Wavelet based Power Quality Monitoring in Grid Connected Wind Energy Conversion System

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ABSTRACT
Recently renewable energy resources especially wind power integration has been far increased in the electric power distribution system. To utilize wind power more effectively, wind energy conversion system is interfaced to grid through power electronics interfaces. In this paper, monitoring of various power quality disturbances at the point of common coupling in grid connected wind energy conversion system have been done. Discrete wavelet transform and wavelet energy function are used for detection of power quality disturbances. The grid connected wind energy conversion system is simulated in MATLAB environment. Power quality disturbances such as voltage sag, voltage swell, interruption and harmonics are investigated. A new diagnostic method in which signal is processed using discrete wavelet transform and wavelet energy function is proposed. Simulation results show the usefulness of the proposed method to find out the power quality disturbances in grid-connected wind energy conversion system accurately and quickly. Voltage signal extracted directly at the point of common coupling is used for detection of power quality disturbances.

Keywords
Discrete wavelet transforms (DWT), power quality (PQ), total harmonic distortion (THD), wavelet energy, wind energy conversion system (WECS).

1. INTRODUCTION
Problem to regulate frequency and voltage in the grid has become more significant due to increasing penetration of wind and other renewable energy sources. Use of power electronics as an interface between the wind turbine and the grid improves behavior of wind power system [1, 2]. But the presence of power electronics interface will produce higher order harmonic and inter harmonic currents during operation at variable speed. The effect of harmonics in the power system can cause degradation in power quality at the consumer's terminal, failure in communication system and increased power losses. When a wind turbine is connected to the distribution system, it may cause the problem of voltage sag and swell. Major issues related to the power quality are voltage fluctuation, switching operation of wind turbine on grid, voltage dips on grid, reactive power requirement and harmonics. The grid cannot accept connection of new generation without strict conditions, due to the real power fluctuation and reactive power requirement of wind plants. Therefore, the penetration of wind power in grid requires handling of power quality issues like voltage variation on grid and switching operation of wind turbine.

Whenever any disturbance occur the identification, classification and characterization of disturbance is required to mitigate the problem. According to the characteristics of the event, an appropriate technique is required to process voltage/current waveform in signal processing. The root mean square (RMS) is the most commonly used to measure voltage amplitude in power system for periodic alternating current (AC). Discrete Fourier transform (DFT) is used for periodic signal to find out its frequency content but not adequate where time information is required in signal analysis. It is also applied to non stationary signals but with added windowing to focus on certain period of time. However, it does not provide exact amplitude and phase values for harmonics whose frequencies different from that of the frequency of window function [3, 4]. The short time Fourier transform (STFT) with windowing is applied to non stationary signal to trace the magnitude variations along with time.

Wavelet transform (WT) is suitable both for stationary as well as non stationary signals even in the analysis window. Different wavelet functions have been used by different authors for detection and investigation of voltage events. Authors in [5-8] applied the wavelet decomposition of first level using mother wavelet db6 to detect the starting and end of a voltage sag/dip. Magnitude of detail coefficient changes significantly associated with the high-frequency components present at the starting and at the end of an event. Most of the time peak value, RMS value, square magnitude, standard deviation, wavelet entropy and energy distribution of these wavelet coefficients are proposed for detection and investigation of different disturbances in power system [9-10].

Each power quality disturbances have distinct deviations in energy curve from the energy curve of their analogous pure sinusoidal signal as observed in [11-13]. Hence, wavelet energy can be used for classification of PQ events. It has been reported by Zhu et al. that the energy distribution pattern of a signal with disturbance in the wavelet domain is a unique representation for each power-quality disturbances. Hence energy distribution curve is used to form linguistic rules for classifier [14]. Cagri Kocaman and Muammer Ozdemir have shown that the moment of occurrence of disturbances doesn't affect wavelet coefficients as wavelet energies change as expected on the occurrence of voltage sag and swell, hence emphasizes the importance of energy function especially when exact time of detection of the PQ event becomes very important. It has been observed that wavelet transform is not only suitable for power quality monitoring, but also used for controlling.

