International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 24 (2015) pp 44246-44253
© Research India Publications. http://www.ripublication.com

Characterization of Power Quality Events based on Hilbert Huang Transform and fuzzy expert system

P. Kalyana Sundaram,

Assistant Professor, Department of Electrical Engineering, Annamalai University, Chidambaram
kalyansundar7@gmail. com

R. Neela,

Professor, Department of Electrical Engineering, Annamalai University Chidambaram
neelaaueee@gmail. com

Abstract

This paper introduces a new technique for the detection and characterization of various power quality events using Hilbert Huang Transform (HHT) and Fuzzy-expert system. The HHT method transforms a time domain function into a space representation both in time and frequency. The HHT method is used to analyze the distorted voltage waveforms and then extract their features. The distorted voltage waveforms are simulated by parametric equations. The extracted features are applied as inputs to the fuzzy-expert system that uses some rules on these inputs to characterize the PQ events. Fuzzy classifier has been implemented and tested for various types of power quality events. The results clearly show that the proposed method has the ability to detect and characterize PQ events. The performance of the proposed method has been evaluated by comparing the results against Hilbert Huang Transform based neural classifiers.

Keywords: Power quality, Power quality disturbances, Hilbert Huang transforms, Empirical mode decomposition, Fuzzy-expert system.

Nomenclature:

$x(t)$	Real signal
$e_+(t)$	Maximum envelop
$e_-(t)$	Minimum envelop
$m(t)$	Local average
$z_i(t)$	Proto mode function
$x_{HT}(t) -$	Hilbert transform signal
λ	Shifting operator
$(-jsgn(\Omega))$	Shifting the negative frequency of $x(t)$
$A(t)$	Envelop signal of $x(t)$
$\theta(t)$	Instantaneous phase signal of $x(t)$

1. Introduction

Power quality has become a important problem over the past few years to both utilities and customers. There are various types power quality issues in the transmission and distribution lines such as sag, swell, interruption, harmonics, sag with harmonics, swell with harmonics, flicker and notches. However in order to improve the electric power quality, the sources and occurrences of such disturbances must be detected and classify. The power quality disturbances were detected and localized into different types using wavelet transform analysis as illustrated in [1]. Analysis of electromagnetic power system transient waveform using wavelet transform has been illustrated in [2]. The short time Fourier transforms (STFT) based power frequency harmonic analyzer has been discussed in [3] for the non stationary signals. The windowed FFT which is the time windowed version of discrete Fourier transform has been applied for power quality analysis to classify a variety of disturbances in [4]. A combination of Fourier and wavelet transform along with fuzzy expert system has been presented in [5] for the automatic monitoring and analysis of power quality disturbances. Wavelet multi resolution analysis based neural network classifier is presented in [6] for the detection and extraction of power quality disturbances. An automated online power quality disturbances classification using wavelet based pattern recognition technique has been illustrated in [7].

The detection, localization and classification of power quality disturbances are based on S-transform and compared with wavelet multi resolution analysis has been presented in [8]. S-transform based neural network classifier is presented in [9] where the analysis takes place of the non stationary signals in the power system. Classifications of various power quality disturbances based on multi resolution S-transform along with fuzzy logic based pattern recognition technique has been illustrated in [10]. The classification of the power quality disturbances in both single and multiple natures using S-transform and Pattern recognition techniques has been implemented in [11].

A combination of wavelet transform along with both ANN and fuzzy logic classifier has been implemented for the PQ events classification in [12]. Probabilistic neural network method along with S-transform based on optimal feature selection for power quality disturbances classification has been illustrated in [13]. Discrete wavelet transform (DWT) along with kalman filter were discussed for the real time classification of power quality classification in [14]. An S-transform based fuzzy and Particle swarm optimization has been presented in [15] and this combines to identify the time series PQ disturbance data and also classified it. A hybrid method of discrete wavelet transform (DWT) along with

kalman filter based fuzzy expert system for the characterization of PQ disturbances has been illustrated in [16]. Classification of power quality disturbances using a combination of Hilbert huang transform (HHT) and Relevance vector machine (RVM) has been presented in [17]. A hybrid power quality monitoring technique based on Ensemble empirical mode decomposition (EEMD) and Hilbert transform (HT) with support vector machine (SVM) classifier has been presented in [18]. Classifications of various non stationary power quality disturbances based on EMD along with Hilbert transform and neural network has been illustrated in [19].
The detection and classification of single and combined power quality disturbances are based on signal spare decomposition (SSD) on overcomplete hybrid dictionary (OHD) matrix in [20]. A HHT method and fuzzy expert system based power quality analyzer in which features are extracted using HHT and disturbances are classified using fuzzy expert system is presented in this paper

2. Proposed Method

The proposed method has two stages namely

i. Feature extraction stage and
ii. Classification stage.

The block diagram for the proposed method is shown in figure 1. In the feature extraction stage the Hilbert Huang Transform is used for extracting features such as peak value and standard deviation. The classification stage consists of the fuzzy expert system. Disturbance waveforms were generated using a set of parametric equations.

