DISCRETE WAVELET TRANSFORM BASED SELECTION OF THE TYPE OF ENTROPY FOR RECOGNITION OF AN IMPULSIVE TRANSIENT

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ABSTRACT

This paper addresses the recognition of an impulsive transient which affects the quality of electric power supplied by utilities using signal processing methods. Transient is one of the power quality disturbances that affect the supply voltage. Due to transient, there will be a momentary rise in the amplitude of voltage. It is necessary to analyze and identify transients to take proper necessary action and to opt for suitable protective devices. Discrete wavelet transform, a mathematical transform technique, is used for detecting the abrupt changes in the voltage signal. Pure sinusoidal and impulsive voltage transient signals are decomposed, using discrete wavelet transform, into approximations and details for ten levels. Different entropy values of approximations and details are obtained for analysis and a suitable type of an entropy out of Shannon, log energy, norm, threshold, and SURE entropy is selected for an identification of voltage transient. The entropy values of low frequency approximations and high frequency details are obtained using command line analysis in MATLAB. The selection process is carried out and on comparison of all the types of entropy, it is analyzed that log energy entropy for approximations and threshold entropy for details can recognize the occurrence of an impulsive transient

Keywords: *approximations; decomposition; details; entropy; impulsive voltage transient*

INTRODUCTION

Electric power is supplied from different electrical power generating systems such as thermal, hydro, nuclear, solar, windpower, biogas, geothermal and ocean power generating systems. Electric power is transmitted and distributed by either overhead transmission lines or underground cables depending on certain factors like land terrain, local ecology, atmospheric weather conditions, distance from generating station, appearance, and area congestion. Overhead lines are subjected to storms, lightning, effect of wind load, and ice loading. Transient is one of the power quality disturbances that affect the supply voltage resulting in a momentary rise in voltage and may be impulsive or oscillatory in nature.

Impulsive transients are caused by lightning. and results in sudden rise of voltage for a very short duration. Impulsive transient is defined as a sudden nonpower frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative) [1]. Either voltage or current transients are momentary and must be detected for preventive measures. In order to design suitable protective equipment, it is necessary detect the voltage transient. Possible causes of impulsive transients are lightning, electrostatic discharge, swithching impulses, and utility fault clearing with the effects of loss of data, possible damage, and system halts [2]. Impulsive spike in voltage or current have typical duration of less than 50 nanoseconds, or in the range of 50 nanoseconds to 1 millisecond, or duration greater than 1 millisecond [1]. The aim of this paper is to select a suitable type of entropy for recognition of impulsive transient out of different types of entropy. Entropy is the concept used in signal processing for identifying any deviations in the signals and for feature extraction. The paper is organized with an explanation about the discrete wavelet transform based analysis of impulsive transient signal which includes generation of pure sine and impulsive voltage transient signals, and wavelet decomposition of pure sine and transient signals using discrete wavelet transform, followed by explanation about different types of entropy and their values. The selection of suitable type of entropy for recognition of impulsive transient is explained ending with conclusion.

DISCRETE WAVELET TRANSFORM BASED ANALYSIS OF IMPULSIVE TRANSIENT

A. *Generation of Voltage Signals*

The deviation in voltage signal is undesirable as electric power supplied must be of constant amplitude of voltage at fundamental frequency of 50 Hz. Time is a vector distributed over one row and 4001 columns with an initial value of 0 with an increment of 0.0001 and final value of 400 msec. Sine and transient signals have elements distributed over one row and 4001 columns. A pure sine voltage signal is generated with 1 pu (per unit) amplitude and transient signal is generated by increasing the amplitude by providing a deviation in the amplitude of sine wave from elements of column numbers from 586 to 630 out of 4001 elements. Impulsive transient,shown in fig. 1, results in a sudden rise in magnitude of voltage at a time of 59 msec greater than the rated voltage amplitude of 1 pu. The mathematical equation used for generating impulsive voltage transient as a function of time is,

$$V(t) = A\sin\omega t + \alpha\exp((t-t_1)/\tau)\sin\omega_n(t-t_1) \quad (1)$$

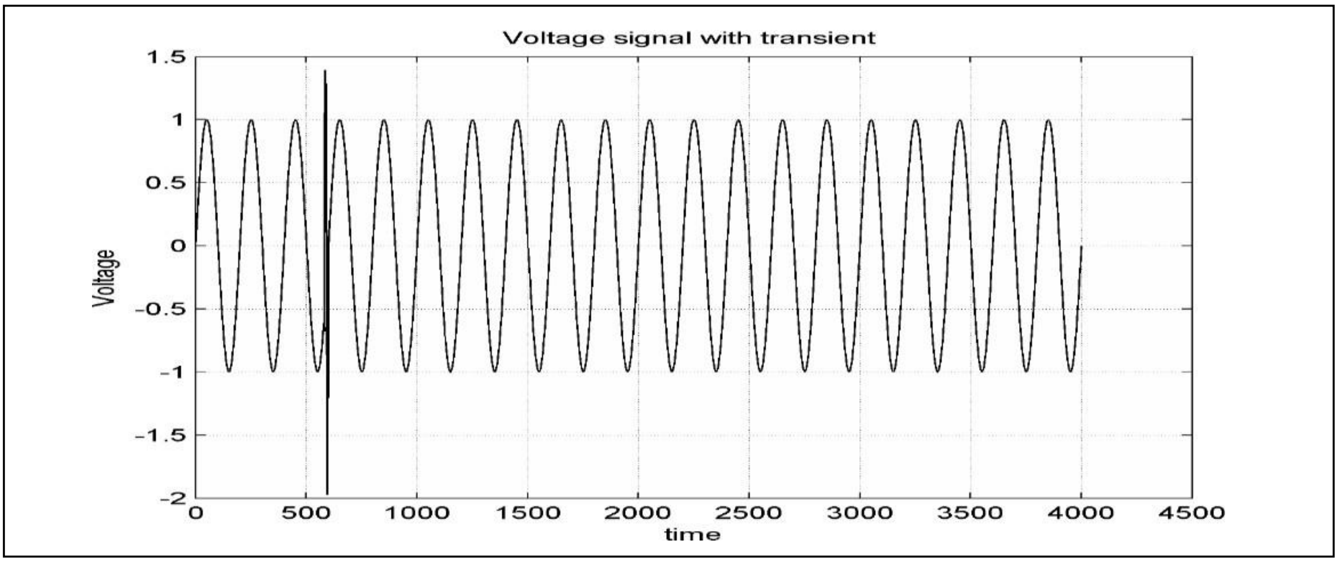


Figure 1. Impulsive voltage transient

The different parameters in (1) on which impulsive transient depends are $\boldsymbol{A}$, $\boldsymbol{\omega}$, $\boldsymbol{\alpha}$, $\boldsymbol{\tau}$, and $\boldsymbol{\omega_n}$ representing amplitude of sine wave, fundamental angular frequency, magnitude of the transient (the magnitude of impulsive spike in the transient can be varied by varying this parameter), settling time of the transient, and transient oscillating angular frequency respectively. The frequency at which an impulsive transient occurs is very high along with rise in amplitude.