A model of direct driven variable speed wind turbine equipped with permanent magnet synchronous generator (PMSG) interfaced to grid has been developed in MATLAB/Simulink® environment as shown in Fig.1 to study various power quality issues. Various disturbances are simulated and analysis has been done using discrete wavelet transform. Fourier transform is widely used traditional technique for finding out total harmonic distortion. However, it is progressively being replaced by wavelet transform and especially used for the post-event processing of the time-varying phenomena.

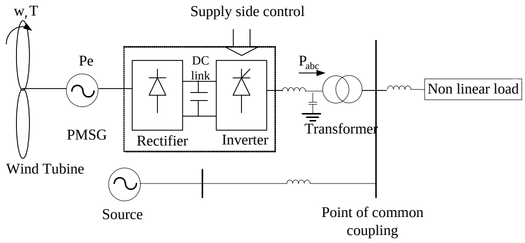

Fig. 1 Model of Grid interfaced wind energy conversion system

This paper is organized in six sections. Standards for integrating wind turbines to grid are mentioned in section 2. Section 3 describes various issues of power quality of variable speed wind turbine connected to grid. Section 4 describes the power quality disturbances detection methodology such as wavelet transform, discrete wavelet transform and multiple resolution analysis. DWT and proposed wavelet energy functions for detection of power quality disturbances in presence of wind energy conversion system are discussed with simulation results in section 5, followed by conclusions in section 6.

2. STANDARDS FOR INTEGRATING WIND TURBINE TO GRID

Integration of wind energy conversion system to the grid largely depends upon the grid characteristics. The basic requirements to connect the WECS to the grid may be summarized as

- Acceptable voltage level to all the consumers connected to the grid should be maintained.
- Power balance should be maintained between all generation units and consumer demand.

The harmonic distortion in system voltage or current may be kept below the limit specified by IEEE 519 standards or IEC 610003-6 [10] as given in Table 1.

Table 1Distortion Limits Recommended by IEEE std 519-1992 for Six Pulse Converters

Odd Harmonics	**Limit in %**	**Even Harmonics**	**Limit in %**
$3^{rd} – 9^{th}$	< 4.0	$2^{nd} – 8^{th}$	< 1.0
$11^{th} – 15^{th}$	< 2.0	$12^{th} – 16^{th}$	< 0.5
$17^{th}– 21^{st}$	< 1.5	$18^{th} – 22^{nd}$	< 0.375
$23^{rd} – 33^{rd}$	< 0.6	$24^{th} – 34^{th}$	< 0.15
$>33^{rd}$	< 0.3	$>34^{th}$	< 0.075

2.1 Power quality requirements

IEC-61400-21 standard outlines the “power quality requirements for grid connected wind turbines”. The IEC methodology goes in three ways-

- Flicker analysis - This method uses current and voltage time series measured at the wind turbine terminals to simulate the voltage fluctuations on a fictitious grid, where wind turbine switching action is the only source of voltage fluctuation.
- Switching operation - Voltage and current transients are measured during switching operation of the wind turbine.
- Harmonic analysis - Carried out by fast Fourier Transform algorithm, the total current harmonic distortion is taken up to 50^{th} harmonic order.

Wind turbines are also responsible for production of inter harmonics apart from harmonics, due to the variable switching frequency of inverter. High frequency harmonics and inter harmonics produced by wind turbines are treated in IEC 61000-4-7, while method for summation of harmonics and inter harmonics is defined in IEC 61000-3-6.

3. POWER QUALITY ISSUES AT POINT OF COMMON COUPLING IN GRID INTERFACED WECS

The power quality problems cause the supply voltage to deviate from its ideal characteristics of constant voltage, constant frequency and purely sinusoidal wave.

3.1 Issue of voltage dips

Voltage dip is a sudden reduction in the value of voltage from 10% to 90 % for a short period of time (1ms to 1 min). The switching of wind turbine results into a sudden reduction of voltage. The calculation of relative percentage change in voltage due to switching operation of wind turbine is done by Eq. (1)

$$d = 100\, K_u \psi_k \frac{S_n}{S_k^*} \tag{1}$$

Where d - relative voltage change,

$K_u \psi_k$ - Voltage change factor,

S_n - Rated apparent power of wind turbine,

S_k^* - Short circuit apparent power of grid.