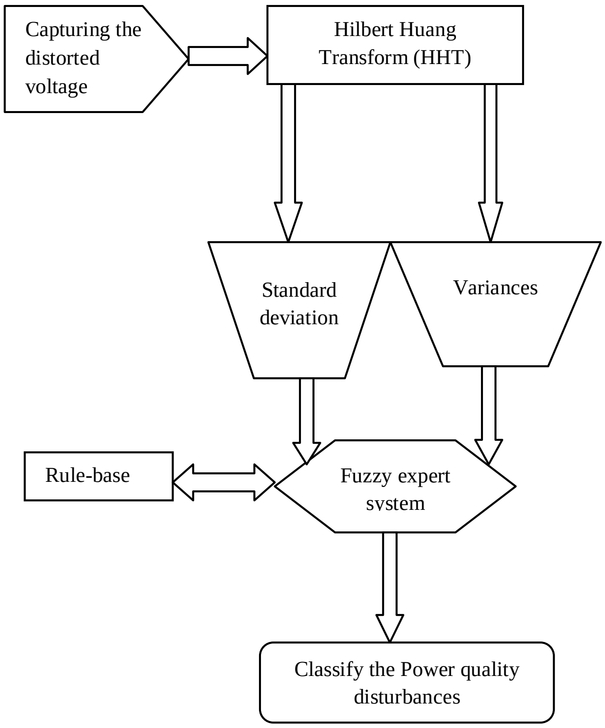


Figure 1. Block diagram of the proposed system

2.1 Feature Extraction Stage using Hilbert Huang Transform

The Hilbert Huang Transform (HHT) is a combination of Empirical Mode Decomposition (EMD) and the Hilbert Transform (HT).

2.1.1 Empirical Mode Decomposition

Empirical Mode Decomposition (EMD) method provide the decomposition a signal $x(t)$ into a set of basics function in an analytical nature called intrinsic mode function (IMF).
The important part of the HHT method is EMD sifting process. EMD sifting process consists of the following steps:

1. Calculate the local extrema of $x(t)$.
2. Find the maximum envelope $e_+(t)$ of $x(t)$by fitting a natural cubic spline through the local maxima.
3. Find the minimum envelope $e_-(t)$ of $x(t)$by fitting a natural cubic spline through the local minima.
4. Compute an approximation to the local average

$$(m(t)) = (e_+(t) + e_-(t))/2 \quad (1)$$

5. Determine the proto-mode function

$$z_i(t) = x(t) - m(t) \quad (2)$$

6. Check and verify $z_i(t)$ is an IMF. An IMF is a wave that satisfies the following conditions:
1) The number of extrema and the number of zero crossings may differ by no more than one.
2) The local average is zero. The threshold used to set this condition is critical to avoid over or under training;
3) To avoid the extraction of accidental IMFs, the conditions must be accomplished in at least two to three consecutive iterations.
7. If $z_i(t)$ is not an IMF, repeat the EMD sifting process by setting $x(t) = zi(t)$. If $z_i(t)$ is an IMF then set $IMF_i(t) = z_i(t)$.

1.1.2 Hilbert Transform

The Hilbert Transform is used to generate an analytical signal obtained by convolving the real signal with the function as shown below.

$$x_{HT}(t) = x(t)\left(\frac{1}{\pi t}\right) \quad (3)$$

$$x_{HT}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} x\left(\frac{\lambda}{(t-\lambda)}\right)d\lambda \quad (4)$$

$$x_{HT}(t) = -jsgn(\Omega)X(\Omega) \quad (5)$$

The output of the Hilbert transform is 90^0 phase shift of the original signal$x(t)$, a complex signal. It is defined as

$$x_c(t) = x(t) + jx_H(t) \quad (6)$$

$$x_c(t) = A(t)\,e^{j\theta(t)} \quad (7)$$

The analytical signal has the information about amplitude as well phase of the signal. It is clear that

$$A(t) = \sqrt{x^2(t) + x_{HT}^2(t)} \tag{8}$$

$$\theta(t) = tan^{-1}\left(\frac{x_{HT}(t)}{x(t)}\right)$$

1.1.2 Fuzzy Expert System

Fuzzy system represents the knowledge and reasons in vague or imprecise for reasoning uncertainty. It provides a simple way to get definite conclusion based upon ambiguous. The accuracy of the fuzzy logic system depends on the knowledge of human experts. The mamdani type of fuzzy inference system used to perform the classification of the PQ events. It has two inputs, one output with 25 rules.

The first input to the system is the value of standard deviation. The input is divided into five trapezoidal membership functions namely VSTD (very small standard deviation), SSTD (small standard deviation), NSTD (normal standard deviation), LSTD (large standard deviation), and VLSTD (very large standard deviation).

The second input to the system is the value of variances. It is broken into five triangular membership functions namely VV (very small variance), SV (small variance), NV (normal variance), LV (large variance), and VLV (very large variance). The fuzzy expert system is shown in figure 2.

The output memberships function and rule viewer of the fuzzy expert system are shown in figure 3 and figure 4.

