Detection and Localization of Power Quality Disturbances Using Space Vector Wavelet Transform: 
A New Three Phase Approach

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Abstract—This paper presents a new three phase approach based on space vector discrete wavelet transform to detect and localize power quality disturbances (PQD). This approach provides high resolution time frequency representation used to detect and localize the disturbances. Supplementary information about detected disturbances (duration and frequency spectrum) extracted in order to characterize them. From the monitored three phase voltage signals a space vector is generated using Clarke Transformation. For normal system voltage the space vector is of constant magnitude signal of 1.5pu. If PQD occurs in any one or all phases of system, results in change of magnitude or frequency or both of the space vector. The space vector is decomposed using Discrete Wavelet Transform (DWT) and the magnitude of detail coefficients is used to detect and localize the PQ disturbances. The proposed technique monitors all three phase voltages simultaneously therefore can offer fast detection than existing single phase based techniques. A practical power system network is used to validate the proposed technique.

Keywords—space vector, discrete wavelet transform, multiresolution signal decomposition, Clarke transform, power quality disturbance, wavelet coefficients.

I. INTRODUCTION

With wide use of power electronics and other nonlinear, time variant loads in the power distribution network, power quality has become a critical issue and attracted attention in power industry and academic. The power quality problems such as voltage sags and swells, impulses, notches, interruptions, flicker or harmonic distortion, which may cause failure or malfunction of equipments, need to be detected and localized to find the cause and source of the disturbances so that their effect can be neutralized using suitable corrective and preventive measures. These disturbances cover a broad frequency range, significantly different magnitude variations and can be stationary or non stationary [1-2].

A number of methods for detection and classification of individual types of disturbances that occurs on the power line have been published [3-9]. In [3], unique features that characterize power quality events and methodologies to extract them from recorded voltage and or current waveforms using Fourier and wavelet transforms presented. The Fourier Transform (FT) based approaches have been successfully applied to stationary signals where the properties of the signals do not vary with time. Consequently, the Short Time Fourier Transform (STFT) uses a time frequency window to localize—in-time-sharp transitions are used for non stationary signals. However, the STFT uses a fixed time time-frequency window, which is inadequate for practical power system disturbances encountering a wide range of frequencies. Therefore, there is a need to apply an analysis technique adaptable to all types of PQD signal required for effective detection and localization. Also, there is need for further improvement of the PQ monitoring systems, which can detect and localize all types of PQD and efficient in terms of computational resources.

In this paper, a new three phase technique to detect and localize the PQD is presented. It monitors all three phase voltages simultaneously which eliminates the limitations of existing single phase based techniques. This paper is organized as follows. Section II describes the different signal processing methods used for detection of PQD. Both Clarke Transform and discrete wavelet transform used to generate a space vector and detect PQD are discussed in section III. In section IV the new proposed space vector discrete wavelet transform (SVDWT) technique for disturbance detection is explained. Finally the conclusion presented in section V.

II. DISTURBANCE DETECTION METHODS

Various signal processing techniques used in power quality disturbances detection are briefly discussed in following subsections.

A. Root Mean Square (RMS)

Although the RMS is not an inherent signal processing technique, yet it is the most used tool. A great advantage of this algorithm is its simplicity, speed of calculation and less requirement of memory. However its dependency of window length is considered as a disadvantage. One cycle window length will give better results in terms of profile than a half cycle window [10]. Moreover, rms does not distinguish fundamental frequency, harmonics or noise components and phase angle information get lost.

B. Fourier Transform (FT)

The Fourier transform (FT) technique is commonly used in practice to provide harmonic information about the signals monitored. FT transforms the signal from time-domain to the frequency-domain. With this tool it is possible to have an
estimation of the fundamental amplitude and its harmonics with a reasonable approximation. FT performs well for estimation of periodic signals in stationary state; however, as reported in [2 & 9], FT alone is not sufficient for the feature extraction due to the transient nature of most of the PQ signals where the time information is required.

C. Short Time Fourier Transform (STFT)

An improvement to FT technique, the short time Fourier transform (STFT) is commonly known as a sliding window version of the FFT, was implemented in [16], where the voltage disturbances were analyzed in time frequency domain. However, STFT has fixed frequency resolution for all frequency and has shown to be more suitable for harmonic analysis of voltage disturbances than binary tree filters or wavelets when is applied to study voltage dips.

D. Wavelet Transform (WT)

Latest advances in electrical power quality monitoring techniques are based on extraction of disturbances data using time frequency analysis. Time frequency analysis is more suitable to detect PQ disturbances which vary in a wide range of time and frequency. Wavelet transformation has unique ability to examine the signal in time and frequency ranges, which makes WT a promising tool for power quality disturbances analysis [6-8].