B. Decomposition of the signal using discrete wavelet transform

Due to transients, there will be a sudden change in the supply voltage. To analyse the abrupt change in voltage, discrete wavelet transform is used for extracting information about the type of change in voltage. By applying discrete wavelet transform (DWT), the signal is decomposed into low frequency approximations and high frequency details. The feasibility of using wavelet analysis in terms of energy profiles is investigated in [5], to detect and classify high frequency transients. Maximum peak feature is extracted in [6], for obtaining an information to detect simultaneously transient and harmonic disturbances by comparing the DWT coefficients of disturbances with the DWT coefficients of pure signal. Daubechies 4 (db4) wavelet is used for analysis. A new wavelet decomposition process which provides additional wavelet coefficcients with border distortions are proposed in [4], for real time detection of transients. The discrete wavelet transform is defined as [11],

$$DWT_{\psi}(m,n) = \int_{-\infty}^{+\infty} x(t)\,\psi^{*}_{m,n}(t)\,dt \qquad (2)$$

The discretized mother wavelet $\boldsymbol{\psi_{m,n}(t)}$ in (2) is given as,

$a_0^{-m/2}$ multiplied by ψ which is a as function of $(t - n a_0^m b_0)$ divided by a_0^m (3)

The scaling and translation parameters are discretized as $a = a_0^m$ and $b = nb_0 a_0^m$, where $a_0 > 1$, $b_0 > 0$, and m, n are positive integers and a, b are dilation and translation parameters respectively. The complex conjugate of mother wavelet in (2) is represented as $\psi^{*}(t)$. The voltagr signal varying in time domain $V(t)$ can be represented by discrete wavelet transform as [11],

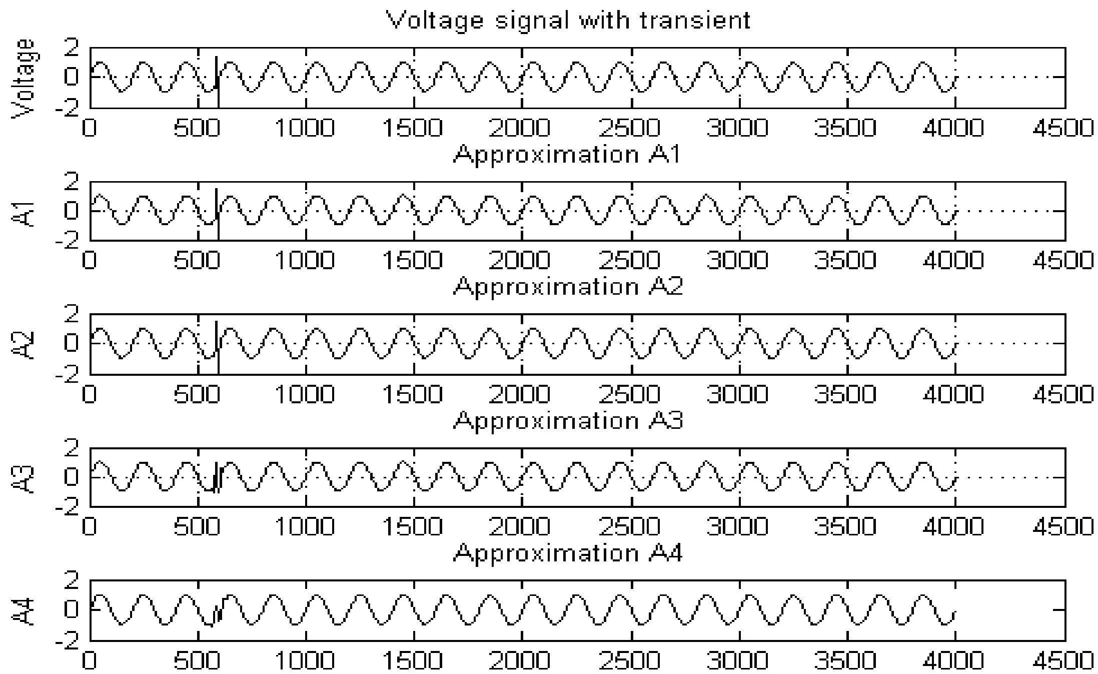
$$V(t) = \sum_k c_j(k) 2^{j/2} \varphi(2^j t - k) + \sum_k d_j(k) 2^{j/2} \psi(2^j t - k) \qquad (4)$$

The first summation in (4) gives approximation of the signal. The second summation gives detail of the signal. The term j is also used to refer scaling parameter and k also refers to shift parameter. The coefficients associated with scaling function $\varphi\ t$ are approximations and coefficients associated with wavelet function $\psi\ t$ are detail coefficients and are given by (5) and (6) respectively.

$$c_j\ k = V\ t\ \varphi_{j,k}\ t\ dt \quad (5)$$

$$d_j\ k = V\ t\ \psi_{j,k}\ t\ dt \quad (6)$$

Wavelet functions will generate detail version of the original signal that is decomposed. Scaling function will generate the approximated version of the original signal that is decomposed. In MATLAB, wavelet toolbox is used to study the usefulness of wavelet transform in power quality and owns a powerful graphic envoronment [7]. In wavelet toolbox, wavelet 1-D graphical tool can be used for generating wavelet tree upto 10 level decompositiion or using the command line function *wavedec* along with mother wavelet db4. For short and fast transient disturbances, db4 and db6 wavelets are better while for slow transient disturbances db8 and db10 are more suitable [10]. Wavelet packet transform is a direct expansion of the structure of the DWT tree algorithm to a full binary tree [8]. For wavelet analysis, only approximation coefficients are decomposed to obtain next level coefficients. Figures 2 and 3 depicts the transient signal decomposed into approximations and details up to four levels. In MATLAB, analysis decomposition function wavedec is used for decomposition of the signals. The decomposition structure utilities [3], *appcoef* and *detcoef* are used respectively for extraction of approximation and detail coefficients. Coefficients are extracted from obtained approximations and details and are of vector length 2004, 1005, 506, 256, 131, 69, 38, 22, 14, and 10 for levels 1 to 10 decomposition respectively. For wavelet packet analysis, both approximation and detail coefficients are decomposed in to another succeeding level coefficents. In wavelet packet tree, the number of elements in levels 1 to 10 are 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 respectively.



