Abstract—This paper presents an application of Empirical Wavelet Transform (EWT) to the power signals for estimation of Power quality Indices (PQIs). This technique first estimates the frequency components present in the distorted signal, computes the boundaries and extracts mono components based on the boundaries computed. Several stationary and non-stationary signals have been analyzed to show the effectiveness of this technique. The PQIs obtained with the proposed technique has been compared with Discrete Wavelet Technique (DWT) and the proposed technique is found to be effective and superior over DWT. The results confirm that the EWT efficiently extracts the mono component signals from the time varying distorted signal and hence this technique would be suitable for real time PQ indices estimation.

Keywords—Empirical Wavelet Transform (EWT), Harmonics, IEEE Std. 1459-2000, Power Quality Indices (PQIs).

I. INTRODUCTION

Recently, Power Quality has gained significant importance with the deregulation of Power System and has become more critical due to the emergence of nonlinear device based new technologies. The power quality disturbances can be either stationary or non-stationary. Since most of the power quality disturbances are non-stationary in nature, an advanced signal processing technique is required to accurately decompose the non-stationary power signal into mono components and determine the instantaneous frequency. IEEE std. 1459-2000 [1], [2] is a standard that provides definitions for calculating the traditional PQIs. The fast computing Fourier Transform (FT), which is still being used, limits its application in analyzing the non-stationary signals because of the spectral leakage [3]. Moreover, FFT does not give time information i.e., where those spectral components appear in time. To overcome this limitation, the Short Time Fourier Transform (STFT) based PQIs for aperiodic signals are suggested in [4]. The recent signal processing techniques for estimation of power quality indices and algorithms for classifying power disturbances are well explained in [5], [6].

The existing PQIs have been reformulated and applied to the power signals using the Discrete Wavelet Transform (DWT) [7], [8]. The DWT provides non-uniform frequency bands, moreover, if suitable sampling frequency and adequate decomposition levels are not chosen, then two or more frequency components will be present in the single sub band. Wavelet Packet Transform (WPT) is an extension of the Wavelet Transform, which is effective in analyzing non-stationary signal and can accurately measure the electrical quantities [9]-[11]. Even though the WPT shows better accuracy, the frequency subdivision scheme is based on a constant prescribed ratio, limiting its adaptability. The suitable selection of sampling frequency and adequate choice of mother wavelet [12] can minimize the leakage errors between wavelet levels [13], [14]. Therefore, it is revealed that the analysis of a signal with the DWT or the WPT requires a proper selection of mother wavelet, decomposition levels and sampling frequency. Moreover, the selection of these parameters differs for the signals containing different frequency components and this limits the application of DWT and WPT to analyze real time non-stationary signals.

In this paper, a fast and adaptive wavelet technique, Empirical Wavelet Transform (EWT) proposed recently [15], is considered to extract the individual frequency components and thereby compute the PQIs. This method has an advantage of adaptability according to the analyzed signal and can isolate the different modes of the signal. The performance of this method has been investigated on ten different signals by taking time varying frequencies and phase angles into account. The accurate frequency estimation and adaptive wavelets makes this technique well suited to analyze the stationary and highly distorted non-stationary signals.

The organization of this paper is as follows, section II presents a brief review of EWT technique required to analyze the signal. In section III, the EWT based PQ indices of single phase system are listed. Section IV considers several test signals and the PQ Indices are calculated for the coefficients obtained from the EWT. This section also provides results which exhibit the effectiveness of this technique. Finally, conclusions are drawn in section V.

II. EMPIRICAL WAVELET TRANSFORM

In [15], Jerome Gilles proposed a new time frequency technique to decompose a multicomponent signal using the adaptive wavelets. This method works as follows. i) Firstly, determine the frequency components of the input signal using FFT. ii) Then, different modes are extracted by proper
segmentation of the Fourier spectrum and iii) Apply scaling and wavelet functions corresponding to each detected support. Segmentation of the Fourier spectrum is the most important step that provides the adaptability to this technique according to the analyzed signal.

