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A new power quality deviation index based on principal curves

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ABSTRACT

In this paper, a new power quality deviation index based on principal curves is proposed. The index provides a quantitative measure, which gives an idea of how much the monitored electrical signal has deviated from the nominal one. Differently of existing indices, the proposed index is a general index, i.e., it can be used for any type of disturbance in the monitored signal. In addition, the proposed index is used to perform a direct approach for detecting disturbances in power signals. This approach is able to detect the beginning and localize the disturbance by analyzing non-overlapping signal windows of one cycle of the fundamental component, leading to a simple method in terms of computational complexity.

1. Introduction

An important task in power quality (PQ) monitoring is to measure the power quality through the use of an index or a group of them. According to [1], the majority of the known indices intend to summarize the degree of distortion of a sinusoidal waveform, how much power loss occurs due to this distortion, and the impact the distortion on telephone and communication circuits causes. In the present paper, we refer to PQ index, in a general sense, as a quantitative measure of deviation from a monitored voltage or current signal to nominal one (perfect sinusoid).

Existing PQ indices are defined both, in time as well as in frequency domains. Common time domain PQ indices are Form factor, Crest factor and RMS value, whereas total harmonic distortion (THD), total demand distortion (TDD) and distortion index (DIN) define the PQ in the frequency domain [2]. According to [3], frequency domain PQ indices are more informative and acceptable. Most of the frequency domain PQ indices are based on Fourier transform. It is known that Fourier transform can provide accurate results only for stationary waveforms and, therefore, Fourier transform-based indices are not applicable for non-stationary or aperiodic signals [4]. Definitions for various PQ indices are provided by the IEEE std 1459-2010 [5]. The main power quality index presented in IEEE Std. 1459-2010 addresses the important concepts of instantaneous power (active and non-active). These concepts are well defined for balancing sinusoidal polyphase system, but are still confusing when the voltages and currents' waveforms are distorted. For this situation there are a lot of papers addressing definitions and implementation [6–8]. These definitions lead to the same results in the case of ideal sinusoidal condition, however they produce different values for non-ideal conditions, so a PQ index that quantify how distorted is the signal could be used as a merit figure to compare the suggested power parameters.

New PQ indices based on wavelet transform have recently been proposed in the attempt of overcoming the limitations of the conventional PQ indices based on Fourier transform to non-stationary waveforms [3,9]. From the aforementioned works, one can notice that the search for a consistent PQ index capable of measuring PQ signal deviations in the largest number of possible situations is an open subject. Also, most of them are designed for a limited number of applications, and can be erroneously used in other. Therefore, to correct quantify the power quality usually a combination of parameters (indices) is required.

In the present paper, a new global PQ deviation index is proposed, which is based on principal curves (PC) [10]. This index is a general and integrated voltage-quality index that quantifies the deviation of the actual voltage from the ideal voltage. The proposed index is a mathematical index with physical meaning coherent

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with the definition of voltage quality as any deviation from a balanced, constant-magnitude and sinusoidal voltage. The proposed PC-based index can also be used in detection and classification procedures, as discussed further down in this paper.

The principal curves technique is considered to be a non-linear generalization of principal component analysis and has recently been used for pattern classification and data clustering. The success of applications with PC is due to its interesting ability of compact data representation [10]. The proposed index performs a direct measure of deviation from the nominal PQ signal, compressing raw information into a single value. In a previous work [11], the authors exploited principal curves for power quality monitoring showing how to analyze, extract features, detect and classify PQ disturbances with principal curves. In this work, differently from [11], only the nominal class (formed by signals non corrupted by disturbances) is represented by a PC and a measure of the distance from a monitored event to the PC is used as a general-purpose PQ deviation index. It provides a quantitative value, which gives an idea of how much a given monitored signal is deviated (in terms of a distance) from the nominal class. No *a priori* knowledge of the disturbance type (classification) is required. Comparisons with other power quality indices are carried out. In addition, a simple disturbance detection system based on the proposed power quality index is designed.

2. Principal curves

Principal curves (PC) were first defined by Hastie and Suetzle [10] as one-dimensional parameterized curves having the property of self-consistency, which pass through the d-dimensional data points described by **X** in the original data space, providing a good representation of them in 1 dimension. Principal curves are non-parametric and consists of a non-linear generalization of the concept of principal components. Mathematical formulations for PC can be found in [10] and were summarized in a previous work [11].

