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Assessment of Power Quality Disturbances in the Distribution System Using Kalman Filter and Fuzzy Expert System

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***ABSTRACT**: The paper presents a novel method for the assessment of the power quality disturbances in the distribution system using the Kalman filter and fuzzy expert system. In this method the various classes of disturbance signals are developed through the Matlab Simulink on the test system model. The characteristic features of the disturbance signals are extracted based on the Kalman filter technique. The obtained features such as amplitude and slope are given as the two inputs to the fuzzy expert system. It applied some rules on these inputs to assess the various PQ disturbances. Fuzzy classifier has been carried out and tested for various power quality disturbances. The results clearly demonstrate that the proposed method in the distribution system has the ability to detect and classify PQ events.*

***Keywords**: Power quality, Power quality events, Kalman Filter, Fuzzy logic, Fuzzy-expert system.*

Nomenclature

$X_{a,b}$ - Continuous wavelet transform
a & b - Dilation and translation parameter
Ψ(t) - Mother wavelet
x_k - State vector
y_k – Voltage sinusoid
z_k - Measurement at the time instant t_k
Φ_k - State transition matrix
H_k - Measurement matrix
w_k & v_k - Model and measurement errors
ω - Fundamental angular frequency
$A_{i,k}$ & θ_k - Amplitude and phase angle of the i^{th} harmonic at time t_k
Δt - Sampling interval
R_k - Covariance matrix of v_k
K_k - Kalman gain
P_K^- - Prior process covariance
Q_k - Covariance matrix of w_k
P_k - Error covariance

I. INTRODUCTION

An increasing demand for reliable and high quality of electrical power and also the increasing number of distorting loads may lead to an increased awareness of power quality by the customers and utilities. The electric power quality becomes poor due to power line disturbances such as sag, swell, interruption, harmonics, sag with harmonics, swell with harmonics, flicker and notches. To improve the power quality, it is essential to detect and classify the disturbances initially. Various types of power quality disturbances were detected and localized based on wavelet transform analysis as illustrated in [1]. Multi resolution wavelets were also applied to analyze and classify the electromagnetic power system transients [2].

Application of wavelets to identify the various power system transient signals such as capacitor switching, lighting impulse, etc has been discussed in [3]. The data processing burden of the classification algorithm has been considerably reduced by compressing the signals through wavelet transform methods as illustrated in [4]. An adaptive neural network based power quality analyzer for the estimation of electric power quality has been demonstrated in [5].

Classification of power quality events using a combination of SVM and RBF networks has been presented in [6]. The Short Time Fourier transform (STFT) based power frequency harmonic analyzer has been discussed in [7] for the classification of non stationary signals. Wavelet transforms along with multi-resolution signal decomposition for the classification of power quality disturbances has been highlighted in [8]. The Fourier and wavelet transform based fuzzy expert system for the detection and classification of PQ disturbances has been demonstrated in [9].

A combined form of Fourier and wavelet transform along with fuzzy classifier has been presented in [10] to analyze voltage sag disturbances and it also identified the location of the sag fault using genetic algorithm. Wavelet transform based neural classifier has been illustrated in [11] of various power disturbances classification. Wavelet multi-resolution technique along with neuro-fuzzy classifier for PQ disturbance detection has been explained [12]. 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 [13] and a fuzzy logic based pattern recognition system along with multi resolution S-transform for power quality event classification has been discussed in [14].

A combination of DFT wavelet transform and Kalman filter has been presented in [15] for the detection and analysis of voltage event in power system. The Kalman filter technique along with wavelet network based neural network classifier has been demonstrated for the classification of PQ disturbances in [16]. A combination of linear Kalman filter and fuzzy expert system has been used for the analysis of power quality events in [17] wherein the signal noise is estimated using a block of DWT. A hybrid method for the real time frequency estimation based on Taylor series and discrete Fourier algorithm has been illustrated in [18]. Classification of both the single and combined nature of power quality disturbances using signal spare decomposition (SSD) has been illustrated in [19].A new type of power quality analyzer in the distribution system is developed based on Kalman filter and Fuzzy expert system. In this paper, features are extracted through Kalman Filter and disturbances are classified using an fuzzy expert system.

