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Determining Five Kinds of Power Quality Disturbances by Using Statistical Methods and Wavelet Energy Coefficients

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Abstract. In this paper, it is tried to compare two methods for determining pure sine and five kinds of power quality disturbances (PQD) such as voltage sag, voltage swell, voltage with harmonics, transients and flicker. These methods are statistical methods and wavelet based effective feature extraction method. Before classifying power quality signals, one of the feature extraction method must be applied. So, these two methods are compared. Firstly, statistical methods are applied to PQD. It is observed that if PQD signal is created at the zero crossing points of the voltage signal, statistical methods give satisfactory result. But occurrence of disturbances at these points is not guaranteed in real systems. It is seen that first method may confuse some PQD according to occurrence place of disturbances. So second method is used for extracting the energy distribution features of PQD constituted in eight different points (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0). Parseval's theorem and multi-resolution analysis (MRA) technique of discrete wavelet technique (DWT) are used. It is observed that this method gives satisfactory results for eight different points.

Key words

Flicker, power quality disturbances, statistical method, transients, voltage sag, voltage swell, voltage with harmonics.

1. Introduction

Electrical power quality (PQ) has become an important issue in the last few years. Voltages obtained from three phase alternative current supply should be sinusoidal and continuous. Also, these voltages are 120 out of phase and have identical magnitudes [1]. In case of this condition is not satisfied, this means PQ is poor. PQ is defined as ''the concept of powering and grounding sensitive equipment in a manner that is suitable to operation ofthat equipment" in the IEEE Std. 1159-1995 [2]. PQ problem appeared when poor operation or malfunction occurred in customers' equipment [3, 4].

PQD such as voltage sag, voltage swell, harmonics, transients and flicker cause poor PQ. Many problems occur as a result of poor PQ. These problems can be misoperations, malfunctions, instabilities, short life and failure of end-use equipment [5]. Reliable and fast detection of disturbances and causes of disturbances must be known before any appropriate mitigating action can be taken. Classification must be done accurately for analyzing supply of disturbances and determining effects of disturbances.

Determination of PQD waveforms is traditionally was examined by visually. This method was too difficult for engineers [6]. The detection of PQD was done by using pre-determined threshold value. Large amounts of data logged by the monitoring systems is difficult with this method [7]. Also Fourier transform (FT), fast Fourier transform (FFT), fractal based method [8], S transform method [9], short time power and correlation transform method [10], WT method [11, 12], Hilbert transform [13], chirp-Z transform (CZT) method [14], d-q transform method [15] and Kalman filter [16] are used for the detection of PQD.

In this study, pure sine and five kinds of PQD such as voltage sag, voltage swell, voltage with harmonics, transients and flicker are tried to determine. For this purpose two methods are used and compared. Firstly, statistical method is applied to constituted PQD. This method gives satisfactory results if these PQD are generated at zero crossing point of voltage signal. But when they are not generated at zero crossing point of voltage signal, some constituted PQD can be confused. So second method is needed. The energy distribution features of PQD and pure sine are tried to extract by using Parseval's theorem and MRA technique of DWT. This method gives satisfactory result whether these PQD are generated at zero crossing point of voltage signal or not.

2. Statistical Method

Mean value (μ), standard deviation (σ), skewness (c) and kurtosis coefficients (k) are given as in the equations below for PQD signals. Equation (1) shows mean value for each x_i component: [17]

$$\mu = \frac{1}{N}\sum_{i=1}^{n} x_i \tag{1}$$

N indicates total data number. Standard deviation is calculated in Equation (2):

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i-\mu)^2} \tag{2}$$

Skewness coefficients are given in Equation (3). Symmetry disturbance of distribution is shown with these coefficients. When skewness coefficients are calculated, Gamma 1 statistical is used.

$$c = \frac{\sum_{i=1}^{N}(x(i)-\mu)^3}{N\sigma^3} \tag{3}$$

Equation (4) shows kurtosis coefficients. Sharpness of maximum value is shown with these coefficients.

$$k = \frac{\sum_{i=1}^{N}(x(i)-\mu)^4}{N\sigma^4} \tag{4}$$

These coefficients have variations when disturbance happen [17].

3. Discrete Wavelet Transform

Wavelet transform has been proven to very efficient in signal analysis [18].The wavelet analysis block transforms the distorted signal into different time-frequency scales. Wavelet analysis employs the expansion and contraction of basis function to detect simultaneously the characteristics of global and local of measured signal [19]. Wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves). The basis function (Mother Wavelet) is dilated at low frequencies and compressed at high frequencies, so that large windows are used to obtain the low frequency components of the signal, while small windows reflect discontinuities.