Consider a discrete signal \( x(k) \) which is sampled at a frequency of \( f_\text{s} \). First, apply the FFT to the signal \( x(k) \), obtain the frequency spectrum and then find the set of maxima \( M = \{ \Omega_i \}_{i=1,2,...,M} \) in the Fourier spectrum and deduce their corresponding frequency \( \omega_i \). Here \( M \) is the total number of frequency components present in the real signal. Now, with this set of frequencies \( \omega = \{ \omega_i \}_{i=1,2,...,M} \) corresponding to maxima, obtain the boundaries \( \varphi_n \) of each segment (the dotted line in Fig. 1) as the center of two consecutive maxima.

\[
\Omega_i = \frac{\omega_n + \omega_{n+1}}{2}
\]

where, \( \omega_n \), \( \omega_{n+1} \) are the frequencies and \( \Omega_n \) is their corresponding boundary and the set is \( \Omega = \{ \Omega_i \}_{i=1,2,...,M-1} \)

Fig. 1 illustrates the detection of boundaries from the Fourier spectrum, where, the red colored triangles shown correspond to the maxima and the dotted lines represent the boundaries computed. It can be clearly seen from the figure that the algorithm is able to isolate the different modes. After obtaining the set of boundaries, a bank of \( M \) wavelet filters comprising of one low pass filter and \( M-1 \) band pass filters are defined based on the well detected boundaries.

The expressions for Fourier transform of the empirical wavelets and scaling function are given by [15]

\[
\psi(\omega) = \begin{cases} 
1 & \text{if } \ (1+\gamma)\Omega_i \leq |\omega| \leq (1-\gamma)\Omega_i \\
\cos\left(\frac{\pi}{2} \beta(\gamma,\Omega_i) \right) & \text{if } \ (1-\gamma)\Omega_i \leq |\omega| \leq (1+\gamma)\Omega_i \\
\sin\left(\frac{\pi}{2} \beta(\gamma,\Omega_i) \right) & \text{if } \ (-1-\gamma)\Omega_i \leq |\omega| \leq (-1+\gamma)\Omega_i \\
0 & \text{otherwise}
\end{cases}
\] (2)

and

\[
\phi(\omega) = \begin{cases} 
1 & \text{if } \ |\omega| \leq (1-\gamma)\Omega_i \\
\cos\left(\frac{\pi}{2} \beta(\gamma,\Omega_i) \right) & \text{if } \ (1-\gamma)\Omega_i \leq |\omega| \leq (1+\gamma)\Omega_i \\
0 & \text{otherwise}
\end{cases}
\] (3)

where \( \beta(\gamma,\Omega_i) = \beta\left(\frac{1}{2}\Omega_i |\omega| - (1-\gamma)\Omega_i \right) \)

where, \( \gamma \) is a parameter to ensure no overlap between the two consecutive transitions areas and \( \beta(x) \) is an arbitrary function defined as

\[
\beta(x) = \begin{cases} 
0 & \text{if } \ x \leq 0 \\
1 & \text{if } \ x \geq 1 \\
\beta(x) + \beta(1-x) = 1 & \text{if } \ x \in [0,1]
\end{cases}
\] (4)

Equipped with this set of filters, the EWT can be defined in the similar way as the normal wavelet transform. The approxi-

mate coefficients are obtained by the inner product of the applied signal \( x \), with the empirical scaling function as given below

\[
W_x(1,t) = \langle x, \phi \rangle = \int x(\tau)\phi(\tau-t) d\tau
\] (5)

The detail coefficients are obtained by the inner product of the applied signal \( x \), with empirical wavelets as given below

\[
W_x(i,t) = \langle x, \psi \rangle = \int x(\tau)\psi(\tau-t) d\tau
\] (6)

This shows that this technique can accurately extract the mono frequency components. Since the basis function is generated according to the information contained in the analyzed signal, this approach is more suitable for decomposing the real time signals.