II. PROPOSED METHOD

The proposed method has two stages namely

i. Feature extraction stage and
ii. Classification stage.

In the feature extraction stage, Kalman Filter is used for extracting features such as amplitude and slope. The classification stage consists of the Fuzzy expert system. Disturbance waveforms were generated using Matlab simulink on the test system.

1.1 Feature Extraction Stage

1.1.1 Wavelet Transform

Wavelet transform is highly useful tool in signal analysis. The continuous wavelet transform of a signal x (t) is defined as

$$X_{a,b}= \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\Psi(\frac{t-b}{a})dt \qquad (1)$$

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\Psi(\frac{t-b}{a}) \qquad (2)$$

The Discrete Wavelet Transform (DWT) calculations are usually carried out for a chosen subset of scales and positions. This is usually done by using filters for computing approximations and details. The approximations are the high-scale, low frequency components of the signal and details are the low-scale, high-frequency components.

The DWT coefficients are computed using the equation:

$$X_{a,b} = X_{j,k} = \sum_{n \in z} x[n] g_{j,k}[n] \qquad (3)$$

where

$a = 2j, b = k2j, j\varepsilon N, k\varepsilon N.$

The wavelet filter g acts as mother wavelet ψ and the covariance of the details is considered as an initial input to the Kalman filter.

2.1.2 Kalman Filter

As Kalman filter has been identified as an optimal estimator with minimum error covariance it has been used here for the purpose of feature extraction. Kalman filter is characterized by a set of dynamic state equations and measurement equations , given a set of observed data, as illustrated below.

$$X_{k+1} = \varphi_k x_k + w_k \tag{4}$$

$$z_k = H_k x_k + v_k \tag{5}$$

In order to obtain a satisfactory performance of Kalman filter, it is necessary to know both the dynamic process and the measurement model. In the power system, the measured signal can be expressed by a sum of sinusoidal waveforms and the noise. Let an observed signal z_k at time t_k be the sum of y_k and v_k, which represents M sinusoids and the additive noise for sampling points. Then

$$z_k = y_k + v_k \tag{6}$$

$$z_k = \sum_{i=1}^{n} A_{k,i} \sin((i\omega k)\Delta T + \theta_{k,i}) + v_k \tag{7}$$

Where k= 1, 2, 3……N .

Each frequency component requires two state variables and hence the total number of state variables is 2n. At any time k, these state variables are defined as

$$\begin{aligned}
&\text{For } 1_{st} \text{ harmonics: } x_1 = A_1 \cos(\theta_1) \quad x_1 = A_1 \sin(\theta_1) \\
&\text{For } 2_{nd} \text{ harmonics: } x_2 = A_2 \cos(\theta_2) \quad x_2 = A_1 \sin(\theta_2) \\
&.\ .\ .\ .\ .\ .\ .\ .\ . \\
&\text{For } n_{th} \text{ harmonics: } x_{2n-1} = A_n \cos(\theta_n) \quad x_{2n-1} = A_n \sin(\theta_n)
\end{aligned} \tag{8}$$

The above set of equations can be written in matrix form as,

$$X_{k+1} = \begin{pmatrix} X_1 \\ X_2 \\ . \\ . \\ . \\ X_{2n} \end{pmatrix}_{k+1} = \begin{pmatrix} 1\ 0 \ldots.\ 0 \\ 0\ 1 \ldots.\ 0 \\ 0\ 0\ 1 \ldots.0 \\ . \\ . \\ . \\ 0\ 0\ 0 \ldots.1 \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ . \\ . \\ . \\ X_{2n} \end{pmatrix}_k + w_k \tag{9}$$

The measurement equation can be similarly expressed in matrix form as

$$z_k = H_k x_k + v_k = \begin{pmatrix} \sin(\omega k \Delta T) \\ \cos(\omega k \Delta T) \\ . \\ . \\ . \\ \sin(n\omega k \Delta T) \\ \cos(n\omega k \Delta T) \end{pmatrix}^T \begin{pmatrix} X_1 \\ X_2 \\ . \\ . \\ . \\ X_{2n-1} \\ X_{2n} \end{pmatrix}_k + v_k \tag{10}$$

The system covariance matrices for w_k and v_k can be written as

$E[w_k w_k^T] = [R_k]$ and $E[v_k v_k^T] = [Q_k]$

The Kalman Filter execution procedure is a recursive one, with steps for time and measurement updates as listed as below.

