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Power Quality Disturbances Classification Using S-transform and Fuzzy System

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Abstract: A novel approach for the classification of various power quality disturbances using S-transform based fuzzy expert system is proposed in this paper. The distorted voltage waveforms are generated using Matlab simulation on the test system. The S-Transform method is used to extract the two input features (Standard deviation and variances) from the distorted voltage waveforms. The features extracted through S-transform are given as input to Fuzzy expert system for the classification of various types of power quality disturbances. The simulation results show that the proposed method is effective and classify the power quality disturbances. The performance of the proposed technique is compared with the kalman filter based fuzzy expert system.

Keywords: Power quality, Power quality disturbances, S-transform, Fuzzy logic, Fuzzy expert system.

Nomenclature

$h(t)$ – Real signal
$S(t,f)$ − Stransform
f − frequency
t − time
$WT(t,f)$ − Continous wavelet transform
$e^{j2\pi f\tau}$ − Phase factor
τ − time variable
$d\tau$ − differential time variable
$W*$ −Complex conjugate of wavelet transform
$W(v,f)$ − Time frequency resolution of wavelet transform

I. INTRODUCTION

Power quality has become an main problem in the electric power system for the past few years. The main reason for the poor quality of electric power is induced by power line disturbances such as sag, swell, interruption, harmonics, sag with harmonics, swell with harmonics, flicker and notches. The data processing burden of classification algorithm has been considerably reduced by compressing the signals through wavelet transform methods as illustrated in [1]. Classification of power quality events using a combination of SVM and RBF networks has been presented in [2]. 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 [3]. An automated online power quality disturbances classification using wavelet based pattern recognition technique has been illustrated in [4].

A combined form of Fourier and wavelet transform along with fuzzy classifier has been presented in [5] to analyzed voltage sag disturbances and also identified the location of the sag fault using genetic algorithm.As wavelet transforms cannot be applied for the analysis of non stationary signals, S-transforms were implemented due to their excellent frequency resolution characteristics. Application of s-transform for power quality analysis has been discussed in [6] and a fuzzy logic based pattern recognition system along with multi resolution S-transform for power quality event classification has been discussed in [7].

The classification of the power quality disturbances in both single and multiple natures using S-transform and Pattern recognition techniques has been implemented in [8]. An S-transform based probabilistic neural network has been presented in [9] and this combines the frequency resolution characteristics of S transform with the pattern recognizing ability of a neural network. The modified S-transform along with the combined form of fuzzy C-means clustering technique and Particle swarm optimization for non stationary power disturbances classification in [10]. The binary feature matrix of the system has been designed using Fourier and S-transform and a rule base has been formulated to classify the power quality events in [11].

The assessment of electric power quality events based on Hilbert transform along with empirical mode decomposition technique has been presented in [12].As Hilbert transform shows greater immunity towards noise, it has been used for the detection and classification of power quality events along with ANN in [13]. A representative quality power vector has been derived for power quality analysis through an adaptive neuro fuzzy interface system in [14]. A combination of linear Kalman filter and fuzzy expert system has been used for the analysis of power quality events in [15] wherein the signal noise is estimated using a block of DWT. Classification of power quality disturbances using the combined form of Hilbert huang transform (HHT) and Relevance vector machine (RVM) has been presented in [16].

The windowed Hilbert huang transform (HHT) used to analyze the non-stationary signal in power quality analysis has been discussed in [17]. Classifications of various non stationary power quality disturbances based on EMD along with Hilbert transform and neural network has been elaborated in [18]. The dual neural network as ADALINE and FFNN has been implemented for the classification of single and combined form power quality disturbance in [19].Classification of both the single and combined nature of power quality disturbances using signal spare decomposition (SSD) has been illustrated in [20]. A S-transform and fuzzy expert system based power quality analyzer in which the features are extracted using S-transform and disturbances are classified using fuzzy expert system is presented in this paper.

1. Proposed Method

The proposed method has two stages namely

i. Feature extraction using S-transform.
ii. Classification stage using Fuzzy expert system.

S-transform is used for extracting features such as variances and standard deviation. MLP neural network is used for classifying the power quality disturbances. The disturbance waveforms are generated using Matlab simulation on the test system.

1.1 Feature Extraction Stage using S-transform

The S-transform is a generalization of the Short-time Fourier transform (STFT) and an extension of the continuous wavelet transforms (CWT). The S-transform will perform multi-resolution analysis (MRA) on a time varying power signal, as its window width varies inversely with the frequency. The main function of the S-transform is a Gaussian modulation cosinusoid. The output of the S-transform is an N x M matrix called the S-matrix whose rows pertain to the frequency and columns to time.

A spectrogram or sonogram, is a visual representation of the spectrum of frequencies. Spectrograms are usually created in one of two ways. They are approximated as a filter bank that results from a series of band pass filters, or calculated from the time signal using the short-time Fourier transform (STFT). These two methods actually form two different Time-Frequency Distributions, but are equivalent under some conditions. S-transform using spectrogram analysis provides better visual analyze of the signal.

The S-transform of a signal $h(t)$ is defined as

$$S(t,f) = \int_{-\infty}^{\infty} h(\tau) w^* (\tau - t, f), e^{-j2\pi f\tau}\, d\tau \qquad (1)$$

Where $S(t,f) = \frac{|f|}{\alpha\sqrt{2\pi}}, e^{-tf^2/2\alpha^2}$ (2)

The integration of S-transform over time results in the Fourier spectrum is given as

$$H(f) = \int_{-\infty}^{\infty} S(t,f) dt \qquad (3)$$

For the gaussian window $\int_{-\infty}^{\infty} S(t,f) dt = 1$ (4)

The original signal can be obtained from S-transform as

$$h(t) = \int_{-\infty}^{\infty} \{ \int_{-\infty}^{\infty} S(\tau,f) d\tau \} e^{j2\pi f\tau}\, df \qquad (5)$$

The S-transform is also represent as the amplitude and phase correction of the continuous wavelet transform

$$S(t,f) = \frac{\sqrt{f}}{2\pi\alpha} e^{j2\pi f\tau}, WT(t,f) \qquad (6)$$

Wavelet transform is given as $WT(t,f) = \sqrt{\frac{|f|}{\alpha}}, e^{-t^2 f^2/2\alpha^2}, e^{j2\pi f\tau}$ (7)

