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Features-clustering-based earth fault detection using singular-value decomposition and fuzzy c-means in resonant grounding distribution systems

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ABSTRACT

The transient zero-sequence current of each feeder in a resonant grounding system is characterized by nonlinearity and nonstationarity when a single-phase-to-ground fault occurs. Because there is a significant difference between the fault transient zero-sequence current waveforms of the fault feeder and the sound feeders, a new fault feeder detection method is presented, based on a time-frequency matrix (TFM) and polarity distribution matrix (PDM) singular values clustering algorithm. By applying a Hilbert-Huang transform band-pass filter and waveform transformation to the transient zero-sequence current waveform of each feeder, the TFM and PDM can be constructed, which are decomposed by singular-value decomposition (SVD). Moreover, the normalized singular values of the TFM and PDM are merged together and are used to form the amplitude-polarity feature matrix (APFM). Thus, the feature quantities including the amplitude and polarity information of each fault transient zero-sequence current waveform are obtained. Then, fuzzy c-means clustering is applied to the APFM so as to detect the fault feeder by dividing the fault feeder and sound feeders into two categories without a certain threshold setting. Simulations were carried out via PACAD/EMTDC® and a physical system under various kinds of fault conditions and factors including asynchronous sample, two-point-grounding fault, and arc fault. Simulated results show that the proposed method has the characteristics of high accuracy and reliability in earth fault feeder detection.

1. Introduction

The line voltage of resonant grounding systems [1] is symmetrical when a permanent single-phase-to-ground fault occurs. It is allowed to continue running for approximately 1 to 2 h according to the technical standards. In order to prevent the sound phase voltage from increasing and the insulation from weakening, which can cause the fault to worsen, the fault feeder must be determined and removed as soon as possible. When a single-phase-to-ground fault occurs in a resonant grounding system, it results in a complex fault situation, faint fault current, and the influences that come into being because of the feeder structure, feeder parameters, and nonlinear characteristics of the voltage and current transformer, as well as the electromagnetic interference. There are significant differences in fault transient zero-sequence currents in the areas of spectrum features, energy distribution, and attenuation characteristics. The problem of fault feeder detection [2–7] has not been well solved for a long time. Thus, it is necessary to investigate a single-phase-to-ground fault detection method for resonant grounding systems.

The research on fault feeder detection based on transient signals, whose amplitude is several times that of the steady signal, has received much attention in recent years. Prony [8], wavelet transforms [9], and the Hilbert-Huang transform (HHT) [10] have been adopted to analyze the transient zero-sequence current signal. A single characteristic quantity of the fault signals, such as amplitude, polarity, energy, energy direction, mutation amount, waveform correlation coefficient, harmonic current, earth capacitance, and information entropy, is always taken as the criterion for the fault feeder detection. Previous studies have achieved a certain effect [10–14]. However, it is difficult to achieve high accuracy and reliability in fault feeder detection under all kinds of earth faults. Cui et al. [10] presented an approach for fault detection and direction determination for transient/intermittent faults. Zero-sequence voltage and current are used as the input signals

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to extract the fault direction via the direction of instantaneous power. However, the method in [10] is not suitable for the situation of polarity inversion that occurs in the transient process. Zhang et al. [11] proposed an improved phase-locked loop to extract the fifth harmonic zero-sequence current for detecting the fault feeder. With the development of modern power electronics technology, a power distribution network contains many electronic devices that are sources of system harmonics. Moreover, the fifth harmonic zero-sequence fault current is weak, and will be drowned in the harmonics generated by these harmonic source devices. Abdel-Fattah and Lehtonen [12] introduced an algorithm based on the transient estimation of the earth capacitance of the background network during the first 1/8 of the power frequency period. However, the effects of feeder impedances and the Petersen coil must be compensated by the proposed compensation factors for overcoming the influence of different transient frequencies. This results in a method that is difficult to use in practice. Elkalashy et al. [13,14] investigated a technique based on a probabilistic method applied to transient features extracted from the zero-sequence currents using the discrete wavelet transform (DWT). The detail coefficient in DWT is used for detecting the fault feeder. An adaptive threshold is used as the input to the probability function for estimating the fault feeder. Unfortunately, the technique in [13,14] is invalid in resonant grounding systems.