The disadvantage of all above methods is that all are single phase based techniques. That takes more time to detect and identify the PQD. Another problem is that the practical disturbances are of different magnitude and having different frequency spectrum no single method explained above can detect or identify them.

In this paper new technique based on three phase approach using space vector discrete wavelet transform (SVDWT) is presented, which eliminates the limitation of existing single phase based techniques.

III. CLARKE TRANSFORM AND DWT

A. Clarke Transform

The Clarke transform is commonly utilized in real time motor control applications. This is due to the fact that in a three phase system the phase quantities are not independent variables. Therefore, it is possible to transform a three phase system to an equivalent two phase representation.

In this paper above concept is applied to offer an alternative method which is able to process all three phase voltages simultaneously.

The Clarke Transform [14] is defined as in (1) transforms the three phase voltages \( V_a, V_b \) and \( V_c \) in three components. The first two components of CT \( X_a \) and \( X_b \) forms a space vector given by eq. (2). The third component of CT represents the zero sequence component \( X_0 \). Eq. (3) gives the magnitude of space vector.

\[
\begin{bmatrix}
X_a[k] \\
X_b[k] \\
X_0[k]
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
1/2 & 1/2 & 1/2
\end{bmatrix} \begin{bmatrix}
V_a[k] \\
V_b[k] \\
V_c[k]
\end{bmatrix}
\]

\[S_V[k] = X_a[k] + jX_b[k]
\]

In [13, 14, 15, and 17], space vector applications for power quality disturbance detection and classification are explained. Space vector analyzed by FT for detection and classification of sags and swells explained in [14]. In [15], space vector with dual hysteretic filter investigated to detect and mitigate PQD.

To test the proposed method power distribution network is modeled using MATLAB SIMULINK as shown in Fig.1.

![Fig. 1 Practical power system network (Simulink model)](image)

The power distribution network considered has a three phase distribution transformer of 100 KV A, 11 KV/415 V (Dyg) supplies different loads, which produce the disturbances during their operation or at the time of switching. The capacitor switching transients get generated at the time of switching the 5 KVAR power factor improvement capacitor bank. Three phase converter of 35 KW used to supply DC power, which produces the notching. The sags and swells on different phases are generated by reducing or increasing the phase voltages. Seven different types of PQD given in Table 1 are considered to generate data for testing. The considered disturbances are of 1-phase sag and swell, combined 1-phase sag and swell (equal and unequal magnitudes), 3-phase balanced sag and swell, 3-phase capacitor switching transients and three phase converter operation notching. Notching is a steady state (S.S.) event. Capacitor switching is a nonstationary disturbance occurred at starting time \( t_{st} = 0.012 \) sec. All type of sag and swell disturbances occur at \( t = 0.025 \)sec. and ended at time \( t_{ed} = 0.125 \) sec.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>PQ Disturbance</th>
<th>Duration (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Capacitor switching</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>Notching</td>
<td>S.S.</td>
</tr>
<tr>
<td>3</td>
<td>Single phase sag</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>Single phase swell</td>
<td>0.025</td>
</tr>
<tr>
<td>5</td>
<td>Combined sag &amp; swell</td>
<td>0.025</td>
</tr>
<tr>
<td>6</td>
<td>Three phase sag &amp; swell</td>
<td>0.025</td>
</tr>
</tbody>
</table>

TABLE.II. PQD CONSIDERED FOR SIMULATION
a) Normal 3-phase supply, b) 80% sag in phase A, c) 120% swell in phase A, d) Equal sag and swell (80% & 120%) in two phases, e) Unequal sag and swell (80% & 140%) in two phases, f) Three phase balanced voltage sag, g) Three phase balanced voltage swell, h) Capacitor switching transients, i) Three phase converter operation (notching)

Fig. 2 shows the three phase voltage and space vector waveforms for different types of disturbances mentioned in table1. In Fig. 2(a), space vector for normal condition of three phase voltage is shown. It is observed that for normal voltage the space vector is of constant magnitude. If PQD occur in any one or more phases, during the disturbance interval, the smoothness (magnitude or frequency or both) of the space vector get changed as in Fig. 2(b) to 2(i). In Fig. 2(b) and 2(c), the effect of 1-phase sag of 80% and 1-phase swell of 120% on characteristics of space vector is shown. for sag and swell of 80% and 120% magnitude on phase The effect on space vector for combined sag and swell of 80% (20% drop in voltage on one phase) and 120% (20% rise in voltage on other phase) on two different phases occurred at same time instant is shown in Fig. 2(d). In Fig. 2(e), the effect of combined sag and swell of 80% and 140% (20% drop and 40% rise in voltage on two different phases) respectively is shown. The space vector characteristics for three phase balanced voltage sag and swell of 80% and 140% magnitude on each phase voltage is shown in Fig. 2(f) and 2(g) respectively. Fig. 2(h) and 2(i) show the space vector magnitude due to disturbances generated by three phase capacitor switching (transients) and converter operation (notching).