The S-transform is now expressed in time frequency resolution as

$$S(t,f) = \int_{-\infty}^{\infty} H(v,f) w^* (v,f), e^{j2\pi v\tau}\, dv \qquad (8)$$

$$w(v,f) = e^{-2\pi^2\alpha^2 v^2/t^2} \qquad (9)$$

The amplitude, phase and envelop mean value are given by

$$A(t) = \frac{\sqrt{f}}{2\pi\alpha} \qquad (10)$$

$$\tilde{A}(t) = T^{-1} \int_0^T A(t) dt \qquad (11)$$

The variance of the signal is the first input to fuzzy system. It is directly computed from the envelop mean value as follows

$$V_{ar}(t) = (S(t,f) - \tilde{A}(t))^2 \qquad (12)$$

The standard deviation is the second input to fuzzy system. It is obtained from the following relationship as given below

$$S_{td}(t) = \sqrt{V_{ar}(t)} \qquad (13)$$

2.2 Fuzzy Expert System

Fuzzy system provides a simple way to get definite conclusion based upon ambiguous inputs. The mamdani type of fuzzy inference system used to perform the classification of the PQ events. It has two inputs and generates one output based on 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 1

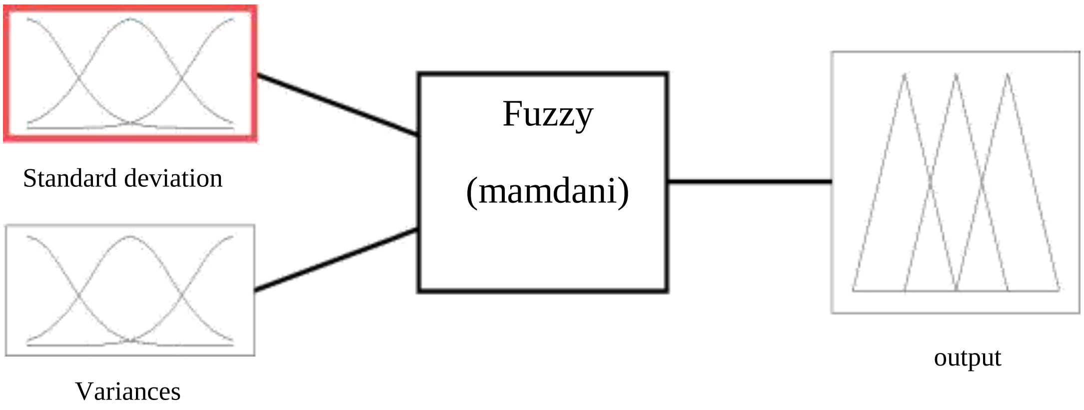

Figure 1. Fuzzy expert system

The output memberships function and rule viewers of fuzzy expert system are shown in figure 2 and figure 3.

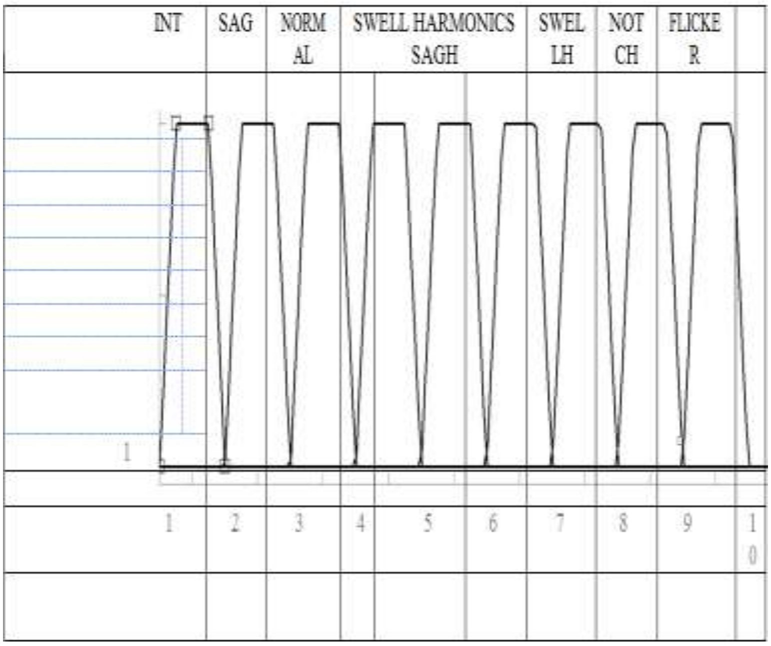

Figure 2. Output membership function

Standard deviation = 0.4	variances = 0.45	output = 3	

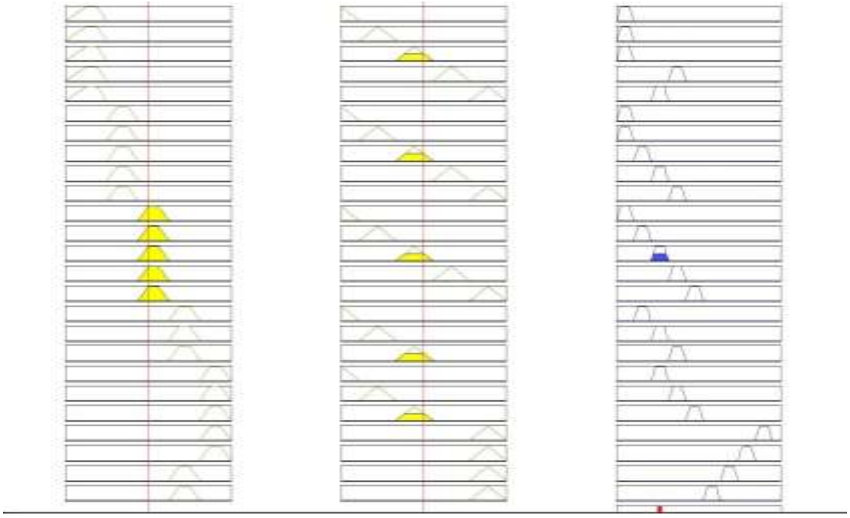

Figure 3.Rule viewer of fuzzy expert system

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

The proposed fuzzy expert system used to analyze and classify the eight types of power quality disturbances. The extracted input features through the S-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

