve the power supply reliability and the economic benefit of power supply departments and consumers, and maintain security of power system equipment, we present a new method of fault line selection based on a feature band Wavelet Packet Analysis in a distribution network.

2. Signal Singularity and Wavelet Modulus Maxima Theory

2.1 The Signal Singularity Analysis

Lipschitz exponent is normally used to express signal singularity. Lipschitz exponent is used to characterize the local features of a function in mathematics to define *f(t)* has following features in the vicinity of t_0[6]:

$$|f(t_0+m)-p_n(t_0+m)|\leq A|m|^{\alpha},\ k<\alpha<k+1 \quad (1)$$

In the formula, m is infinitesimal, then the Lipschitz exponent of *f(t)* in the vicinity of t_0 is α. α characterizes the regularity of the function. Lipschitz exponent of the function in certain point expresses its signal singularity in that point. The bigger α is, the more smooth the function is ; and the function is continuously differentiable at that point. The smaller α is, the bigger signal singularity is at that point.

2.2 The Wavelet Modulus Maxima Theory

Assumed that the wavelet function $\psi(t)$ is compactly supported, and n-order vanished-moment and n-times are continuously differentiable. If the Lipschitz exponent of *f(t)* at t_0 is α_0 ($\alpha_0 < n$), and *f(t)* is n-times continuously differentiable at t_0, then it can be said that wavelet transform ($|WT_f(a,b)|$) has the maximum at t_0. This conclusion has explained the corresponding relation between signal singularity position and wavelet modulus maxima position[7,8].

The polarity of wavelet modulus maxima expresses the movement directions of the catastrophe point, and the magnitude of the wavelet modulus maxima expresses the change intensity of the catastrophe point. The fault selection in it has used this advantage. The signal singularity detection theory points out that the sudden signal change has great relationship with amplitude. Practically, the method to use signal singularity to detect catastrophe point is to analyze the signal with multi-resolutions. After the signal has been decomposed to a certain level, the catastrophe point signal is found out. Its coefficient after wavelet transforms has wavelet modulus maxima and detect the wavelet modulus maxima so as to determine the time faults happen [9].

3. Wavelet Analysis Theory

Wavelet Packet Analysis is a fine analytical method by which the frequency band is further divided into multiple layers, and the high frequency is divided in a more deep-going way. On the basis of the character of the signal, it can select the frequency band so that it can match the signal frequency properly and improve the time frequency resolution. Therefore, Wavelet Packet Analysis has extensive values in use[10].

Wavelet packet transform: Define subspace U_j^n as the closure space of function $u_n(t)$ and subspace U_j^{2n} as the closure space of function $u_{2n}(t)$. Let $u_n(t)$ satisfy the following two-scale equation:

$$\begin{cases} u_{2n}(t)=\sqrt{2}\sum_{k\in z}h(k)u_n(2t-k) \\ u_{2n+1}(t)=\sqrt{2}\sum_{k\in z}g(k)u_n(2t-k) \end{cases} \quad (2)$$

In the equation, $g(k)=(-1)^k h(1-k)$, function u_n (n=0, 1, …) is called wavelet packet determined by orthonormal scaling function $u_0 = \phi$.

If $g(k) = (-1)^k h(1-k)$, then g_j^n can be expressed as:

$$g_j^n(t) = \sum_l d_l^{j,n} u_n(2^j t - l) \tag{3}$$

Wavelet packet decomposition: $\{d_l^{j,2n}\}$ and $\{d_l^{j,2n+1}\}$ can be obtained from $\{d_l^{j+l,n}\}$.

$$\begin{cases} d_l^{j,2n} = \sum_k a_{k-2l} d_k^{j+1,n} \\ d_l^{j,2n+1} = \sum_k b_{k-2l} d_k^{j+1,n} \end{cases} \tag{4}$$

In the equation, a_j and b_j are decomposed sequences of the multi-resolution analysis. As the scale j increases, the space decomposition rate of the orthogonal wavelet basis function increases, and the frequency resolution decreases, which is its defect. However, the wavelet packet has the characteristic that the spectrum window becomes wider and wider when j increases, which makes up the defect of the orthogonal wavelet transform, and has better time frequency characteristics[11,12].

