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Transformer differential protection using wavelet transform

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ABSTRACT

This paper will propose a cascade of minimum description length criterion with entropy approach along with artificial neural network (ANN) as an optimal feature extraction and selection tool for a wavelet packet transform based transformer differential protection. The proposed protection method provides a reliable and computationally efficient tool for distinguishing between internal faults and inrush currents. The role of minimum description length criterion with entropy approach has been found to improve the efficiency of ANN with the dimensionality reduction of the feature vector. This reduction plays a major role in preventing the redundancy effect that can occur when using several features in an intelligent based monitoring system.

1. Introduction

Power transformer protection is a priority for power utilities because power transformers are among the most expensive and reliable types of equipment in the power system network. Transformer differential protection allows only for internal fault and proposed scheme provides stability against external faults, presenting a good dynamic and steady-state performance, as it can be observed in the simulation and real time results. However, the reliability of the differential relay may be compromised due to malfunctioning when an inrush current phenomenon occurs. Therefore, differential relays should be equipped with a discrimination facility to detect inrush currents as a normal transient state and internal faults' currents.

In order to overcome some of the concerns that have been raised in the use of the second restraint method [1], several intelligent based monitoring techniques have been alternatively recommended for differential current classification. Artificial neural networks (ANN) were proposed for discriminating transformer inrush currents from internal fault currents. Both time response [2] and consecutive windowed samples were successful features implemented in the ANN based methods [3,4]. Probabilistic neural networks (PNN) with particle swarm optimization for attaining optimal smoothing factor was another approach proposed for enhanced efficiency of the classifier. The proposed feature vector was composed of voltage to frequency ratio along with the amplitude of the current signal [5].

Wavelet based feature extraction of transformer differential current was proposed as an enhanced classification rate with different approaches [6,7]. The difference between the amplitudes of wavelet coefficients was proposed in order to obtain faster performance and reduce the dependency on certain thresholds in the relaying scheme [6]. A cascade of artificial neural networks and wavelet transform has proven to be efficient in obtaining acceptable discrimination accuracy. The feature vector is determined by the composition of the energies of the first, second and third detail signals that are decomposed from the discrete wavelet transform of the differential current signal. The detail spectral energies of level-3 decomposition were determined at three different instances, forming a 9-feature-input vector to the ANN [8]. Another proposed method for pattern recognition of the differential current signal is a combination of decision trees and wavelet analysis. In addition to wavelet coefficients, other features, such as the RMS and percent differential currents, restraining current, second and fifth harmonics, were applied [9]. More stable features were generated for differential current monitoring by extracting fewer coefficients for internal fault and inrush current detection [10]. Wavelet packet transform with optimal selection of the mother wavelet and resolution level, which are implemented using the minimum description length criterion (MDL), have been successfully applied for transformer differential protection [11]. Unlike [11], this paper proposes not only optimal mother wavelet family but also presents optimal decomposition level. Moreover, the proposed paper uses ANN approach to discriminate inrush and

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internal fault conditions thanks to extensive computer simulations. Additionally, CT saturation concept with Jiles–Atherton modeling technique is also taken into account in the simulations. The efficiency of the wavelet packet transform was also verified with a novel implementation using the Butterworth passive filters [12].

It is also worth mentioning that all of the proposed techniques have shown an outstanding classification rate, but with less emphasis on the feature selection step for optimal classification. Although MDL has been implemented in [11] for optimal selection of the mother wavelet and resolution level and the optimal number of wavelet coefficients were proposed in [9], less effort was necessary to optimize the feature vector for dimensionality reduction. In a smart grid environment where reliability is a crucial aspect, the redundancy effect of the feature vector of an intelligent based monitoring system must be prevented. Feature selection for optimal combination of features is an essential step to reduce the redundancy effect. This redundancy may affect the overall performance of the monitoring system by reducing the classification capability [13].

This paper presents a new scheme for power transformers differential protection in which the concept of the optimized neuro-wavelet technique is introduced. This includes a novel selection algorithm of wavelet based transformer differential current. The MDL and the entropy criterion are used for optimal selection of the mother wavelet and the resolution level and present dimensionality reduction in the feature vector. The energy levels of the detail coefficients are used as feature vector. The validity of the proposed algorithm is tested through ANN based classifier of power transformer inrush and internal fault differential currents as well as differential currents resulted from terminal faults. The suggested algorithm enlightens the idea of an optimal selection technique as opposed to an arbitrarily selection technique, which ensures an optimal selection of differential current features in the ANN classifier. The proposed technique has achieved the maximum possible classification rate with the minimum number of features used to monitor the transformer inrush and internal fault currents.