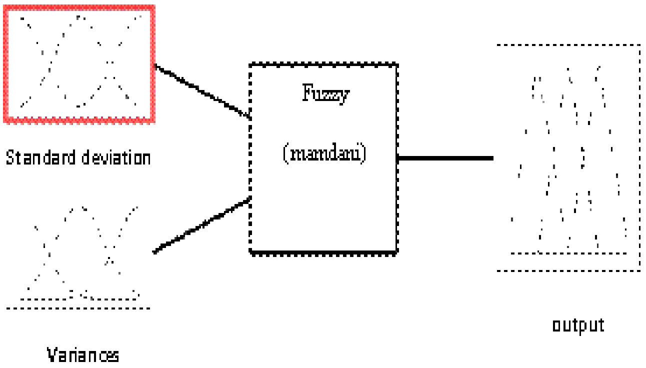


Figure 2. Fuzzy expert system

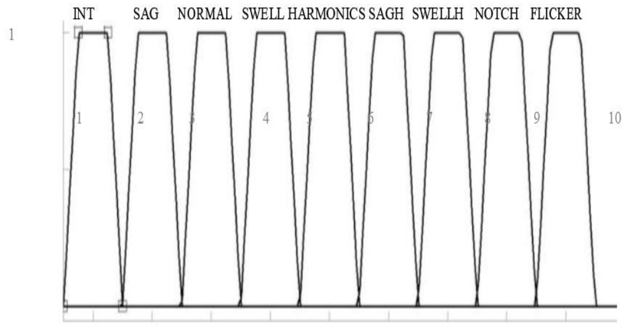


Figure 3. Output membership function

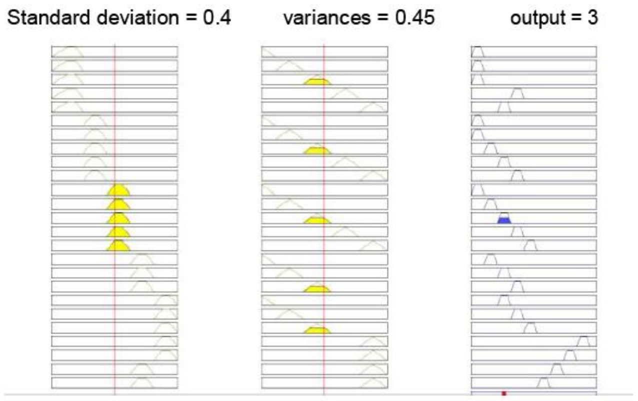


Figure 4. Rule viewer of fuzzy expert system

The brief rule sets of fuzzy expert system are given below:

1) If (Standard deviation is VSTD) and (variances is VV) then (output is INTERRUPTION).
2) If (Standard deviation is VSTD) and (variances is SV) then (output is INTERRUPTION).
3) If (Standard deviation is VSTD) and (variances is NV) then (output is INTERRUPTION).
4) If (Standard deviation is VSTD) and (variances is LV) then (output is SWELL).
5) If (Standard deviation is VSTD) and (variances is VLV) then (output is NORMAL).
6) If (Standard deviation is SSTD) and (variances is VV) then (output is INTERRUPTION).
7) If (Standard deviation is SSTD) and (variances is SV) then (output is INTERRUPTION).
8) If (Standard deviation is SSTD) and (variances is NV) then (output is SAG).
9) If (Standard deviation is SSTD) and (variances is LV) then (output is NORMAL).
10) If (Standard deviation is SSTD) and (variances is VLV) then (output is SWELL).
11) If (Standard deviation is NSTD) and (variances is VV) then (output is INTERRUPTION).
12) If (Standard deviation is NSTD) and (variances is SV) then (output is SAG).
13) If (Standard deviation is NSTD) and (variances is NV) then (output is NORMAL).
14) If (Standard deviation is NSTD) and (variances is LV) then (output is SWELL).
15) If (Standard deviation is NSTD) and (variances is VLV) then (output is HARMONICS).
16) If (Standard deviation is LSTD) and (variances is VV) then (output is SAG).
17) If (Standard deviation is LSTD) and (variances is SV) then (output is NORMAL).
18) If (Standard deviation is LSTD) and (variances is NV) then (output is SWELL).
19) If (Standard deviation is LSTD) and (variances is VLV) then (output is SAG WITH HARMONICS).
20) If (Standard deviation is LSTD) and (variances is VLV) then (output is SWELL WITH HARMONICS).

21) If (Standard deviation is VLSTD) and (variances is VV) then (output is NORMAL).
22) If (Standard deviation is VLSTD) and (variances is SV) then (output is SWELL).
23) If (Standard deviation is VLSTD) and (variances is NV) then (output is HARMONICS).
24) If (Standard deviation is VLSTD) and (variances is VLV) then (output is FLICKER).
25) If (Standard deviation is VLSTD) and (variances is VLV) then (output is NOTCH).

3. Classification Stage using fuzzy expert system

The proposed fuzzy expert system used for detects and characterize the eight types of power quality disturbances. The extracted input features through the Hilbert Huang Transform are applied as inputs to the fuzzy expert system in order to classify the disturbances.

Fuzzy logic with the rule based expert system has emerged the classification tool for PQ events. The rules of this technique are based on modeling human experience and expertise.

3.1 Flowchart of the Proposed Method

The flowchart for the Classification of Power Quality disturbances is shown in below.

It has three different blocks.

