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Fast fault detection and classification based on a combination of wavelet singular entropy theory and fuzzy logic in distribution lines in the presence of distributed generations

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ABSTRACT

This paper proposes a new method of fault detection and classification in asymmetrical distribution systems with dispersed generation to detect islanding and perform protective action based on applying a combination of wavelet singular entropy and fuzzy logic. In this method, positive components of currents at common coupling points are decomposed to adjust detailed coefficients of wavelet transforms and singular value matrices, and expected entropy values are calculated via stochastic process. Indexes are defined based on the wavelet singular entropy in positive components and three phase currents to detect and classify the fault. This protection scheme is put forward for fault detection and is investigated in different types of faults such as single-phase to ground, double-phase to ground, three-phase to ground and line to line in distribution lines in the presence of distributed generations, and different locations of faults are verified when the distributed generation is connected to the utility. The major priority of the proposed protection scheme is its reduction in time (10 ms from the event inception) in distinguishing islanding and protection transmission lines in the presence of distributed generations.

Introduction

Distributed generation (DG) is one of the significant events that have occurred in the electrical industry in power network in recent years. With the DG units in distributed networks, the behavior of the system is changed and these units have different effects on the system which each of them can investigate, separately. One of the major impacts of these units is on the distributed network protection. When the DG units are entered in the distribution networks, the behavior of protective devices has changed due to the fact that number of DG units can be changed, as well as the widespread distribution of these units is high [1–8].

DG unit is the electrical energy sources that are connected to the distribution networks. This resource has low capacity and volume in production and a low cost driven than enormous generators and power plants. Also the connection of this units to the distribution network has a lot of interests, such as economic issues in the power plants development, reduction in environmental pollution, high efficiency of these sources in power generation, power quality to customers, reduction losses in distribution networks, improvement of voltage profile, and liberalization of network capacity [2,3].

System is not radial after the connection of DG and this means a loss of coordination between the protective equipment. The effectiveness of DG is depended on size, type and location of DG, that harmony is preserved, and no scope for coordination will be left in some cases [4–6].

Different methods for fault detection and classification have been recently reported. For all algorithms, extracting the features of fault signal is importance. Fault detection based upon the Rate of Change of Frequency (ROCOF) is proposed in [9]. In [10] the Hypothesis Testing Technique is presented. In Ref. [11], the Real-valued Negative Clone Selection (RNCS) algorithm is investigated. The Vector Surge (VS) technique is suggested in [12], [13] while High Impedance technique is introduced in [14]. Authors of [15] presented Under/Over Voltage (U/OV) relay. The Wavelet Singular Entropy Index (WSEI) technique is proposed in [16] for islanding detection. An effective feature extraction method using wavelet transform (WT) is investigated in [17]. Ref. [18] suggests WTs suited for analysis of non-stationary signals measured by protection devices. A direct building algorithm for Micro-grid distribution ground fault (MGDGF) analysis is proposed in Ref. [19]. The directional over-current and earth fault protections used to protect the

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Micro-grid (biomass generator) in Malaysia are investigated in [20]. In [21], WT is used to capture the high-frequency traveling waves for fault detection, classification and fault phase selection. A methodology for fault classification based on wavelet multi-resolution analysis (MAR) is presented in [22]. An Adaptive Neural Fuzzy Inference System (ANFIS) based fault classification scheme in neutral non-effectively grounded distribution system is proposed in Ref. [23]. Preprocessing the fault current and voltage signal sample using hyperbolic S-transform (HS-transform) yields the change in energy and standard deviation at the appropriate window variations used for fault detection and fault classification in [24]. Different types of fault such as single-phase to ground, double-phase to ground, three-phase to ground and line to line may occur in the system in different locations. U/OV relay detects various fault types and offers a better performance than ROCOF relay. A ROCOF relay has difficulties in detecting faults in different locations. However, if the time delay is lowered enough without attracting nuisance or false tripping, the ROCOF relay may operate relatively faster than U/OV relays in equal conditions [15]. WSEI is an effective protection scheme that is used to detect islanding and able to detect it within 10 ms from the event inception [16], also High-impedance Faults Analysis in Distribution Networks Using an Adaptive Nero Fuzzy Inference System in [25].

Shahid et al. [26] present two novel techniques for fault detection and classification in power Transmission Lines (TL). The proposed approaches are based on One-Class Quarter-Sphere Support Vector Machine (QSSVM). The first technique, Temporal-attribute QSSVM (TAQSSVM), exploits the temporal and attribute correlations of the data measured in a TL for fault detection during the transient stage. The second technique is based on a novel One-Class SVM formulation, named as Attribute-QSSVM (A-QSSVM), that exploits attribute correlations only for automatic fault classification.

