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A new classification method for transient power quality combining spectral kurtosis with neural network

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ABSTRACT

This paper aims to develop a new idea for the classification of transient disturbances on power quality. The method is based on the combination of spectral kurtosis (SK) and artificial neural network (ANN). The SK is a high-order statistical moment which can detect the non-Gaussian components in a signal. Through the introduction of SK and its properties, we propose a classification plan for five transient disturbances combining SK and ANN. Firstly, the high frequency parts of five disturbance signals are extracted with DB4 wavelet transform (WT). Secondly, their SK values are respectively computed based on short time Fourier transform (STFT) and WT. Because the features of SK based on WT for five disturbance signals are not clearly distinguished, we propose a new computation method of SK based on Butterworth Distribution (BUD). Lastly, we choose the maximum, minimum and average values of SK based on STFT and BUD as the eigenvectors for the transient disturbance classification, which are input into RBF neural network. The simulation results show that the recognition rate of five transient disturbances is high, and the classification method proposed in the paper for transient power quality combining SK with ANN is efficient and feasible.

1. Introduction

Power quality (PQ) is an issue that needs continual attention, which has sharpened because of the increased number of loads sensitive to power quality and has become tougher as the loads themselves become important causes of the degradation of quality [1–3]. New and powerful tools for the analysis and operation of power systems such as the artificial intelligence and advanced mathematical tools were adopted [4]. The wavelet transform (WT), artificial neural network (ANN) and their combination were often proposed and adopted for the analysis and diagnosis of PQ problems [5,6]. The method of extracting the squared wavelet transform coefficients at each scale as inputs to the neural networks for classifying the disturbance type was proposed in [7,8]. The ideal of preprocessed discrete WT coefficients as inputs to a refined neuro-fuzzy network to train and classify the power system disturbance type was adopted in [9]. Chung et al. presented a novel classifier using a rule-based method and a wavelet packet-based hidden Markov model [10]. Other artificial intelligence methods such as support vector machine (SVM) [11,12], fuzzy logic [13], adaptive fuzzy logic [14], expert systems [15], genetic algorithms [16,17], and particle swarm optimization (PSO) [18,19] were often adopted for the classification of PQ problems, too. Other advanced mathematical tools were adopted, such as S-Transform [20–22], Hilbert–Huang transform [23,24], and mathematical morphology [25,26].

Higher order statistics are known to be effective tools to detect deviations from Gaussianity [27]. A Gaussian process is completely identified by its first and second cumulants (such as mean and variance). If the process is non-Gaussian, the lower order cumulants can only fit the best Gaussian model while completely ignoring the non-Gaussian behavior of the considered data of an event. Hence, first- and second-order cumulants, which are lower order cumulants, are not capable of depicting the differences between different types of non-Gaussian processes [28]. The higher order statistics have been tried to apply in power quality event analysis. A novel PQ event detection and classification method using higher order cumulants as the feature parameter, and quadratic classifiers as the classification method was proposed in [29]. After the detection of a PQ event, local maxima and minima of the cumulants around the event instant were used for the event-type classification. In [30], PQ event detection, classification and characterization using higher-order sliding cumulants (which were calculated over high-pass filtered signals to avoid the low-frequency 50-Hz sinusoid), whose maxima and minima were the coordinates of two-dimensional feature vectors was proposed, and the classification strategy was based in competitive layers.

The SK is a spectral descriptor originally devised by Dwyer for overcoming the inefficiency of the power spectral density to detect and to characterize transients in a signal [31]. The spectral kurtosis (SK) was firstly introduced by Dwyer as a statistical tool which can

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indicate not only non-Gaussian components in a signal, but also their locations in the frequency domain. Dwyer initially used it as a complement to the power spectral density, and demonstrated that it usually supplements the latter in problems concerned with the detection of transients in noisy signals [32]. Vrabie considered that SK means the deviation of some process to Gaussian distribution, and applied SK in the diagnosis of bearing faults [33]. Antoni systematically defined SK and gave the proof about the SK's abilities with the detection of non-stationary and non- Gaussian signals containing the colored noise [34]. Later, Antoni proposed the fast computation algorithm of SK and realized its applications in the detection and diagnosis of rolling-element bearing vibrations [35–37].

The SK is a statistical tool which can indicate the presence of series of transients and their locations in the frequency domain. If SK is adopted to analyze the transient signals with much noise, their transient statistical features could be better characterized. There are plentiful transient components in transient PQ problems. In addition, ANN has the strong classification and recognition capabilities. Based on these reasons, a new method combining SK with ANN is proposed to classify the transient disturbances of power quality. With the features of SK for five transient disturbances, they can be considered as the input of ANN for training and classifying. In order to prove the capabilities of combining SK with ANN for the transient disturbances classification, the simulation results are given and discussed in the end.

