Power Quality Analysis Using Higher-Order Statistical Estimators: Characterization of Electrical Sags and Swells

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Abstract. This work presents the detection results involving two common electrical disturbances: sags and swells. Variance, skewness and kurtosis have been used to improve statistical characterization. The measurement procedure is funded in the tuning of the signal under test via a sliding window over which computation is developed. Locking is possible because these power quality disturbances keep the frequency of the power line. Statistical features reveal the inherent properties of the signals: amplitude, frequency and symmetry. The paper primarily examines a number of synthetics in order to extract the theoretical statistical features. Then the algorithm is corroborated using real-life signals, obtaining an accuracy of 83%. This stage is part of the design of an instrument for the measurement of the power quality.

Keywords: Higher-Order Statistics (HOS), Power-Quality (PQ), Sag, Swell.

1 Introduction

Power Quality (PQ) anomalies' tracking has been enhanced during the last eight years grace to the use of new signal processing techniques [1]. These efforts have been focused in the analysis, characterization, classification and data compression. Motivated by this issue, this paper focuses on the use of easy-to-compute statistical estimators to detect sags and swells. Another higher-order statistics estimators have been formerly used involving PQ analysis with success [2], [3].

The worldwide interest in PQ is double fold. Equipment has become more sensitive to voltage disturbances, and at the same time the industrial equipment

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cause voltage disturbances. There is also the need for standardization and performance criteria for consumers and utilities. This paper concentrates on two of the PQ phenomena that primarily affect customers: sags and swells. During a voltage sag, the voltage is not zero but is still significantly less than in normal operation. The extreme situation is described by an interruption, in which the voltage goes to zero, which is the worst quality of supply. Swells are momentary over-voltages in the power line sine wave. These events are roughly of the same frequency of the ideal power-line sine wave.

PQ problems' solutions implies the acquisition and monitoring of long data registers, along with an automated detection and classification strategy, which allows the identification of the cause of these anomalies. These perturbations are intrinsically non-stationary (transients); moreover noise processes are commonly present. So it is necessary a battery of observations (sample registers) to get statistical confidence. The implemented algorithms in the measurement systems for this purpose have been traditionally based in spectral analysis and wavelet transforms. Other tools are threshold-based functions, linear classifiers and Bayesian networks [2]. During the last 10 years researchers have introduced a strategy based in higher-order statistics (HOS), dealing with PQ analysis [4],[3], and other fields of Science and Technology (e.g, [5,6]). This is due to the fact that 2^{nd}-order moments and cumulants do not give information related to the symmetry and shape of the waveform.

From the former hypothesis, the detection procedure is summarized hereinafter. The expected 50-Hz of the waveform exhibits a particular constant statistical behavior (stationarity), i.e. with concrete stable statistics. Any disturbance that alters these constants keeping its frequency (50 Hz), will exhibit stable statistical state, but with different parameters from the undistorted situation. Furthermore, perturbations which does not preserve the frequency, will be targeted but will not exhibit constant statistical parameters.

The paper is structured as follows. The following Section 2 explains the fundamentals and the importance for PQ monitoring. Higher-Order Statistics are outlined then in Section 3. Results and conclusions are presented in Section 4 and Section 5, respectively.

2 Summary on Power Quality Characterization

Nowadays, a great deal of electronic equipments enter the cities and businesses. Consequently the subjects related to PQ and its relationship to vulnerability of installations is getting more importance. Assessment of voltage quality and power disturbances involves looking at deviations of the voltage or current from the ideal single-frequency sine wave. Regulation in European countries proposes to use the standard EN-50160 to define the voltage quality intervals. This norm actually describes the electricity through the technical characteristics to fulfill to be considered as a compliant product [7,8].