The steps required to analyze the signal and estimate the PQIs using the EWT are as follows.

1. Apply the FFT to the discrete signal \( x(k) \).
2. Estimate the frequency components of the applied signal \( \{\omega_1, \omega_2, ..., \omega_M\} \) and then detect the boundaries \( \{\Omega_1, \Omega_2, ..., \Omega_{M-1}\} \) of each frequency, \( \omega_i \).
3. Perform filtering with the scaling function and empirical wavelets to extract the components of different modes.
4. Compute the single phase PQIs using the formulas listed in section III.

III. EWT BASED SINGLE PHASE POWER QUALITY INDICES

This section presents the brief review of Single Phase PQ indices recommended in [1] and [2] and the EWT based reformulated indices. Consider the single phase system having non sinusoidal periodic voltage and current containing the fundamental and harmonic components as

\[
v(t) = \sum_{n=1}^{H_{\text{max}}} V_n \sin(2\pi f_n t - \theta_n)
\] (7)

and

\[
i(t) = \sum_{n=1}^{H_{\text{max}}} i_n \sin(2\pi f_n t - \alpha_n)
\] (8)

Where, \( t \) is the time and \( H_{\text{max}} \) is the maximum frequency components.
component present in the signal. \(V_n, f_n, \theta_n\) are the amplitude, frequency and phase angle of the \(n\)th component of voltage signal, respectively and \(I_n, f_n, \alpha_n\) are the amplitude, frequency and phase angle of the \(n\)th component of current signal, respectively.

Now, for this set of voltage and current, EWT is applied and the corresponding mono component signal coefficients of voltage and current are obtained. The approximate coefficients are obtained by inner product of the input signal with the scaling function \(\phi_{1,k}\) and the detail coefficients are obtained by inner product of the input signal with the empirical wavelets \(\psi_{j,k}\) as explained in detail in section II of this paper.

\[
W_{1,k} = \langle v(k), \Phi_{1,k} \rangle, \quad W'_{1,k} = \langle i(k), \Phi_{1,k} \rangle
\]

\[
W_{j,k} = \langle v(k), \Psi_{j,k} \rangle, \quad W'_{j,k} = \langle i(k), \Psi_{j,k} \rangle
\]

where, \(j\) is the harmonic level.

A. RMS calculations

The RMS value of the non-sinusoidal voltage \([2]\) is defined as

\[
V_{rms} = \sqrt{V_1^2 + V_H^2} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} W_{1,k}^2 + \frac{1}{N} \sum_{j=1}^{J} \sum_{k=1}^{N} W_{j,k}^2}
\]

The RMS value of the non-sinusoidal current \([2]\) is defined as

\[
I_{rms} = \sqrt{I_1^2 + I_H^2} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} W'_{1,k}^2 + \frac{1}{N} \sum_{j=1}^{J} \sum_{k=1}^{N} W'_{j,k}^2}
\]

where, \(V_1\) and \(I_1\) are the RMS values of the fundamental frequency components of the voltage and current, respectively. \(V_H\) and \(I_H\) are the RMS values of the harmonic voltage and harmonic current. Also \(W_{1,k}\) and \(W'_{1,k}\) are the EWT coefficients of voltage and current at level one and sample \(k\) while \(W_{j,k}\) and \(W'_{j,k}\) are the EWT coefficients of voltage and current at any level \(j\) higher than the level one and sample \(k\). \(N\) is the total length of the signal.

