# Comparison of Statistical Methods and Wavelet Energy Coefficients for Determining Two Common PQ Disturbances: Sag and Swell

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## Abstract

**This paper presents statistical methods and wavelet based effective feature extraction method for power quality (PQ) disturbance classification problem. The PQ signals used in this study are two common types named as swell and sag. First, the signals consisting of sag and swell are determined by using statistical methods. In the previous studies, validation of PQ disturbances for obtaining skewness and kurtosis coefficients were created at the zero crossing points of the voltage signal. In practice, occurrence of disturbances at these points is not guaranteed. So in this paper, disturbances are constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics. Skewness and kurtosis coefficients of the constituted signals are calculated in local frames. These coefficients are obtained during one period long sliding frame. It has been observed that in swell and sag events this statistical method gives different results depending on moment occurrence of disturbances. So another method is needed. Multi-resolution analysis (MRA) technique of discrete wavelet technique (DWT) and Parseval's theorem are employed to extract the energy distribution features of sag and swell signals constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$).**

## 1. Introduction

It is required that voltages obtained from three phase alternative current supply have identical magnitudes and are 120 out of phase. These voltages should be sinusoidal and continuous [1]. If voltage goes beyond these expected or accepted criterions, this means PQ is poor. A simpler definition might be: "PQ is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy" [2].

Harmonics, voltage fluctuations, voltage sag, voltage swell, transients, flicker, impulses, notches, momentary interruptions, wave faults cause poor PQ. Poor PQ may bring about many problems such as short life, instabilities, malfunctions, misoperations and failure of end-use equipment [3]. In order to improve PQ, the sources and causes of such disturbances must be known before appropriate mitigating actions can be taken [1]. If the disturbances classification is done accurately, effects of disturbances can be determined and the supply of disturbances can be analyzed. So appropriate precautions can be taken for these disturbances.

In this paper; signals consisting of only voltage swell and voltage sag are dealt with. According to IEEE 1159-1995, voltage swell lasted from 0.5 period to 1 minute in power frequency is the increase in effective value of voltage. Typically magnitudes are between 1.1 pu and 1.8 pu [4]. Voltage sag lasted from 0.5 period to 1 minute in power frequency is the decrease in effective value of voltage. Typically magnitudes are between 0.1 pu and 0.9 pu [5].

In this research, the signals consisting of PQ disturbances (swell, sag) are generated to simulate common types of PQ events. First, the signals are determined by using statistical methods. The signals are created at the zero crossing points of the voltage signal. In practice, occurrence of disturbances at these points is not guaranteed. For this reason, disturbances are constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics in order to understand if this statistical methods is dependent or independent from the moment of occurrence of disturbances. The generated signals have a sampling rate 512 samples per cycle, at a frequency of 50 Hz. It is accepted that total seven periods of which the first two periods are healthy, the following three periods consist of disturbances (any of the signals consisting of voltage swell and voltage sag) and again the following two periods are healthy. In Fig.3-4, disturbances are generated in sequentially $0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$ degrees delay. Skewness and kurtosis coefficients are obtained during one period long sliding frame. In order to compare skewness and kurtosis coefficients obtained from PQ disturbances at different points, total seven periods accepted for every disturbance which is constituted on the same axis. It has been observed that in common PQ events (swell and sag) this statistical method gives different results depending on the moment of occurrence of disturbances. So it is needed another method for distinguishing PQ disturbances. This method is based on wavelet and Parseval theorem. First, two distorted signals (swell and sag) are generated at zero crossing points of the voltage signals by using MATLAB. Then Daubechies-4 wavelet function is adopted for signals and then Parseval's theorem is employed to extract the energy distribution features of PQ signals. It's seen that this method has different characteristics for PQ signals generated in this study. Then this methodology is adopted for PQ signals constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics in order to understand if this method is dependent or independent from the moment of occurrence of disturbances. It is seen that proposed methodology is independent from the occurrence of disturbances.

## 2. Statistical Method

Mean value $(\mu)$, standard deviation $(\sigma)$, skewness $(c)$

and kurtosis coefficients $(k)$ are calculated for voltage sag and swell signals. Terms that will be calculated according to each $x_i$ component and total data number $(N)$ can be given with equations below. Mean value is calculated in Equation (1): [6]

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

Where µ is arithmetic average.
Standard deviation is like Equation (2).

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

Skewness coefficients which indicate symmetry disturbance of distribution is calculated in Equation (3).

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

Gamma 1 statistical is used in calculation of skewness coefficients. Kurtosis coefficients which indicate sharpness of maximum value is calculated in Equation (4).

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

When disturbance occurs both skewness and kurtosis coefficients change [6].

## 3. Discrete Wavelet Transform (DWT)

Wavelet transform has been proven to very efficient in signal analysis [7].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 [8]. 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. In Fig. 1 Mallat's wavelet tree is shown.