Time update

1) Project the state ahead

$$X_{k+1}^{-} = \Phi_k x_k \tag{11}$$

2) Project the error covariance ahead

$$P_{k+1}^{-}=\Phi_k P_k \Phi_k^T + v_k$$

Measurement update

1) Compute the Kalman gain

$$K_K = P_K^{-} H_K^T (H_K P_K^{-} H_K^T + R_K)^{-1}$$

2) Update estimate with measurement

$$x_k = x_K^{-} + K_K (z_K - H_K) x_K^{-} \tag{12}$$

3) Update the error covariance

$$P_k = (I - K_K H_K) P_K^{-}$$

Time and measurement update equation (11) & (12) are alternatively solved. After each time and measurement update pair, the process is repeated using the previous posterior estimates to project the new a prior estimates. At any given instant k, the amplitudes of the fundamental and harmonic frequencies are computed from estimated variables as

$$A_{i,k} = \sqrt{X_{1.K}^2 + X_{2,K}^2} \tag{13}$$

$$A_{i,k} = \sqrt{X_{2i-1.K}^2 + X_{2,Ki}^2} \quad i = 1,2, \dots \dots \dots . n \tag{14}$$

Slope of the signals, $Slope_{,k} = (A_{i,k} - A_{i,k} - 1)/\Delta T$ (15)

2.1.3 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 VSA (very small amplitude), SA (small amplitude), NA (normal amplitude), LA (large amplitude), and VLA (very large amplitude).The second input to the system is the value of slope. It is broken into five triangular membership functions namely VSS (very small slope), SS (small slope), NS (normal slope), LS (large slope), and VLS (very large slope). The fuzzy expert system is shown in figure 1.

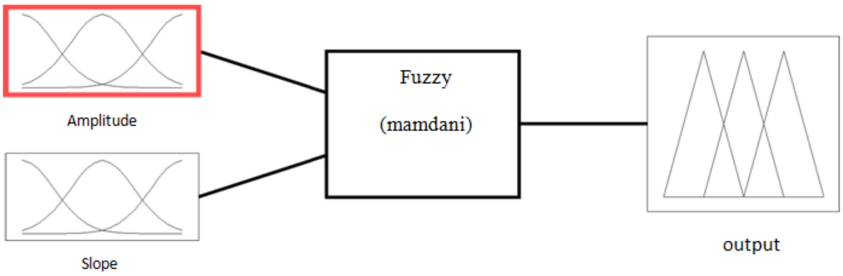


Figure 1.Fuzzy expert system

The memberships function and rule viewer of the fuzzy expert system are in fig 2 and figure 3.