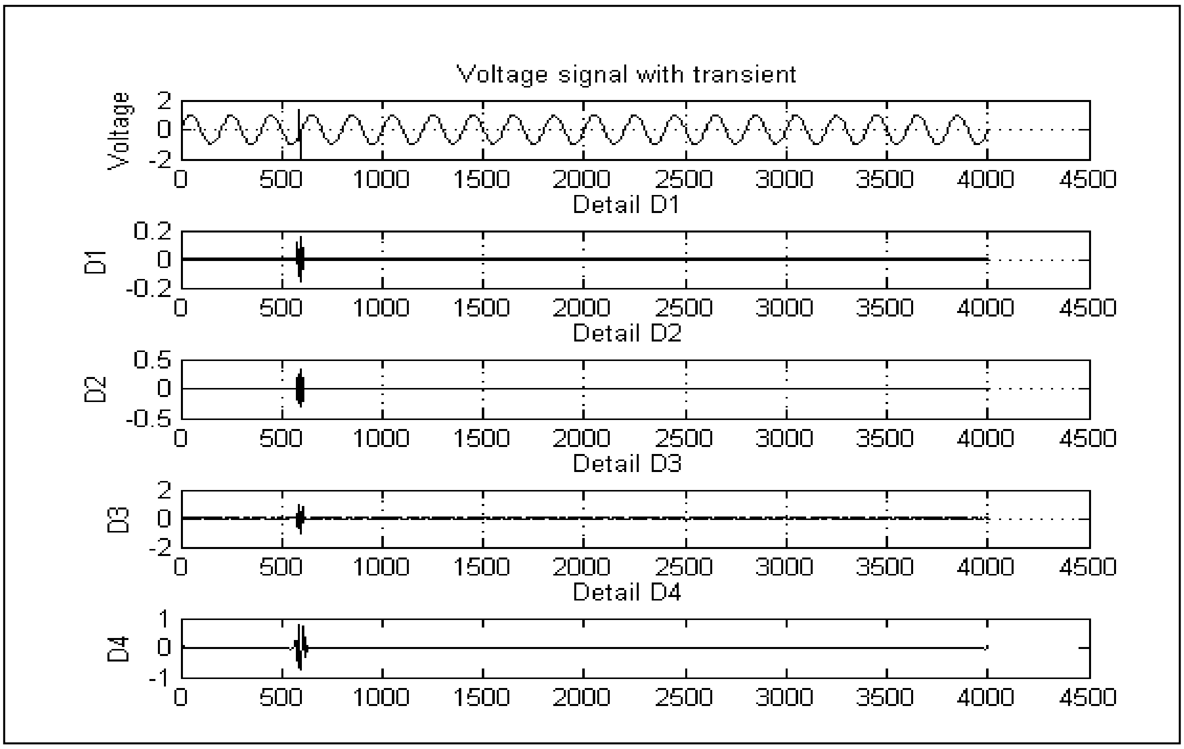


Figure 3. Voltage transient signal with four level details

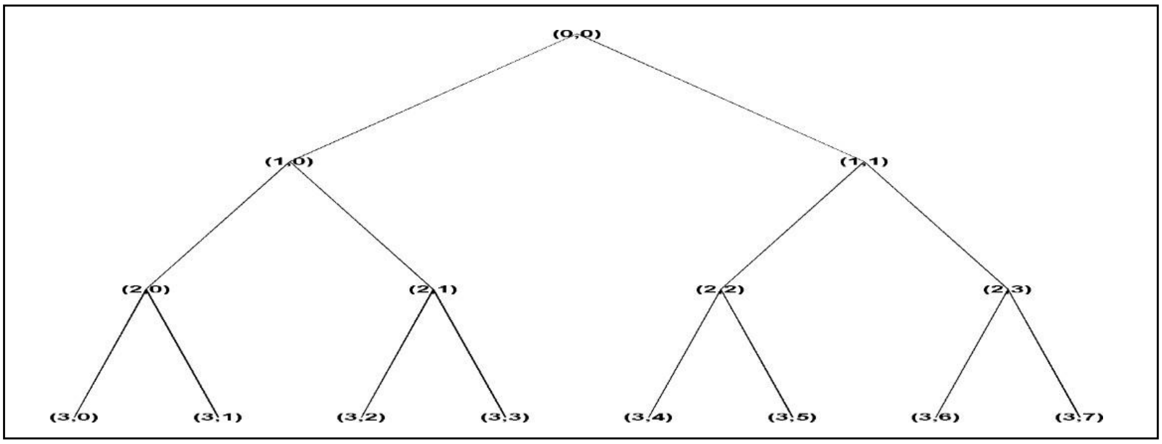


Figure 4. Wavelet packet tree for three level decomposition

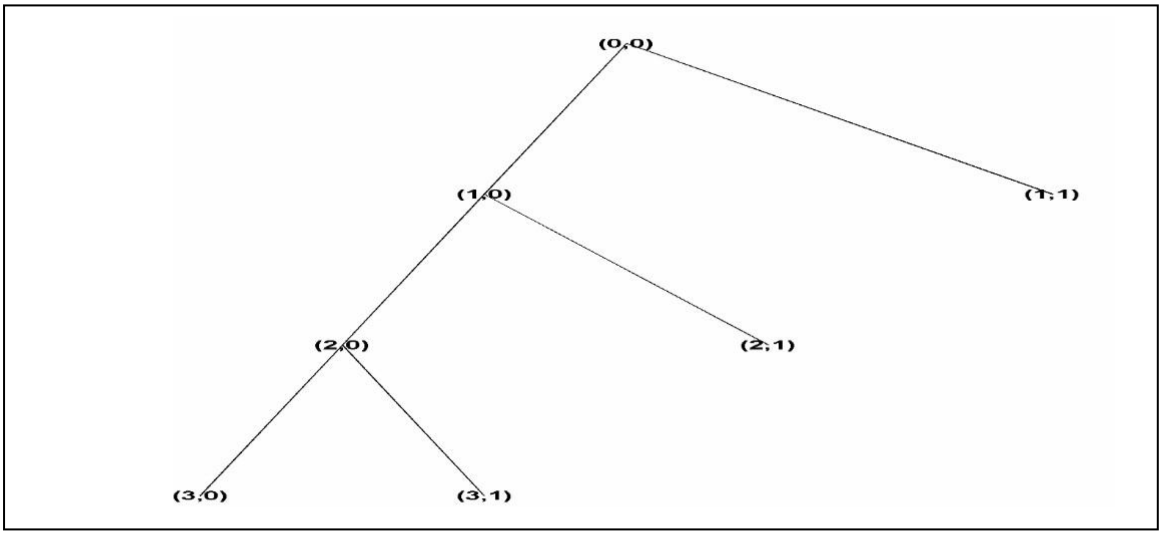


Figure 5. Wavelet tree for three level decomposition extracted from wavelet packet tree

From wavelet packet tree shown in fig 4 for three levels, wavelet tree, shown in fig. 5, can be obtained directlly from toolbox or can be extracted usint the command line function *wp2wtree*. The transient signal can be directly loaded in toolbox or exported as "*.mat*" file in MATLAB.

