Postprint of Research on Fault Line Selection in Distribution Networks Based on Characteristic Frequency Band Wavelet Packet Analysis

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Abstract

Through analysis of the transient process of single-phase grounding faults in distribution networks, a novel method is proposed that performs wavelet packet decomposition on the transient grounding capacitive current, extracts the frequency band with maximum energy using the energy method, and utilizes modulus maxima and signal singularity theory on the characteristic frequency bands of each line to identify the fault line. The line selection principle of this method is introduced, and simulation experiments demonstrate that the method possesses characteristics of accuracy, reliability, and strong adaptability, holding significant practical application value.

Full Text

Research on Fault Line Selection in Distribution Network Based on Feature Band Wavelet Packet Analysis

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Abstract

Through analysis of the transient process during single-phase-to-ground faults in distribution networks, this paper proposes a novel method for fault line identification. The method decomposes the transient grounding capacitive current using wavelet packet analysis, extracts the frequency band with maximum energy via the energy method, and applies modulus maxima and signal singularity theory to the characteristic frequency bands of each line to determine the fault line. The principle of the line selection method is introduced, and simulation experiments demonstrate that the proposed method offers high accuracy, reliability, and strong adaptability, making it valuable for practical applications.

Keywords: Distribution network, fault line selection, feature band, wavelet packet, singularity detection

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1 Introduction

China' s medium- and low-voltage distribution networks widely employ small-current grounding systems [1-2]. In power systems, the most common and hazardous faults are short circuits between phases or between phase and ground. Single-phase grounding faults occur most frequently in distribution networks, accounting for over 80% of all faults. In such cases, the system' s line voltage remains symmetrical, and the fault current is relatively small, allowing continuous operation without immediate tripping for 1-2 hours. However, after a single-phase grounding fault occurs, the voltage to ground of the other two phases increases by a factor of $\sqrt{3}$. When intermittent arc grounding occurs, it may cause arc-ground overvoltage, which threatens system insulation or leads to phase-to-phase short circuits and tripping accidents [3]. Therefore, rapid and accurate fault line selection is crucial for safe and reliable operation of distribution networks.

Currently, extensive research on fault line selection has been conducted both domestically and internationally, yielding many methods such as the first half-wave method, signal injection method, and correlation analysis method, along with corresponding devices. However, these methods and devices have certain limitations, and many problems remain unresolved [4]. In view of this, this paper proposes a new method for single-phase grounding fault line selection in distribution networks based on wavelet packet extraction of characteristic frequency bands combined with modulus maxima singularity detection theory, aiming to improve power supply reliability, enhance economic benefits for both power supply departments and users, and ensure the safety of power grid equipment.

2 Wavelet Packet Analysis Theory

Compared with various signal analysis methods, wavelet packet analysis provides finer resolution by performing multi-level division of frequency bands. It further decomposes the high-frequency components that are not subdivided in multi-resolution analysis and can adaptively select frequency bands according to the characteristics of the analyzed signal to match the signal spectrum, thereby improving time-domain resolution. Consequently, it has broad practical application value [5].

Wavelet Packet Transform: Let subspace U_j^m be the closed space of function $u_m(t)$, and U_j^{2m} be the closed space of function $u_{2m}(t)$. Let $u_m(t)$ satisfy the two-scale equation:

$$u_{2m}(t) = 2 \Sigma h(k)u_m(2t - k)$$
$$u_{2m+1}(t) = 2 \Sigma g(k)u_m(2t - k)$$

where $g(k) = (-1)^k h(1-k)$. The functions $u_m(t)$, $m = 0, 1, \cdots$ are called wavelet packets determined by the orthogonal scaling function $u_0 =$.

The wavelet packet decomposition is: from $\{d^l_{j+1,m}\}$ obtain $\{d^l_{j,2m}\}$ and $\{d^l_{j,2m+1}\}$, where: $d^l_{j,2m} = \Sigma a_{k-2l} d^k_{j+1,m}$ $d^l_{j,2m+1} = \Sigma b_{k-2l} d^k_{j+1,m}$

Here, a_j and b_j are the decomposition sequences of multiscale analysis.