- Block-1-Extraction of the features
- Block-2 Classification of PQ disturbances and
- Block-3 Identification of the disturbances

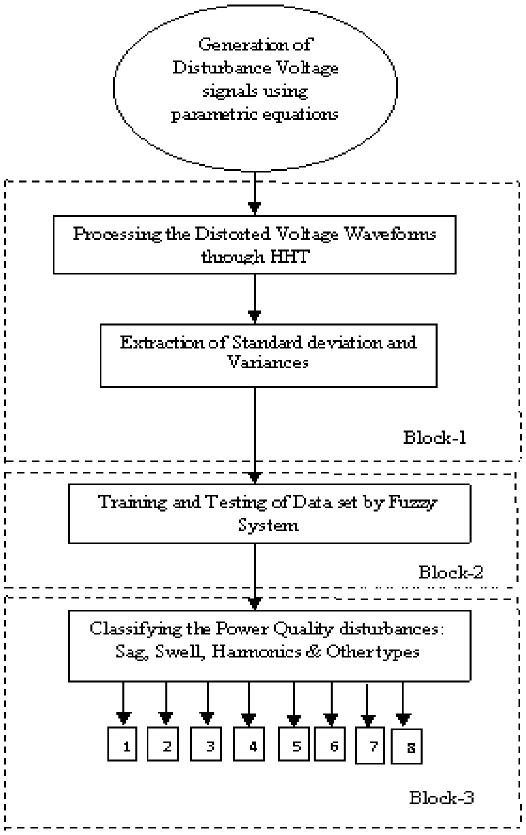


Figure 5. Flowchart for the Classification of PQ disturbances

4. Simulation and Test Results

A set of parametric equations were used to Training and Test data for various classes of disturbances and this method of data generation offers the advantages such as a wide range of parameters can be generated in a controlled manner, signals closer to real situation can be simulated. The nine types of different power quality disturbances, namely pure sine (normal), sag, swell, outage, harmonics, sag with harmonic, swell with harmonic, notch and flicker were considered. Signal generation models and their control parameters are shown in table 1.

Table1. Power Quality Disturbance Model

SN	PQ events	Symbols	Model	Parameters
1	Pure Sine	S1	$f(t) = \sin(\omega t)$	
2	Sag	S2	$f(t) = A(1 - \alpha(u(t - t_1) - u(t - t_2)))\sin(\omega t)$	$0. 1\leq\alpha\leq 0. 9; T\leq t_2 - t_1\leq 9T$
3	Swell	S3	$f(t) = A(1+\alpha(u(t - t_1) - u(t - t_2)))\sin(\omega t)$, $t_1<t_2$, $u(t) = \sum_{0,t\leq 0}^{1,t\geq 0}$	$0. 1\leq\alpha\leq 0. 8; T\leq t_2 - t_1\leq 9T$
4	Outage	S4	$f(t) = A(1 - \alpha(u(t - t_1) - u(t - t_2)))\sin(\omega t)$	$0. 9\leq\alpha\leq 1; T\leq t_2 - t_1\leq 9T$
5	Harmonics	S5	$f(t) = A(\alpha_1\sin(\omega t) + \alpha_3\sin(3\omega t) + \alpha_5\sin(5\omega t) + \alpha_7\sin(7\omega t)$	$0. 05\leq\alpha_3\leq 0. 15; 0. 05\leq\alpha_5\leq 0. 15; 0. 05\leq\alpha_7\leq 0. 15; \sum\alpha_i^2 = 1$
6	Sag and Harmonics	S6	$f(t) = A(1 - \alpha(u(t - t_1) - u(t - t_2)))(\alpha_1\sin(\omega t) + \alpha_3\sin(3\omega t) + \alpha_5\sin(5\omega t))$	$0. 1\leq\alpha\leq 0. 9; T\leq t_2 - t_1\leq 9T; 0. 05\leq\alpha_3\leq 0. 15; 0. 05\leq\alpha_5\leq 0. 15; \sum\alpha_i^2 = 1$
7	Swell and Harmonics	S7	$f(t) = A(1+\alpha(u(t - t_1) - u(t - t_2)))(\alpha_1\sin(\omega t) + \alpha_3\sin(3\omega t) + \alpha_5\sin(5\omega t))$	$0. 1\leq\alpha\leq 0. 8; T\leq t_2 - t_1\leq 9T; 0. 05\leq\alpha_3\leq 0. 15; 0. 05\leq\alpha_5\leq 0. 15; \sum\alpha_i^2 = 1$
8	Notch	S8	$y(t) = (\sin(\omega_d t) + \mathrm{sign}(\sin(\omega_d t))*[\sum_{n=1}^{i} k*[u(t - (t_1+0. 002n)) - u(t - (t_1+0. 002n))]$	$0. 1\leq k\leq 0. 4; 0. 01T\leq t_2 - t_1\leq 0. 05T; 0\leq t_2, t_1\leq 0. 5$
9	Flicker	S9	$y(t) = [1+\alpha\sin(2\pi\beta t)]\sin(\omega_d t)$	$0. 1\leq\alpha\leq 0. 2; 5H_z\leq\beta\leq 20H_z$

These input signals are applied to the fuzzy expert system to get accurate classified disturbances. The PQ disturbance signals generated using the Matlab based parametric equations. The various classes of PQ disturbances and the standard empirical mode decomposition (EMD) with intrinsic mode function (IMF) components are shown in figure 6(a) to

6(i). The plots of Hilbert energy spectrum of various PQ disturbances in time-frequency nature are shown in figure 7(a) to 7(i). Figure 8 represent the feature extraction of various PQ disturbances.

