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Signal clustering of power disturbance by using chaos synchronization

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ABSTRACT

This study develops and applies a chaos synchronization-based detection method for an engineering application of monitoring power quality disturbance. The new method can detect minor dynamic changes in signals. Likewise, prominent characteristics of system signal disturbance can be extracted by this technique. The method is then combined with the extension recognition algorithm to accurately apply to signal clustering of power disturbance. According to extensive computer simulation results and a comparison among three typical chaotic systems, it is confirmed that the proposed method is well applicable using various chaotic systems, mostly with very high accuracies. As compared with other traditional methods, the new method is shown to have higher accuracy, faster computing speed and better expandability. It is foreseen that if the method can be implemented by system-on-chip in the near future, it will find many real engineering applications such as hand-held power quality analyzers and auxiliary means for on-line real-time detection, among others.

Introduction

From the definition of IEEE Standard Dictionary of Electrical and Electronics Terms, power quality refers to “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment.” It is widely defined as “the degree of satisfaction of users with the power supply quality of power companies.”

In recent years, as a variety of precision equipment are used in the applications of electronic equipment and distributed power sources in the high-tech industry, the requirement for power quality has become increasingly desirable [1]. Noticeably, the causes for power quality events include natural disasters, human factors, external object contact, equipment deterioration, and circuit specifications [2]. In a power system, due to nonlinear loads (e.g., commutation equipment and welders), the electric energy converters in the equipment create a large amount of non-fundamental frequency current flows into the power system, causing current harmonics [3]. The above factors can cause voltage sags, swells, and interruptions or harmonics of power systems. Therefore, the state of a power system should be online measured by a monitoring instrument, thereby improving the power supply quality.

A power engineer needs to recognize and classify the detected power system signals when monitoring and analyzing the power quality problem, so as to attain the goal for accurate diagnosis and analysis [4]. An existing problem is, as has been commonly observed, that most if not all present instruments for monitoring power systems identify the states of the power system signals according to long-term voltage measurements, such as the root-mean-square (RMS) value of voltage in unit time as well as the variance of the value in unit time, or to detect whether there is voltage sag or power harmonics according to the changes in voltage peaks and frequencies.

In order to analyze various power quality problems accurately, multiple electric power characteristics should be measured, but then the analysis becomes very time consuming [5,6]. Previous studies [7] use the Fourier Transform to analyze the frequency contents as the basis of classifying frequencies. The current needs to remain for a period of time, and then the conversion takes an even longer time. Since the information of time disappears after the Fourier Transform is taken, the aforementioned studies suggest to use the Short-Time Fourier Transform. Although the relevance between time and frequency domains can be expressed after Short-Time Fourier Transform [8], the window of Short-Time Fourier Transform has a fixed width. In other words, when the time domain requires higher resolution, the resolution of the frequency will be reduced. Therefore, it is not an ideal method for analyzing instantaneous electric power signals, and moreover it cannot detect the electric power signals with significant noise. As a result, Fourier Transform has relatively lower detection accuracy. In order to overcome this defect, several studies use the Wavelet Transform

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[9] to analyze power system signals, which suggest approximate the window width between frequency domain and time domain to provide higher time-domain resolution for the high frequency part of a signal, and to provide higher frequency-domain resolution for its lower frequency part. Therefore, in the transient period of a power system, Wavelet Transform has improved the defect of Fourier Transform, so that more prominent characteristics may be extracted by Wavelet Transform as the input characteristics used by many artificial intelligence algorithms such as Neural Network Algorithm (NNA) [10], Fuzzy Theoretic (FT) scheme [11], and Genetic Algorithm (GA) [12]. However, the number of characteristics extracted by Wavelet Transform is obviously larger, and likewise the noise interference in the power system cannot be recognized clearly, thus the power quality monitor accuracy is reduced.

Some other studies use classification schemes, such as *K*-means clustering algorithm [13], *C*-means clustering algorithm [14], and Support Vector Machine (SVM) [15]. The *K*-means and *C*-means clustering algorithms are both mean-square-error clustering schemes, and their cluster numbers are determined randomly. If the cluster numbers are selected correctly, they can yield very good recognition results. On the contrary, if the cluster numbers are allocated incorrectly, the recognition rates will decrease significantly. Since this method adopts random allocation, there may be electric power signal classification errors, so that the recognition accuracy may be affected. The SVM is a new sorting algorithm based on statistics. It divides the input signals into two different sets by a hyperplane in space. The combination of multi-SVM is obtained in multi-signal states, but the optimal classification must be calculated. Therefore, some optimization algorithms are used, such as particle swarm optimization [16], GA [17], and annealing algorithm [18], to determine appropriate parameter values, which improve the classification to yield better results.