Acceptable limit of voltage dip is 3% in most of the cases.

3.2 Switching operation of wind turbine on the grid

Switching operations of wind turbine can cause voltage fluctuations such as voltage swell, voltage sag which may cause considerable voltage variation. The maximum permissible limit of switching operation within 10-minute period and 2-hr period are defined in IEC 61400-3-7 standard. Voltage variation during switching operation of wind turbine also depends on grid voltage. According to IEEE standards, voltage sag means reduction in the amplitude of voltage in the range of 0.1 – 0.9 p.u. and then returns to the normal level after a very short time period between 10 ms to 1 min. Voltage sag is caused by short circuit faults in the power network, start up of induction motors or generators and single phase earthed faults. It is also caused by large electrical loads such as electrical motors or arc furnaces at the time of starting with severe current distortion.

3.3 Harmonics

The harmonics distortion is mainly caused by non-linear load such as variable speed drives, electric arc furnaces, SMPS and household equipments. The distorted current due to non linear load when interacts with power system impedance increases harmonics. The voltage and current harmonics (standard IEC 61000-3-6) should be limited to acceptable level at the point of common coupling. According to IEC 61400-21 standards, harmonic measurements are only required for variable speed wind turbine equipped with power electronic converters. The current harmonics due to switching converters also distorts the supply current.

4. METHODOLOGY TO DETECT POWER QUALITY DISTURBANCES

Whenever there is a need to extract precise information from the raw data mostly voltage and current waveforms in power system, signal processing is to be used. Power conditioner designer would need to know the worst case disturbance levels in more detail. Both the magnitude and phase angle are equally very important for the conditioner operation.

WT is more appropriate than the Fourier techniques, if one is not sure about exact frequency components in the signal. The wavelet transform has been used for extracting power quality disturbances such as voltage sag and swell, impulsive and oscillatory transients, voltage fluctuation and notching. In wavelet transform time-domain signal pass through various high pass and low pass filters. This filter-bank operation decomposes the signal into high frequency and low frequency components. This procedure is repeated till it has decomposed the signal to a certain pre-define level. This operation is known as sub-band decomposition. A contracted version of the mother wavelet is used for temporal analysis of signal which corresponds to high frequency, while a dilated version of mother wavelet corresponds to low frequency and is used for frequency analysis.

Wavelet transform is classified into discrete wavelet transforms (DWT) and continuous wavelet transforms (CWT). The prime difference between discrete wavelet transform and continuous wavelet transform is that, discrete wavelet transform uses an explicit subset of scale and translation values and continuous wavelet transform uses all possible scales and translation. All the wavelet functions used in the transformation are derived from the mother wavelet through translation (τ) and scaling (s).

$$X_{WT}(\tau, s) = \frac{1}{\sqrt{s}} \int x(t).\varphi^* \frac{(t-\tau)}{s}\, dt \qquad (2)$$

In continuous wavelet transform as given in Eq. (2), where *x (t)* is the signal to be analyzed, basis function *φ(t)* is the mother wavelet.

4.1 Discrete Wavelet Transform

Discrete wavelet transform (DWT) converts a time domain discretized signal into its corresponding wavelet domain. Principally, the discrete wavelet transformation has two phases- determination of wavelet coefficients and calculation of detailed and approximated version of the original signal, in different scales of resolutions in the time domain. In filtering process the original signal is passed through two complementary filters and produces approximate and detail coefficients.

The discrete wavelet transform is discretized logarithmically in a dyadic grid $s = 2^m$, $\tau = n2^m$ where n and m are integer values. Substituting the value of s and τ in Eq. (2), it is possible to use the discrete wavelet transform that uses certain subset of scale parameter s and translation parameterτ. The signal reconstruction using DWT will be as accurate as using CWT [16]. However, to reduce time and amount of calculations in analysis, DWT is better choice. The Eq. (3) used for discrete wavelet transform given below is derived from the same mother wavelet function.

$$\psi_{m.n}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-n2^m}{2^m}\right) \qquad (3)$$

To extend the frequency resolution, decomposition of signal is done repeatedly and signal can be realized into two lower frequency ranges. This process is known as multi resolution analysis (MRA) as shown in Fig.2 and goal of MRA is to represent a complex signal by several simple signals to study them separately.This decomposition has half the time resolution since only half of each filter output describes the signal. Conversely, each output has half the frequency band of the input so the frequency resolution has been doubled.