As the scale j decreases, the spatial resolution of the orthogonal wavelet basis function becomes lower while the frequency resolution becomes higher. To address this issue, wavelet packet decomposition is adopted, which can further subdivide the gradually widening frequency window as j increases, thereby compensating for the shortcomings of orthogonal wavelet transform and providing better time-frequency characteristics [6].

3 Signal Singularity Analysis and Modulus Maxima Theory

3.1 Signal Singularity

Signal singularity is typically represented by the Lipschitz exponent. Mathematically, the Lipschitz exponent is a measure that characterizes the local features of a function. It is defined as: if function f(t) has the following characteristics near t_0 [7]:

$$|f(t_0 + k) - p_n(t_0 + k)| \quad A|k|^{}$$

where k is a small quantity and   represents the regularity of the function at that point. The Lipschitz exponent at a point indicates the degree of singularity: the smaller the , the greater the singularity; the larger the , the smoother the function and the more continuous and differentiable it is at that point.

3.2 Relationship Between Modulus Maxima Theory and Lipschitz Exponent

Let the wavelet function $\Psi(t)$ have m-order vanishing moments, compact support, and be m-times continuously differentiable. If function f(t) has a Lipschitz exponent of $_0$ ($_0 < m$) at point t_0 and is m-times differentiable near t_0, then the wavelet transform ($|WT_f(a,b)|$) has a maximum value at t_0. This conclusion demonstrates a one-to-one correspondence between singular point locations in signals and wavelet transform modulus maxima [8].

The polarity of wavelet transform modulus maxima indicates the direction of the 突变点 (mutation point), while the magnitude represents the intensity of the change. The fault line selection in this paper utilizes this significant advantage. Signal singularity detection theory indicates that signal 突变 (mutations) are closely related to amplitude. In practice, the method for detecting signal 突变 points using wavelet analysis involves: performing multi-scale analysis of the signal, decomposing it to a certain level, identifying signals with mutations whose wavelet transform coefficients have modulus maxima, and determining the fault occurrence time by detecting these modulus maxima points [9].

4 New Fault Line Selection Method Based on Wavelet Packet Feature Band Extraction

4.1 Definition of Feature Band

In a neutral point arc suppression coil grounding system, when a single-phase grounding fault occurs instantaneously, the zero-sequence voltage u_0 and transient grounding current i_d.os are expressed as:

u_0 = U_m sin(t +)
i_d.os = i_C.os + i_L.os = e^{- t} sin(_0 t) + I_Lm cos e^{-t/ _L}

where _0 is the natural oscillation angular frequency;   is the power frequency angular frequency; L_0 is the equivalent inductance of three-phase lines and power supply transformers in the zero-sequence circuit; and _L is the inductance time constant.

Typically, _0/ is relatively large, and the frequencies of i_C.os and i_L.os differ significantly. Therefore, in the initial stage of a grounding fault, the main characteristics of the transient grounding current are determined by the transient capacitive current [10].

4.2 Feature Band Extraction

Using the Power System Toolbox in Matlab' s Simulink library, a 110/10kV power grid system model can be established. As shown in [Figure 1: see original paper], the line lengths are set as: L1 = 9 km, L2 = 16 km, L3 = 24 km, L4 = 13 km, L5 = 27 km. The positive-sequence and zero-sequence impedances of the lines are shown in .

Decomposing the fault transient current using wavelet packet analysis essentially involves passing the signal through a conjugate orthogonal filter bank combining high-pass and low-pass filters, continuously dividing the signal into different frequency bands. Each time the filter bank operates, the sampling interval doubles and the number of data points halves.