Wavelet singular entropy (WSE) is used in [27] for fault detection and classification in transmission lines. In this paper, system is without the presence of DG, in which with respect to the uses of these units in recent years, it is necessary to consider these resources. The ability of wavelet singular entropy is proven under various conditions such as fault resistance, fault distance and fault type.

The Wavelet Singular entropy technique, which combines applications and benefits of Haar wavelet transform [28], Singular Value Decomposition (SVD) [29,30], and spectrum entropy [31], is proposed to define indexes for fuzzy logic system in this paper. This method is effective and has a high speed in fault detection and classification in distribution lines in the presence of distributed generations. Three phase current signals are retrieved at the point where the relay is placed; in the next step the positive component of current signals is calculated, then analyzed by Haar wavelet transform; and the detailed coefficient will be retrieved. The SVD technique is used to compute the singular value from the detailed coefficient matrix, which computes WSE of the positive component and three phase current signals to use as inputs of fuzzy logic for fault detection and classification.

Power grids protection is an important issue that is able to detect fault and isolate the fault part. In this paper, a protection scheme based on a combination of wavelet singular entropy and fuzzy logic is presented for distribution lines in the presence of DG which each DG is able to exploit in islanding condition. Relay performance is investigated in different locations for fault detection and classification. A new algorithm is defined as the inputs of fuzzy logic system in fault classification based on the maximum value and minimum value of the WSE in the absence of fault and out of this area at the fault time.

The remainder of the paper is organized as follows. 'Wavelet singular entropy fuzzy logic' investigates the Wavelet Singular Entropy and defines the principle of Wavelet Transform, singular value decomposition, Shannon entropy and fuzzy logic. The system modeling, simulation tests and results are considered in 'System model and simulation results'. Finally, in 'Conclusion', main conclusions are analyzed.

Wavelet singular entropy fuzzy logic

Wavelet transform theory

Wavelets are useful tools for analysis of a signal that cuts up data, and then translates and scales versions of a single function [28,32]. Haar wavelet, the most basic and simplest WT, which is defined as follows, is used in this paper [28]:

$$\mathrm{haar}(2^p+n,\theta)=\begin{cases}\sqrt{2^p}; & n/2^p \leqslant \theta \leqslant (n+0.5)/2^p\\ -\sqrt{2^p}; & (n+0.5)/2^p \leqslant \theta \leqslant (n+1)2^p\\ 0; & \text{otherwise}\end{cases} \tag{1}$$

That can be: $p = 1, 2, \ldots$. And $n = 0, 1, \ldots, 2^p - 1$

Then, If $n = 0$ and $2^p = 1$, then the Haar wavelet is defined as follows:

$$\Psi(\theta)=\begin{cases}1 & \text{for} \quad 0\leqslant\theta\leqslant 0.5\\ -1 & \text{for} \quad 0.5\leqslant\theta\leqslant 1\\ 0 & \text{otherwise}\end{cases} \tag{2}$$

Then, $\Phi(t)$ is scaling function [22]:

$$\Phi(\theta)=\begin{cases}1 & \text{for} \quad 0\leqslant\theta\leqslant 1\\ 0 & \text{otherwise}\end{cases} \tag{3}$$

Generally, WT is a series of band-pass filters that consists of successive pairs of high-pass and low-pass filters. For each pair, approximations are high-scale low frequency components, while the details are low-scale high-frequency ones. Details and approximations derived from the WT coefficient matrix are required.

Singular value decomposition

Singular value decomposition is a method to decompose the matrix to 3 matrices as follows. Let $J_R \in C^{m*n}$ and $\sigma_i\ (J_R)(i = 1,\ldots,r; \leqslant \min\{m,n\})$ be the nonzero singular values of J_R, then the SVD is defined as follows [9]:

$$J_R = UDV^T \tag{4}$$

where $U \in C^{m*r}$, $V \in C^{n*r}$ and $D \in C^{r*r}$, that "D" is a diagonal matrix that is given as follows [12]:

$$D=\begin{bmatrix}\sigma_1 & 0 & \ldots & 0\\ 0 & & & \vdots\\ \vdots & \sigma_i & & 0\\ 0 & \ldots & 0 & \sigma_r\end{bmatrix};\ i=1,\ldots,r \tag{5}$$

Then $Q \in C^{1*r}$, where matrix 'Q' made by diagonal elements of matrix 'D', with respect to the matrix 'D' is given as follows:

$$Q=\mathrm{diag}[D]=[\sigma_1\sigma_2\ldots{}_{r-1}\sigma_r] \tag{6}$$

with $\sigma_1 \geqslant \sigma_2 \geqslant \ldots \geqslant \sigma_{r-1} \geqslant \sigma_r > 0$.

The $\sigma_i\ (i = 1, 2, \ldots, r)$ are called the nonzero singular values of matrix J_R.

Shannon entropy

Shannon entropy in time domain is an important uncertainty measure of signal for evaluating structures and patterns of ana-