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-(a) – Features extraction such as standard deviation and variances
- Block-(b) – Detection and classification of the power quality disturbances

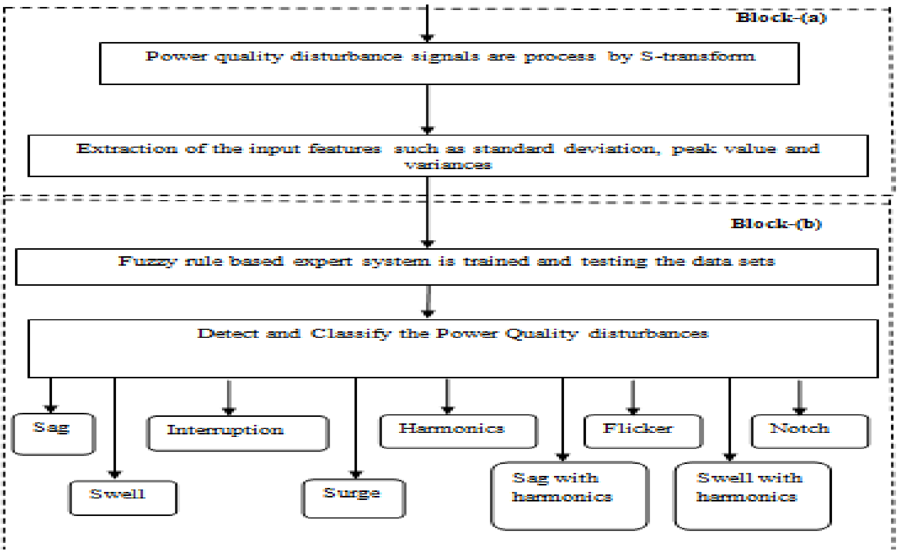

Figure 4. Flowchart for the Classification of Power Quality disturbances

4. Simulation and Test Results

Testing data were generated using Matlab simulink on the test system model for various classes of disturbances and the 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. The single line diagram for the test system and the Matlab simulation block diagram are shown in figure 5 and figure 6.

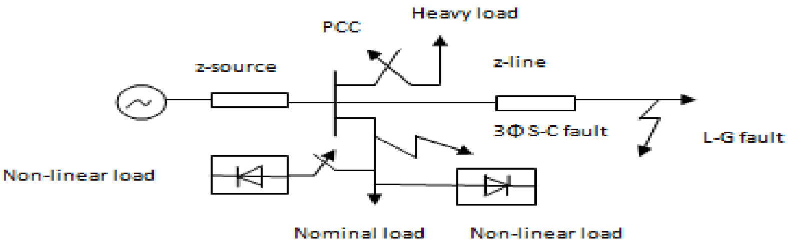

Figure 5.Single line diagram of test system model

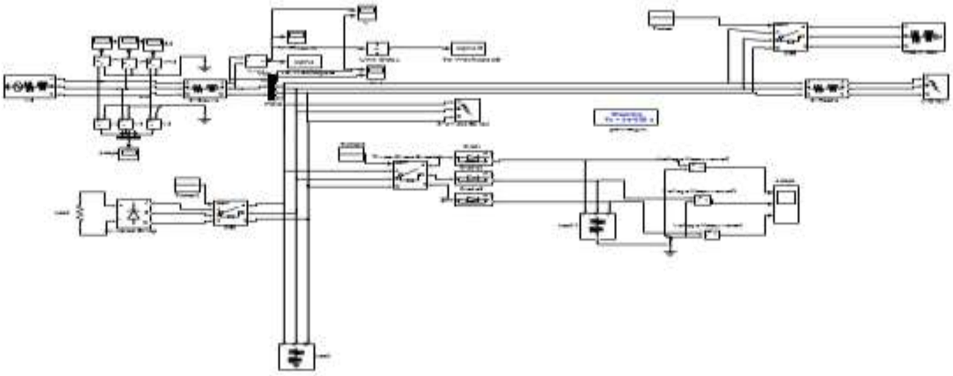

Figure 6.Matlab simulation block diagram for the test system model

These input signals are applied to the fuzzy expert system to get accurate classification of disturbances. The PQ disturbance signals generated using the Matlab based parametric equations. The following case studies are presented to highlight the suitability of the application of the proposed method.

Pure sine wave is a normal voltage signal of amplitude 1 V at the frequency 50 Hz and its waveform is as shown in the figure 7(a).The time frequency analysis of S-transform and the spectrogram representation of the pure sine wave are shown in the figures 7(b) and 7(c). The standard deviation and variances of the pure sine wave are shown in the figures 7(d) and 7(e).

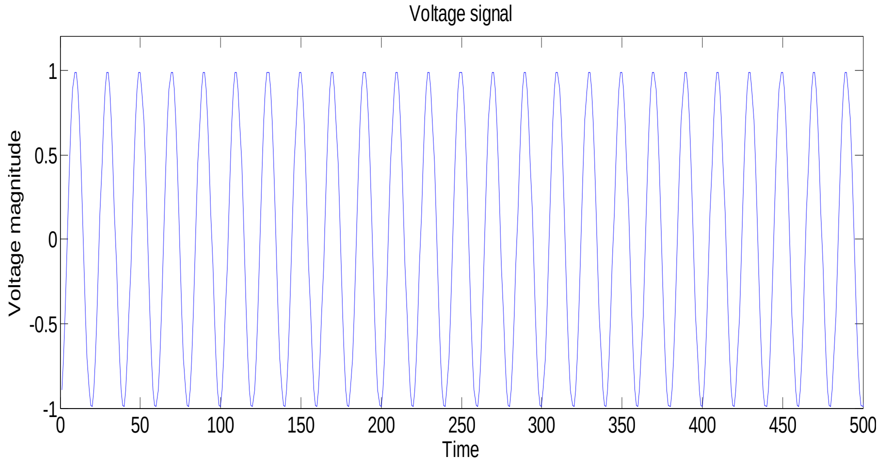

Figure 7(a)

Figure 7(b)