DIFFERENT TPES OF ENTROPY CRITERIA

The available entropy types are Shannon entropy, log energy entropy, norm entropy, threshold entropy and SURE entropy. Entropy is termed as *entropy (wavelet packet)* in [3], as the applications are used for wavelet packet analysis. Approximations and detail vectors for decomposition levels 1 to 10 consists of 2004, 1005, 506, 256, 131, 69, 38, 22, 14, and 10 elements respectively. Two signals of pure sine and transient signals are considered for analysis. The term level refers to level of decomposition. . A comparision is made between entropy of approximation and detail coefficients of both pure sinusoidal signal and transient signal. Notation that is used for different entropy types for approximations and details ase tabulated in table I. Entropy values of approximations and details for decomposed pure sinusoidal signal and impulsive transient signal for ten levels using discrete wavelet transform are tabulated in tables II and III.

Shannon entropy is nonnormalized entropy involving the logarithm of the squared value of each signal sample given as, $-s_i^2 \log(s_i^2)$ [3]. The Shannon entropy values are obtained for both level 1 to 10 approximations and detail coefficient vectors returned as real numbers as tabulated in tables II and III. Figures 6 and 7 depict the Shannon entropy curves obtained for extracted approximation and detail coefficient vectors from levels 1 to 10 decomposition. Log energy entropy is the logarithm of "energy" entropy, defined as the sum over all samples given as, $\log(s_i^2)$ [3]. The log energy entropy values are obtained for both level 1 to 10 approximations and detail coefficient vectors returned as real numbers as tabulated in tables II and III. Figures 8 and 9 depict log energy entropy curves obtained for extracted approximation and detail coefficient vectors from levels 1 to 10 decomposition. The concentration in l^p norm with $1 \leq p$ [3]. The norm entropy vales are always positive. The parameter p for calculating norm entropy values is taken as 1.5. The norm entropy values are obtained for both level 1 to 10 approximations and detail coefficient vectors returned as real numbers as tabulated in tables II and III. Figures 10 and 11 depict norm entropy curves obtained for extracted approximation and detail coefficient vectors from levels 1 to 10 decomposition.

Threshold entropy is described as the number of samples for which the absolute value of the signal exceeds a threshold ε [3]. Threshold value is chosen as 0.5 as the parameter p representing threshold value is $0 \leq p$. The threshold entropy values are obtained for both level 1 to 10 approximations and detail coefficient vectors returned as real numbers as tabulated in tables II and III. Figures 12 and 13 depict threshold entropy curves obtained for extracted approximation and detail coefficient vectors from levels 1 to 10 decomposition. SURE (Stein's Unbiased Risk Estimate) is a threshold-based entropy in which the threshold equals $2\overline{\log_e (n \log_2(n))}$, where n is the number of samples in the signal [3]. The threshold values for levels 1 to 10 are 4.47, 4.29, 4.10, 3.90, 3.69, 3.47, 3.25, 3.02, 2.81, and 2.64 respectively. The threshold value is not the same for all levels of decomposition as SURE entropy depends on number of samples and for each level of 1 to 10 approximation and detail signals the number of samples are 2004, 1005, 506, 256, 131, 69, 38, 22, 14 and 10 respectively. The SURE entropy values are obtained for both level 1 to 10 approximations and detail coefficient vectors returned as real numbers as tabulated in tables II and III. Figures 14 and 15 depict SURE entropy curves obtained for extracted approximation and detail coefficient vectors from levels 1 to 10 decomposition.

Table I. Notation used for different types of entropy criteria

Notation used	***Description of the type of entropy***
E_{SA}	Shannon entropy for approximations
E_{SD}	Shannon entropy for approximations
E_{LA}	Log energy entropy for approximations
E_{LD}	Log energy entropy for details
E_{NA}	Norm entropy for approximations
E_{ND}	Norm entropy for details
E_{TA}	Threshold entropy for approximations
E_{TD}	Threshold entropy for details
E_{SUA}	SURE entropy for approximations
E_{SUD}	SURE entropy for details

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Table II. Entropy values of approximations and details for decomposed pure sinusoidal signal for ten levels using discrete wavelet transform

Level	E_{SA}	E_{SD}	E_{LA}	E_{LD}	E_{NA}	E_{ND}	E_{TA}	E_{TD}	E_{SUA}	E_{SUD}
1	-306.90	0.0000	-693.22	-30409	1872.6	0.0022	1540	0	-2.9000	-2004
2	-1000.3	0.0000	-52.03	-12007	1574.7	0.0220	840	0	996.10	-1005
3	-1693.5	0.1000	142.34	-4238.0	1324.4	0.1219	440	0	1495.2	-506.0
4	-2386.6	0.2000	160.31	-1531.0	1114.1	0.3414	230	0	1806.4	-255.9
5	-3079.2	2.800o	131.04	-348.00	937.20	4.0092	118	1	1215.4	-129.4
6	-3609.6	-62.500	79.120	-28.000	758.40	100.00	66	55	645.20	57.10
7	-372.00	-3632.5	21.750	47.000	162.90	599.13	36	36	211.30	331.6
8	-11.300	-387.80	-10.860	14.000	46.500	132.68	16	18	7.2000	135.7
9	-41.600	-9.8000	7.2500	-19.000	69.400	10.110	12	7	26.600	-2.000
10	-125.70	-76.400	10.570	-8.000	104.90	24.150	9	5	57.700	15.50

Table III. Entropy values of approximations and details for decomposed impulsive transient signal for ten levels using discrete wavelet transform