In this way useful information from the original signal get divided into different frequency bands. Calculation of time of occurrence of any event can be done easily from length of time window and number of windows processed. According to IEEE standards, Daubechies wavelet family is very accurate for analyzing PQ disturbances among all the wavelet families. Daub4 and Daub6 wavelets are good choice for short and fast transient disturbances while for slow transient disturbances Daub8 and Daub10 are more suitable. However, the selection of appropriate mother wavelet without knowing the types of transient disturbances is a difficult task.

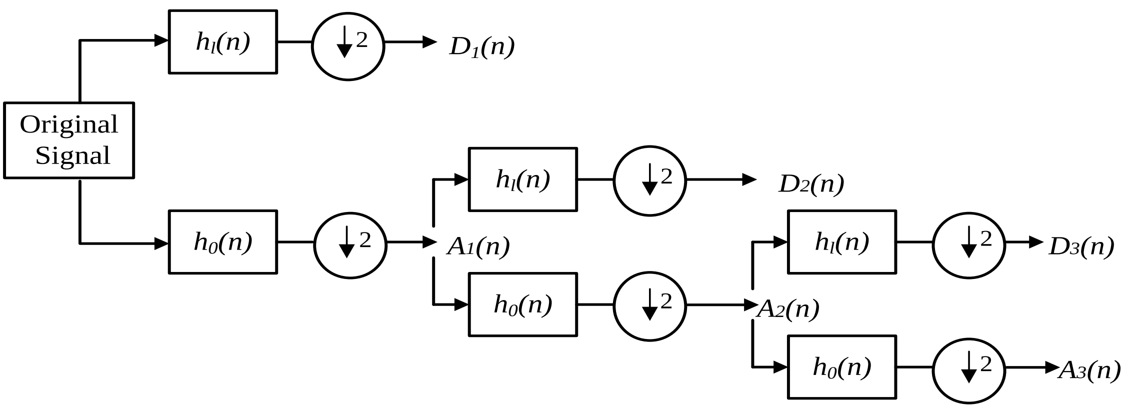

Fig. 2 Three-level analysis of filter bank structure of DWT

4.2 Proposed Method to find out power quality disturbances

Wavelet multiple resolution analysis has been found to be an optimal starting method for detection and analysis of an unknown event. Wavelet time localization property helps to find such events. The energy distribution of a distorted signal can be use as feature for classification of power quality problems as energy of signal get distributed in different frequency bands according to type of problem. The difference in wavelet domain energy distribution of two consecutive frames can be used to detect disturbance and further can be used for classification of PQ events. By doing so, fast and consistent detection of any kind of disturbances can be done which help to realize real time system in low cost for monitoring of power quality. Fig.3 shows the flowchart of proposed method.

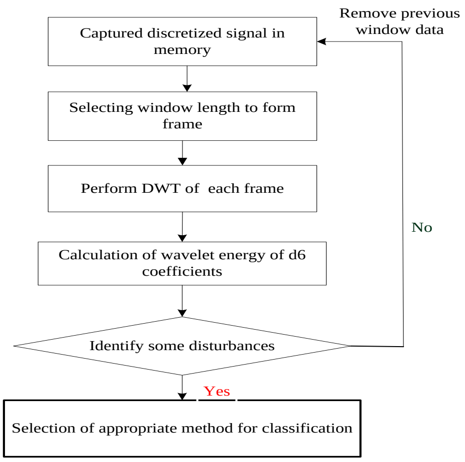

Fig. 3 Flowchart to find out disturbances

A mother wavelet must be oscillatory, with a short support and has at least one or two vanishing moment for power quality applications [17-18]. The selection of mother wavelet is done on the basis of literature available for the analysis of power system disturbances [19]. Db4 is used as the mother wavelet since it has given good performance. A sampling rate of 12.8 kHz is chosen and decomposition into six levels is done for simulation study. WT will decompose the signal into 6 levels D1–D6 as shown in Table 2.