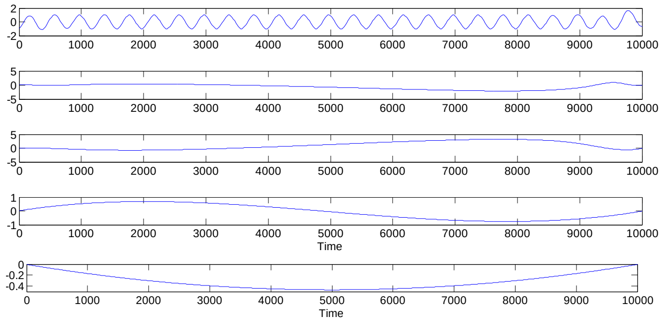


Figure 6(a) Decomposition of the sine wave signal

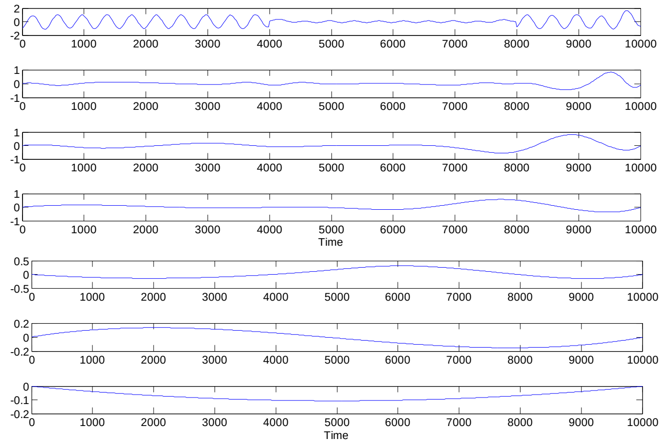


Figure 6(b) Decomposition of the signal with voltage sag disturbances

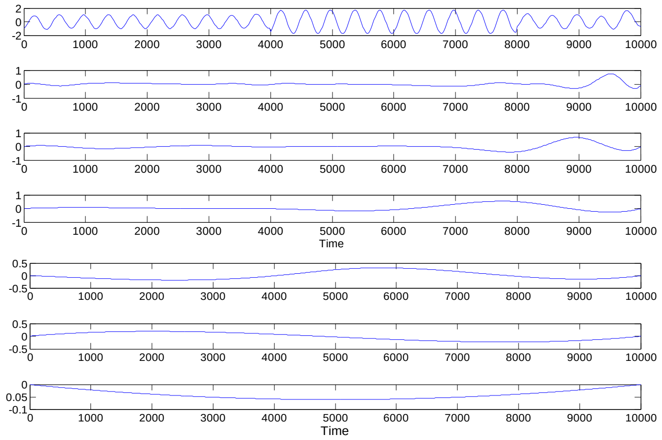


Figure 6(c) Decomposition of the signal with voltage swell disturbances.

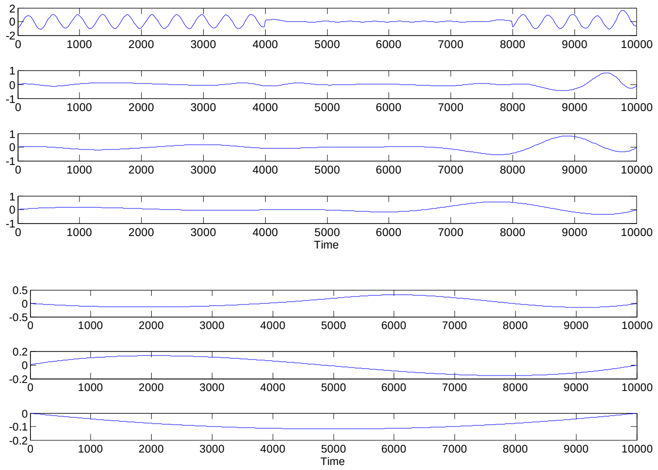


Figure 6(d) Decomposition of the signal with outages.

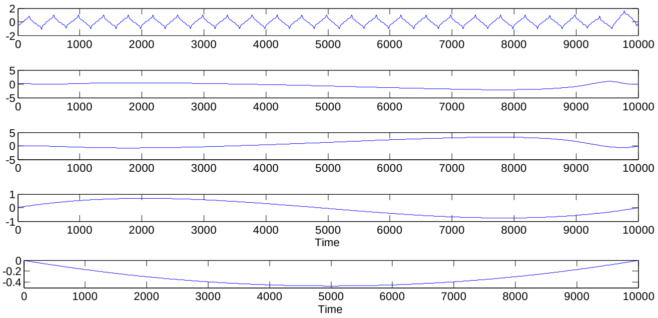


Figure 6(e) Decomposition of the signal with harmonics.