The voltage sag and interruptions (dips) are the nemeses of the industrial processes. The first is defined as any low voltage event between 10 and 90% of the nominal RMS voltage lasting between 0.5 and 60 cycles. Momentary voltage interruption is any low-voltage event of less than 10% of the nominal RMS voltage lasting between 0.5 cycles and 3 seconds. In medium voltage distribution networks, sags are mainly caused by power system's faults. Fault occurrences elsewhere can generate voltage sags affecting consumers differently according to their location in the network. Even though the load current is small compared to the fault current, the changes in load current during and after the fault strongly influence the voltage at the equipment. It has been proved that the 85% of power supply malfunctions attributed to poor PQ are caused by sags of fewer than one second duration. Comparing with dips, sags affect more customers and may cause grave problems, creating problems to sensitive systems which operate within narrow voltage ranges, or do not have adequate filtering elements.

On the other hand, under operating conditions of a power system there is risk of damaging due to a momentary excess of voltage. Although by themselves they would be abnormal, it is possible to distinguish between surges and swells. A surge is an over-voltage that can reach thousands of volts, lasting less than one cycle of the power frequency, that is, less than 16 milliseconds. A swell is longer, up to a few seconds, but does not exceed about twice the normal line voltage.

Power system surges, based on waveform shapes, can be classified into "oscillatory transients" and "impulsive transients" [9]. Oscillatory transient surges show a damped oscillation with a frequency range from 400 Hz to 5 kHz or more. Impulsive transient surges present a fast rise time in the order of 1 ns-10 μs over the steady state condition of voltage, current or both, that is unidirectional in polarity (primarily either positive or negative), reaching hardly twice the peak amplitude of the signal. They are damped quickly, presenting a frequency range from 4 kHz to 5 MHz, occasionally reaching 30 MHz. They have been extensively studied in [2]

In the following Section we present higher-order statistics in the time-domain in order to describe the signal processing tool.

3 Higher-Order Statistics

Higher-order cumulants are used to get additional information about non-Gaussian data. For $\{x(t)\}$, an rth-order stationary random process. We define the rth-order cumulant as the joint rth-order cumulant of the variables $x(t)$, $x(t+\tau_1)$,..., $x(t+\tau_{r-1})$ [2],

$$\begin{aligned} &C_{r,x}(\tau_1,\tau_2,\dots,\tau_{r-1}) \\ &\quad = Cum[x(t),x(t+\tau_1),\dots,x(t+\tau_{r-1})] \end{aligned} \tag{1}$$

The second-, third- and fourth-order cumulants of zero-mean $x(t)$ can be formulated via:

$$C_{2,x}(\tau) = E\{x(t)\cdot x(t+\tau)\} \tag{2a}$$

$$C_{3,x}(\tau_1, \tau_2) = E\{x(t) \cdot x(t + \tau_1) \cdot x(t + \tau_2)\} \tag{2b}$$

$$\begin{aligned} &C_{4,x}(\tau_1, \tau_2, \tau_3) \\ &= E\{x(t) \cdot x(t + \tau_1) \cdot x(t + \tau_2) \cdot x(t + \tau_3)\} \\ &- C_{2,x}(\tau_1)C_{2,x}(\tau_2 - \tau_3) \\ &- C_{2,x}(\tau_2)C_{2,x}(\tau_3 - \tau_1) \\ &- C_{2,x}(\tau_3)C_{2,x}(\tau_1 - \tau_2) \end{aligned} \tag{2c}$$

By making zero the time lags, $\tau_1 = \tau_2 = \tau_3 = 0$, in Eq. (2), we get:

$$\gamma_{2,x} = E\{x^2(t)\} = C_{2,x}(0) \tag{3a}$$

$$\gamma_{3,x} = E\{x^3(t)\} = C_{3,x}(0, 0) \tag{3b}$$

$$\gamma_{4,x} = E\{x^4(t)\} - 3(\gamma_{2,x})^2 = C_{4,x}(0, 0, 0) \tag{3c}$$

The former Eq. (3) are estimates of the variance, skewness and kurtosis of the distribution in terms of cumulants at zero lags. Normalized kurtosis and skewness are defined as $\gamma_{4,x}/(\gamma_{2,x})^2$ and $\gamma_{3,x}/(\gamma_{2,x})^{3/2}$, respectively. We will use and refer to normalized quantities because they are shift and scale invariant. If *x(t)* is symmetrically distributed, its skewness is necessarily zero (but not *vice versa*, almost impossible situations); if *x(t)* is Gaussian distributed, its kurtosis is necessarily zero (but not *vice versa*). In the experimental section, results are obtained by using sliding cumulants, i.d. a moving window in the time domain over which to compute the each cumulant (3^{rd} and 4^{th}-order cumulants for zero lags). Based on these premises, hereinafter we expose the experimental results.

4 Results

Records' analysis is performed from a working hypothesis, which states that the sliding window to extract HOS features must enclose an exact number of cycles of the 50 Hz (0.02 s) power-line. Moving the sliding window along a healthy signal, each HOS feature is constant. disturbances in the power line will produce changes from this constant values. Furthermore, if the coupled disturbance generates another 50-Hz signal, processing will return different constant values.

To illustrate this, Fig. 1 shows processing results over a synthetic resulting from the addition of different signals, each 0.06 seconds length. The analysis outputs constant values associated to segments A, F and G, which remain their frequency constant, 50 Hz. By the contrary, the signals (or segments) with different frequencies (B, C, D, E) do not give stabilized HOS values. The particular case of signal H represents an uniform noise process, and its HOS analysis which outputs semi-stabilized results.

The following step is the definition of a healthy signal. A pure sinusoidal signal with a normalized amplitude is associated to the following constant values

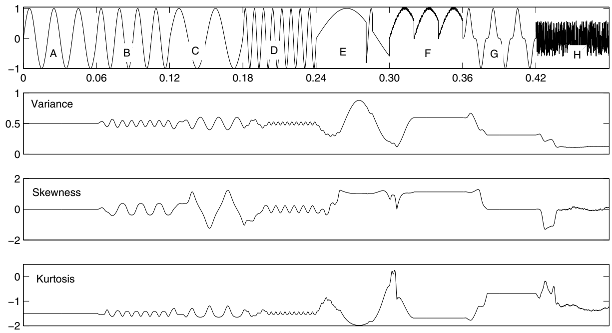

Fig. 1. Procedure of analysis over a segmented synthetic. The goal of this graph is to demonstrate that the 50-Hz anomalies outputs a constant value zone.

for the HOS estimators: 0.5 for the variance, 0 for the skewness and -1.5 for the kurtosis. The simple characterization of healthy signals, according to the proposed methodology, helps to detect any coupled disturbance as a deviation in the HOS values. Furthermore, if the disturbance alters the waveform, keeping at the same time the frequency value, some additional characteristics of the event can be inferred. If the event only involves a change in the amplitude, preserving the sinusoidal form (sag or swell), the skewness and kurtosis values will remain in 0 and -1.5 respectively (healthy values), but the value of variance will change, depending on the increment of amplitude, because the sliding variance gives information related to the power. Thus, from the starting line of the skewness and kurtosis healthy values, sags and swells can be completely characterized considering the variance-amplitude relationship.

Kurtosis' deviations from the ideal case are produced by changes in the pure sinusoidal shape. Attending to the skewness, the symmetry of the altered waveform can be classified as asymmetric (skewness$\neq$0) or symmetric (skewness=0). This is used to classify a 50 Hz waveform as healthy, sag, swell, symmetric and asymmetric.

Following the on site measurement philosophy, we have designed a new synthetics which remains the 50-Hz frequency. Fig. 2 shows the results of the proposed analysis performed on a synthetic, which comprises nine 0.06 seconds segments. A discontinuous line marks the statistical values associated to a healthy signal (variance=0.5; skewness=0; kurtosis=-1.5). The perturbations introduced in the signal modify the HOS values from the healthy ones.