Level	E_{SA}	E_{SD}	E_{LA}	E_{LD}	E_{NA}	E_{ND}	E_{TA}	E_{TD}	E_{SUA}	E_{SUD}
1	-315.30	0.2000	-672.09	-30124	1889.0	0.2501	1525	0	22.700	-2003.9
2	-1015.3	0.7000	-1.9474	-11854	1587.9	1.2960	841	0	1021.0	-1004.2
3	-1697.1	-7.7000	219.50	-4159.0	1331.2	9.2210	441	5	1508.0	-493.80
4	-2384.7	-8.8000	175.41	-1493.0	1114.7	8.1990	230	4	1787.8	-245.40
5	-3071.7	3.0000	126.74	-300.00	934.40	10.125	115	3	1202.9	-120.30
6	-3578.8	-58.300	77.730	-52.000	755.60	99.011	66	53	644.20	55.300
7	-365.70	-3634.8	19.670	46.000	157.50	602.25	36	35	207.20	332.6
8	-11.400	-377.10	-11.170	13.000	41.500	130.26	15	19	7.4000	131.6
9	-39.300	-5.7000	6.8900	-20.000	61.100	8.8400	11	7	25.600	-4.3000
10	-114.70	-55.400	10.050	-8.0000	92.000	20.677	9	5	57.400	14.700

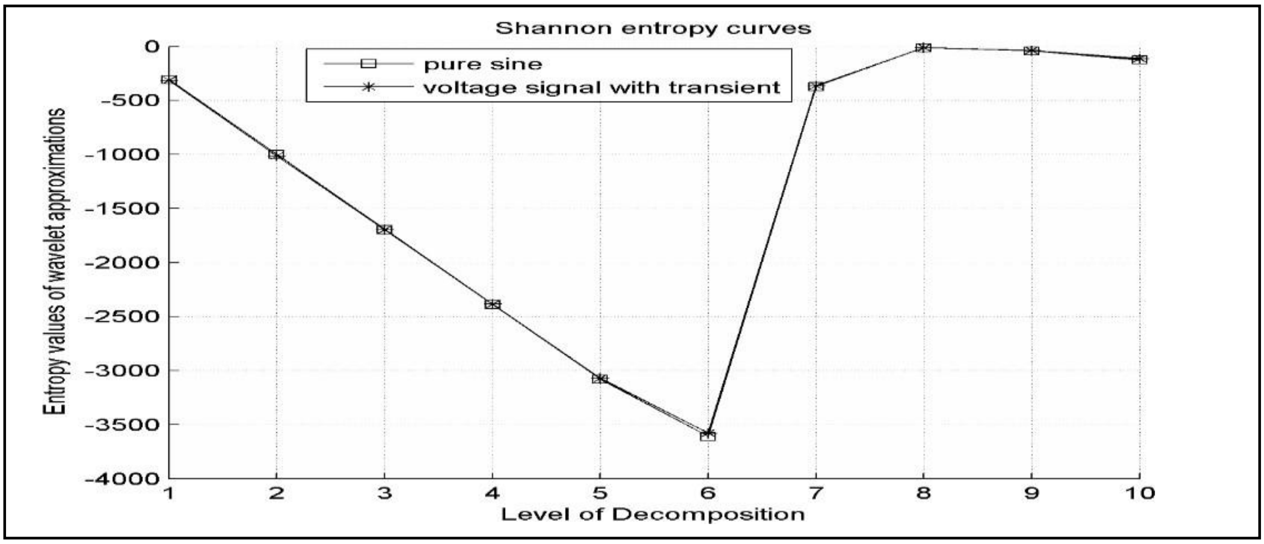

Figure 6. Shannon entropy curves of approximations from levels 1 to 10 for pure sine and transient signals

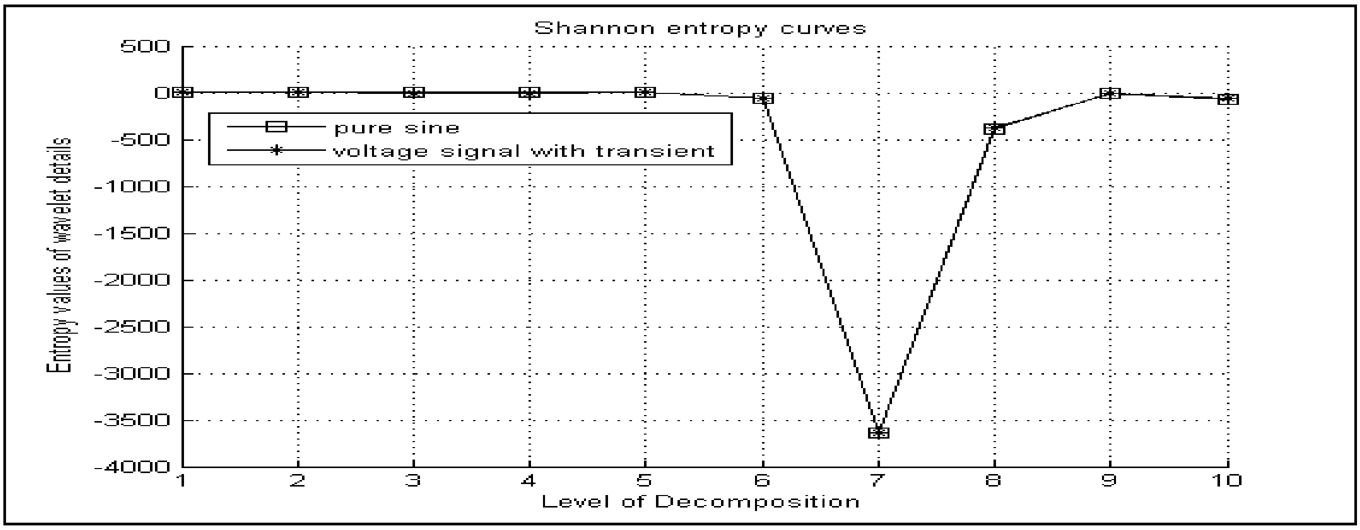

Figure 7. Shannon entropy curves of details from levels 1 to 10 for pure sine and transient signals