Table 2 Frequency division for DWT filter for 12.8 kHz sampling rate

Wavelet Level	Frequency Band (Hz)	Centre Frequency (Hz)	Power quality phenomena
D1	3200-6400	4800	High frequency transients
D2	1600-3200	2400	System response transients
D3	800-1600	1200	System response transients
D4	400-800	600	Characteristic harmonics
D5	200-400	300	Characteristic harmonics
D6	100-200	150	Characteristic harmonics
A6	0-100	50	Fundamental frequency

From the Table 2, it can be observed that the transient energy will be captured in levels D1–D3 and the energy in level A6 will track the variations of grid voltage/current with frequency around the nominal frequency. Wavelet energy measure based on wavelet analysis is able to observe the unsteady signal and complexity of the system at time-frequency plane.

The wavelet energy spectrum at instant k and scale j is given by Eq. (4)

$$E_j = \sum_{k=1}^{N} |D_{jk}|^2 \ , j = 1,2, \dots\dots, l \qquad (4)$$

Where D_{jk} is the value of wavelet detail coefficients obtained in decomposition from level 1 to level l. N is the total number of the coefficients at each decomposition level and Ej is the energy of the detail coefficients at decomposition level j.

4.3 Frame length

Coefficients of wavelet transform represent the energy of the signal. These coefficients will be used to measure the magnitude of the disturbance in distorted signal. For real time application of wavelet transform as a power quality monitoring tool, it is essential to detect disturbances in minimum time. Hence, any distorted signal is processed through time window of fixed length frame. Length of the frame decides the number of sample points of discrete data signal included in the frame for which wavelet energy has to be calculated. The time window moves forward along the signal and wavelet energy is calculated for each frame. Frame length decides the response time of the method. If length of the frame is long it will take more time in calculation and response time will get delayed.

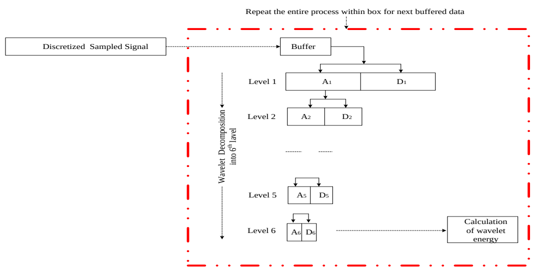

Fig. 4 Wavelet energy calculation block

The number of step used for the calculation of wavelet energy of detail coefficients are shown in fig. 4. The important factor which need to be decided judiciously are sampling frequency, size of buffer and level of decomposition. A fixed frame length of sample points 128 is used in this paper to obtain fast response time. The sampling frequency selection has been done according to Nyquist theorem and level of decomposition is 6^{th} level.

5. SIMULATION RESULTS AND DISCUSSIONS

Simulation results to investigate the power quality disturbances such as sag, swell, momentary interruption are given in Fig. 5 to Fig. 12. The horizontal axis is marked for the index of sample points/number of frames while the voltage magnitude/wavelet energy is marked on the vertical axis. Grid voltage signal is captured at the point of common coupling which is processed by taking a frame length of 128 sample points. Discrete wavelet transform into 6^{th} level is applied on frame and further wavelet energy of detail coefficients D6 has been calculated and plotted.

Voltage signal without disturbance and corresponding wavelet energy plot is given in Fig.5 and Fig.6 respectively. From Fig.6

it is clearly noticed that wavelet energy for each frame is approximately constant in case of normal condition when there is no disturbance in grid.