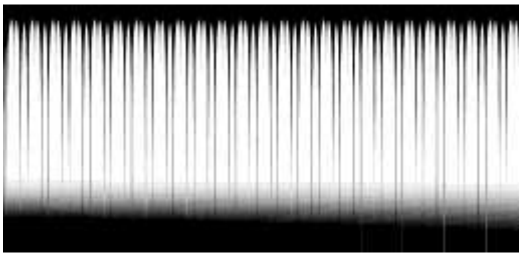

Figure 7(c)

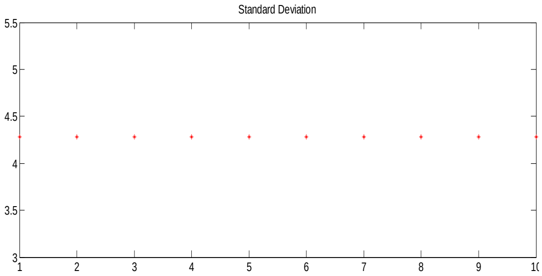

Figure 7(d)

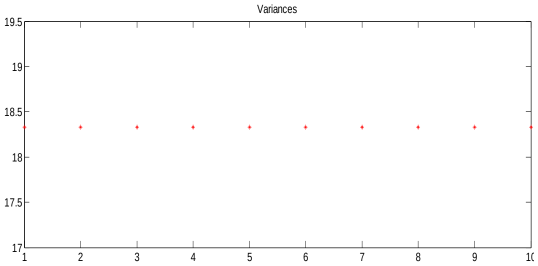

Figure 7(e)

Voltage sag (or) **voltage dips** cause a decrease of 10-90% in system voltage. The duration of the sag disturbance is 0.2 to 0.4 cycles in 1 min. It is generated by the occurrence of a single line to ground fault for 10 cycles. The voltage dip waveform is shown in the figure 8(a). The time frequency analysis of S-transform and the spectrogram representation are shown in the figures 8(b) and 8(c). The standard deviation and the variances of the voltage sag are shown in the figures 8(d) and 8(e).

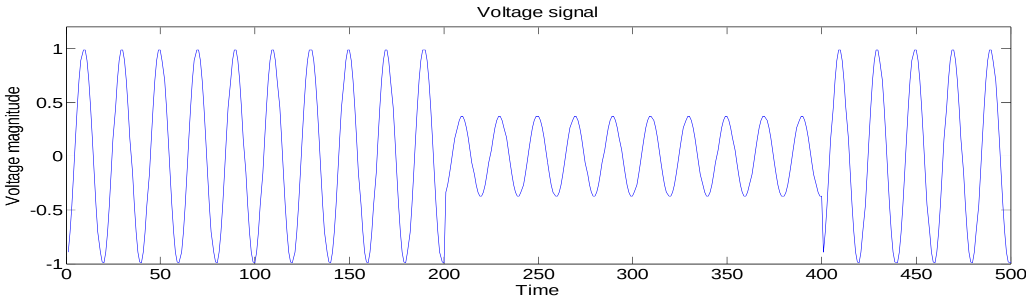

Figure 8(a)

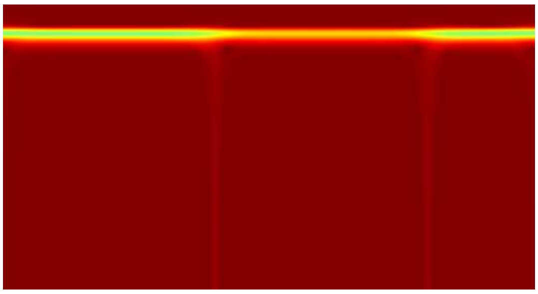

Figure 8(b)

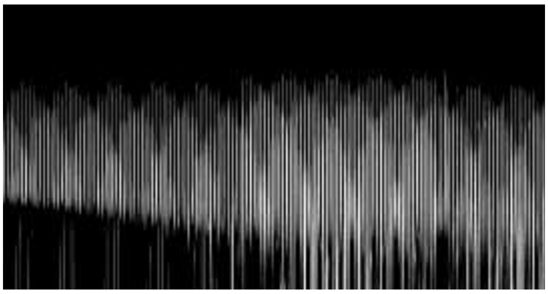

Figure 8(c)

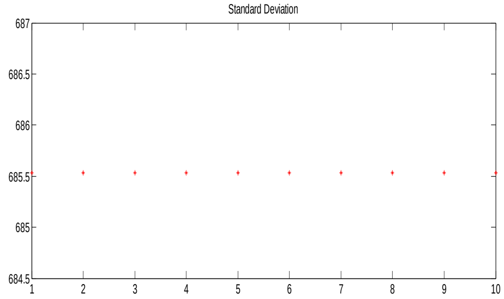

Figure 8(d)

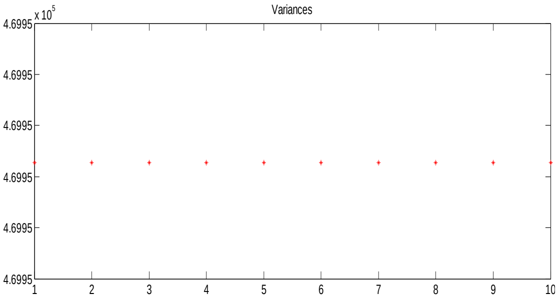

Figure 8(e)

Voltage swell causes the rise of 10-90% of the system voltage. It is generated by disconnecting the heavy load for 10 cycles. The duration of the swell disturbance is 0.2 to 0.4 cycles in 1 min. The voltage swell waveform is shown in figure 9(a). The time frequency analysis of S-transform and the spectrogram representation are shown in the figures 9(b) and 9(c). The standard deviation and the variances of the voltage swell are shown in the figures 9(d) and 9(e).