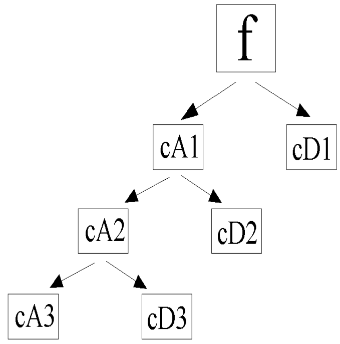


**Fig 1:** Signal decomposition (Mallat's wavelet tree). F is discreet signal, A is approximation and D is detail.

## 4. Parseval's Theorem in DWT Application

In Parseval's theorem, assuming a discrete signal $f[n]$ is the current that flows through the 1Ω resistance, then the consumptive energy of the resistance is equal to the square sum of the spectrum coefficients of the Fourier transform in the frequency domain [8].

$$\frac{1}{N}\sum_n |f(n)|^2 = \sum_k |a_k|^2 \quad [1,8] \tag{9}$$

where N is sampling period and $a_k$ is the spectrum coefficients of the Fourier transform.

To apply the theorem to the DWT, we use equation (9) to obtain equation (10) that is Parseval's theorem in the DWT application [8].

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

The first term on the right of Equation (10) denotes energy of approximation coefficients and the second term on the left of Equation (10) denotes energy of detail coefficients. The second term giving that energy distribution features of the detail version of distorted signal will be employed to extract the features of power disturbance [8].The process can be represented mathematically by Equation (11).

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

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

We make the Equation (11) to normalize by Equation (12).

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

## 5. Determining PQ Disturbances By Using Statistical Method

In Fig. 3-4 eight different zones stated side by side indicates skewness and kurtosis coefficients of PQ disturbances constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) sequentially.

### A. *Analysis On Voltage Swell Signal Constituted In Different Points*

Signals consisting of voltage swell were generated in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$). Fig.2 shows voltage swell constituted in $0^0$ and $45^0$ as an example. Amplitude of voltage swells generated in this study is %120 pu.

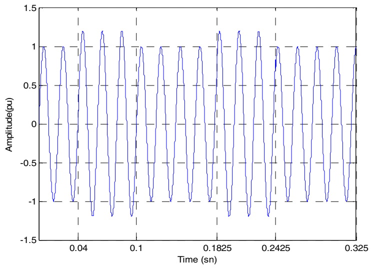


**Fig 2:** Simulated signal consisting of voltage swells

Figure 3 shows skewness and kurtosis coefficients of Zone 1 of which the first two periods are healthy, the following three periods consist of swell disturbance (zero crossing points of signal) and again the following two periods are healthy. In Zone 1, it's seen that when voltage swell occurs, skewness coefficients rise and when voltage swell lasts, skewness coefficients decrease. We consider Zone 1 as a reference and if we compare with the signal consisting of voltage swell generated in other zones, it's seen that skewness and kurtosis coefficients obtained from $90^0$, $135^0$, $180^0$, $225^0$, $270^0$ delays aren't same as 0 degrees delay. So it's concluded that skewness and kurtosis coefficients obtained for voltage swell depends on moment occurrence of voltage swell.

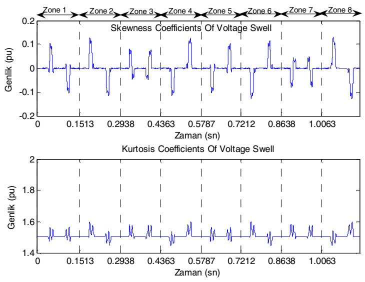


**Fig 3:** Skewness and kurtosis coefficient of voltage swell signal constituted in different points

*B. Analysis On Voltage Sag Signal Constituted In Different Points*

Signals consisting of voltage sag of which amplitudes were %80 pu were constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) because of having different characteristics. Simulations of these signals were done at MATLAB in order to obtain skewness and kurtosis coefficients.

In Fig 4 it's seen that when voltage sag occurs at Zone 1, skewness coefficients decrease and when voltage swell lasts, skewness coefficients rise. Sag disturbance were created zero crossing points of signal at Zone 1. If skewness coefficients in Fig. 3 obtained from Zone 1 are compared with skewness coefficients in Fig. 4 obtained from Zone 1, it's seen that compared coefficient zones are inverses of each other. However, it's seen that kurtosis coefficients in Fig 3 looks like kurtosis coefficients in Fig 4. Therefore for signals consisting of voltage swell or voltage sag skewness coefficients obtained from different zones were compared with Zone 1.