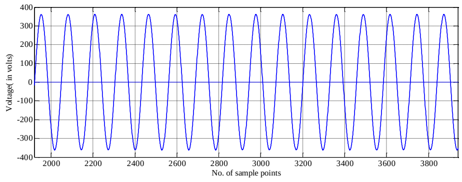

Fig.5 Voltage signals without any disturbance (Phase A)

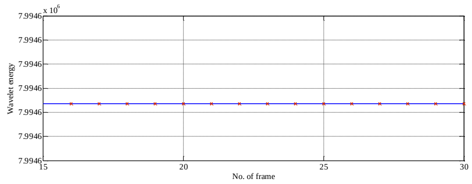

Fig.6 Wavelet energy plot per frame of voltage signal (Phase A)

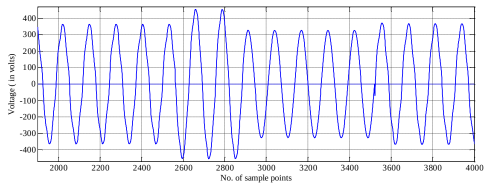

Fig.7. Grid voltage during grid disturbance (Phase A)

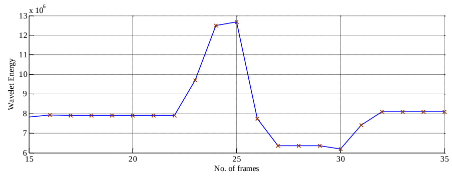

Fig.8. Wavelet energy plot per frame for grid voltage (Phase A)

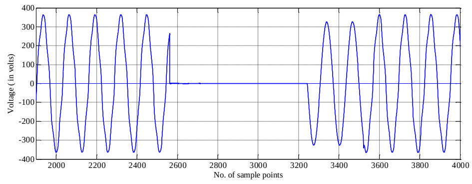

Fig. 9 Grid voltage with voltage interruption (Phase B)

Fig.7 shows the grid voltage during disturbance in the form of both sag and swell. Changes in wavelet energy of a frame during voltage swell and sag are shown in Fig.8. The indication of event is clearly observed through wavelet energy plot. There is large change in frame energy of the signal. For voltage swell frame energy increases from 7.92E+06 to 12.5E+06 which are further reduced to 6.35E+06 and roughly have same values for next four frames of voltage sag shown in Fig.8.

The corresponding wavelet energy plot for the case of power interruption of 10ms as shown in Fig. 9 is given in Fig.10. Fig.9 exhibits that wavelet energy from frame 21 starts decreasing and become very less for frames 23-27 during momentary voltage interruption as compared to frame energy in normal case. Similarly, it can be observed from Fig.11 and Fig.12, that voltage sag results in change of frame energy in the range of 5.86E+06 to 6.93E+06. Without any disturbance wavelet energy for a frame is 7.71E+06.

A frame size of 128 sample point in a cycle with cycle time equal to 0.02 is selected and wavelet energy for each frame is calculated using Eqn. 4 which is shown in Table 3 for specific frames. As disturbance starts from time 0.45s and persists till 0.55s, major changes in wavelet energy from frame 23 to frame 27 can be noticed obviously. On line processing time required to find out the disturbances is 2.5 cycles which is very small. Complete list for change in wavelet energy for all the 3-phases are shown in Table 3 (From frame 23 to frame 32).

Table 3 Wavelet Energy distribution for different frames

Parameter	**Frame 23**	**Frame 24**	**Frame 25**	**Frame 26**	**Frame 27**	**Frame 28**	**Frame 29**	**Frame 30**	**Frame 31**	**Frame 32**
Energy (Phase A)	7.92E+06	7.91E+06	**9.71E+06**	**1.25E+07**	**1.27E+07**	**7.75E+06**	**6.35E+06**	**6.35E+06**	**6.35E+06**	6.20E+06
Energy (Phase B)	7.29E+06	6.50E+06	**6.97E+03**	**6.73E+01**	**6.44E+01**	**2.44E+01**	**1.11E+01**	**2.23E+06**	**5.45E+06**	6.04E+06
Energy (Phase C)	7.71E+06	7.71E+06	7.34E+06	**5.86E+06**	**5.99E+06**	**6.14E+06**	**6.93E+06**	**6.70E+06**	**6.74E+06**	**6.74E+06**

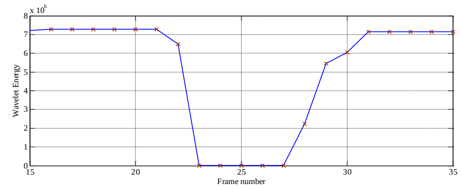

Fig. 10 Wavelet energy plot per frame for grid voltage (Phase B)