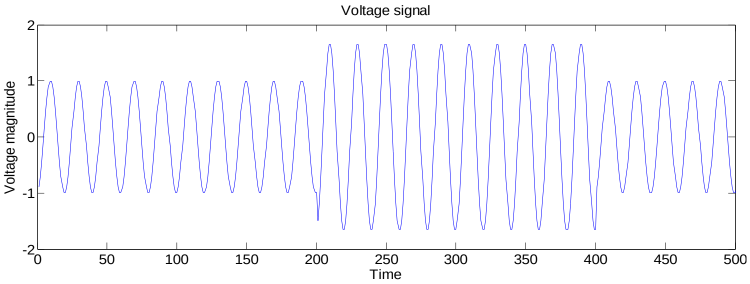

Figure 9(a)

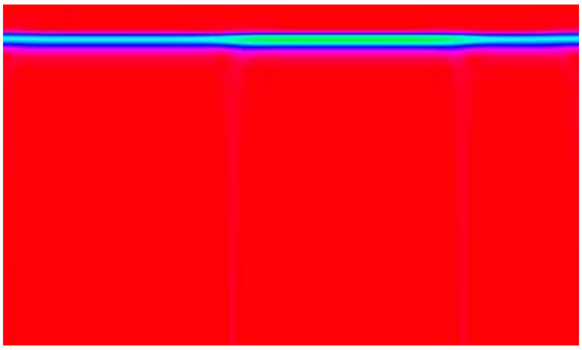

Figure 9(b)

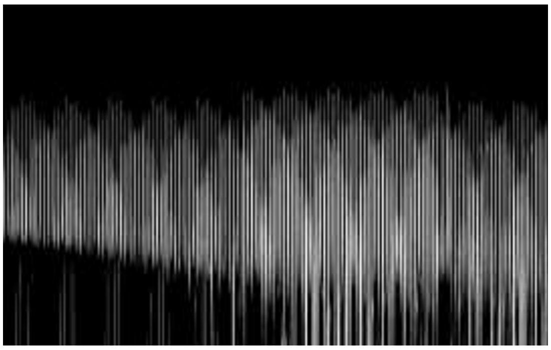

Figure 9(c)

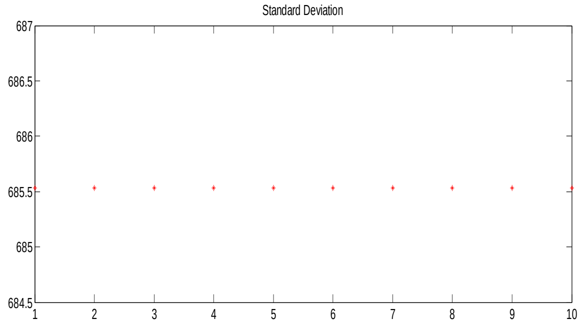

Figure 9(d)

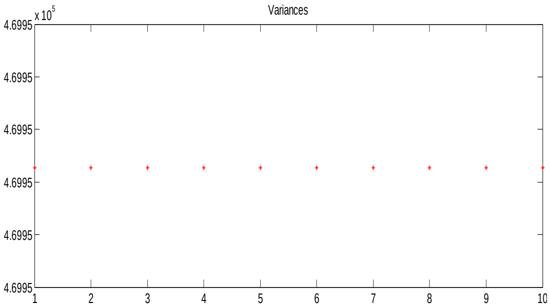

Figure 9(e)

Voltage surge causes a sudden increase of the system voltage for a short duration of 0.28 to 0.32 cycles in less than 1 minute. It occurs while disconnecting a heavy load for one quarter cycle as shown in the figure 10(a). The time frequency analyses of S-transform and spectrogram representation are shown in the figures 10(b) and 10(c). The standard deviation and the variances of the voltage swell are shown in the figures 10(d) and 10(e).

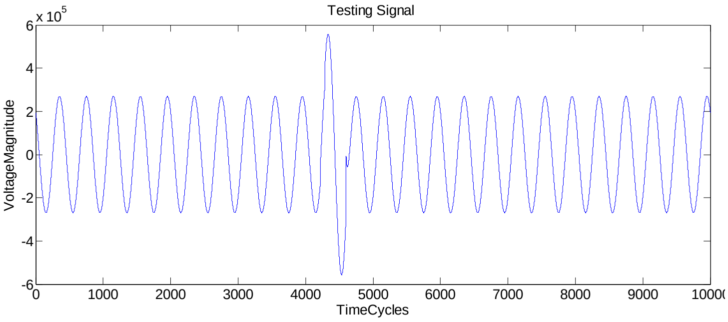

Figure 10(a)

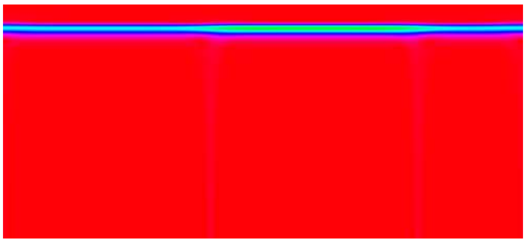

Figure 10(b)

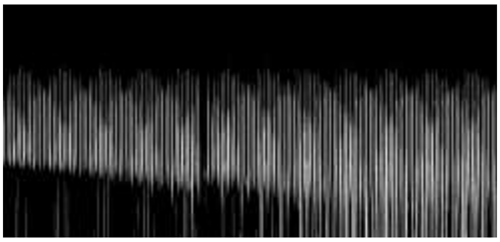

Figure 10(c)

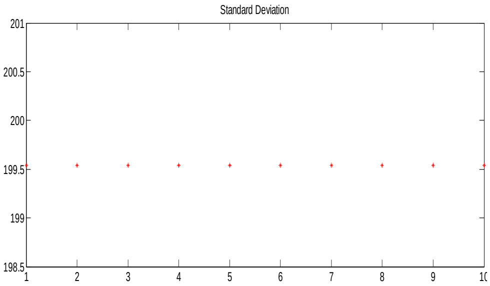

Figure 10(d)

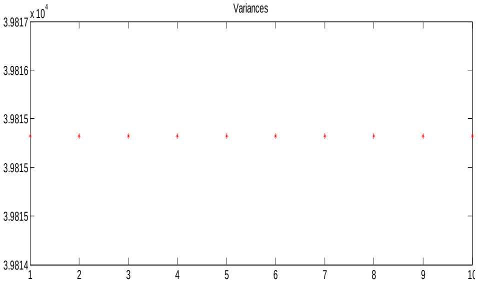

Figure 10(e)

Outages may be seen as a loss of voltage on the system for the duration of 0.5 cycles to 1min. An outage is generated by simulating a 3-phase dead short circuit to ground. The voltage waveform of an outage event is shown in the figure 11(a). The time frequency analysis of S-transform and the spectrogram representation are shown in the figures 11(b) and 11(c). The standard deviation and the variances of the voltage swell are shown in the figures 11(d) and 11(e).