B. Total Harmonic Distortion (THD)

The total harmonic distortion of voltage and current is as follows

\[
V_{thd} = \frac{\sqrt{\sum_{j=2}^{N} I_j^2}}{V_1} \quad \text{and} \quad I_{thd} = \frac{\sqrt{\sum_{j=2}^{N} I_j^2}}{I_1}
\]

C. Active Power

The fundamental active power \(P_1\) is defined as

\[
P_1 = \frac{1}{N} \sum_{k=1}^{N} W_{1,k} \times W'_{1,k}
\]

The harmonic active power is defined as

\[
P_H = \sum_{j=2}^{J} P_j
\]

where, \(P_j = \frac{1}{N} \sum_{k=1}^{N} M_{j,k} \times M'_{j,k}\)

The total active power is defined as the sum of the fundamental active power and the harmonic active power

\[
P = P_1 + P_H
\]

D. Apparent Power

The fundamental apparent power is defined as

\[
S_1 = V_1 I_1
\]

The current distortion power can be defined as

\[
D_I = V_H I_1
\]

The voltage distortion power can be defined as

\[
D_V = V_1 I_H
\]

The total harmonic distortion power is defined as

\[
D_{THD} = \frac{\sqrt{S_1^2 + D_V^2 + D_I^2 + S_H^2}}{S_1}
\]

The total apparent power is

\[
S = \sqrt{S_1^2 + D_{THD}^2 + S_H^2}
\]

The non-fundamental apparent power is defined as

\[
S_N = D_I^2 + D_V^2 + S_H^2
\]

The non-active power \(N\) is defined as

\[
N = \sqrt{S_N^2 - P^2}
\]

E. Reactive Power

The fundamental reactive power is defined as

\[
Q_1 = \sqrt{S_1^2 - P_1^2}
\]

The reactive power at each wavelet level can simply be computed from the corresponding active and apparent power at each wavelet level thus applying the time-domain concept at each wavelet level. The harmonic reactive power at each wavelet level is

\[
Q_j = \sqrt{S_j^2 - P_j^2}
\]

The harmonic reactive power can be define as

\[
Q_H = \sum_{j=2}^{J} Q_j
\]
So the total reactive power also called Budeanu’s reactive power can be defined as

$$Q_B = Q_r + Q_H$$

(28)

F. Power Factors

The displacement power factor is defined as

$$dPF = \frac{P_d}{S}$$

(29)

The total power factor is the ratio of total active power to total apparent power

$$PF = \frac{P}{S}$$

(30)

In order to measure the quality of the transmitted power especially the oscillation behavior, Willems proposed the use of the oscillation power factor

$$PF_{osc} = \frac{P}{\sqrt{P^2 + \frac{1}{2} S^2}} = \sqrt{\frac{1}{2} PF^2}$$

(31)

G. Harmonic Pollution

The harmonic pollution is defined as the ratio of the non-fundamental apparent power to the fundamental apparent power

$$HP = \frac{S_{N}}{S_1}$$

(32)

IV. SIMULATION RESULTS AND DISCUSSIONS

The EWT technique has been verified using 10 test signals considering a variety of stationary and non-stationary conditions. However, due to the space constraints, simulation results of only 2 signals are presented in the paper. The signals are simulated in the MATLAB environment with sampling frequency of 10 kHz i.e., 200 samples/cycle. First, the true values are computed as per the IEEE standard definitions and then the PQIs are calculated for the mono frequency components obtained from the EWT. The percentage difference has been calculated for all the indices using the mathematical expression shown below by

$$\% \text{ difference} = \frac{\text{Indices}_{true} - \text{Indices}_{calculated}}{\text{Indices}_{true}} \times 100$$

(33)

To show the effectiveness of the EWT-, DWT-based PQ Indices are also calculated considering the same parameters proposed in [6] and the percentage difference obtained with these techniques has been compared with the EWT technique. The sampling frequency, mother wavelet and decomposition levels of the DWT are considered same for all the case studies to compare the performance of the DWT and the EWT.