2. Materials and methods

2.1. Wavelet based feature extraction using MDL and entropy criteria

Real time classification of power transients is very challenging because the high frequency content superimposed on the power frequency signals are usually non-periodic, short term, and non-stationary waveforms. Wavelet transform (WT) is proposed in order to extract discriminative features which will help in differentiating between transients associated with islanding event and those created from any other event, such as temporary fault. Similar to Fourier transform, which breaks the signal into sinusoidal waves of different frequencies, WT breaks the signal into a shifted and dilated version of a short term waveform called the mother wavelet. Mathematically, the continuous wavelet transform (CWT) of a signal can be represented in (1).

$$CWT_x^{(\varphi)}(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\varphi^* \left(\frac{t-b}{a}\right) dt \tag{1}$$

where a is the scale, b is the translation or position, $i_d(t)$ is the analyzed differential current signal, and φ is the mother wavelet. The definition of CWT demonstrates how the wavelet analysis is a measure of the resemblance between the wavelet and the original signal. The calculated coefficient refers to the correlation or similarity between the function and the wavelet at the current scale. If the coefficient is relatively large then the signal is similar to the wavelet at this point in the time-scale plane. In the practical implementation of CWT there will be redundant information; therefore, for the ease of computational purposes, the scale and translation variables are discretized. The discrete wavelet transform is described in (2)

$$DWT_\varphi f(m,n) = \sum_k f(k)\varphi^*_{m,n}(k) \tag{2}$$

where, $\varphi_{m,n}$ is the discretized mother wavelet. In wavelets applications, choosing an appropriate mother wavelet plays an important role in analysis and depends on the application. Various basis functions have been proposed, including Haar, Morlet, Mexican, Daubechies, bi-orthogonal, etc. While selecting the most suitable wavelet family in analyzing power system transients is of vital importance, the selection of the optimal wavelet family is essential for optimal performance of the classifier. Therefore, discrete wavelet transform (DWT) is used with MDL and entropy criteria for optimal selection of the mother wavelet and the resolution level. DWT basically decomposes the differential current signal into approximation and details different resolution levels which can be employed for detecting the transient nature of the transformer inrush and internal fault currents. The differential current signal is decomposed when the sampling frequency is 4 kHz and the window length is one cycle. Standard deviation is used to represent the energy of the nominated details as input features [15]. It should be noted that the proposed algorithm is employed to improve the selection of the wavelet-based transformer differential current features, thereby improving the classifier performance, rather than developing the wavelet based classifier itself.

MDL data criterion is used for the selection of a wavelet function and applied to the simulation and real time data. The Shannon entropy based criterion is used in order to find an optimum level of resolution for the proposed protection algorithm. The entropy based criterion calculates the entropy of each subspace consisting of detail coefficients ('d') and approximation coefficients ('a') at each level of resolution of the DWT. It compares the entropy of a parent subspace with those of its children's subspaces in order to find out the optimum level of resolution using the optimum mother wavelet. The criterion states that if the entropy of a signal at a new level is higher than that of the previous level, the decomposition of the signal is not needed [16]. A similar dimension reduction method is given in [17] to distinguish two classes, which is based on descriptive statistics i.e. order 1 and 2 conditional moments of the predictors. The proposed method does not require any additional calculation and present high accuracy.

2.2. Artificial neural network classifier

Feed forward multi-layer perceptron ANN with back propagation algorithm is used as a tool to evaluate the proposed optimal feature vector and compare its efficiency with other commonly used features. Fig. 1 shows a general structure for ANN used in pattern classification applications.where details (d_1, d_2, and d_3) in the first layer are sent to the hidden layer in weighted links. The net activation of the hidden layer is calculated as in (3)

$$net_j = \sum_{i=1}^{d} d_i w_{ji} + w_{j0} \tag{3}$$

where 'd' is the number of details recommended in the feature modeling process and 'w_{ij}' are the weights between the 'ith' input unit and the 'jth' hidden unit. The output of the hidden layer is a nonlinear function of its net activation as shown in (4)

$$y_j = f(net_j) \tag{4}$$