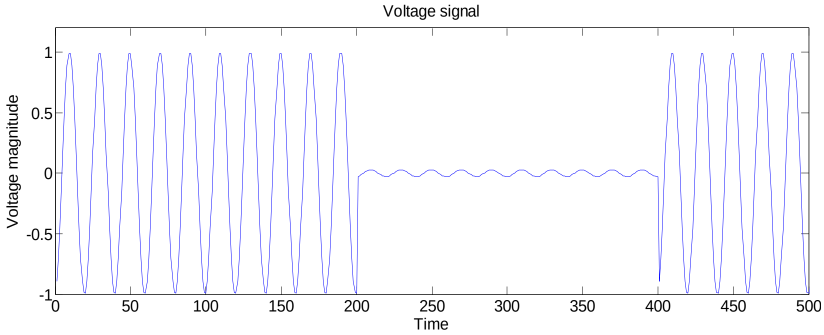

Figure 6(a)

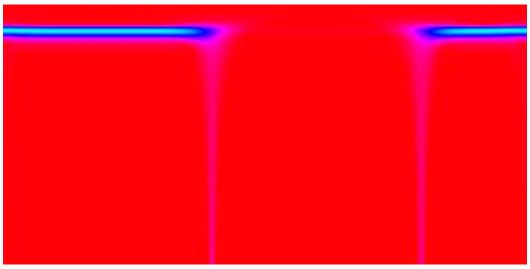

Figure 6(b)

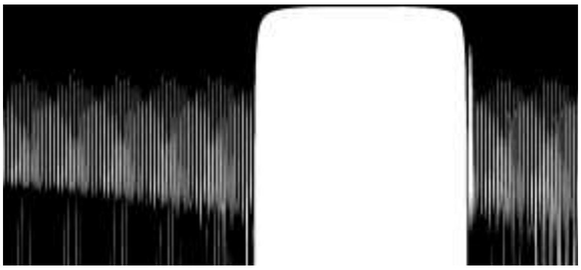

Figure 6(c)

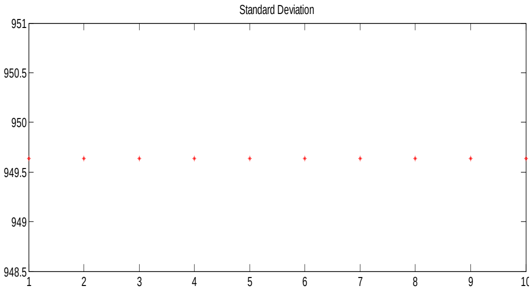

Figure 6(d)

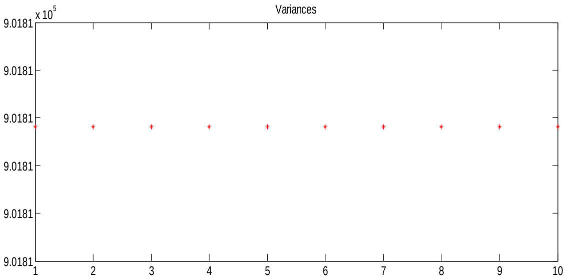

Figure 6(e)

Harmonics are generated by connecting a non linear load to the system for 10 cycles. Figure 12(a) shows the distortion of voltage waveform and their corresponding time frequency analysis of S-transform and the spectrogram representation are shown in the figures 12(b) and 12(c). The standard deviation and variances of harmonics are shown in the figures 12(d) and 12(e).

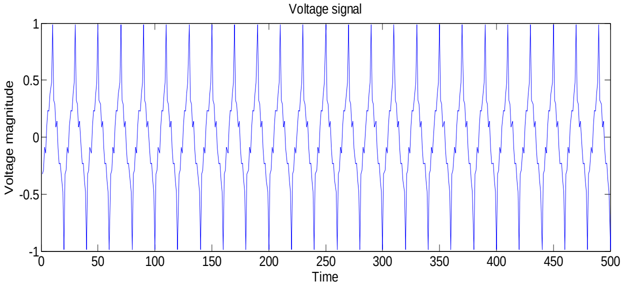

Figure 12(a)

Figure 12(b)

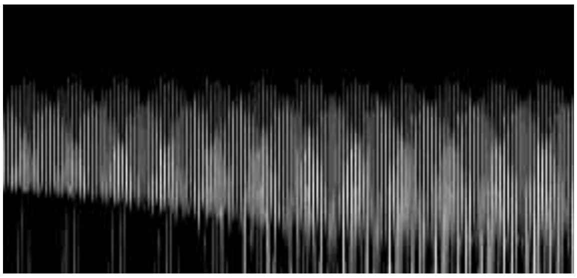

Figure 12(c)

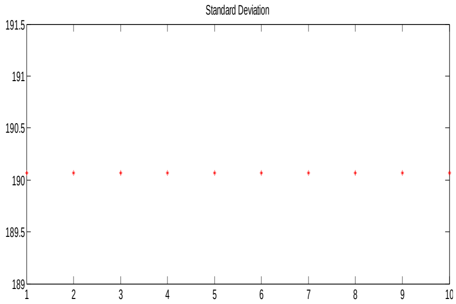

Figure 12(d)

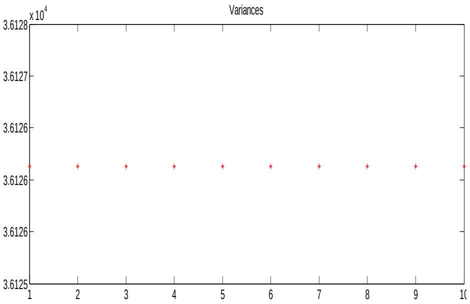

Figure 12(e)

Sag with harmonics are caused by the presence of a nonlinear load and occurrence of single line to ground fault for a duration of 0.2 to 0.4 cycles .The waveform which contains harmonic distortion with sag event is shown in the figure 13(a). The time frequency analysis of S-transform and the spectrogram representation of the harmonics are shown in the figures 13(b) and 13(c). The standard deviation and the variances of the harmonics are shown in the figures 13(d) and 13(e).