Discrete Wavelet transform is shown in Equation (5):

$$Wf(m,n) = 2^{-m/2}\int f(t)\varphi(2^{-m}t-n)dt \tag{5}$$

where m is frequency, n is time. In practice wavelet series are in Equation (6):

$$f(t) = \sum_{k=-\infty}^{+\infty} C_k\phi(t-k) + \sum_{k=-\infty}\sum_{k=-\infty}^{+\infty} d_{j,k}\varphi(2^j t-k) \tag{6}$$

$$\phi(x) = \sqrt{2}\sum_n h_0\phi(2x-n) \tag{7}$$

where $\phi(x)$ is scale function and h_0 is low pass filter coefficient.

$$\varphi(x) = \sqrt{2}\sum_n h_1\varphi(2x-n) \tag{8}$$

Where $\varphi(x)$ is wavelet function and h_1 is high pass filter coefficient.

4. Parseval's Theorem in DWT Application

The square sum of the spectrum coefficients of the Fourier transform in the frequency domain is equal to total energy of resistance according to Parseval's theorem. In this theorem, a discrete signal f[n] is assumed as the current and it flows through the 1Ω resistance [19].

$$\frac{1}{N}\sum_n |f(n)|^2 = \sum_k |a_k|^2 \quad [1,19] \tag{9}$$

where N indicates sampling period and a_k is the spectrum coefficients of the Fourier transform. Eqution (9) is used to obtain equation (10) in Parseval's theorem. So the theorem is applied to the DWT.

$$\frac{1}{N}\sum_t |f(t)|^2 = \frac{1}{N_J}\sum_k |a_J(k)|^2 + \sum_{J=1}^{J}\left(\frac{1}{N_J}\sum_k |d_J(k)|^2\right) \tag{10}$$

Energy of approximation coefficients is shown in the first term on the right of Equation (10) and energy of detail coefficients is shown in the second term on the left of Equation (10). Energy distribution features of the detail version of distorted signal are given in the second term. So the second term is applied to extract the features of power disturbance [19]. Equation (11) gives the process.

$$P_J = \frac{1}{N_J}\sum_k |d_{j,k}|^2 = \frac{\|d_J\|^2}{N_J} \tag{11}$$

where $\|d_J\|$ is the norm of the expansion coefficient d_j.

Equation (11) is normalized by Equation (12).

$$P_J^D = (P_J)^{1/2} \tag{12}$$

5. Determining PQD by Using Statistical Method

Skewness and kurtosis coefficients of PQD are given in Fig.1. PQD are created in eight different points (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0) respectively. Eight different zones are stated side by side. Sampling frequency is 25.6 kHz.

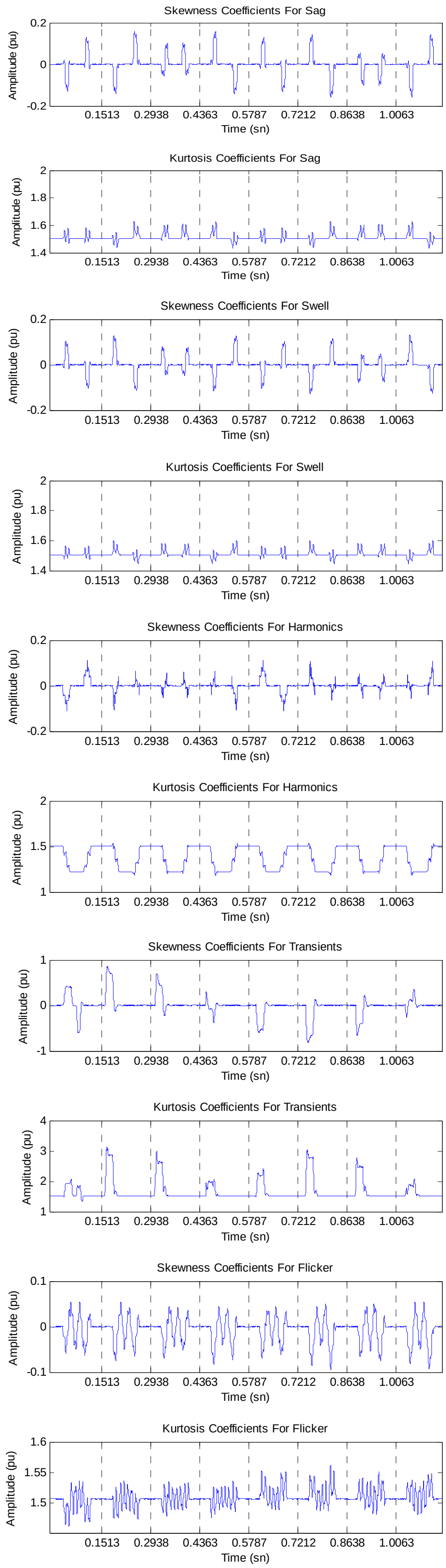


Fig. 1. Skewness and kurtosis coefficients of PQD constituted in eight different points.