According to an appropriate bandwidth, the fault transient signal sampling sequence is decomposed using wavelet packet analysis. The energy of each frequency band signal after decomposition is calculated as:

E = Σ (_k$^{\{(j)(m)\}})$2

where _k^{(j)(m)} are the coefficients of the wavelet packet decomposition in the (j,k) sub-band, and each sub-band contains m coefficients.

Using wavelet packet multi-resolution analysis on the fault zero-sequence current, the feature band is selected based on the principle of maximum energy to obtain the main characteristics of the transient capacitive current. After removing the lowest frequency band where the power frequency resides, for distribution networks with ungrounded neutral points, the feature band is the high-frequency band with maximum energy; for distribution networks with neutral points grounded through arc suppression coils, the feature band is the high-frequency band with the second-largest energy [11]. This avoids the possibility of incorrect line selection due to small signal band energy and measurement/calculation errors, providing a reliable basis for accurate line selection.

4.3 Line Selection Principle

(1) The energy of the feature band for non-fault lines is always greater than zero, while that for the fault line is always less than zero, and its absolute value equals the sum of energies of other non-fault lines.

(2) During bus faults, the feature band energies of all lines are greater than zero, and the polarity of modulus maxima points for all lines is the same.

(3) The polarity of modulus maxima points for the fault line is opposite to that of non-fault lines, and the magnitude of the fault line' s modulus maxima is the largest.

5 Matlab Simulation Experiments

5.1 Simulation Experiment 1

Assume an A-phase grounding fault occurs on line L4 at a distance of 3 km from the bus at T = 0.019 s. According to the analysis method proposed in this paper, the system bus zero-sequence voltage and each outgoing line' s zero-sequence current waveforms are obtained as shown in [Figure 2: see original paper] and [Figure 3: see original paper], respectively.

Using the db10 function, the zero-sequence current of each outgoing line is decomposed via wavelet packet analysis. For a system with neutral point grounded through an arc suppression coil, the high-frequency band with the second-largest energy is extracted, and the feature band waveforms of each line' s zero-sequence current are shown in [Figure 4: see original paper].

From [Figure 4: see original paper], it can be clearly observed that the waveforms of non-fault phases (lines L1, L2, L3, L5) have the same polarity and are all upward, while the fault phase (line L4) has opposite polarity to the non-fault phases, and its amplitude is essentially equal to the sum of non-fault phase amplitudes. According to the line selection principle, this proves that line L4 in the system has experienced a fault.

5.2 Simulation Experiment 2

Assume a bus grounding fault occurs at T = 0.025 s. The high-frequency band with the second-largest energy is extracted from each outgoing line' s zero-sequence current waveform, as shown in [Figure 5: see original paper].

From [Figure 5: see original paper], it can be clearly observed that the current waveforms of all outgoing lines have essentially the same polarity, with no significant amplitude fluctuations and relatively close values. This proves that all sub-lines in the system are normal and only the bus has experienced a fault. Additional simulation results under various conditions are shown in .

As shown in , for single-phase grounding faults occurring at different fault distances, different fault initial angles, and different fault times, the analysis method proposed in this paper can provide correct line selection results. Moreover, this line selection method exhibits strong resistance to transition resistance.

6 Conclusion

This paper studies fault line selection for single-phase grounding faults in distribution networks using wavelet packet transform, reaching the following conclusions:

(1) A new method is proposed that utilizes wavelet packet analysis for transient zero-sequence capacitive current multi-resolution analysis, extracts the feature band based on energy magnitude principles, and analyzes polarity and amplitude relationships according to feature band waveforms combined with modulus maxima singularity detection theory for fault line selection.

(2) A simulation model for single-phase grounding faults in distribution networks is established. Extensive simulation results demonstrate that this line selection method effectively improves fault line selection accuracy and has strong practicality. It also exhibits robust resistance to transition resistance and is unaffected by factors such as TA unbalanced current, fault location, fault time, fault initial angle, and operating mode, showing excellent reliability and flexibility.

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Note: Figure translations are in progress. See original paper for figures.