In this paper, principal curves were extracted using the k-segments algorithm [12], which has been shown to perform well for power quality signals [11]. The extraction algorithm uses an incremental method to avoid local optima. The extraction of principal curves using this algorithm is performed in three steps: (i) a center corresponding to the average value of data is defined, and from this center, the first segment toward the first principal component is obtained; (ii) a new point to be taken as the center is defined and the events to form the new grouping are defined. Then the first segment is recalculated, since the set of events that defines it has changed. The two segments obtained are joined by a straight (non-smooth) line. For the next segments, the same procedures are performed; (iii) it is checked whether the algorithm has reached the maximum number of segments defined by the user or if there was convergence. If convergence did not happen and if the maximum number of segments defined by the user was not achieved, go back to (i). Convergence occurs when the largest possible grouping has less than three segments.

3. DataBase

Synthetic voltage signals were generated by MatLab software with a sampling frequency (f_s) equal to 15,360 Hz. The nominal signals were generated according to Eq. (1).

$$v(n) = x(t)|_{t=nT_s} = V_m \sin(\omega_0 n + \phi) + r(n), \quad (1)$$

where $n = 0, \ldots, N-1$, $T_s = \frac{1}{f_s}$ is the sampling period, $V_m = 1$ is the nominal amplitude, $\omega_0 = 2\pi f_0$, in which $f_0 = 60$ Hz is the power system frequency, and ϕ is the phase of the signal. An additive noise ($r(n)$) was considered with normal distribution, such as the signal-to-noise ratio (SNR) is 60 dB. According to [13], the power system has SNR ranging from 50 to 70 dB.

Seven classes of PQ disturbances are considered: harmonics, sags, swells, oscillatory transients, notches, outages and spikes. The events were simulated following the definitions of IEEE standard [14]. A total of 1000 events were generated for each class and 1000 signals were generated without disturbances. All disturbances were also generated with a SNR of 60 dB.

Analysis with real data were performed on 60 experimental measurements of PQ disturbances (obtained from the IEEE work group (P1159.3) [15]).

4. A PC-based power quality index

In this section, a PC-based PQ deviation index is proposed. The idea is to use a principal curve to provide a compact representation of the nominal class. For this, the PC of the nominal voltage signal class is extracted from the synthetically generated nominal signals by using the k-segments algorithm [12]. The synthetic nominal signals were used to construct the principal curve with the aim of ensuring that the achieved principal curve represents/models as good as possible the ideal voltage signals. With this, even the smallest power signal deviations can be captured by the proposed method.

After this, the extracted PC is used as a 1 dimensional signature of the nominal class and: closer is the event from the PC better it is in terms of power quality, and further is the event from the PC worse it is, i.e., higher is the level of deviation compared to the nominal signal.

4.1. 3-D representation of PC

In order to elucidate the construction of the PC from nominal class, a 3-dimensional representation of PC is given in this section. It is important to say that this representation is only illustrative since the real PC data space considered here is d-dimensional. However, it is an useful analysis to help the understanding of PC construction from power system voltage signals.

In PC d-dimensional space, a given voltage signal $v[n]$ with $n = 0, \ldots, N-1$ samples is viewed as a point in a N-dimensional space such that each sample value corresponds to the same value in the respective n coordinate. Thus, the dimension of the PC space for voltage signals is given by the number of samples at the measured voltage signal processed. Then, to illustrate voltage signals in PC space, three distinct samples from $v[n]$ ($v[N/3]$, $v[2N/3]$ and $v[N]$) are considered, in order to produce a 3-dimensional space.

Fig. 1(a) shows the distribution of a given sinusoidal signal $v[n]$ considering only three samples. One can see that the data distribution looks like a circle on three dimensions which is due to the periodic nature of the sinusoidal signals. Let us consider a PC with only three segments (Fig. 1(a)). Here, it is important to remember that the k-segments algorithm [12] constructs the principal curve iteratively adding segment to segment and at the end the segments (thicker lines) are joined by a straight (thinner line). However, the k-segments algorithm provides an open PC. It is easy to see that the nature of data requires a closed PC. Thus, we propose the inclusion of an additional segment linking the endpoints of the PC, making thus a closed PC as it is shown in Fig. 1(a). Nevertheless, one can see that this PC gives a poor representation of the data and more segments must be considered to construct a PC which better represents these data.

Although the 3-D analysis does not represent the completely PC space, this is important for revealing details like these ones discussed above, which cannot be visualized in higher dimensions. A quantitative way of measuring how good is the PC and define the