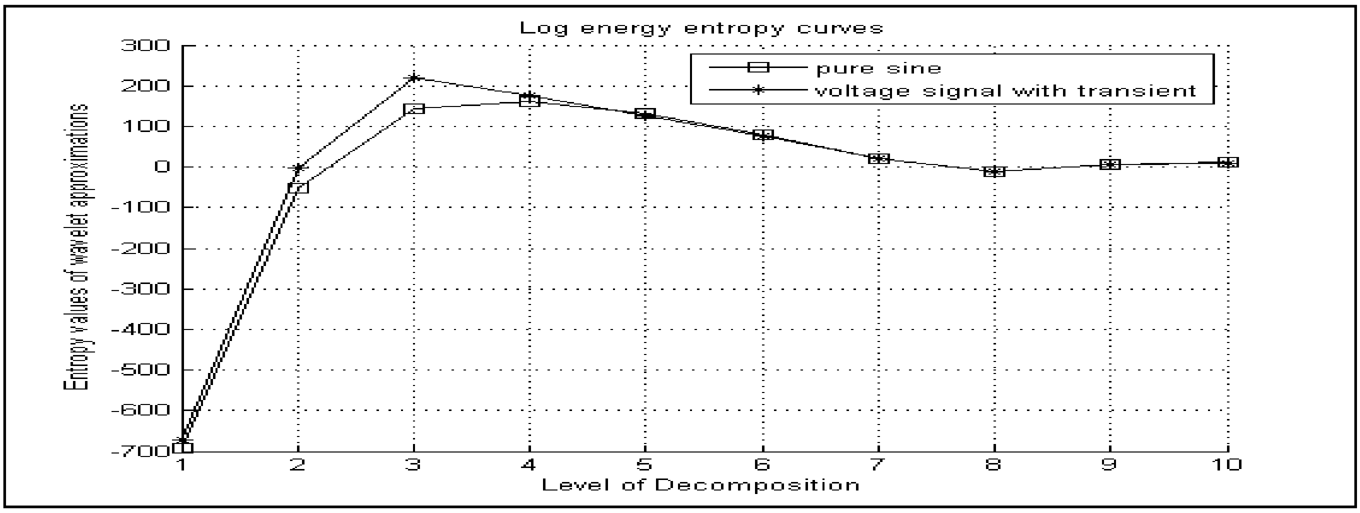

Figure 8. Log energy entropy curves of approximations from levels 1 to 10 for pure sine and transient signals

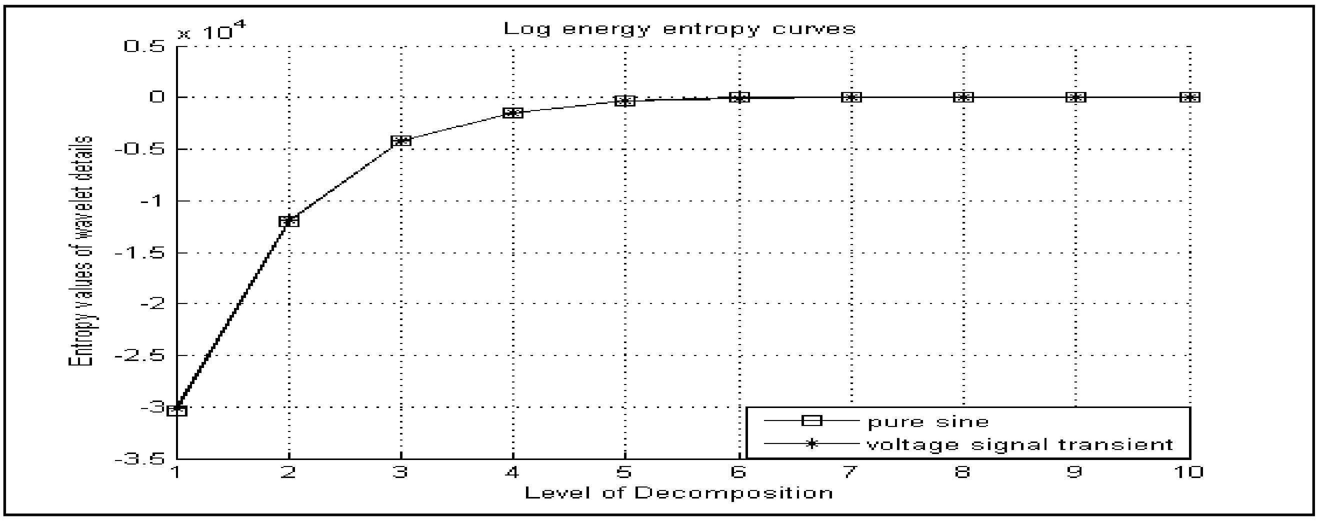

Figure 9. Log energy entropy curves of details from levels 1 to 10 for pure sine and transient signals

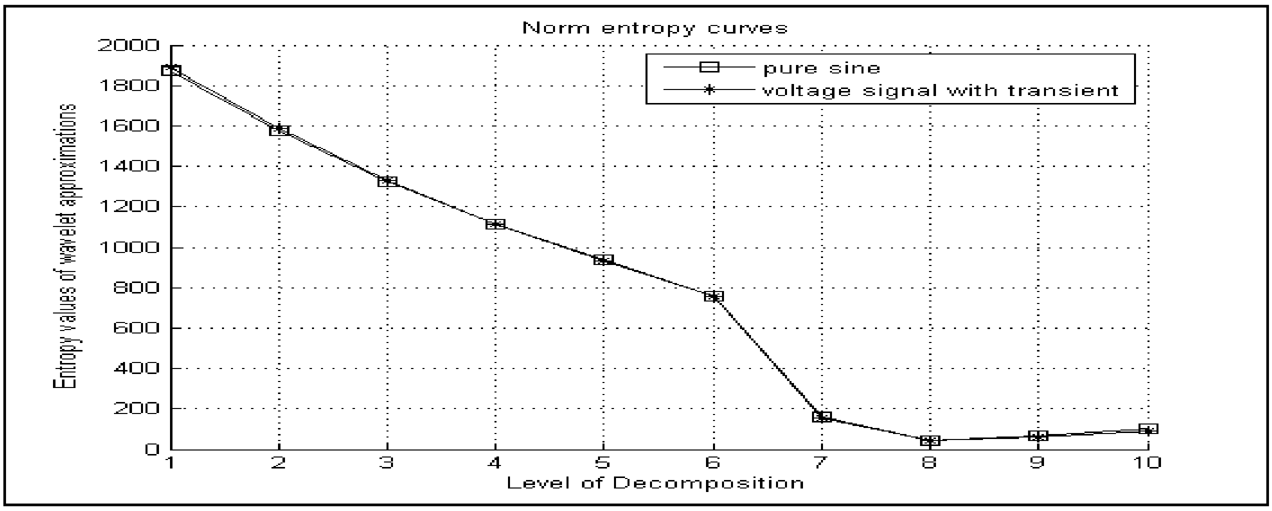

Figure 10. Norm entropy curves of approximations from levels 1 to 10 for pure sine and transient signals