A. Case study-1: Stationary signal

In the first case, the algorithm is tested for stationary signals containing three frequency components each. The frequency, amplitude and phase angle of voltage and current signal are

<table>
<thead>
<tr>
<th>Indices</th>
<th>IEEE standard Definitions</th>
<th>EWT based Indices</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage RMS</td>
<td>$V_1 = 7.0711$ $V_3 = 2.1213$ $V_7 = 0.8485$</td>
<td>$V_{true} = 7.0727$ $V_{true} = 2.1153$ $V_{true} = 0.8497$</td>
<td>$0.0226$</td>
</tr>
<tr>
<td>Current RMS</td>
<td>$I_1 = 1.4142$ $I_3 = 0.5657$ $I_7 = 0.3536$</td>
<td>$I_{true} = 1.4144$ $I_{true} = 0.5651$ $I_{true} = 0.3538$</td>
<td>$0.0141$</td>
</tr>
<tr>
<td>THD</td>
<td>$V_{th} = 0.3231$</td>
<td>$V_{th} = 0.3223$</td>
<td>$0.0000$</td>
</tr>
<tr>
<td>Active Power</td>
<td>$P_1 = 8.6602$ $P_3 = 0.8485$ $P_7 = 0.0778$</td>
<td>$P_{true} = 8.6639$ $P_{true} = 0.8442$ $P_{true} = 0.0783$</td>
<td>$0.0427$</td>
</tr>
<tr>
<td>Apparent Power</td>
<td>$S_1 = 9.9999$ $S_3 = 1.2000$ $S_7 = 0.3006$</td>
<td>$S_{true} = 10.038$ $S_{true} = 1.1953$ $S_{true} = 0.3006$</td>
<td>$0.0000$</td>
</tr>
<tr>
<td>Reactive Power</td>
<td>$Q_1 = 5.000$ $Q_3 = 0.8485$ $Q_7 = 0.2898$</td>
<td>$Q_{true} = 5.0012$ $Q_{true} = 0.8461$ $Q_{true} = 0.2902$</td>
<td>$0.0240$</td>
</tr>
<tr>
<td>Distortion Power</td>
<td>$D_1 = 4.7171$ $D_3 = 3.2310$ $D_7 = 1.5241$</td>
<td>$D_{true} = 4.7151$ $D_{true} = 3.2242$ $D_{true} = 1.5196$</td>
<td>$0.0424$</td>
</tr>
<tr>
<td>Power Factor</td>
<td>$PF = 0.8251$</td>
<td>$PF = 0.8250$</td>
<td>$0.00$</td>
</tr>
<tr>
<td>Harmonic Pollution</td>
<td>$HP = 0.5917$</td>
<td>$HP = 0.5908$</td>
<td>$0.1521$</td>
</tr>
</tbody>
</table>
listed in Table I and II, respectively. The phase angles for all frequency components of voltage signal are zero. In Fig. 2 the extracted mono frequency components of current using the EWT are shown. It can be clearly observed that the EWT technique is able to accurately estimate the actual frequency components present in the distorted signal. It can also be noticed that no two frequency components are combined in any mode and it do not overestimate the number of frequency components.

Table III shows the PQIs obtained by the EWT and also IEEE standards. From the table, it is clear that the EWT is efficient in estimating the indices with very small percentage difference.

Fig. 3 depicts the percentage difference of PQIs calculated by the DWT and the EWT. Since adequate selection of parameters was made for the DWT, the results from DWT are also closer to the true values. However, the EWT provides better results than the DWT.

B. Case study-2: Nonstationary signal

To test the efficiency of the proposed technique for nonstationary signals, a non-stationary voltage and current signal of 5secs duration are simulated. The amplitude, frequency and phase angle of voltage and current signal are listed in Tables IV and V, respectively.

Fig. 4 shows the extracted mono components of the non-stationary current signal. It can be seen that the EWT provides

