Analysis of Power Quality Disturbances using M-band Wavelet Packet Transform

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***Abstract*—The increased use of non-linear loads, power electronic switches and changing regulations in today's power distribution system has made power quality (PQ) a major concern.Poor PQ may lead to partial or complete failure of equipment, loss of important data etc. The mitigation strategy can also be planned only if these PQ disturbances are correctly monitored. Conventional way of identifying PQ disturbances using Fourier Transform produces unrealistic results in case of non-stationary PQ disturbances. So, in order to measure it accurately, Wavelet packet transform is explored with its capability. In this paper, an attempt has been made to analyse PQ disturbances using M-band Wavelet packet transform. For Power quality disturbances such as voltage sag, voltage swell, momentary interruptions, voltage sag plus harmonics, voltage swell plus harmonics and flicker a statistical parameter RMS is computed for each WPT coefficient. Analysis is done for different magnitudes and time durations of PQ disturbances which are simulated as per their IEEE 1159-2009 standards definition.**

***Keywords*—Power Quality, M-band wavelet packet transform, IEEE Standards.**

I. INTRODUCTION

The causes of power quality disturbances must be known for improving the quality of the electric power[1]-[2].Pollution has been introduced into power systems by nonlinear loads such as transformers and saturated coils; however, perturbation rate has never reached the present levels [3].The various types of PQ disturbances are defined in IEEE standards 1159-2009 in terms of their frequency, magnitude and duration.With the deregularized distribution system and with more than one utility available to supply power in the same area, the quality of power has become one of the most important aspects to select the best utility [4]. Accurate evaluation of the electric power quality requires accepted and approved indices to quantify the effect of different power quality disturbances [5].The accurate indication of PQ is the ubiquitous demand of deregularized power system. The acceptable PQ indices should be able to show the amount of deviation from the desired pure power supply [6], [7].

Fourier transform fails to give time information and gives amplitude frequency representation. The short time Fourier transform (STFT) can localize the time factor depending on the chosen fixed window width. Thus, STFT is always a compromise between the time and frequency resolution. Wavelet transform overcomes this difficulty. Standard 2-band wavelets are not suitable for high frequency signals with relatively narrow bandwidth. To overcome this shortcoming, M-band orthonormal wavelets were created as a direct generalization of the 2-band wavelets [8].They offer fast access to a rich menu of bases from which the "best basis" can be chosen [9].The standard wavelet decomposition gives logarithmic frequency resolution [10].The M - band WPT decomposition generates mixture of logarithmic and linear frequency resolution. The M - band wavelet produces large number of sub bands which improve the accuracy. This motivates to use the M-band decomposition for analysis of power quality disturbances. In this paper, M-band WPT is applied for the analysis of various PQ disturbances such as voltage sag, voltage swell, momentary interruptions, voltage sag plus harmonics, voltage sell plus harmonics and flicker.A statistical parameter RMS value is calculated for each WPT coefficient at each level of decomposition for the simulated PQ disturbances. The results are analysed for different magnitudes of disturbances as well as for different time durations. The results are also drawn for the pure signal.

This paper is organized as follows: section II discusses theory of M-band wavelet transform to serve the required objective. Section III presents simulation results. Section IV presents the analysis of simulation results. Finally section V concludes the paper.

II. M-BAND WAVELET TRANSFORM

The wavelet transform maps function $f(x) \in L^{2(R)}$ onto a scale-space plane. The wavelets are obtained from a single prototype function $\psi(x)$ by scaling parameters a and shift parameters b [11], [12]. The continuous wavelet transform of a function $f(x)$is given as,

$$W(a,b) = \int f(x)\psi_{a,b}(x)dx \qquad (1)$$

Where $\psi_{a,b}(x) = a^{-\frac{1}{2}}\psi\left(\frac{t-b}{a}\right)$is a window function called the mother wavelet, a is a scaling parameter and b is a translation parameter .M-band wavelet decomposition is a direct generalization of the above two-band case [13], [14].

Let $\phi(x)$ be the scaling function satisfying,

$$\phi(x) = \sum_k h(k)\sqrt{M}\ \phi(Mx-k) \qquad (2)$$

In addition there are M-1 wavelets which also satisfy,

$$\psi^{(j)}(x) = \sum_k \sqrt{M}\, h^{(j)}\psi(Mx-k) \qquad (3)$$

$$\phi_{ik}(x) = \sum_k M^{-\frac{i}{2}}\phi(M^{-i}x-k) \qquad (4)$$

$$\psi_{ik}^{j}(x) = \sum_k M^{-\frac{i}{2}} \psi^{(j)}(M^{-i}x - k),\ j = 1,2 \ldots, M-1 \qquad (5)$$

Equation (4) and (5) represent scaling function and M-1 wavelets in discrete form respectively.