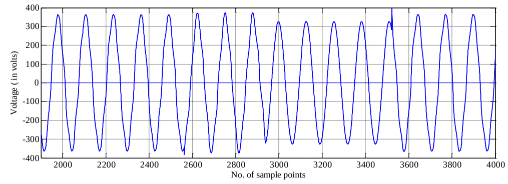

Fig. 11 Grid voltage during grid disturbance (Phase C)

Approximate coefficients will have maximum magnitude as it contains fundamental component in A6. As a general rule, wavelets with large numbers of coefficients present lower spectral leakage than wavelets with small numbers of coefficients, and are better suited for analysis of harmonic components [20]. Here the decomposition is done into six levels only.

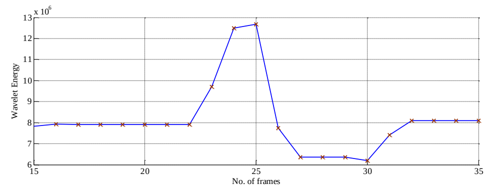

Fig. 12 Wavelet energy plot per frame for grid voltage (Phase C)

The wavelet sampling frequency is taken 12.8 kHz and decomposition helps to find out, in which frequency range, the disturbance energy is concentrated.

Energy distribution for wavelet coefficients in presence of 3rd harmonics is shown in Fig. 14. The presence of 3rd harmonic is visible in frequency band of level 6 detail coefficients. Energy distribution for wavelet coefficients in presence of 5th and 7th harmonics is depicted in Fig. 15. Signal strength of D5 detail coefficients increases because of presence of 5th and 7th harmonics components which lies in frequency band of scale 5 detail coefficients. The energy distribution of detail coefficients for harmonics is confirmed according to Table 2 showing list of different frequency bands. Leakage of frequency spectrum is very small due to proper selection of sampling frequency.

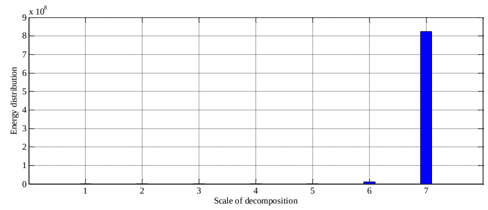

Fig.13 Energy of wavelet coefficient of a signal without harmonic distortion

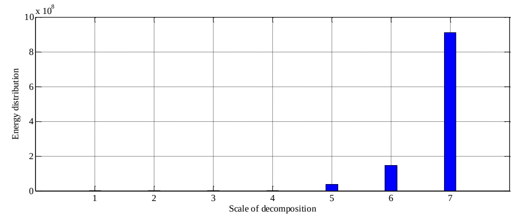

Fig.14 Energy distribution for detail coefficients in presence of 3rd harmonics

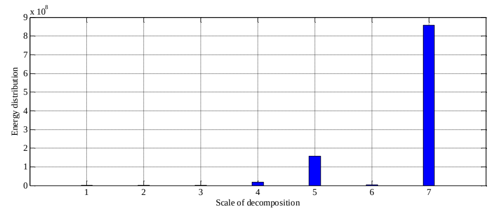

Fig.15 Energy distribution of detail coefficients in presence of 5th and 7th harmonics

6. CONCLUSION

Discrete wavelet transform is a useful tool for the analysis of distorted signal. The wavelet detail and approximation coefficients energy has been investigated for detection of harmonics. Other power system disturbances such as voltage sag, voltage swell and momentary interruptions has been processed in a time window at the point of common coupling in grid connected WECS. The distinctive feature of the proposed wavelet energy based method is the ability to detect an event in 2.5 power frequency cycles. The proposed method provides meaningful disturbance detection in real-time simulations and it can be further implemented in a digital signal processor in order to detect disturbances in very less time. The difference in wavelet domain energy distribution of two consecutive frames has been used to detect disturbance. Proposed method can be extended for detection and classification of various other transients disturbances also. It has been found that selection of mother wavelet and proper levels of decomposition plays very important role in detection of disturbances.

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