Zone 1 has the healthy first two periods, the following three periods of it includes PQD (zero crossing points of signal) and following two periods are healthy in Fig. 1 for all PQD. Skewness coefficients decrease when voltage sag occurs at Zone 1 as a reference and skewness coefficients rise when voltage sag lasts. Kurtosis coefficients of voltage sag are similar as kurtosis coefficients of voltage swell. So skewness coefficients obtained from different zones are compared with Zone 1 for voltage swell and voltage sag. Skewness coefficients rise or decrease according to occuring and lasting of voltage swell in Zone 1 for voltage swell. If Zone 1 is considered as a reference and compared with the other zones, skewness and kurtosis coefficients obtained from 90^0, 135^0, 180^0, 225^0, 270^0 delays aren't same as 0^0 is seen. Skewness coefficients of voltage with harmonics seems to skewness coefficients of voltage sag. Voltage with harmonics and voltage sag are distinguished with their kurtosis coefficients. Skewness and kurtosis coefficients obtained from all zones are different for all zones in transient signals. Skewness and kurtosis coefficients of flicker don't resemble to skewness and kurtosis coefficients of other PQD. It is seen that this statistical method gives different results for voltage sag, voltage swell and transients depending on occurrence place of PQD.

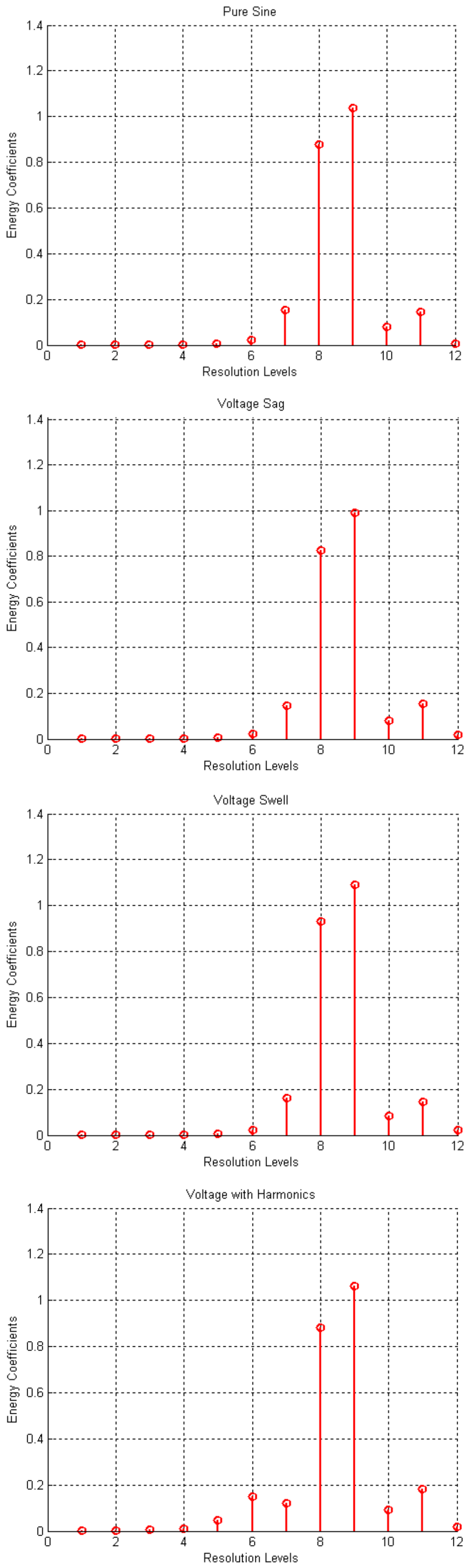
6. Determining PQD by Wavelet Energy Coefficients

Voltage sag, voltage swell, voltage with harmonics, transients and flicker are generated at duration of 150 periods length by using MATLAB in order to distinguish these PQD. Reference is pure sine voltage. Sampling frequency is 25.6 kHz. The energy of distorted signal can be resolved at different resolution levels in different ways. It is seen in Equation (11). It depends on the power quality problem. So the coefficient d_j of the detailed version at each resolution level is used for extracting the features of the distorted signal. Daubechies-4 wavelet function is chosen. Equation (11) gives the energy distributions of detail coefficients. Frequency band intervals of wavelet transformation at multi resolution analysis are seen in Table 1.