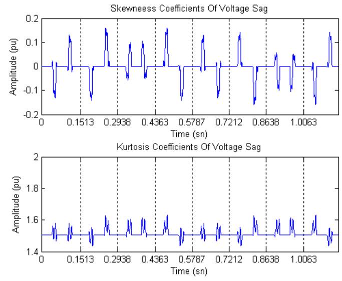


**Fig 4:** Skewness and kurtosis coefficient of voltage sag signal constituted in different points

## 6. Determining PQ Disturbances by Using Wavelet Energy Coefficients

In order to distinguish voltage sag and swell, pure sine voltage, voltage consisting of sag and voltage consisting of swell were generated at duration of 150 periods length by using MATLAB. Pure sine voltage was considered as a reference. Sampling period is 25.6 kHz. As seen in Equation 11, the energy of distorted signal can be partitioned at different resolution levels in different ways depending on the power quality problem. Therefore, we will examine the coefficient $d_j$ of the detailed version at each resolution level to extract the features of the distorted signal for classifying different power quality problems. Daubechies-4 wavelet function was adopted to perform discrete wavelet transform. Energy distributions of detail coefficients were obtained by using Equation 11.

In Table 1 frequency band intervals of wavelet transformation at multi resolution analysis are seen.

Table 1: 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 |

Fig. 5, 6, 7 shows energy distribution features of pure sine and signals consisting of voltage sag and swell. In order to compare energy distribution features of pure sine and other power quality disturbances, energy distribution features of pure sine is obtained in Fig. 5.

As seen in Table 1, d8 and d9 energy coefficients are important for voltage sag and voltage swell because voltage sag and voltage swell are at power frequency 50 Hz only their amplitudes change. When energy distribution of PQ disturbances (sag and swell) is compared with energy distribution of pure sine as a reference it is seen that decrease

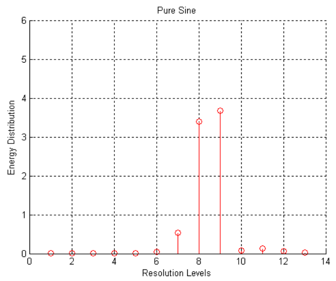


**Fig 5:** Energy distribution diagram of pure sine wave

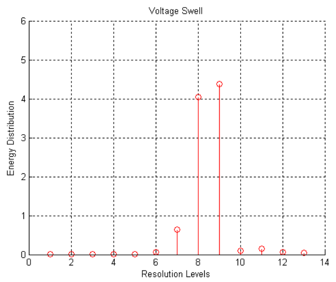


**Fig 6:** Energy distribution diagram of voltage swell

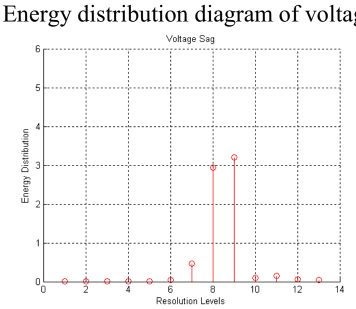


**Fig 7:** Energy distribution diagram of voltage sag

in d8 and d9 coefficients for voltage sag and increase in d8 and d9 coefficients for voltage swell. Up to now, validations of PQ disturbances for obtaining coefficients of energy distribution were created zero crossing points of the voltage signal. In practice, occurrences of disturbances at these points are not guaranteed. So in this paper, disturbances are constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics. It's examined that variation of energy level or energy levels which are important for PQ disturbance constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$). Importance of energy level or energy levels for PQ disturbance is decided by using Table 1.

## 7. Voltage Swell Constituted In Different Points

When voltage swell occurs in power system frequency of signal cannot change only amplitude of signal changes. So signal is at power frequency 50 Hz. d8 and d9 coefficients are important for voltage swell. In Fig.8 variation of d8 and d9 coefficients are seen for signal consisting of voltage swell in eight different points.

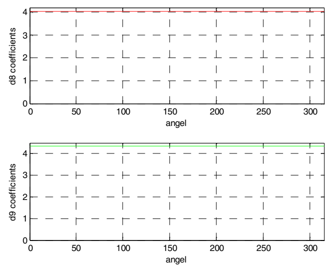


**Fig 8**: Variations of d8 and d9 coefficients for eight different angles

## 8. Voltage Sag Constituted In Different Points

When voltage sag occurs in power system frequency of signal cannot change only amplitude of signal changes. So signal is at power frequency 50 Hz. d8 and d9 coefficients are important for voltage sag. In Fig 9 variation of d8 and d9 coefficients are seen for signal consisting of voltage sag in eight different points.