<table>
<thead>
<tr>
<th>Parameters of Voltage Signal</th>
<th>Time (S)</th>
<th>Amplitude, Frequency and Phase angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.12</td>
<td>10,50,0</td>
<td>0 - 5,150,0 0 - 2,350,0 2,350,0</td>
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<tr>
<td>0.12-0.28</td>
<td>2,100,0</td>
<td>5,150,0 3,5,250,0 2,350,0</td>
</tr>
<tr>
<td>0.28-0.37</td>
<td>10,50,0</td>
<td>0 - 5,150,0 0 - 2,350,0 2,350,0</td>
</tr>
<tr>
<td>0.37-0.50</td>
<td>2,100,0</td>
<td>0 - 5,150,0 0 - 2,350,0 2,350,0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of Current Signal</th>
<th>Time (S)</th>
<th>Amplitude, Frequency and Phase angle</th>
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</thead>
<tbody>
<tr>
<td>0.0-0.12</td>
<td>4,50,30</td>
<td>0 - 1.8,150,0 1.5,250,0 0.7,350,0</td>
</tr>
<tr>
<td>0.12-0.28</td>
<td>0.8,100</td>
<td>1.8,150,0 1.5,250,0 0.7,350,0</td>
</tr>
<tr>
<td>0.28-0.37</td>
<td>1.0949</td>
<td>0 - 1.5,250,0 0.7,350,0</td>
</tr>
<tr>
<td>0.37-0.50</td>
<td>0.4482</td>
<td>0 - 1.5,250,0 0.7,350,0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Quality Indices Obtained</th>
<th>Indices</th>
<th>IEEE standard</th>
<th>EWT based</th>
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<td>V1</td>
<td>7.0711</td>
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<td></td>
<td>V2</td>
<td>1.0777</td>
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<td></td>
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</tr>
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<td>V4</td>
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<td>3.0413</td>
</tr>
<tr>
<td></td>
<td>V5</td>
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<tr>
<td></td>
<td>V6</td>
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<tr>
<td></td>
<td>V7</td>
<td>1.2806</td>
<td>1.2807</td>
</tr>
<tr>
<td></td>
<td>VH</td>
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</tr>
<tr>
<td></td>
<td>Vrms</td>
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</tr>
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<td>Current RMS</td>
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<td></td>
<td>I2</td>
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<tr>
<td></td>
<td>I3</td>
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<td>1.0950</td>
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<tr>
<td></td>
<td>I4</td>
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Fig. 3. Percentage difference for the two approaches for case study-1

Fig. 4. Extracted mono components of the non-stationary current signal
an accurate estimates of the even harmonics as well and decomposes the input signal into different frequency components with respect to time. However the DWT with the same sampling frequency and decomposition level may fail in this case due to the more number of frequency components present in this signal as compared to the signal in the case study-1. Moreover, the DWT will result two or more frequency components in a single sub-band which has been overcome by the EWT.

The PQ indices obtained from the IEEE standard definitions and the EWT for non-stationary signal are listed in Table VI. It can be noted that the maximum difference is just 0.5 percentage, which is considerably less and for rest of the indices the percentage differences is very small. The results clearly indicate that the EWT is more efficient in analyzing the signal with highly non-stationary nature and subsequently estimating the indices.

It can be observed from Fig. 5, that the percentage differences for the DWT based PQ indices are very large. The reason behind this is that the DWT with the same parameters cannot isolate the frequency components accurately if more number of harmonics is present in the signal as compared to case-1. The values obtained using the EWT are close to zero even in the case of non-stationary signal. This is due to the adaptive nature of the basis wavelets used in the EWT, which do not require either selection of mother wavelet or decomposition levels.

V. CONCLUSION

The paper presents an application of a new signal processing technique, Empirical Wavelet Transform to compute the Power Quality Indices as defined in IEEE Std. 1459-2000. The algorithm uses adaptive scaling functions and wavelets for accurately extracting the frequency components present in the signal. The proposed method has been tested on several single phase stationary and non-stationary signals, of which two examples are presented. Based on the results, the EWT proved to be adaptive and also accurate in estimation of PQIs as compared to the DWT, which depends on the mother wavelet, number of levels and sampling frequency. In the case of multiple close frequency components occurring in the signal, EWT is able to isolate them while the DWT will give those close frequency components in the same sub band. The proposed technique is very useful for its application in real time power quality monitoring and can extract relevant characteristics, which can be used as inputs to classify the Power Quality disturbances.

REFERENCES