From the results it can be conclude that when the PQD occur the characteristics such as frequency contents and magnitude of space vector get changed. It is also observed that the space vector has unique for different group of PQD.

This paper applies above concept to offer an alternative method which is able to detect and localize the PQD in three phase voltage signals simultaneously by analyzing the space vector using DWT.

B. Descrete Wavelet Transform (DWT)

The DWT is one useful mathematical tool to decompose disturbance signals in time domain in to several scales at different levels of resolution through dilation and translation [8-9]. This property of DWT is known as multiscale signal decomposition (MSD) technique which decomposes a signal in to scales with different time and frequency resolutions. In power quality disturbance (PQD) signals, many disturbances contain the sharp edges, transitions, and jumps. Through dyadic filter banks MSD can easily be achieved. So, MSD technique discriminates disturbances from the original one and analyzes them separately. The ability of wavelet to focus on short time intervals for high frequency components and long intervals for low frequency components improves the analysis of signals with localized impulses and oscillations, particularly in the presence of a fundamental and low order harmonic.

There are many types of DWT in regard to the choice of mother wavelet function; however, in practical applications a
dyadic transformation of DWT with multiresolution analysis (MRA) is usually used for detecting PQD [9]. The wavelet coefficients of the sampled signals, \( s(n) \), decomposed by \( L \)-scale MSD defined as:

\[
d_j(k) = \sum_{n=1}^{N} s(n) h_j(n - 2^j k) \quad j = 1, 2, \ldots, L \tag{4}
\]

\[
c_L(k) = \sum_{n=1}^{N} s(n) g_L(n - 2^L k) \tag{5}
\]

Where \( d_j(k) \) is the detail coefficients at the \( j \)th scale, \( c_L(k) \) the approximate coefficients at the last scale, \( h \) and \( g \) denote the impulse responses followed by filtering in MSD, and \( N \) is the number of sampled data in a finite interval. Since the family of dilated wavelet constitutes an orthogonal basis, it is then possible to exactly reconstruct the original signal from its coefficients.

Power quality problems are characterized by their maximum amplitudes, crest voltages, RMS, frequency, statistics of wavelet coefficients, instantaneous voltage drops, number of notches, duration of transients etc. These characteristics are unique identifying features of different PQD.

Wavelet transform can obtain both time and frequency information of the signals which is very attractive feature in analyzing time series because time localization of spectral components can be obtained.

One advantage of wavelet analysis is its ability to perform local analysis. Wavelet analysis is able to reveal signal aspects that other analysis techniques miss, such as trends, breakdown points, discontinuities, etc. This property of wavelet analysis is used to detect and localize the PQD.

IV. SVDWT Technique For Disturbance Detection And Localization

The space vector generated of different PQD has been analyzed using wavelet multiresolution signal decomposition (MSD) to detect and localize the disturbance. SVDWT analyses used in this paper detect variation in the space vector magnitude and frequency and determine the disturbance interval. To apply wavelet transform to identify time intervals following steps are taken:

i) Generate PQD space vector signal data with known initial and final times.

ii) Apply DWT with suitable mother wavelet.

iii) Identify the disturbances intervals with the help of wavelet coefficients.

Different algorithms have been applied by many researchers for fast detection of PQD [14-16]. In this paper MRA algorithm has been applied on generated PQD data to test the proposed technique. Many commercial power quality monitoring instruments have sampling rates of 256 samples/cycle since the majority of power quality events have frequency contents below 5 KHz [1]. Hence, the PQD data generated is sampled at 12.8 KHz of sampling frequency for 8 cycles i.e. 2048 samples and is analyzed to six levels of resolution using eq. (4) and (5). Higher level scaling of wavelet is more suitable but taking the benefit of computational efficiency and practical consideration six level decomposition with Daubechies mother wavelet Daub6 is observed sufficient to get appropriate information.

By using MATLAB Wavelet Blockset and DSP (Digital Signal Processing) tools SVDWT algorithm is implemented. Table 2 shows the frequency bands of approximate and detail WTC after SVDWT analysis for six decomposition levels.

It can be seen that DWT coefficients at the interval of disturbance are much higher than other times. First scale detail coefficient signal \( (d_1) \) includes the highest frequency band detects the disturbance instantaneously. The high scale approximate coefficient signal \( (a_6 & d_6) \) detects low frequency band of signal in sixth scale. This decomposition gives time and frequency information of signal with good resolution.