Table I. – Frequency Band Intervals at Multi Resolution Analysis

Resolution Levels	Frequency Intervals
d1	6400-12800
d2	3200-6400
d3	1600-3200
d4	800-1600
d5	400-800
d6	200-400
d7	100-200
d8	50-100
d9	25-50
d10	12.5-25
d11	6.25-12.5
d12	3.125-6.25
d13	1.5625-3.125
a13	0-1.5625

Energy distribution features of pure sine and PQD are seen in Fig. 2. Energy distribution features of pure sine are considered as reference for comparing energy distribution features of pure sine and PQD.



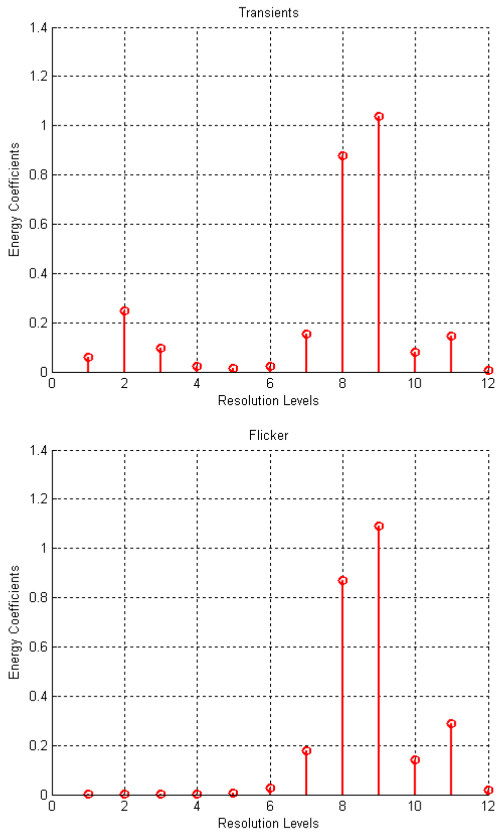


Fig. 2. Energy distribution diagram of pure sine, voltage sag, voltage swell, voltage with harmonics, transients and flicker.

Voltage sag and voltage swell are at power frequency 50 Hz. Their amplitudes change. So d8 and d9 energy coefficients are important for voltage sag and voltage swell. It is seen in Table 1. Decrease in d8 and d9 coefficients for voltage sag and increase in d8 and d9 coefficients for voltage swell are seen when energy distribution of voltage sag and voltage swell are compared with energy distribution of pure sine. Increase in d1 and d2 energy coefficients are seen for 4 kHz transients. It is seen that increase in d6 and d7 coefficients for harmonics with 3^{rd} and 5^{th}. For 58 Hz flicker has 8 Hz flicker frequency, increase in d11 coefficients are seen.

PQD were created zero crossing points of the voltage signal in previous papers for obtaining coefficients of energy distribution. In practice, occurrences of disturbances at these points are not guaranteed. So PQD are constituted in eight different points (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0) in this paper. These points have different characteristics. Variation of energy level/energy levels which are important for PQD constituted in eight different points (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0) are examined.

Variation of d8 and d9 coefficients are seen in Fig. 3 and Fig. 4 for voltage swell and voltage sag in eight different points, respectively. Variation of d2 coefficients for transients are seen in Fig. 5 in eight different points. It is not examined the effect of occurrence place of voltage with harmonics and flicker so as to these disturbances can occur all of the signal.

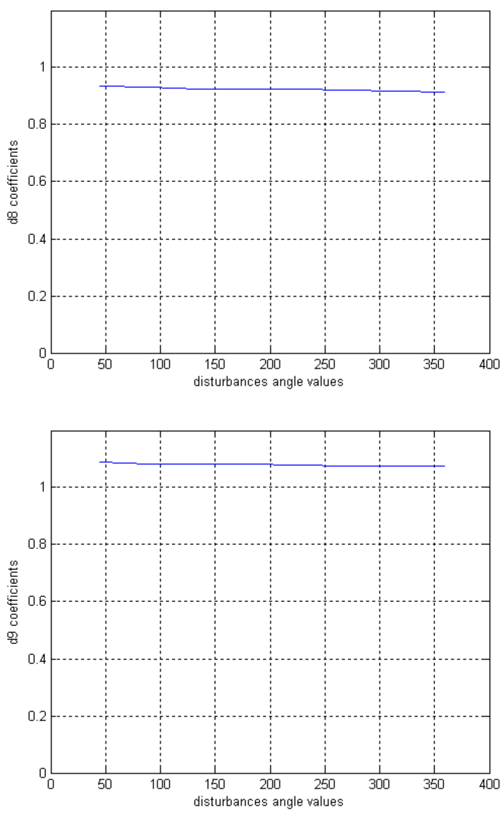


Fig. 3. Variations of d8 and d9 coefficients for signal consisting of voltage swell in eight different points, respectively.