4. New Fault Line Selection Method Based on Feature Band Wavelet Packet Analysis in Distribution Network

4.1 The feature band

4.1.1 Definition of Feature Band

Using wavelet packet multi-resolution analysis of transient zero sequence currents, if the neutral point of distribution network is ungrounded, the maximum energy at the high frequency band is the feature band; if it is a neutral point via arc suppression coil grounding of a distribution network, the second large energy is the feature band.

When a single phase-to-ground fault occurs in neutral by an arc extinction coil grounding system, zero sequence voltage u_0 and transient grounding current $i_{d.os}$ at fault moment are[13,14]:

$$u_0 = U_m \sin(\omega t + \varphi) \tag{5}$$

$$i_{d.os} = i_{C.os} + i_{L.os} \tag{6}$$

In the formula, $i_{C.os} = (u_0/L_0\omega_0)e^{-\delta t} \sin \omega_0 t$, $i_{L.os} = I_{Lm} \cos \varphi\ e^{-t/\tau L}$, so the formula above can be described as follows:

$$i_{d.os} = (u_0/L_0\omega_0)e^{-\delta t} \sin \omega_0 t + I_{Lm} \cos \varphi\ e^{-t/\tau L} \tag{7}$$

where ω_0 characterizes natural oscillation angular frequency; ω characterizes power angular frequency; L_0 characterizes equivalent inductance of three phase circuit and power transformer in zero sequence circuit; τ_L characterizes inductive time constant. Generally, ω_0/ω and the difference between frequency of $i_{C.os}$ and $i_{L.os}$ are relatively great, so, at the initial stage of the grounding fault, the main feature of the transient grounding current is determined by transient capacitance current[15,16].

In the multi-resolution analysis of the zero sequence current and transient signal by wavelet packet, the high frequency band with maximum energy is called the feature band in network with an isolated neutral, and the high frequency band with second largest energy is called the feature band in neutral grounding via arc extinguishing coil system; meanwhile, all the above concept is defined after the removal of the lowest frequency band of power frequency.

4.1.2 The Extraction of the Feature Band

Decomposition of the fault transient current by wavelet packets, in essence, is to divide the signal into different sub-bands continuously through conjugate orthogonal filters combined with high-pass and low-pass. The sampling interval doubles, and the data points halves every time the filter works.

Decomposing the fault transient signal sample sequence by wavelet packets on the basis of appropriate frequency band width, the corresponding energy of each frequency band is obtained from Formula (8).

$$\varepsilon = \sum_n \left[\omega_k^{(j)}(n)\right]^2 \tag{8}$$

where $\omega_k^{(j)}(n)$ characterizes the coefficient of the (j, k) sub-band after wavelet packet decomposition, and each sub-band has an coefficient.

Select the feature band on the principle of maximum energy so as to get the main characteristics of the transient current by multi-resolution analysis of the zero sequence current and transient signals by wavelet packets.

As for the neutral grounding via an arc extinguishing coil system, the high frequency band with the second large energy is the feature band [17]. This can avoid the error selection because of the low energy frequency band or the calculation and measurement error, which provide a basis for reliable and accurate fault line selection.

4.2 The Principle and Step of Fault Line Selection

4.2.1 The Principle of Fault Line Selection

Based on wavelet packet analysis and signal singularity analysis and modulus maximum theory, the principle of fault line selection is summarized as follows:

1) The sum of the no-fault line feature band energy is always greater than zero, the sum of the fault line feature band energy is always smaller than zero, and its absolute value equals the sum of the other no-fault line energy.
2) The polarities of the wavelet modulus maxima points of the fault line and the no-fault line are opposite, and the magnitude of the fault line wavelet modulus maxima is the biggest.
3) When bus fault happens, the energy of all feature bands is greater than zero, and all wavelet modulus maxima have the same polarity.

4.2.2 The Step of Fault Line Selection

1) Based on wavelet packet multi- resolution decomposition of transient zero sequence current, the transient zero sequence current of each line is calculated in each frequency band, and the energy of all lines is calculated according to the frequency band, and the characteristic frequency band is determined.
2) Through a number of simulation calculation and comparison of the frequency band energy, the most prominent waveform of the frequency band can be selected by comprehensive comparison.
3) Compared with the feature band wavelet coefficients of waveform in each line, if there is a line waveform polarity and other lines waveform is the opposite polarity, the amplitude of approximately equals in other articles of the line voltage, and the line will be the fault line.
4) Compared with the wavelet coefficients of the characteristic frequency band of each line, if the polarity of the waveform of each line is the same as that of other lines, the amplitude difference is not great. This must be a bus fault.