2. SK and its properties

2.1. The definition of SK

SK is originally defined as the normalized fourth-order moment of the real part of the Short Time Fourier transform (STFT), and suggested using a similar definition on the imaginary part in parallel. For the stationary case, Wold-Cramer's decomposition uniquely describes any stationary stochastic process as the output of a causal, linear, and time-invariant system excited by strict white noise.

$$Y(t)=\int_{-\infty}^{t} h(t-\tau)X(\tau)d\tau \tag{1}$$

For the non-stationary case, $h(t,s)$ means the causal impulse response at time t of a system excited by an impulse at time t–s, then

$$Y(t)=\int_{-\infty}^{t} h(t,t-\tau)X(\tau)d\tau \tag{2}$$

The frequency counterpart of (2) is

$$Y(t)=\int_{-\infty}^{\infty} e^{j2\pi ft}H(t,f)dX(f) \tag{3}$$

where $H(t,f)$ is the time-varying transfer function of the system, which can be considered as the complex envelope signal $Y(t)$ at frequency point f. In the actual system, $H(t,f)$ is random and be represented with $H(t,f,\omega)$, and ω means the random variable of the filter's time-varying characteristic. Let $H(t,f)$ be conditioned to a given ω. The second order instantaneous moment, which measures the strength of the energy of the complex envelope at time t and frequency f, can be defined as follow.

$$S_{2nY}(t,f)=E\{|H(t,f)dX(f)|^{2n}\omega\}/df=|H(t,f)|^{2n}S_{2nX} \tag{4}$$

For instance, for $n=1$, the defined instantaneous moment decomposes the energy contained in $Y(t)$ over the time-frequency plane (t,f). The fourth-order spectral cumulant of a conditionally non-stationary process is defined as:

$$C_{4Y}(f)=S_{4Y}(f)-2S_{2Y}^{2}(f),f\neq 0 \tag{5}$$

It can be shown that the larger the deviation of a process from Gaussianity, the larger its fourth order cumulant. Therefore, the energy normalized fourth-order spectral cumulant will give a measure of the peakiness of the probability density function of the process at frequency f.

The SK can be defined as follow [34].

$$K_Y(f)=C_{4Y}(f)/S_{2Y}(f)=S_{4Y}(f)/S_{2Y}^{2}(f)-2,f\neq 0 \tag{6}$$

2.2. The properties of SK

There are many properties of SK, which can be found in [34]. We only list two important properties that will be used in the paper.

Property 1. The SK of a purely stationary Gaussian process $Y(t)$, not conditionally non-stationary, is independent of frequency f and is given by

$$K_Y(f)=k_X,f\neq 0 \tag{7}$$

k_X is the kurtosis of a white Gaussian process $X(t)$. Specially, the SK of a purely stationary Gaussian process $Y(t)$ is zero, namely

$$K_Y(f)=0,f\neq 0 \tag{8}$$

Property 2. The SK of a conditionally non-stationary process $Z(t)=Y(t)+N(t)$, where $N(t)$ is an additive stationary noise independent of $Y(t)$, is given by

$$K_Z(f)=K_Y(f)/[1+\rho(f)]^2,f\neq 0 \tag{9}$$

where $\rho(f)=S_{2N}(f)/S_{2Y}(f)$ is the noise-to-signal ratio, which is the function about frequency f.

It is worth pointing out that the SK of some process is close to zero when $\rho(f)$ is great. Otherwise, the SK is close to $K_Y(f)$ if $\rho(f)$ is small. Through the searching of whole frequency domain, the frequency band with maximum SK can be obtained.

For example, we construct a signal $x(t)$ that includes three components. The first part is sinusoidal signal whose frequency is 100 Hz, amplitude is constant and initial phase is zero. The second part is sinusoidal signal whose frequency is 300 Hz, amplitude is according to the exponential decay and initial phase is zero. The third part is Gaussian white noise $n(t)$. It can be represented as follow.

$$x(t)=\sin(2\pi\times 100t)+0.5e^{-5t}\sin(2\pi\times 300t)+n(t) \tag{10}$$

If the sampling frequency is 1 kHz, and the sampling time is 2.048 s. The SK of $x(t)$with STFT is computed, where the window is Hamming window, the window owns 128 data points, and a data point is moved for each time computation. The SK of $x(t)$ is drawn in Fig. 1.

In Fig. 1, we can find that the SK at 100 Hz is -1, the SK at 300 Hz is 6.38, and the SK at other frequency range steady fluctuates near zero. The simulation result shows the SK can clearly characterize the three different components of signal. In fact, the result also reflects the SK's properties.

3. Transient power qualities

The power quality issues caused by various disturbances in the power system can be divided into steady state and transient problems [38]. The characteristic of steady state PQ mainly means the waveform distortion, including harmonic, inter harmonic and voltage fluctuations. Transient power quality problems are often characterized by amplitude, spectrum and transient duration,