Wavelet packet transform (WPT) is considered as a generalization of the wavelet transform since the decomposition is performed on both the approximations (low frequency components) and the details (high frequency components) of any waveform. M band wavelet used in this work is the generalization of standard 2 band wavelet. M channel filters and M band wavelets are closely related [15]-[16].In M channel filter bank the bandwidth of the filter bank is divided into M bands as shown in Fig. 2.Fig 1 gives the idea 2 level decomposition of 1-D signal using M band wavelet packet transform with M=3. At level (0,0) the sampled signal is passed through first level of three-band biorthogonal linear phase wavelet filters in order to get one approximate coefficient and two detailed coefficients i.e. (1,0) ,(1,2) and (1,3).This process is continued till the desired level of decomposition is achieved. Fig. 2 shows the implementation of M band wavelet with M=3 up to decomposition level 2.

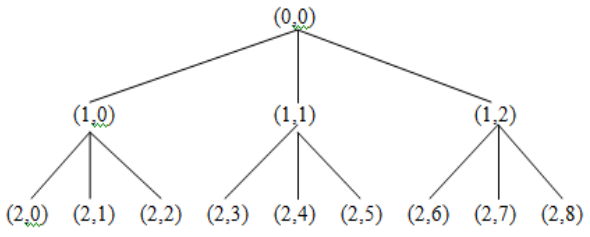


Figure 1 Two Level decomposition of 1-D signal using M-band WPT with M=3

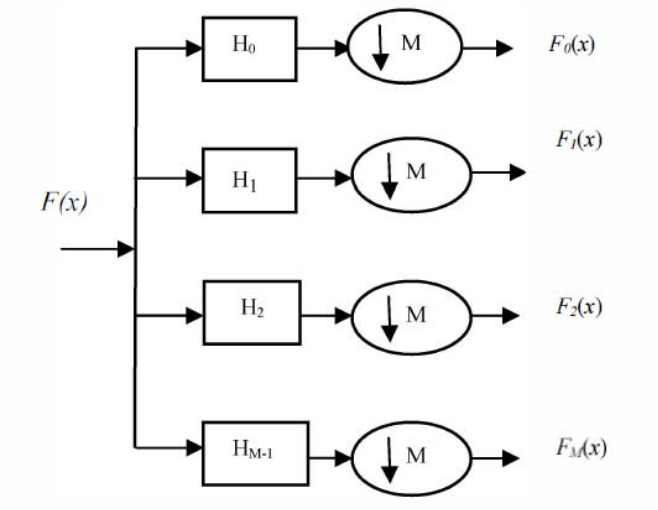


Figure2 M channel analysis filter bank

Thus WPT analyses both high and low frequency contents of the signal. In addition to this M-band wavelet generates more number of sub bands as compare to standard 2 band WPT.This makes M band WPT a strong contender for PQ analysis.

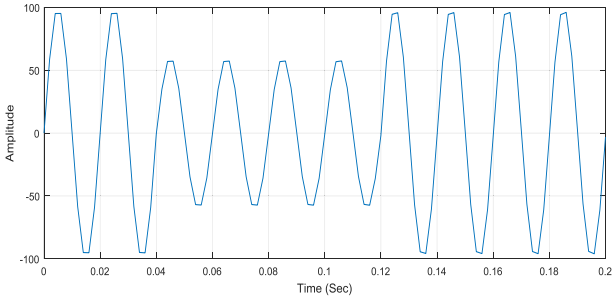
III.PQ DISTURBANCES AND STATISTICAL PARAMETER CALCULATION

Power quality disturbances such as voltage sag, voltage swell, momentary interruptions, voltage sag plus harmonics, voltage sell plus harmonics and flicker are generated using MATLAB environment with variation in magnitude and time as per IEEE 1159-2009 standards. Simulated signals are processed with 3 Band WPT up to level two using 3-band biorthogonal linear phase wavelet filters. Fig. 3(a)-3(c) shows voltage sag, voltage swell, momentary interruptions, voltage sag plus harmonics, voltage sell plus harmonics and flicker with 20 kHz sampling frequency for the analysis.