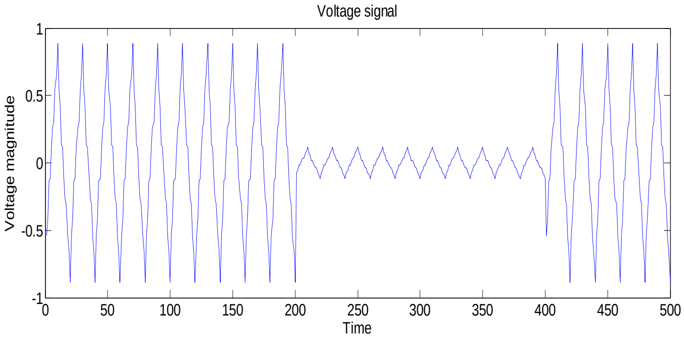

Figure 13(a)

Figure 13(b)

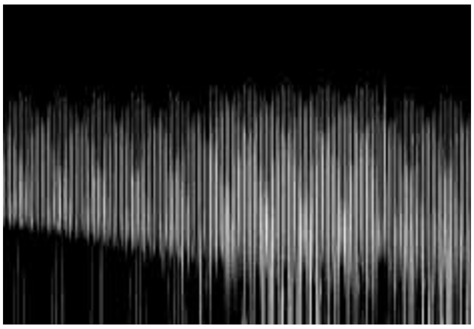

Figure 13(c)

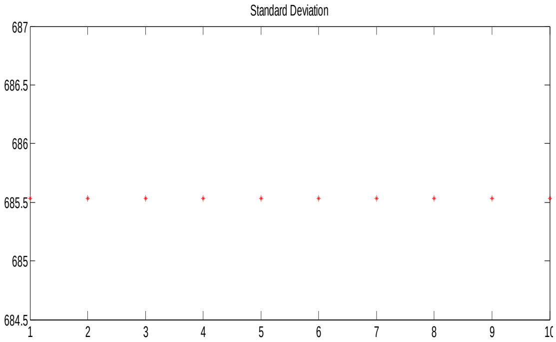

Figure 13(d)

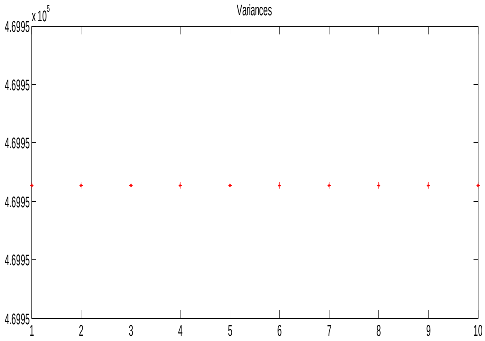

Figure 13(e)

Swell with harmonics is caused by the presence of nonlinear load and disconnecting the heavy load for 5 cycles in the duration of 0.2 to 0.4 cycles. The waveform for harmonic distortion with swell is shown in the figure 14(a). The time frequency analysis of S-transform and the spectrogram representation are shown in the figures 14(b) and 14(c). The standard deviation and variances of the swell with harmonics are shown in the figures 14(d) & 14(e).

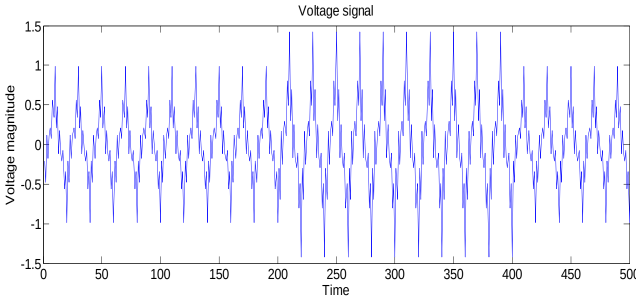

Figure 14(a)

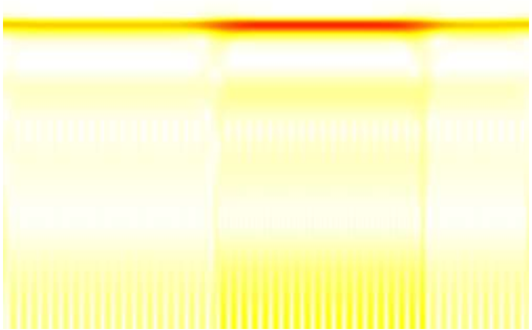

Figure 14(b)

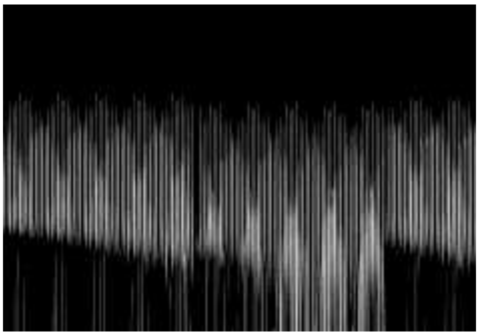

Figure 14(c)

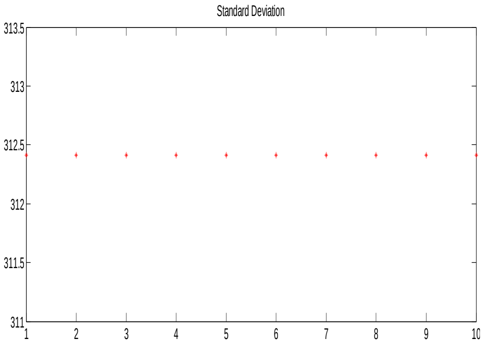

Figure 14(d)

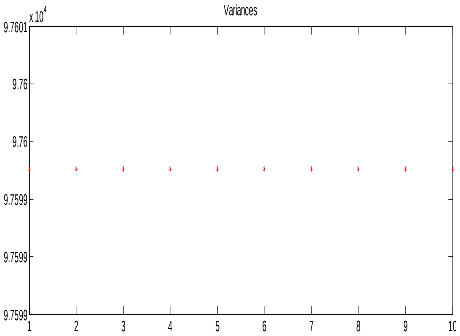

Figure 14(e)

Flicker disturbance is caused by a continuous and rapid variation of the system load. It is simulated by the continuous connection and disconnection of the heavy load. The waveform of flicker is shown in the figure 15(a). The time frequency analysis of S-transform and the spectrogram representation of the flicker is shown in the figures 15(b) and 15(c). The standard deviation and the variances of the flicker are shown in the figures 15(d) and 15(e).

