Electric Power Systems Research 79 (2009) 1408–1415

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A new reactive, distortion and non-active power measurement method for nonstationary waveforms using wavelet packet transform

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ARTICLE INFO

Article history:
Received 15 September 2007
Accepted 22 April 2009
Available online 7 June 2009

Keywords:
Power system harmonics
Wavelet packet transform
Nonstationary waveforms

ABSTRACT

The definitions of power components that are contained in the IEEE Standard 1459-2000 [IEEE Std. 1459-2000, Definitions for the measurement of electric quantities under sinusoidal, non-sinusoidal, balanced or unbalanced conditions, 2000] are based on the Fourier transform (FT) which is suitable only for the case of stationary waveforms. However, for nonstationary waveforms, the FT produces large errors. Therefore, the power components based on this transform become inaccurate. A new approach based on the wavelet packet transform (WPT) for defining these power components is developed in this paper. The advantages of using the wavelet transform are that it can accurately represent and measure nonstationary waveforms, providing uniform frequency bands while preserving both time and frequency information. In addition, this paper addresses the problem of choosing the most appropriate mother wavelet for power components measurements. The results of applying both approaches to stationary and nonstationary waveforms show that the currently used definitions according to the IEEE Standard 1459-2000 result in large errors for the case of nonstationary waveforms while the proposed approach (WPT based) gives more accurate results in this situation.

1. Introduction

Electric power system waveforms can be classified into two types; stationary and nonstationary waveforms. Stationary waveform is defined as a waveform where all its statistical properties do not change with time [2]. The main loads that generate stationary waveforms are personal computers (PCs), televisions, energy saving lamps, HVDC links, flexible ac transmission (FACT) and other power-electronic converters.

On the other hand, nonstationary waveforms are those with statistical properties that change with time and are also called time evolving waveforms. Electric arc furnaces (EAFs), electric welders, capacitor switching, motor starting and transformers energization are examples of loads that generate these nonstationary waveforms.

Power components such as active, reactive, distortion, non-active and apparent power are defined by the IEEE Standard 1459-2000 [1] using fast Fourier transform (FFT). For the case of stationary waveforms, the FFT can provide accurate results; however, for the case of nonstationary waveforms, the FFT introduces large errors due to spectral leakage and picket fence phenomena [3]. Fig. 1 shows a stationary current waveform of frequency 180 Hz with amplitude 50 A. The FFT spectrum shows exactly the third harmonic at 180 Hz and amplitude 50 with no spectral leakage. Fig. 2 shows an example of a nonstationary current waveform at 180 Hz. The current amplitude changes with time; it starts from an initial value of 50 A for 0.083 s and then the amplitude drops to 10 A. The FFT spectrum shows a 30 A component at 180 Hz (which does not exist in the original waveform) plus other components that are spread along the frequency axis. Spectral leakage is very clear here which leads to inaccurate results. Moreover the time at which the waveform drops from 50 to 10 A is not accessible through the FFT because it provides amplitude–frequency spectrum so therefore time information is lost.

Based on this fact, the measurement of these power components according to the IEEE Standard 1459-2000 [1] would be acceptable only for the case of stationary waveforms but it would not be acceptable for nonstationary waveforms which exist in large amounts due to today's electric power system non-stop dynamic operating conditions.

The wavelet transform, which is considered as a time–frequency transform, is capable of handling and accurately representing nonstationary waveforms in too many applications in different disciplines [4–30]. The power of the wavelet stems from the fact that it can provide variable frequency resolution while preserving time information. This is an important requirement for the analysis and measurement of the nonstationary waveforms which possess time-variant characteristics and this is lost when using the FFT.

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0378-7796/$ – see front matter.
doi:10.1016/j.epsr.2009.04.018

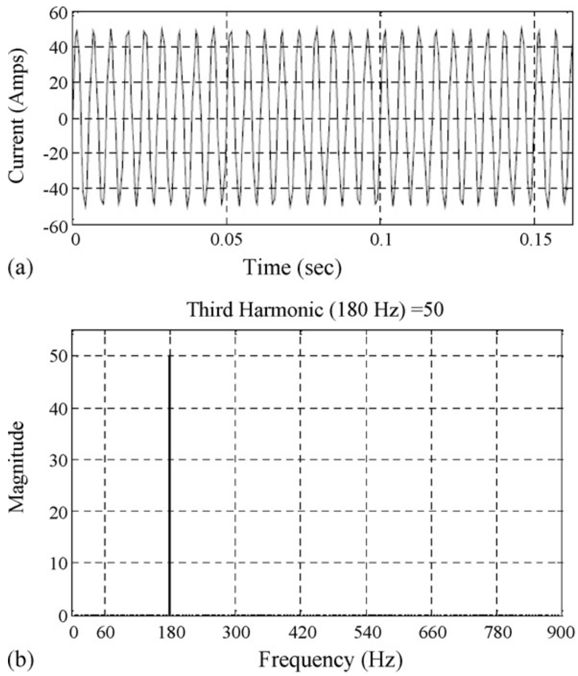

Fig. 1. Stationary waveform. (a) Time-domain waveform and (b) FFT spectrum.