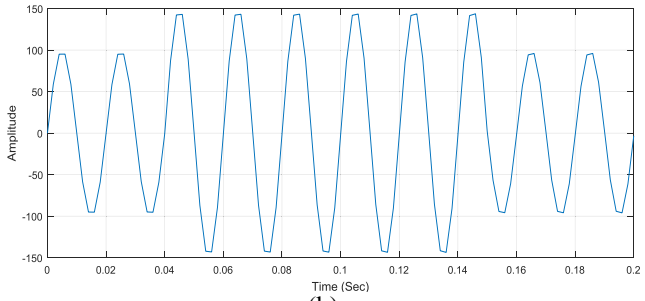
A statistical parameter RMSwpt based on the RMS value of the M-band WPT co-efficient is computed for each decomposition (i,j) and for all the PQ disturbances as:

$$RMSmwpt = \frac{1}{n}\sqrt{\sum_{k=1}^{n}(x_k)^2} \qquad (6)$$

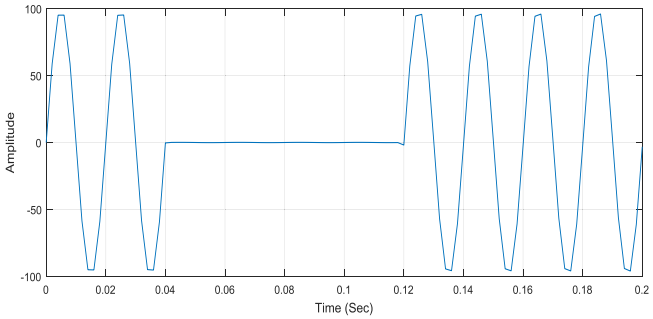
Where, n=length of the (i,j)th M band WPT decomposition.



(a)

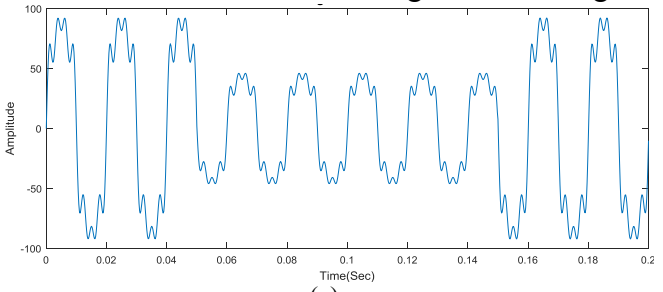


(b)

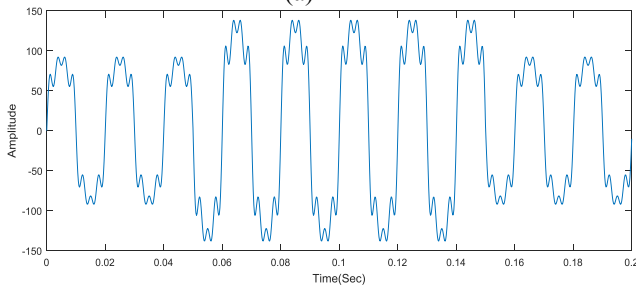


(c)

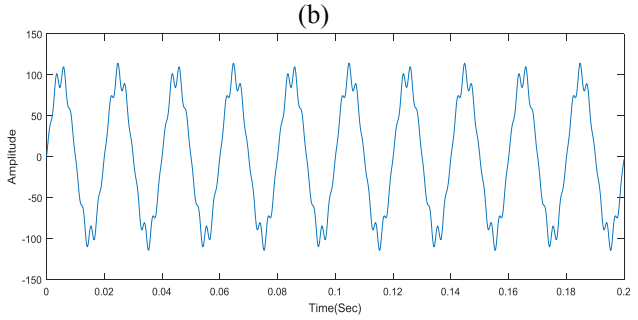
Figure3 (a) Voltage Sag (b) Voltage Swell (c)Momentary Interruption



(a)



(b)