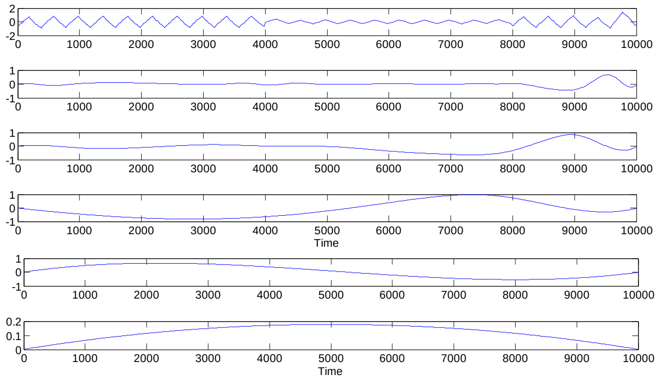
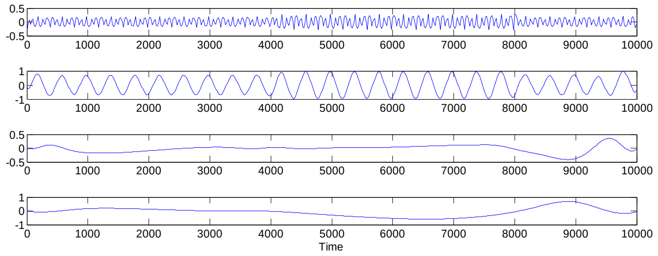


Figure 6(f) Decomposition of the signal in sag with harmonics disturbances



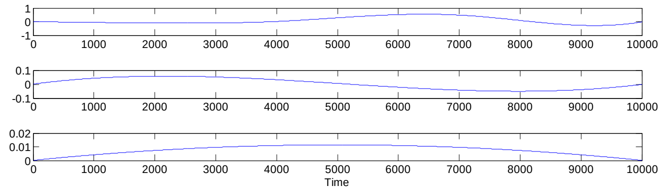


Figure 6(g) Decomposition of the signal in swell with harmonics disturbances.

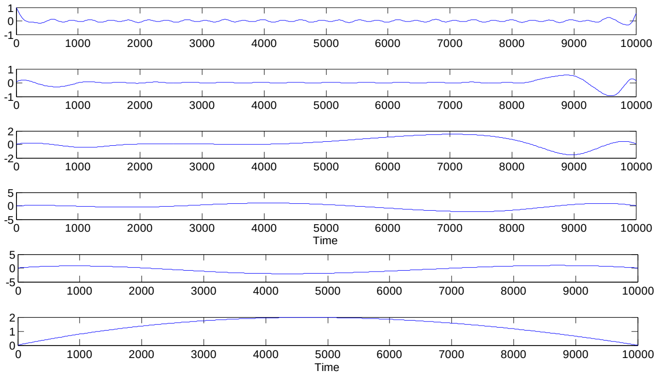


Figure 6(h) Decomposition of the signal with flicker

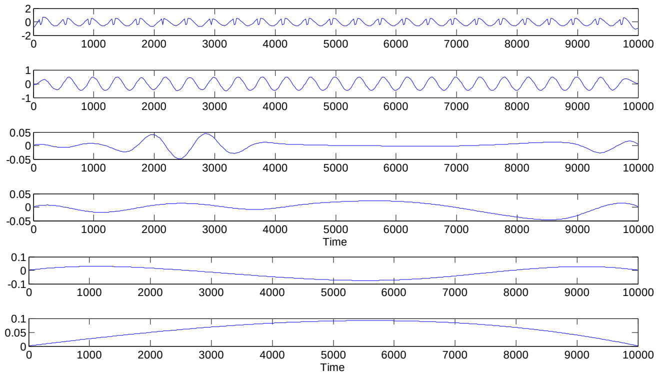
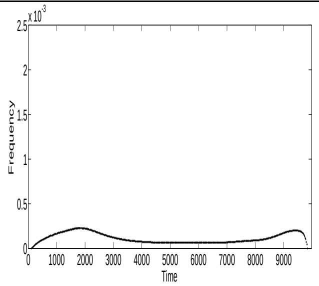
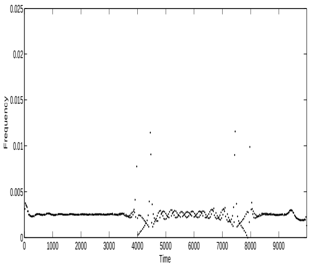
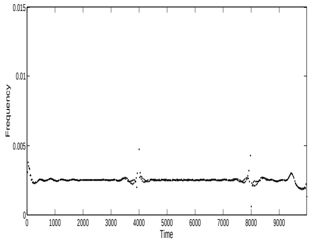
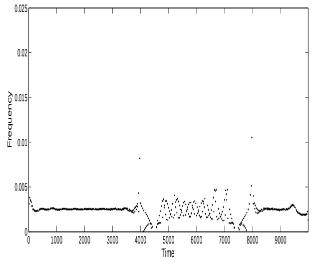
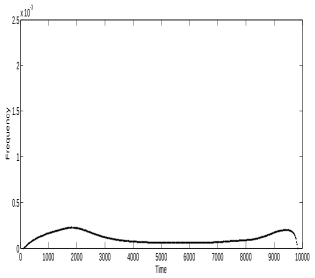
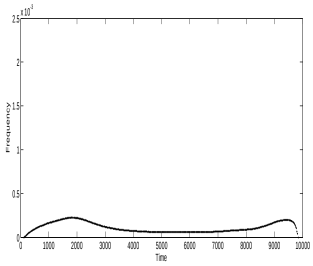
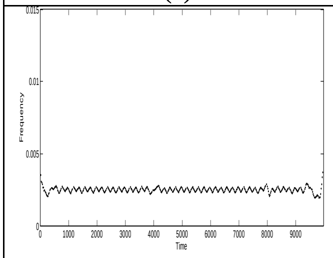
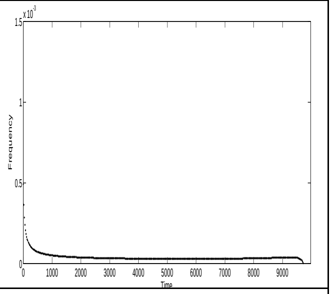
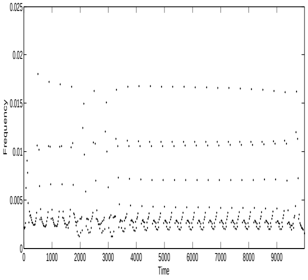