<table>
<thead>
<tr>
<th>Approx. WTC</th>
<th>Frequency Band (Hz)</th>
<th>Detail WTC</th>
<th>Frequency Band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1 level</td>
<td>0-1250</td>
<td>d1 level</td>
<td>3200-6400</td>
</tr>
<tr>
<td>a2 level</td>
<td>0-1600</td>
<td>d2 level</td>
<td>1600-3200</td>
</tr>
<tr>
<td>a3 level</td>
<td>0-500</td>
<td>d3 level</td>
<td>800-1600</td>
</tr>
<tr>
<td>a4 level</td>
<td>0-400</td>
<td>d4 level</td>
<td>400-800</td>
</tr>
<tr>
<td>a5 level</td>
<td>0-200</td>
<td>d5 level</td>
<td>200-400</td>
</tr>
<tr>
<td>a6 level</td>
<td>0-100</td>
<td>d6 level</td>
<td>100-200</td>
</tr>
<tr>
<td>a7 level</td>
<td>0-50</td>
<td>d7 level</td>
<td>50-100</td>
</tr>
<tr>
<td>a8 level</td>
<td>0-25</td>
<td>d8 level</td>
<td>35-50</td>
</tr>
<tr>
<td>a9 level</td>
<td>0-12.5</td>
<td>d9 level</td>
<td>12.5-25</td>
</tr>
<tr>
<td>a10 level</td>
<td>0-6.25</td>
<td>d10 level</td>
<td>6.25-12.5</td>
</tr>
<tr>
<td>a11 level</td>
<td>0-3.125</td>
<td>d11 level</td>
<td>3.125-6.25</td>
</tr>
<tr>
<td>a12 level</td>
<td>0-1.56</td>
<td>d12 level</td>
<td>1.56-3.125</td>
</tr>
<tr>
<td>a13 level</td>
<td>0-0.78</td>
<td>d13 level</td>
<td>0.78-1.56</td>
</tr>
</tbody>
</table>
Fig. 3 SVDWT analysis of PQD

(a) Normal three phase supply, (b) 1-ph sag, (c) 1-ph swell, (d) Equal 1-ph sag and swell, (e) Unequal 1-ph sag and swell, (f) Balanced 3-ph sag, (g) Balanced 3-ph swell, (h) Capacitor switching transients, (i) 3-ph converter notching.

Fig. 3(a) -3(i) shows the SVDWT analysis of PQD signals using MRA. Though the decomposition is performed up to six levels only three levels detail coefficient signals (d6, d3, and d1) are shown in Fig. 3. The five different signals shown in the waveforms are space vector, detailed WT coefficients at levels d6, d3, d1 and squared level 1 (sq.d1). The reason for squaring wavelet coefficient is to reduce the effect of noise in the signals. In Fig. 3(a), for normal three phase voltage the space vector magnitude is constant and the SVDWT analysis gives zero values of WTC at all scales. Fig. 3(b) to 3(i) shows the effect of changed characteristics of space vector during the disturbance on WTC values at different resolution levels. It is observed that at the time of occurrence and at the end of disturbance the WTC values much higher than other time. This feature of WT is utilized to know the start time (t_{st}) and the end time (t_{ed}) of disturbance. Then eq. (6) is used to measure disturbance duration Δt and applied to categorize the disturbance as instantaneous, momentary or temporary.

\[ \Delta t = t_{ed} - t_{st} \]  

At the lowest scale (scale 1) the mother wavelet is most localized in time and oscillates most rapidly within a short period of time. As the wavelet goes to higher scales, the analyzing wavelet become less localized in time and oscillate less due to the dilation. The lower decomposition levels (1-3) of Figs. 3(b) to 3(g) hardly show any nonzero coefficients due to absence of frequency components at these high frequencies except at the start and end of PQD. Higher resolution levels,
corresponding to lower frequencies start to pick up the disturbances. Fig. 3(h) shows the start of the transient phenomenon that decays gradually with time. This may give sense to soon sort of discharging or decaying transients, involving capacitor energization. Fig. 3(i) shows the transient phenomenon due to switching of semiconductor devices of the converter. This is high frequency phenomenon, get detected at lower scales.

This proves that as the scale increases the accuracy of disturbance time resolution decreases, and frequency resolution increases. Hence good time localization is at low scale and good frequency localization at high scale.

V. CONCLUSIONS

A new three phase technique (SVDWT) explained in this paper is a powerful tool for feature extraction of power quality disturbances. The detection and time localization of PQD is fast and efficient. From the results it can be concluded that the SVDWT is suitable tool to analyze PQ disturbances when time and frequency information required simultaneously. Also it can detect almost all types of PQD very fast and accurately. The only drawback is that it fails to detect gradual changing events.

REFERENCES