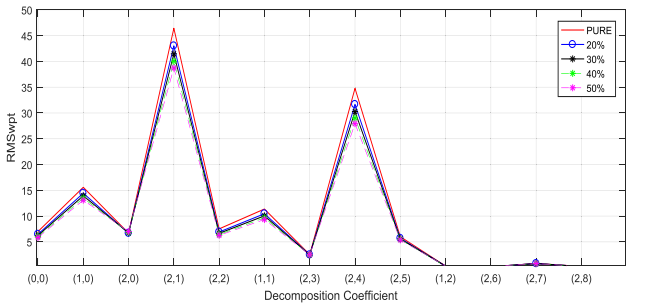


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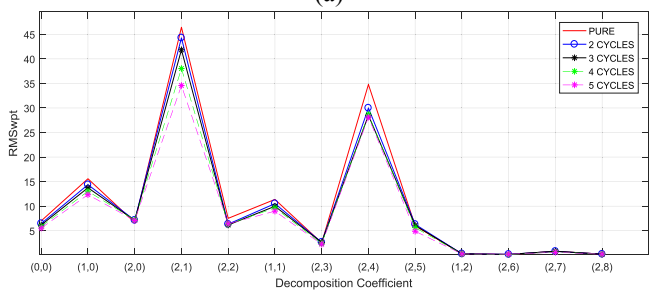
Fig..4 (a) Voltage sag+harmonics(b)Voltageswell+harmonics(c) Flicker

Fig.4 (a) and (b) show simulated Harmonics along with 50% voltage sag and Harmonics with 50% voltage swell for 5 cycles duration. Also flicker captured for time duration of 0.2 seconds are given in Fig.4(c).

IV. RESULT ANALYSIS AND DISCUSSION



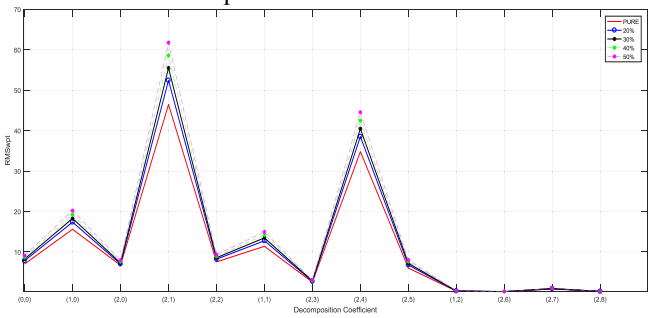
(a)



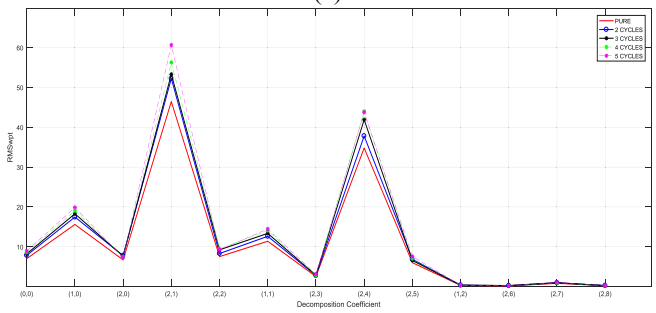
(b)

Fig. 5. RMSwptanalysis for (a) Voltage sag of 20-50% magnitude (b) voltage sag of 2-5 cycles

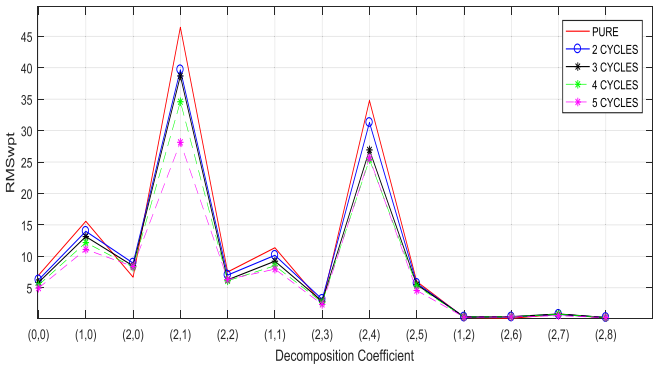
M-band WPT with M=3 is applied on simulated power quality disturbances till decomposition level two as shown in fig 1. The statistical variable RMSwpt is computed for each M-band WPT coefficient and is plotted against the respective M-band WPT decompositions.



(a)



(b)



(c)

Fig. 6 RMSwptanalysis for (a) Voltage swell of 20-50% magnitude (b) voltage swell of 2-5 cycles (c) momentary interruption of 2-5 cycles.

Fig. 5 (a)-(b) show the plot of RMSwpt (i,j) of Voltage sag to its M-band WPT decomposition with variation in sag magnitude and cycle variation respectively. Plots also show the behaviour of the RMSwpt (i,j) for pure signal.