The fault transient zero-sequence current waveform of each feeder in a resonant grounding system contains information of the polarity, amplitude, and shape. Moreover, it can be characterized by nonlinearity and nonstationarity when a single-phase-to-ground fault occurs. Because there is a significant difference between the fault feeder and sound feeders, a good approach to fault feeder detection could be through waveform similarity recognition [15–17]. Guo et al. [15] developed a fault feeder detection approach with a stretching transformation applied to transient zero-sequence currents by using the ratio of the equivalent earth capacitance between two feeders. A phase-section analysis and Euclidean distance calculation are used to obtain the characteristic matrix of the transient zero-sequence current. A fuzzy k-means clustering algorithm is applied to detect the fault feeder without a threshold setting. In this case, the short feeder in the resonant grounding system is sound, and its small earth capacitance will cause many zero crossings in the transient zero-sequence current. As a result, the correlation with other sound feeders will decrease, reducing the reliability of the fault feeder detection method in [15] on the basis of the correlation coefficient of the undecomposed transient waveforms. For this reason, the method in [15] is difficult to use in practical engineering. In order to improve the degree of similarity and the fault feeder detection margin, the macroscopical changing trend and time-frequency local feature of transient zero-sequence current must be taken into account. Guo et al. [16] investigated a technique with wavelet packet decomposition and reconstruction as well as signal enhancement applied to process the fault transient zero-sequence current waveform of each feeder. By calculating the waveform difference feature matrices in each time window, the relative entropy is obtained, which is helpful to define the difference degree for the same time window among feeders. Equal-weight voting is adopted to count the preliminary fault feeder detection results in all time windows. Then, the fault feeder can be detected according to the result of equal-weight voting and a certain threshold setting. Therefore, the number of time windows and the threshold setting for the fault feeder detection criterion are required. Guo et al. [17] presented an approach based on the similarity of the time-frequency spectrum matrix of the fault transient zero-sequence current signals. Regarding the time-frequency spectrum matrix as the pixel matrix of a digital image, a method for image similarity recognition combined with a comprehensive similarity coefficient is used for the fault feeder detection. Unfortunately, the threshold setting for the fault feeder detection criterion according to many simulated results is inevitable. A novel single-phase-to-ground fault protection scheme was presented for neutral ineffectively earthed power systems [18] and bus-connected powerformers [19,20]. Two cluster centers of the non-fault group and fault group are obtained by applying a cluster algorithm to the selected features of historical data. The distances between the detected feature sample and the cluster centers of the non-fault and the fault are calculated. The detected feature sample belongs to the cluster with shorter relative distance to itself. The proposed protection scheme with an explicit physical mechanism has many advantages over conventional ones, such as the absence of a threshold setting, updatable historical data, and high sensitivity and robustness.

In this study, a new fault feeder detection method is presented, based on a novel amplitude and polarity similarity recognition algorithm for fault transient zero-sequence current waveforms. By means of adopting empirical mode decomposition (EMD) to the fault transient zero-sequence current waveforms of all feeders, corresponding intrinsic mode function (IMF) components can be acquired. Then, the Hilbert time-frequency spectrum of the transient zero-sequence current can be obtained by applying the Hilbert transform to the IMF components. By applying the HHT band-pass filter to the IMF components of transient zero-sequence current in each feeder, the components of different frequency bands can be extracted; then, the time-frequency matrix (TFM) is constructed. The fault transient zero-sequence current waveforms of each feeder are divided into several equal intervals along the time axis. Each sampling point in one interval is reset to zero or one according to its value. Then, the polarity distribution matrix (PDM) for each feeder is constructed from those changed sampling points in each interval. Moreover, the normalized singular value of the TFM and PDM are merged together. Thus, the feature quantities including the amplitude and polarity information of each fault transient zero-sequence current waveform are obtained. In addition, fuzzy c-means (FCM) clustering is applied to these normalized singular values so as to detect the fault feeder without a certain threshold setting. In this way, this approach can resolve the problems of conventional fault feeder detection methods, including suitability for all fault conditions and difficulty in threshold setting.

2. Proposed fault feeder detection algorithm

After a single-phase-to-ground fault occurrs in a resonant grounding system, the transient zero-sequence currents in all feeders will be acquired at the substation. The transient component of zero-sequence currents in a fault feeder is composed of the free transient oscillating component of capacitive currents in sound feeders and the dc transient component of inductive current via an arc-suppression coil. The amplitude of the high-frequency oscillating damped component and dc damped component via an arc-suppression coil may not be canceled out. By superposing the different amplitudes and similar frequencies, the amplitude of the transient zero-sequence current in a fault feeder may rise. The transient component of zero-sequence current in the sound feeders is composed only of the free high-frequency oscillating damped component of the capacitance grounding current. As a result of the excitation from the same zero-sequence voltage source, the transient zero-sequence currents in different sound feeders have the same variation trend. The transient component of zero-sequence current has similar free oscillating frequencies, but different amplitudes because of the different parameters of sound feeders. Moreover, the direction of the transient zero-sequence currents of the fault feeder and sound feeders is opposite.