Figure 6(i) Decomposition of the signal with notch disturbances.

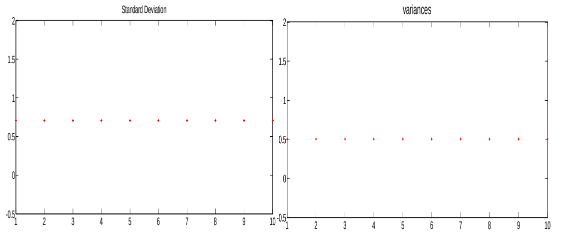
	
7(a)	7(b)

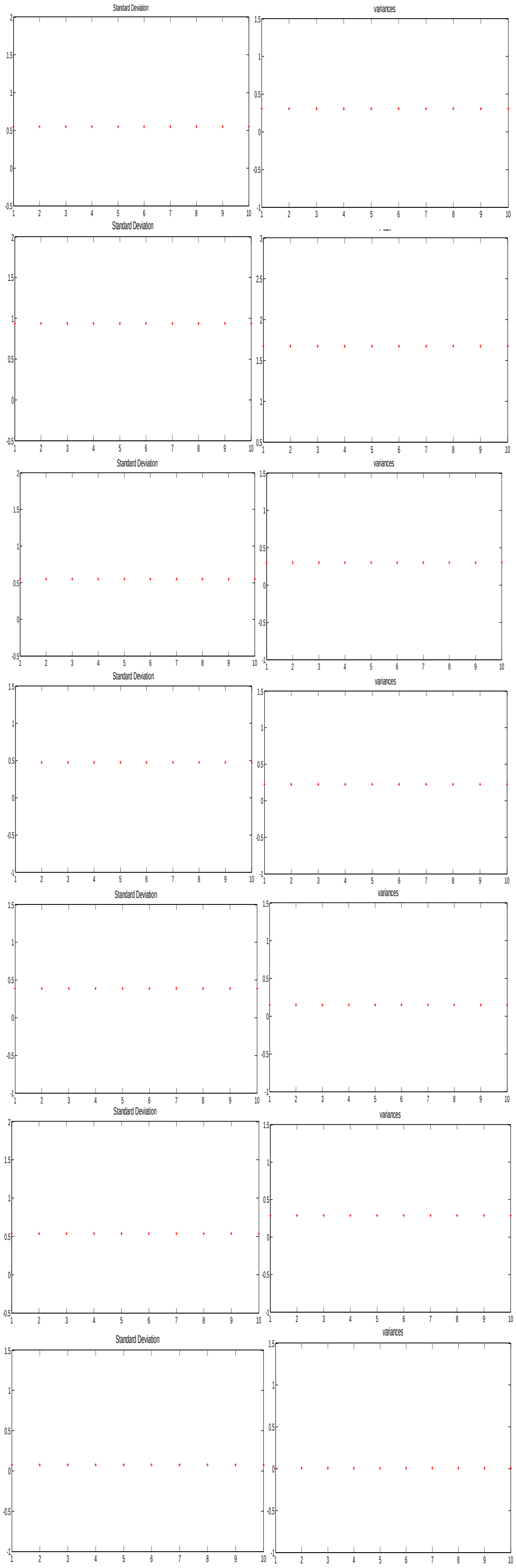
	
7(c)	7(d)
	
7(e)	7(f)
	
7(g)	7(h)

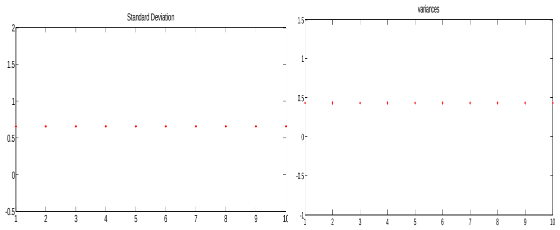


7(i)

The time-frequency analysis of hilbert spectrum;7(a)sinewave. 7(b)sag. 7(c)swell. 7(d)outages. 7(e)harmonics. 7(i)notch. 7(f)sag with harmonics. 7(g)swell with harmonics. 7(h)flicker.







Extraction of two input features such as standard deviation and variances using Hilbert Huang Transform in the various Power quality events are shown in figures; 8(a)sine wave. 8(b)sag. 8(c)swell. 8(d)outages. 8(e)harmonics. 8(f)sag with harmonics. 8(g)swell with harmonics. 8(h). flicker. 8(i). notch

.