Fig.5 shows that the value of statistical parameter RMSwpt(i,j) decreases from the pure as the magnitude or cycle duration of disturbance increases especially for the decompositions belonging to the left hand side of the decomposition tree in Fig.1 (i.e. for lower frequency bands). It can be observed from Fig. 6 (a) and (b) that In case of voltage swell value of RMSwpt(i,j) increases from pure with increase in magnitude or cycle duration of the disturbance. Similar plot for momentary interruption with variation in cycle duration is given in Fig 6(c). In this case the behaviour of the RMSwpt with variation in cycle duration is same as voltage sag. Thus the used statistical variable is useful for depicting voltage sag, voltage swell and momentary interruption too.

It can be observed from Fig.7 (a)-(b) that for Voltage sag plus harmonics the value of RMSwpt decreases from pure for

the lower frequency band whereas in case of voltage swell plus harmonics it increases from pure. For flicker the values are slightly higher than that of pure signal.

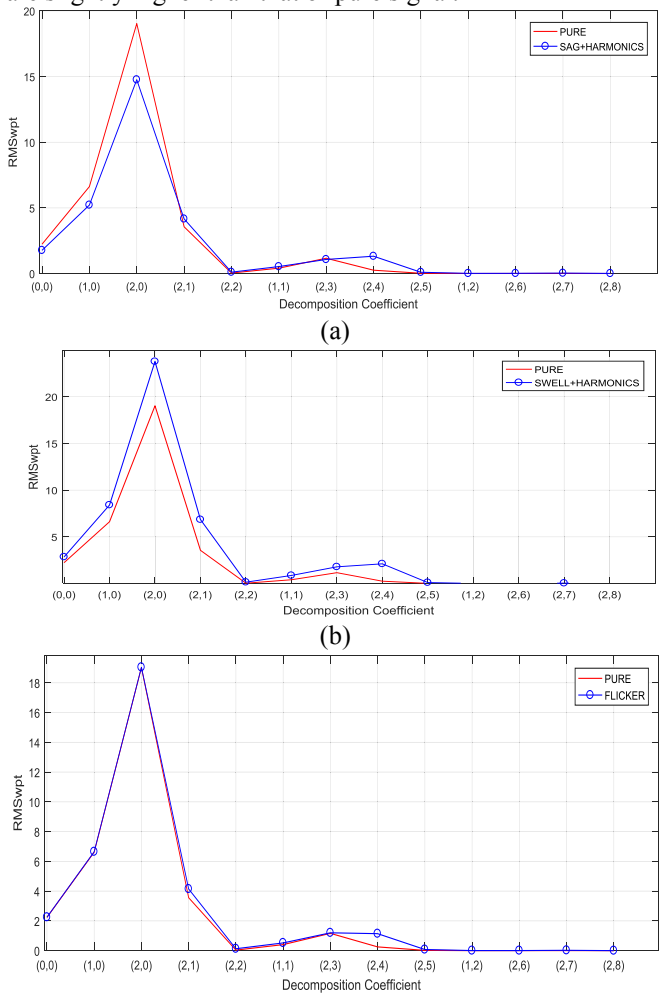


Fig.7 RMSwpt Decomposition level for (a) Voltagesag plus harmonics (b) Voltage swell plus harmonics(c) Flicker

Fig 5,6 and 7 show that there is a Prominent change in the value of RMSwpt(i,j) at decomposition level (2,1) and (2,4) for voltage sag, swell, momentary interruption, flicker, Voltage swell plus harmonics and also for Voltage sag plus harmonics. Detailed analysis of RMSwpt at this two decomposition levels are presented in the tabular form below.

Table 1. RMSwpt(2,1) and RMSwpt(2,4) analysis for voltage sag magnitude variation and time duration variation

Sr.No.	Sag Magnitude (%)	Duration (Cycles)	RMSwpt(2,1)	RMSwpt(2,4)
1	Pure	4	46.440	34.783
2	20	4	43.029	31.660
3	30	4	41.475	30.272
4	40	4	40.036	29.021
5	50	4	38.728	27.926
6	50	2	44.273	29.982
7	50	3	41.843	28.501
8	50	4	38.025	28.693
9	50	5	34.567	28.122

It can be observed that as magnitude of voltage sag increases the RMSwpt decreases linearly for both the decomposition levels. Also as time duration of voltage sag with constant magnitude increases the values of RMSwpt(2,1) and RMSwpt(2,4) decrease.