The interpretation is as follows. The healthy fragments of the signal (labeled 'H' in the upper sub-figure of Fig. 2) can be identified by the HOS healthy constants. Changes in the amplitude, keeping its sinusoidal shape, (sag and swell) are characterized by the skewness and kurtosis values similar to the healthy ones and a specific variance related to the event's magnitude. Changes in the sinusoidal shape produce variations in the kurtosis. Attending to the skewness, these shape's disturbances can be classified as symmetrical ('S') or asymmetrical ('A').

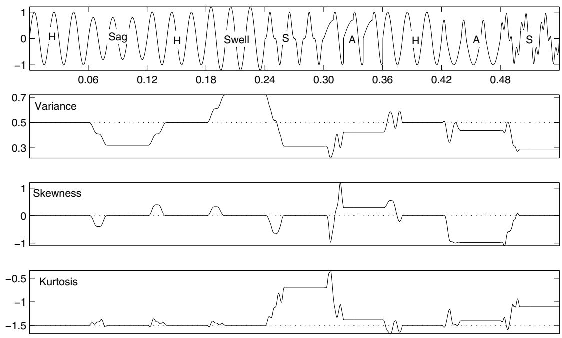

Fig. 2. On site measurement simulation which shows the evolution of the constant values associated to three statistics (variance, skewness and kurtosis)

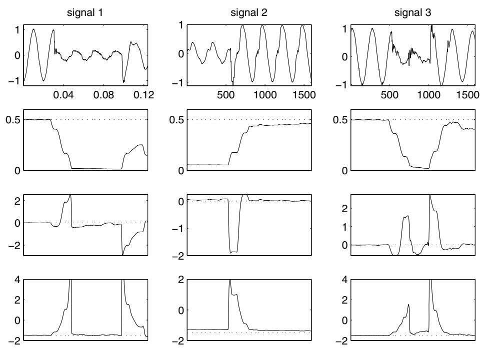

Fig. 3. Performance example over real life signals

Additionally to the synthetics, the performance has been tested using real-life signals, available from the IEEE working group P1159.3 web site. Fig. 3 shows three representative signals; graphical results are organized in columns. In the first column, signal 1 starts with a healthy fragment (the three statistical parameters matches the healthy state) which is followed by a swell. When the swell finishes, the signal does not recover the healthy status. Signal 2 in the second column is totally distorted; absence of purity. The third signal starts healthy, but suddenly goes into chaos, which seems to be the result of a number of simultaneous anomalies. This third column reveals the limits of the suggested procedure, because in fact it is not possible to reveal signal's anomalies.

The procedure has been tested using the above mentioned set of signals, obtaining an 83% of accuracy.

5 Conclusions

This work proves that a change in any statistic is indicative of a sag or swell in the power-line. The working premise involved in the proposed HOS analysis is focused in the characterization of a healthy signal (normalized sinusoidal signal of 50 Hz) by its higher-order statistical features. Any perturbation in the healthy signal modifies these statistics, and allows detection.

The signal processing methodology is based in a tuned 50-Hz sliding window over which compute each estimator; thus processing the 50-Hz events outputs a set of constant values which characterizes the type of anomaly. This tuned window allows signal analysis without preprocessing, i.e. preserving original information and without introducing nonlinear behaviors.

Results over the synthetics analysis has allowed the identification of the variance, skewness and kurtosis associated to a healthy signal. It has been proved that amplitude variations, without altering the shape of the waveform, keep the skewness and kurtosis values, and the variance gives information of the new amplitude. Kurtosis changes with the sinusoidal shape, characterizing the signal's symmetry via the skewness.

As a final observation it is mentioned the strong need for large amounts of measurement data obtained in power networks. Next to that, theoretical and practical power-system knowledge and signal processing knowledge are needed. This conveys the need for a close cooperation among power-system researchers, signal processing researchers, and network operators.

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