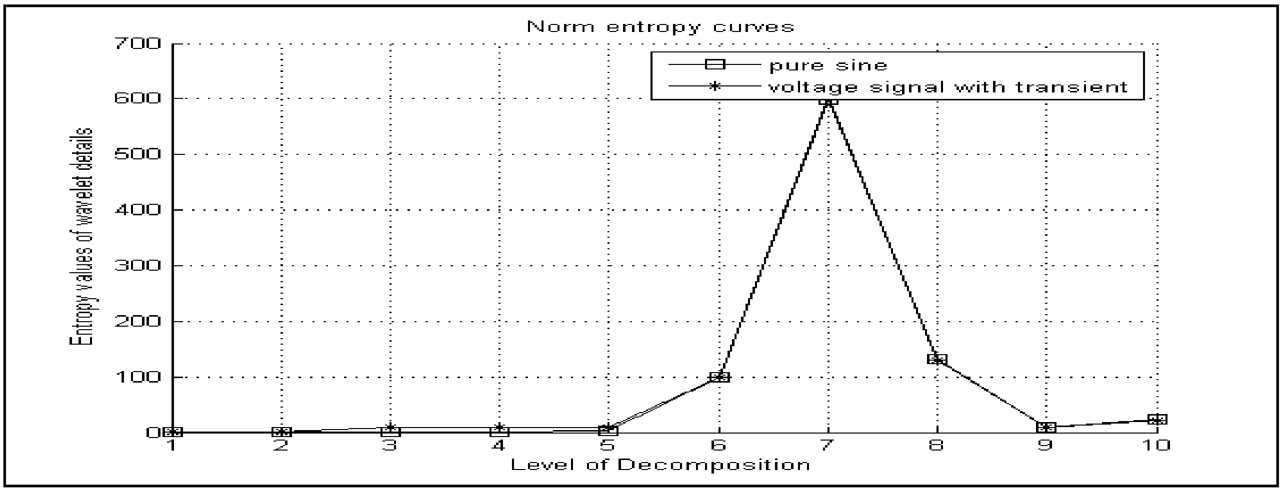

Figure 11. Norm entropy curves of details form levels 1 to 10 for pure sine and transient signals

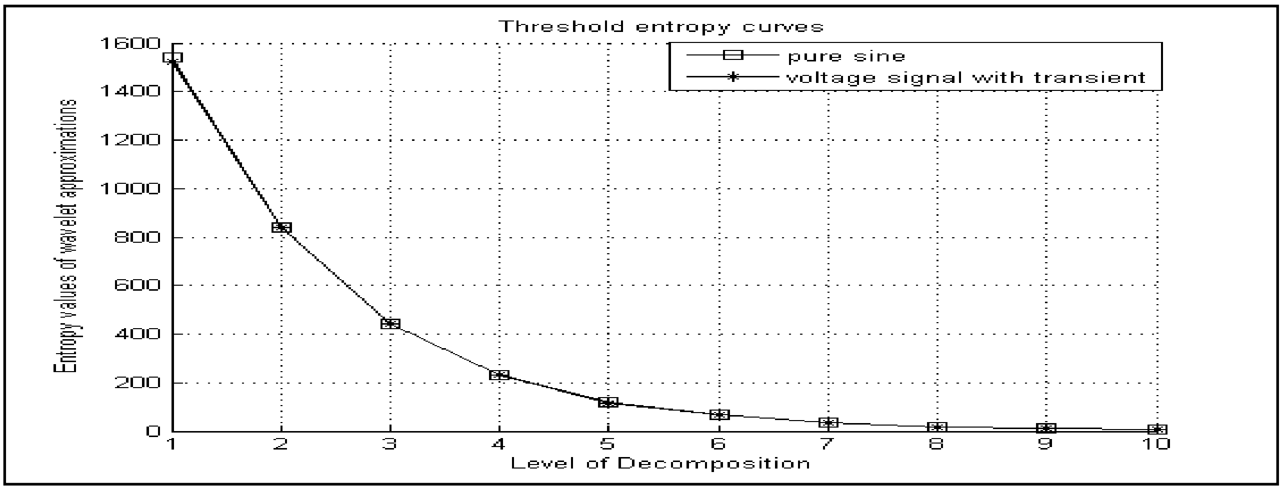

Figure 12. Threshold entropy curves of approximations from levels 1 to 10 for pure sine and transient signals

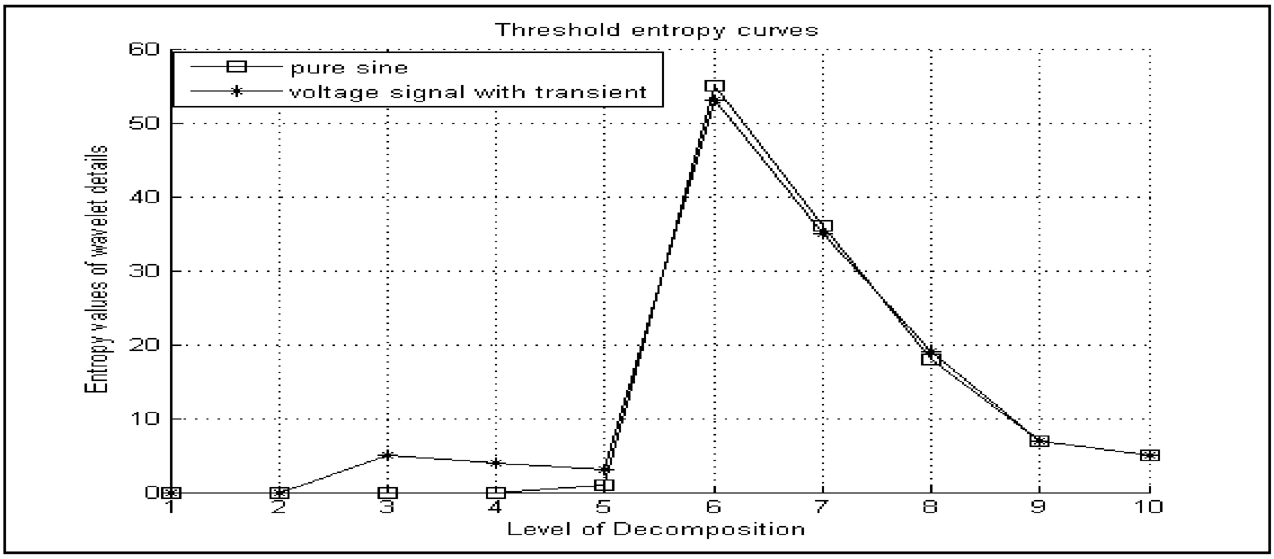

Figure 13. Threshold entropy curves of details from levels 1 to 10 for pure sine and transient signals