Table 2.RMSwpt(2,1) and RMSwpt(2,4)analysis for voltage swell magnitude variation and time duration variation

Sr.No.	Swell Magnitude (%)	Duration (Cycles)	RMSwpt(2,1)	RMSwpt(2,4)
1	Pure	4	46.440	34.783
2	20	4	52.411	38.501
3	30	4	55.478	40.465
4	40	4	58.588	42.476
5	50	4	61.734	44.533
6	50	2	52.223	37.794
7	50	3	53.291	41.896
8	50	4	56.275	43.998
9	50	5	60.636	43.769

Analysis of RMSwpt(2,1) and RMSwpt(2,4) for voltage sag and voltage swell with variation in magnitude (keeping constant duration) and with variation in time duration (keeping constant magnitude) is given in Table 1 and Table 2 respectively. Results for pure signal are also given in the same table

Fig 8 shows the Graphical representation of RMSwpt(2,1) and RMSwpt(2,4) analysis for voltage sag and swell with magnitude variation.Graph also includes the values for pure signal.Linear relationship is observed from the graph.

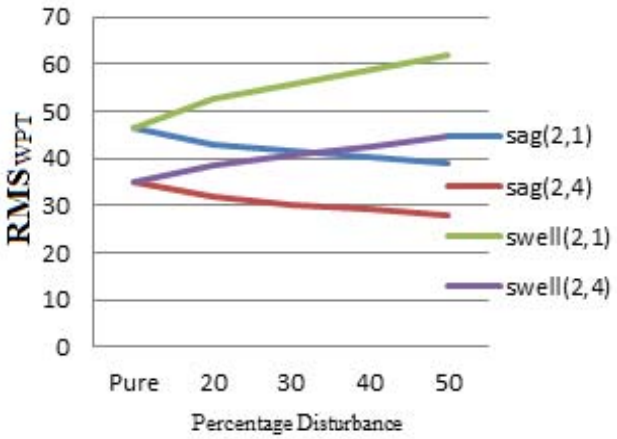


Fig 8: RMSwpt(2,1) and RMSwpt(2,4) analysis for voltage sag and swell magnitude variation.

Results of similar analysis for Momentary interruptions with variation in duration is given in Table 3.With increase in time duration the value of RMSwpt (2,1) and RMSwpt(2,4) decreases from pure.

Table 4. shows the RMSwpt(i,j) values at each WPT coefficient upto decomposition level 2 (Fig. 1) for voltage sag and swell with fixed magnitude and time duration along with Harmonics. Table also contains the results for flicker.Here prominent change is observed at decomosion coefficient (2,0) for PURE signal as well as for all three PQ disturbances.

Table3. RMSwpt analysis for Momentary interruption with variation in time

duration

Sr.No.	Duration (Cycles)	RMSwpt(2,1)	RMSwpt(2,4)
1	PURE	46.439	34.783
2	2	39.679	31.289
3	3	38.697	26.932
4	4	34.594	25.413
5	5	28.137	25.665

Table 4 RMSwpt values for PQ disturbances with fixed magnitude and time duration

Sr. No.	Decomposition coefficient	RMSwpt for			
		Pure	Sag + harmonic	Swell + harmonic	Flicker
1	(0,0)	2.234	1.767	2.848	2.246
2	(1,0)	6.620	5.216	8.409	6.649
3	(2,0)	19.035	14.759	23.773	19.044
4	(2,1)	3.558	4.159	6.852	4.146
5	(2,2)	0.038	0.104	0.148	0.13
6	(1,1)	0.406	0.529	0.868	0.519
7	(2,3)	1.164	1.072	1.792	1.200
8	(2,4)	0.253	1.319	2.112	1.143
9	(2,5)	0.020	0.096	0.107	0.078
10	(1,2)	0.002	0.011	0.014	0.007
11	(2,6)	0.005	0.015	0.019	0.007
12	(2,7)	0.005	0.032	0.044	0.024
13	(2,8)	0.001	0.007	0.007	0.002

V. CONCLUSION

A statistical parameter RMSwpt is computed for various PQ disturbances which are processed under M-band wavelet packet transform with M=3. Decomposition is carried out till level 2 using 3-band biorthogonal linear phase wavelet filters. RMSwpt is computed and analysed at each WPT decomposition coeffecient for each PQ disturbance.

For Voltage sag,voltage swell and momentry interruption prominent change in the value is observed at decomposition coefficeients (2,1) and (2,4).

Hence further analysis of RMSwpt(2,1) and RMSwpt(2,4) is carried out for those PQ disturbances. The results shows the linear relationship. This results can be further used for detection of various PQ disturbances.

M-band WPT gives scope for more feature extractions as compare to conventional 2 band WPT. The M - band WPT produces large number of sub bands which improve the accuracy. This can help to do micro level analysis of PQ disturbance. Hence this work can be used further for detection and measurement of various PQ disturbances.

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