Our previous work for calculating and measuring the power components was concerned with steady-state harmonic distortion using discrete wavelet transform as in [31,32], while [33,34] were concerned with harmonics and inter-harmonics distortion using wavelet packet transform.

This paper, introduces a new approach for calculating and measuring the active, reactive, non-active, distortion and apparent power for the case of electric power system nonstationary waveforms or time-varying harmonics using the wavelet packet transform (WPT).

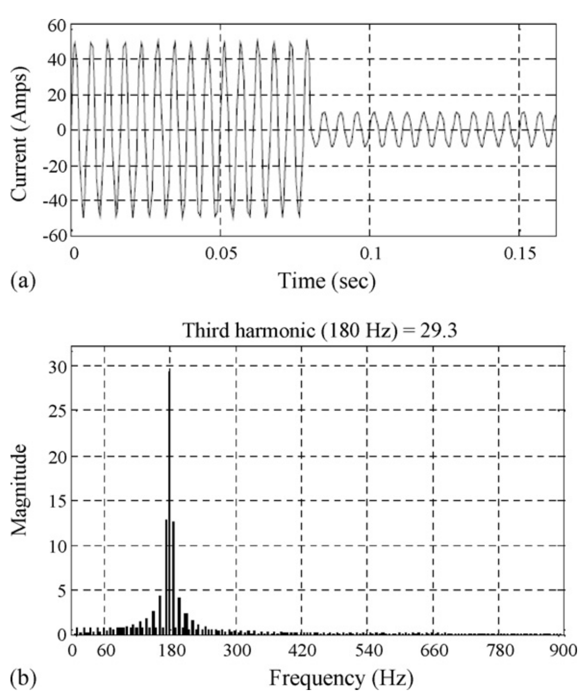

Fig. 2. Nonstationary waveform. (a) Time-domain waveform and (b) FFT spectrum.

Section 2 briefly reviews the FFT based power components definitions that have been adopted by the IEEE Standard 1459-2000 [1], while Section 3 provides the basics for the wavelet transform and wavelet packet transform. Section 4 contains the new approach that has been developed for defining these power components using WPT, Section 5 includes numerical examples and finally Section 6 contains our conclusions.

2. Power components according to the IEEE Standard 1459-2000

In nonsinusoidal situations the voltage and current can be expressed according to [1] as follows:

$$v(t) = v_1(t) + v_H(t), \qquad i(t) = i_1(t) + i_H(t) \tag{1}$$

$$v_1(t) = \sqrt{2}V_1 \sin(\omega t - \alpha_1), \qquad i_1(t) = \sqrt{2}I_1 \sin(\omega t - \beta_1) \tag{2}$$

$$v_H = \sqrt{2}\sum_{h \neq 1} V_h \sin(h\omega t - \alpha_h) \tag{3}$$

$$i_H = \sqrt{2}\sum_{h \neq 1} I_h \sin(h\omega t - \beta_h) \tag{4}$$

where the subscript '1' indicates the fundamental component, while the subscripts 'H' and 'h' refer to the non-fundamental components and the harmonic order. Here α_1, β_1 represent the fundamental voltage and current phase angle, respectively, while α_H and β_H represent the harmonic voltage and current phase angle, respectively.

The fundamental, harmonic and total active powers are defined as

$$P_1 = V_1 I_1 \cos\theta_1, \qquad P_H = \sum_{h \neq 1} V_h I_h \cos\theta_h, \qquad \theta_1 = \alpha_1 - \beta_1 \tag{5}$$

$$P = P_1 + P_H \tag{6}$$

where the RMS value for the voltage and currents are

$$V = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt}, \qquad I = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{7}$$

$$V^2 = V_1^2 + V_H^2, \qquad V_H^2 = \sum_{h \neq 1} V_h^2 \tag{8}$$

$$I^2 = I_1^2 + I_H^2, \qquad I_H^2 = \sum_{h \neq 1} I_h^2 \tag{9}$$

The fundamental reactive power, Budeanu's harmonic reactive power and Budeanu's reactive power are defined as

$$Q_1 = V_1 I_1 \sin\theta_1, \qquad Q_H = \sum_{h \neq 1} V_h I_h \sin\theta_h, \qquad Q_B = Q_1 + Q_{BH} \tag{10}$$

The apparent power S, non-active power N and Budeanu's distortion power D_B are

$$S = VI, \qquad N = \sqrt{S^2 - P^2}, \qquad D_B = \sqrt{N^2 - Q_B^2} \tag{11}$$

$$S^2 = P^2 + Q_B^2 + D_B^2 \tag{12}$$

3. Wavelet transform

3.1. Introduction

The wavelet transform is a time–frequency representation of any waveform $s(t)$ using a stretched (or squeezed) and translated basis function called wavelet. This basis function is called mother