According to the above fault line selection criteria, the flow diagram of selection line is shown in Fig. 1.

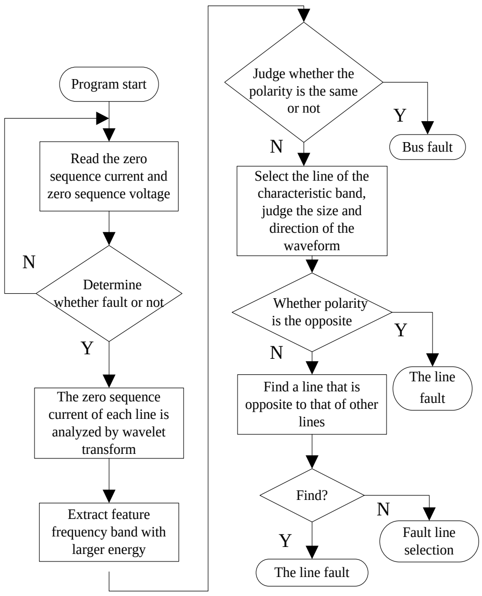

Figure 1: Flow diagram of selection line

5. MATLAB Simulation Experiment

Establish a network system model by a power system tool box of Simulink in MATLAB[18,19]. As shown in Fig. 2, it assumes that the length of the transmission lines: l_1 = 13km, l_2 = 15km, l_3 = 8km, l_4 = 19km, l_5 = 25km.

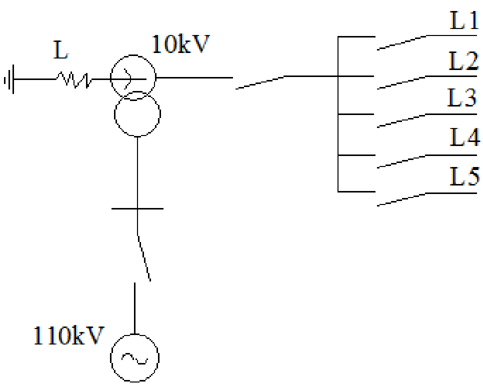

Figure 2: Power system model

Positive sequence impedance and zero sequence impedance of outing lines are shown in Tab.1.

Table 1: Positive sequence impedance and zero sequence impedance of outing lines

	positive sequence impedance	zero sequence impedance
R(Ω/km)	0.55	0.68
L(H/km)	0.9437×10^{-3}	4.3146×10^{-3}
C(F/km)	69.83×10^{-9}	48.70×10^{-9}

Besides, the transformer reactance can be expressed as Z_r, and $Z_r = 0.7017 + j0.5121\ \Omega$.

5.1 Simulation experiment 1

Assumed that the fault happens in phase A of line 4, 2.4kms is away from the bus when T = 0.028s. According to the method, it obtains the zero sequence voltage waveform of the bus, and the zero sequence current of the outing liness as Figs. 3 and 4.

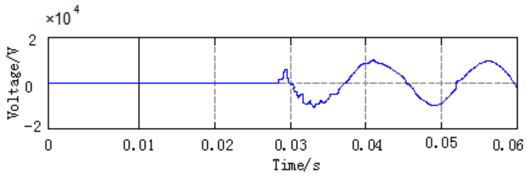

Figure 3: Zero sequence voltage waveform of the bus

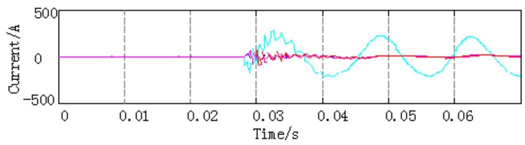

Figure 4: Zero sequence current of the outing lines

It uses function db10[20] to decompose zero sequence current of each outing line by wavelet packets and then extracts the second largest energy high frequency band of the neutral grounding via an arc extinguishing coil system. Each line's zero sequence current feature band is shown in Fig.5.