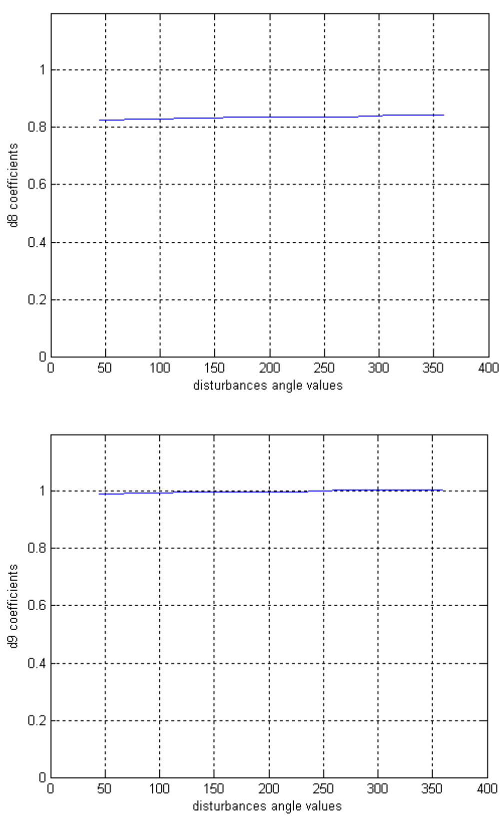


Fig. 4. Variations of d8 and d9 coefficients for signal consisting of voltage sag in eight different points, respectively.

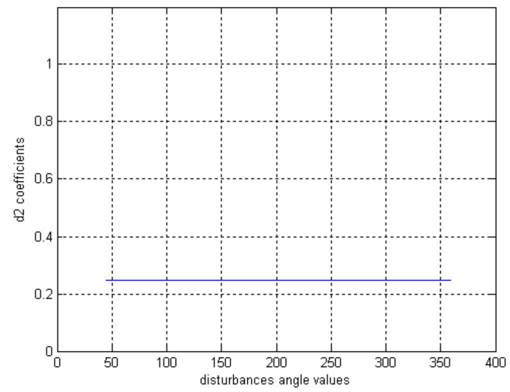


Fig. 5. Variations of d2 coefficients for transients in eight different points.

7. Conclusion

Pure sine and five kinds of PQD such as voltage sag, voltage swell, voltage with harmonics, transients and flicker are determined by using two methods. These methods are statistical methods and wavelet based effective feature extraction method. These methods are compared. Firstly statistical methods are applied to five kinds of PQD. Skewness and kurtosis coefficients are calculated for these PQD. These methods give satisfactory results when PQD are created zero crossing points of the voltage signal. In practice, occurrences of disturbances at these points are not guaranteed. So PQD are generated in 0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0 and 315^0. These eight different points have different characteristics. Skewness and kurtosis coefficients of PQD are calculated in local frames. These coefficients are achieved with one period long sliding frame. It is seen that while occurrence place of PQD affects this method for voltage sag, voltage swell and transients but it does not affect this method for voltage with harmonics and flicker. When these five kinds of PQD are examined, this is important problem. So it is needed another method. It is tried to extract the energy distribution features of PQD and pure sine by using Parseval's theorem and MRA technique of DWT. When energy distribution diagrams of PQD and pure sine, it is seen that this method gives satisfactory results. PQD and pure sine can be separated visually. Afterwards PQD are generated in 0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0 and 315^0. Variation of energy level/energy levels which are important for PQD constituted in eight different points (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0) are examined. d8 and d9 coefficients are important for voltage sag and swell. Because these PQD are at power system frequency 50 Hz. While their amplitude change but their frequency are constant at 50 Hz. It is observed that variation of d8 and d9 coefficients at eight different points for voltage sag and voltage swell are not significant and variation of d2 coefficients at eight different points for transients are at constant value. It is not examined the effect of occurrence place of voltage with harmonics and flicker so as to these disturbances can occur all of the signal. Consequently, it is seen that occurrence place of PQD does not affect second method for five PQD and gives satisfactory results when compared with first method. In future real time data will be applied and compare with simulation results.

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