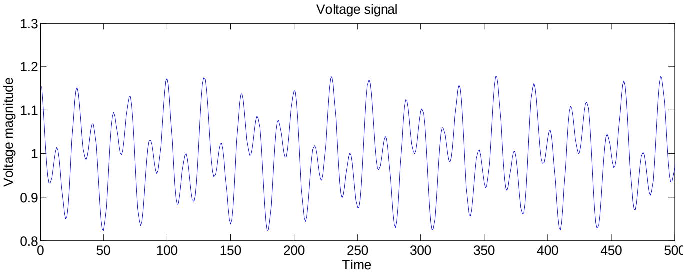

Figure 15(a)

Figure 15(b)

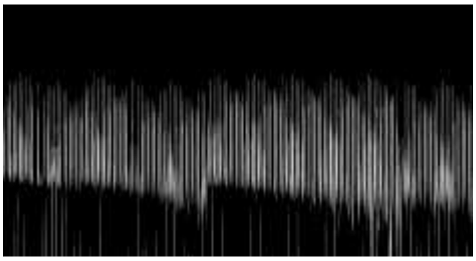

Figure 15(c)

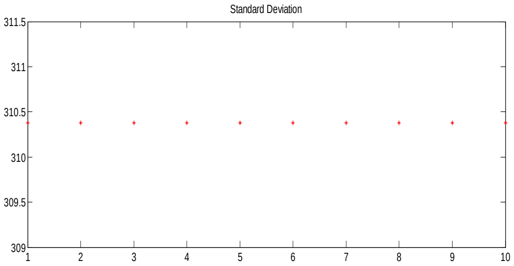

Figure 15(d)

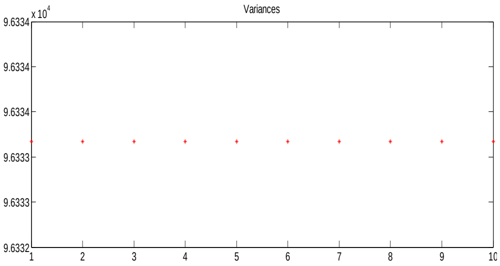

Figure 15(e)

Notch is a disturbance of the nominal power voltage waveform lasting for less than half a cycle. The disturbance is initially of opposite polarity and hence it is to be subtracted from the waveform. It is generated by the connection of the 3 phase non-linear load. The voltage notch waveform is shown in the figure 16(a). The time frequency analysis of S-transform and the spectrogram representation are shown in the figures 16(b) and 16(c). The standard deviation and variances of notch are shown in the figures 16(d) and 16(e).

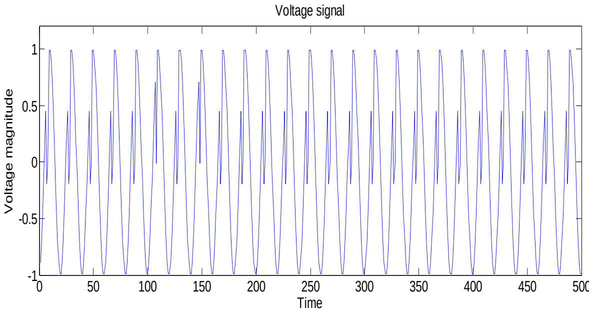

Figure 16(a)

Figure 16(b)

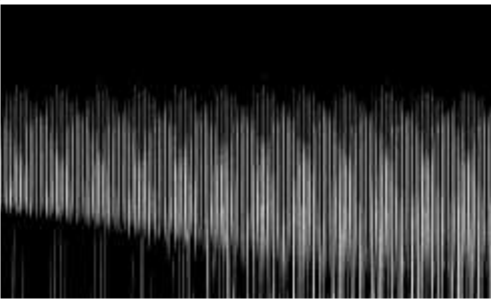

Figure 16(c)

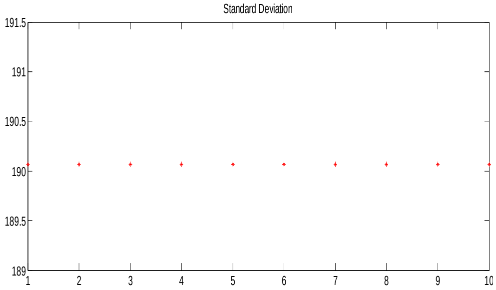

Figure 16(d)

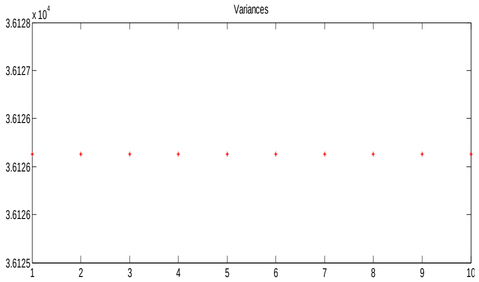

Figure 16(e)

Table 3.Classification accuracy

Sno	Power Quality Disturbances	Percentage of Accuracy		
		Input Features	S-transform based fuzzy expert system	Kalman filter based fuzzy system
1	Pure Sine	100	100	100
2	Voltage Sag	100	98	100
3	Voltage Swell	100	98	100
4	Voltage Surge	100	98	98
5	Outages	100	98	100
6	Harmonics	100	97	97
7	Sag with Harmonics	100	98	98
8	Swell with Harmonics	100	98	98
9	Flicker	100	100	96
10	Notch	100	100	96
Overall accuracy			98.5	98.3

II. CONCLUSION

This paper proposes a novel method based S-transform and Fuzzy expert system for classification of various Power quality disturbances. The Power quality disturbance waveforms were generated through Matlab simulink. The input features were extracted through S-Transform and Fuzzy expert system has been applied for classifying the power quality disturbances. The method enables the accurate classification of all nine types of Power quality disturbances. Simulation results demonstrate that the performance and accuracy of the S-transform. The classification accuracy has been validated by comparing the results obtained by the proposed technique against kalman filter based fuzzy expert system. The results shows that the proposed technique performs very well in classification of power disturbances.

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