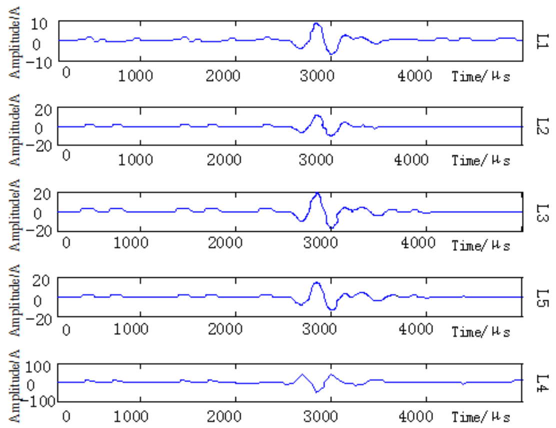

Figure 5: Feature band waveform

As shown in Fig. 5, the polarity of no-fault line is positive. The waveform of the fault phase (line 4) is opposite to the no-polarity, and its amplitude equals the sum of the no-fault lines. According to fault line selection principle, the fault occurs in line 4.

5.2 Simulation experiment 2

Assumed that the fault happens in bus when T = 0.034s, and then extracts the second largest energy high frequency band of zero sequence voltage waveform of each outing line as Fig. 6.

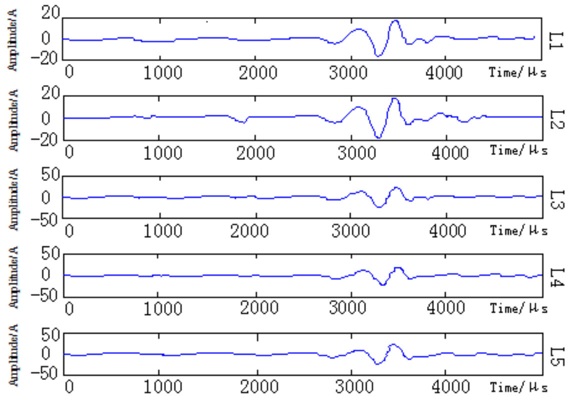

Figure 6: Feature band waveform

As shown in Fig. 6, the polarity of each outing line current waveform is the same, their amplitudes approach and don't have large fluctuation. Therefore, the outing lines are normal, and the fault occurs in the bus. More simulation experiments are shown in Tab. 2.

Table 2: Fault line selection in other situations

Fault lines	Fault distance (km)	Fault starting angle (°)	line selection result
L1	8	90	L1
L1	10	120	L1
L2	4	240	L2
L2	14	45	L2
L3	3	75	L3
L3	7	100	L3
L4	14	150	L4
L4	2	70	L4
L5	19	20	L5
L5	6	85	L5
Bus	0	0	Bus
Bus	0	170	Bus

As shown in Tab. 2, when single phase-to-ground fault happens, the method can give the right fault line selection results in different positions and times. At the same time, grounding fault line selection has well stood to resistance ability and isn't impacted by fault starting angles.

6. Conclusion

By researching single phase-to-ground fault based on feature band Wavelet Packet in a distribution network, it draws conclusions as follows:

1) The proposed fault line selection method is for a large amount of simulation in all kinds of fault points and fault times and different grounding distances. Testing results show that it can accurately select the fault line and accurately determine fault bus.
2) The effects of transient zero sequence small currents and the short times are considered, and a new method of fault line selection is given. By using wavelet packets to carry on the multi-resolution analysis of transient zero sequence capacitive currents, the relationship between polarity and amplitude to select the fault line can be studied in accordance with the size of the principle of energy distill feature band and the waveform characteristic band, as well as modulus maxima singularity detection theory. The method of line selection eliminates the influence of the zero sequence current which is too small on the fault line selection, and improves the accuracy of the line selection.
3) A simulation model of single phase-to-ground fault in a distribution network is established. A large number of simulation results show that the line selection method can improve the accuracy of fault line selection and has good practicability. Meanwhile, it also has a strong ability to avoid the transition resistance to determine the bus fault and which line fault effectively, not affected by factors of the fault locations, CT imbalanced currents or operated modes, for example, with high flexibility and reliability.

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