Table 3. Classification accuracy

Sno	PQ disturbance	Percentage of Accuracy		
		Input Feature	Hilbert Huang Transform based MLP Neural network	Hilbert Huang Transform based fuzzy expert system
1	Voltage Sag	100	100	100
2	Voltage Swell	100	99	99
3	Outages	100	98	99
4	Harmonics	100	99	99
5	Sag with Harmonics	100	100	98
6	Swell with Harmonics	100	99	98
7	Flicker	100	100	100
8	Notch	100	100	100
Overall accuracy			99. 25	99. 13

5. Conclusion

A new technique based on Hilbert Huang transform (HHT) and fuzzy expert system has been proposed for characterizing the various types of Power quality disturbances. The Power quality disturbance waveforms were generated through parametric equations. Through HHT method the input features such as standard deviation, and variances were extracted and fuzzy logic approach has been applied for classifying the various PQ disturbances. The method enables the accurate classification of all nine types of PQ disturbances. Simulation results demonstrate that the performance and accuracy of the Hilbert Huang transform techniques. The results show that the proposed system performs very well in detection and characterization of PQ disturbances.

References

[1] Surya Santoso, Edward J. Powers, and W. Mack Grady, “Electric power quality disturbances detection using wavelet transform analysis”, IEEE Transaction, 1994.

[2] David C. Robertson Octavia I. Camps, Jeffrey S. Mayer, William B. Gish, “Wavelet and electromagnetic power system transients”, IEEE Transaction on power delivery, Vol 11, no., April 1996.

[3] Paul S. Wright, “Short time Fourier transforms and wigner-ville distributions applied to the calibration of power frequency harmonic analyzers”, IEEE Transaction on instrumentation and measurement, Vol 48, no. 2, April 1999.

[4] G. T. Heydt, P. S. Fjeld, C. C. Liu, D. Pierce, L. Tu,G. Hensley, “Applications of the windowed FFT to Electric Power quality assessment”, IEEE Transaction on power delivery,oct 1999.

[5] Mladen Kezunovic, “Advanced assessment of the power quality events”, IEEE Transaction, 2000.

[6] Surya Santoso, Edward J. Powers, W. Mack Grady, and Antony C. Parsons, “Power quality disturbance waveform recognition using wavelet based neural classifier-part 1: theortical foundation”, IEEE Transaction on power delivery, Vol 15, no. 1, January 2000.

[7] A. M. Gaouda, S. H. Kanoun and M. M. A. Salama, “On-line disturbance classification using nearest neighbor rule”, Electric power systems research, 2001.

[8] P. K Dash, G. Panda and B. K. Panigrahi, “Power quality analysis using S–transform”, IEEE Transaction on power delivery, Vol 18, no. 2, April 2003.

[9] P. K Dash, I. W. C. Lee, “S-transform-based intelligent system for classification of power quality disturbance signals”, IEEE Transaction on industrial electronics, Vol 50, no. 4, August 2003.

[10] M. V. Chilukuri, P. K. Dash, “Multi resolution S-transform-based fuzzy recognition system for power quality events”, IEEE Transaction on power delivery, Vol 19, no. 1, January 2004.

[11] Fengzhan Zhao, Rengang Yang, “Power quality disturbance recognition using S-transform”, IEEE transaction on power delivery, Vol 22, no. 2, April 2007.

[12] Mamun Bin Ibne Reaz, Florence Choong, Mohd Shahiman Sulaiman and Masaru Kamada, “ Expert system for power quality disturbance classifier”, IEEE transaction on power delivery, Vol 22, no. 4, July 2007.

[13] S. Mishra, C. N. Bhende, and B. K. Panigrahi, “Detection and classification of power quality disturbances using S-transform and Probabilistic neural network”, IEEE transaction on power delivery, Vol 23, no. 1, January 2008.

[14] Enrique Perez, Julio Barros, “A proposal for on-line detection and classification of voltage events in power systems”, IEEE transaction on power delivery, Vol 23, no. 4, October 2008.

[15] H. S. Behera, P. K. Dash, B. Biswal, “Power quality time series data mining using S-transform and fuzzy expert system”, Applied soft computing, 2010.

[16] Abdelazeem A. Abdelsalam, Azza A. Eldesouky, Abdelhay A. Sallam, “Characterization of power quality disturbances using hybrid technique of linear kalman filter and fuzzy-expert system”, Electric power system research, 2012.

[17] Faeza Hafiz, A. Hasib Chowdhury, and Celia Shahnaz, “An approach for classification of power quality disturbances based on Hilbert Huang transform and Relevance vector machine”, IEEE transactions, 2012.

[18] Okan Ozgonenela, Turgay Yalcina, Irfan Guneyb, and Unal Kurtc, “A new classification for power quality events in distribution systems”, Electric power system research, 2013.

[19] B. Biswal, M. Biswal, S. Mishra and R. Jalaja, “Automatic Classification of Power Quality Events Using Balanced Neural Tree”, IEEE Transaction on Industrial electronics. Vol 61, January 2014.

[20] M. Sabarimalai manikandan, R. Samantary, Innocent Kamwa,”Detection and classification of Power Quality disturbances using sparse signal decomposition on hybrid dictionaries”, IEEE Transactions on Instrumentation and measurement, Vol 64, No. 1, Jan 2015.