On the other hand, chaos theory has been applied in different fields in recent years, in particular with chaos detection [19]. A subtle change in an electric power signal can be detected based on chaos theory, where power system signals are used to validate the accuracy of chaos-based methods. Recent studies have remedied some defects in chaos-based methods, as reported in [20].

Moreover, chaos synchronization has been used to detect power quality changes, where electric power signals are classified by, for example, the Particle Swarm Optimization Probabilistic Neural Network (PSO-PNN), which was used for detection through chaos synchronization [21]. The signal response to each type of power qualities is observed from the underlying chaos waveform. However, in this method, complex classification needs to be carried out before detection, so the detection needs a longer time. Moreover, power systems with noise have not been discussed in the literature before. From the same approach, this study simplifies the method in [20] for detection, which can now significantly shorten the detection time and also well handle electric power signals with noise.

More precisely, this study remedies the defects found in various methods proposed in previous investigations, by using chaos synchronization-based technique to extract fewer characteristics from power system signals in a shorter time. Noise interference in the power system can be easily identified by using chaotic characteristics. The dynamic trajectories in the chaos synchronization are extracted from the power system by using this method. The error trajectories are then used to avoid using the general power system characteristics such as voltage, current, and power, which are more costly to obtain and to use.

This study implements power system detection mechanism, hoping to reduce both the characteristic number of extracted waveform and the computing time. The extension recognition method will be used to analyze the state of the power system disturbance, so as to maintain the accuracy of identification and shorten the detection time.

The proposed method is then verified and validated by extensive numerical simulations on a power system setting, using some typical chaotic systems as examples, demonstrating its effectiveness for potential engineering applications.

Architecture of power quality monitoring and analysis

Power disturbance in general may be classified as voltage disturbance and current disturbance, which provide voltage and current deviations from the ideal sine waves, which have potential impacts on power grids or electrical equipment. It is usually resulted from human factors, natural disasters and power system characteristics. Common electric power signals are listed in Table 1 [22–25].

All of the present measuring instruments identify whether there is voltage sag, swell or power interruption, through long-term voltage monitoring, calculating the voltage RMS value in unit time, and observing the variation of the value in unit time. They may also identify whether there is voltage flicker or power harmonics according to the changes in voltage peaks and frequencies. In order to analyze various power quality problems accurately, multiple electric power characteristics should be measured. It has been observed that there may be misrecognition when the electric power system is subject to noise interference.

Given the above background, this study is motivated to try utilizing the dynamic trajectories of a chaotic system to convert the power quality disturbance waveform, so as to extract fewer characteristics in shorter time, and to increase the accuracy of detection based on the sensitive characteristics of chaos.

Specifically, this study designs a chaotic synchronization detector to convert the input signal waveform, and extract prominent characteristics from the waveform. The extension theory in pattern recognition will then be used to identify the type of the power disturbance signals. The overall scheme is shown in Fig. 1.

The proposed detection method

The proposed chaos synchronization-based method uses the sensitive characteristic of chaotic dynamic trajectories to identify the disturbance waveform of a power system accurately and rapidly, such as normal voltages, voltage swells, voltage sags, voltage interruptions and voltage harmonics. It is well known that if there is noise in the disturbance waveform, most traditional methods generally cannot recognize the correct characteristics accurately. One contribution is that the chaos synchronization-based technique can overcome this main defect of most traditional methods, and can also increase the accuracy level of power quality analysis significantly.

Chaos synchronization detection method

The modern chaos theory was initiated by meteorologist Edward N. Lorenz in 1963 [26]. For any subtle change in initial condition of a chaotic system, the system state changes significantly after a long period of time. In addition, when two chaotic systems with slightly different parameters have the same initial conditions, there will also be significant differences between the two states after a long period of time. Therefore, the notion of chaos synchronization was proposed in 1990 [27] to carefully study how to synchronize two chaotic system trajectories. Fig. 2 is a schematic diagram of two chaotic states achieving synchronization.

In a general setting, the two chaotic systems are called Master System and Slave System, respectively. When the master and slave