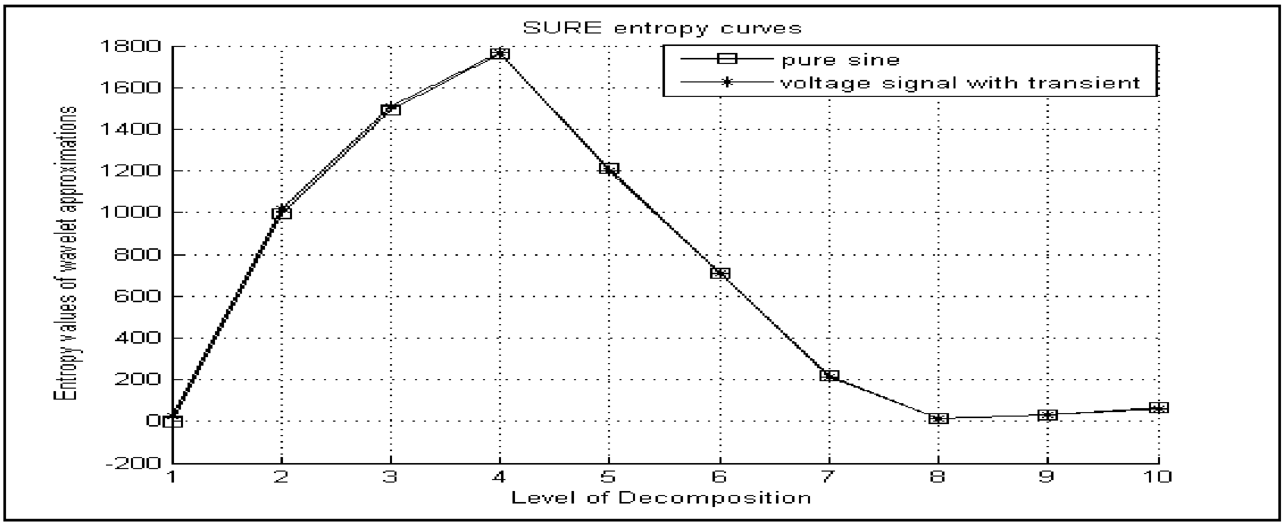

Figure 14. SURE entropy curves of approximations from levels 1 to 10 for pure sine and transient signals

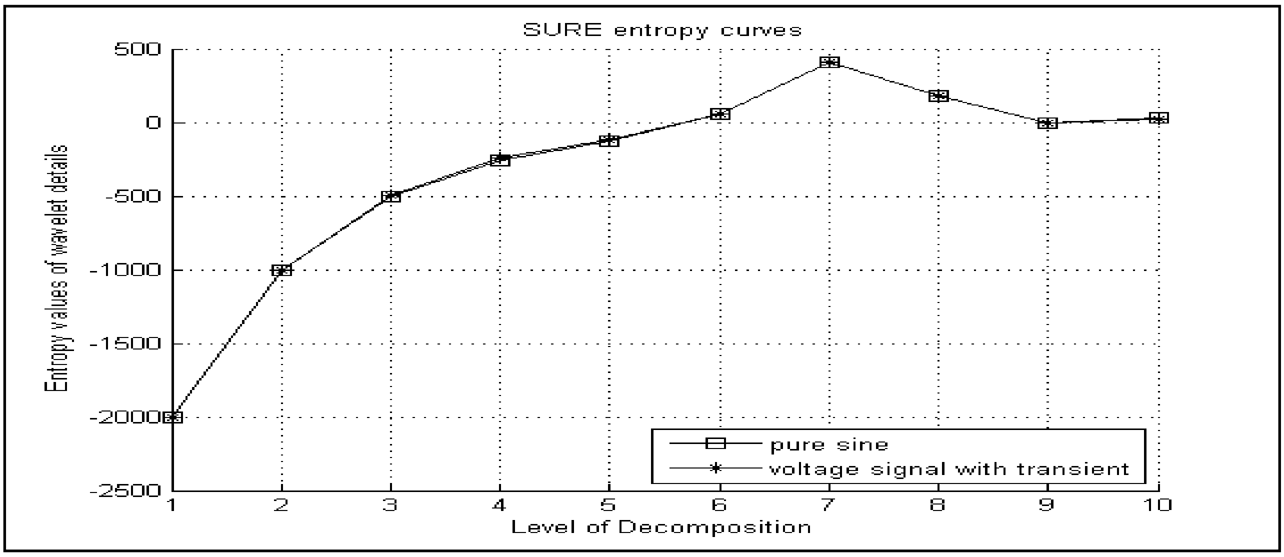

Figure 15. SURE entropy curves of details from levels 1 to 10 for pure sine and transient signals

Fundamental definitions of various wavelet entropy measures, are presented in [9], with some unique capabilities in feature picking up of transient signals and their calculations. In toolbox, for a wavelet packet tree or wavelet tree the nodes can be directly labelled as any one of depth_pos (depth position), index, entropy, opt. ent (optimal entropy), length, type (approximations or details), and energy. The entropy values can also be calculated using command line function *wentropy* where the entropy values are returned as real numbers. Figures 6 to 15 show a comparison between the entropy values of both pure sine wave and transient signals. From all the ten figures a notable deviation in both pure sine and transient signals approximation and detail coefficient entropy values are observed in figures 8 and 13.

SELECTION OF THE TYPE OF ENTROPY FOR RECOGNITION OF IMPULSIVE VOLTAGE TRANSIENT

Fig. 8 shows a sudden rise in log energy entropy values for levels 2 and 3 approximations. Fig. 13 also shows a sudden in threshold entropy values for levels 3 and 4 details. Approximations are low frequency version of the original signal and details are high frequency version of the original signal. Original signal refers to both pure sine wave and impulsive voltage transient. Table IV gives the deviation in the entropy values using log energy entropy and threshold entropy.

Table IV. Entropy values of pure sine and transient signals with a notable deviation

Level	*Log energy entropy of approximations*		*Level*	*Threshold entropy of details*	
	sine signal	*transient*		*sine signal*	*transient*
2	-52.03	-1.9474	3	0	5
3	142.34	219.50	4	0	4

Log energy entropy is indicating a sudden rise in entropy values of approximations for only 2 levels out of 10 levels and threshold entropy is also indicating a sudden rise in entropy values of details for only 2 levels out of 10 levels.

CONCLUSION

An impulsive transient refers to a sudden rise in the magnitude of voltage. In order to analyze a transient signal, the signal is decomposed into approximations and details for 10 levels. Coefficients are extracted using MATLAB command line functions. Entropy values, which are real numbers, are obtained for levels 1 to 10 approximation and detail coefficient vectors of both pure sinusoidal voltage signal and impulsive voltage transient signal. The different types of entropy are Shannon, log energy, norm, threshold, and SURE entropy. All the types of entropy are analyzed and only two out of the five entropy are showing a sudden rise in the entropy values indicating that a transient has occurred. Log energy entropy of levels 2 and 3 approximations and threshold entropy of levels 3 and 4 details are giving an information about transient. Log energy entropy for approximations and threshold entropy for details are selected for recognizing as impulsive voltage transient.

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