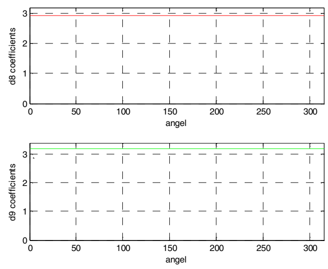


**Fig 9:** Variations of d8 and d9 coefficients versus eight different angles

## 9. Comparison of Statistical Method to Wavelet Energy Coefficients for Determining PQ Disturbances

To compare statistical method to wavelet energy coefficients, data from a real system is acquired. The system is the secondary side of a 33,6 kV. transformer which is monitored under NPQR ( National Power Quality Project) by a PQ monitor designed and implemented by TÜBİTAK-UZAY. The sampling frequency of the monitor is 25.6 kHz and a sample waveform of voltage with 0.4 s. length is given in Fig.10 the sample waveform involves both swell and sag disturbances and this can be a good example for comparing the methods mentioned.

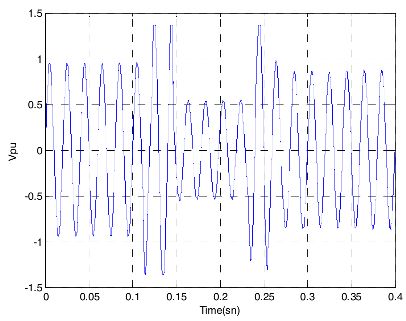


**Fig10**: Sample waveform taken from real system

Variations of skewness and kurtosis coefficients for the sample are given in Fig. 11. It can be seen in Fig.11 that skewness coefficients that are used for determining swell and sag disturbances decrease at the moment of swell because the moment of occurrence is not at zero crossing point and therefore it is determined as sag disturbance. Similarly, skewness coefficients increase at the moment of sag and it is determined as swell disturbance. These problems continue with some PQ disturbances occurring different angles.

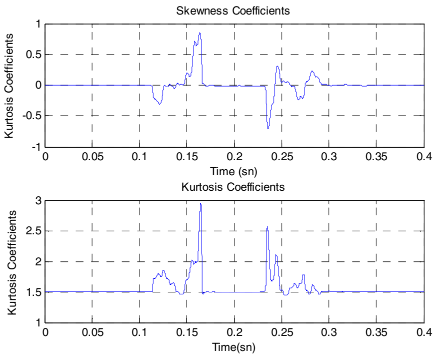


**Fig 11:** Variations of skewness and kurtosis coefficients

Waveforms of wavelet energy coefficients are given in Fig. 12. These waveforms are obtained with the calculations of d8 and d9 energy coefficients which are important for sag and swell disturbances at each period. d8 and d9 thresholds for a referred 20 periods pure sine are 0.2994 and 0.4442, respectively. These energies increase and decrease as expected at the occurrence of swell and sag disturbances. The moment of occurrence doesn't affect these coefficients and as a result it can be seen that this method is independent from the moment of occurrences.

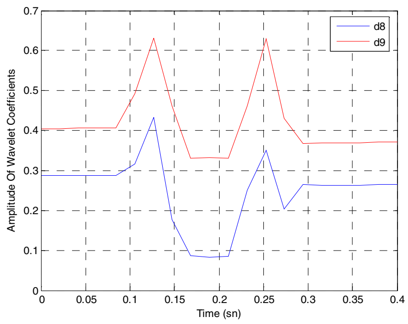


**Fig 12:** Waveforms of wavelet energy coefficients

## 10. Conclusion

The PQ signals used in this study are two common types named swell and sag. First, the signals consisting of sag and swell are determined by using statistical methods. In the previous studies, validation of PQ disturbances for obtaining skewness and kurtosis coefficients were created zero crossing points of the voltage signal. In practice, occurrences of disturbances at these points are not guaranteed. So in this paper, disturbances are constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics. Skewness and kurtosis coefficients of constituted signals are calculated in local frames. These coefficients are obtained during one period long sliding frame. It has been observed that in swell and sag events this statistical method gives different results depending on moment occurrence of disturbances. So it was needed another method. Multi-resolution analysis (MRA) technique of discrete wavelet technique (DWT) and Parseval's theorem are employed to extract the energy distribution features of sag and swell signals. Energy distribution diagrams give satisfactory results and voltage sag and swell can be separated visually by looking these diagrams. Then disturbances are constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$) having different characteristics. It's examined that variation of energy level or energy levels which are important for PQ disturbance constituted in eight different points ($0^0$, $45^0$, $90^0$, $135^0$, $180^0$, $225^0$, $270^0$, $315^0$). Importance of energy level or energy levels for PQ disturbance is decided by using Table 1. d8 and d9 coefficients are important for voltage sag and swell. When voltage swell occurs d8 coefficients change between 4.0289-4.0398 with %0.269 variation while d9 coefficients change between 4.3594-4.3726 with %0.301 variations. When voltage sag occurs d8 coefficients change between 2.9384-2.947 with %0.291 variation while d9 coefficients change between 3.1952-3.2055 with %0.321 variations. It's seen that variation of energy level or energy levels which are important for PQ disturbance constituted in eight different points isn't considerable.

## Acknowledgement


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