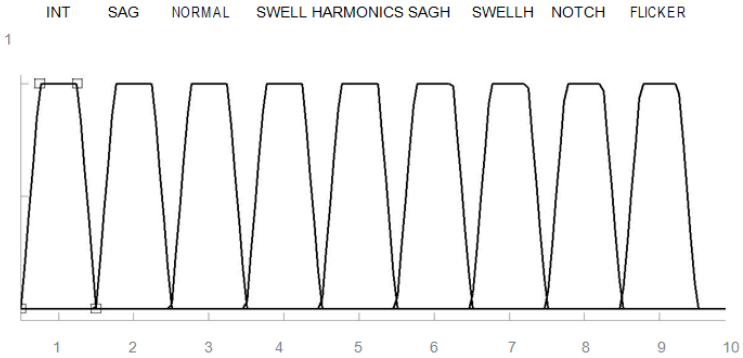


Figure 2. Output membership function

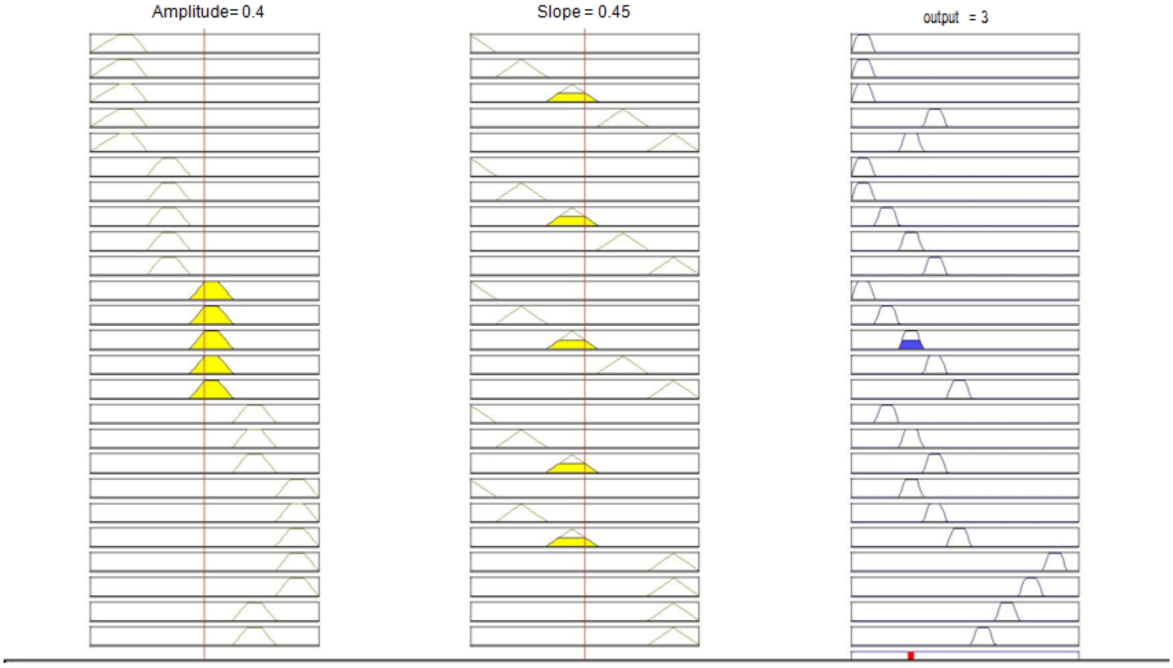


Figure 3. Rule viewer of fuzzy expert system

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

1) If (Amplitude is VA) and (Slope is VSS) then (output is INTERRUPTION).
2) If (Amplitude is VA) and (Slope is SS) then (output is INTERRUPTION).
3) If (Amplitude is VA) and (Slope is NS) then (output is INTERRUPTION).
4) If (Amplitude is VA) and (Slope is LS) then (output is SWELL).
5) If (Amplitude is VA) and (Slope is VSS) then (output is NORMAL).
6) If (Amplitude is SA) and (Slope is VSS) then (output is INTERRUPTION).
7) If (Amplitude is SA) and (Slope is SS) then (output is INTERRUPTION).
8) If (Amplitude is SA) and (Slope is NS) then (output is SAG).
9) If (Amplitude is SA) and (Slope is LS) then (output is NORMAL).
10) If (Amplitude is SA) and (Slope is VLS) then (output is SWELL).
11) If (Amplitude is NA) and (Slope is VS) then (output is INTERRUPTION).
12) If (Amplitude is NA) and Slope is SS) then (output is SAG).
13) If (Amplitude is NA) and (Slope is NS) then (output is NORMAL).
14) If (Amplitude is NA) and (Slope is LS) then (output is SWELL).
15) If (Amplitude is NA) and (Slope is VSS) then (output is HARMONICS).
16) If (Amplitude is LA) and (Slope is VSS) then (output is SAG).
17) If (Amplitude is LA) and (Slope is SS) then (output is NORMAL).
18) If (Amplitude is LA) and (Slope is NS) then (output is SWELL).
19) If (Amplitude is LA) and (Slope is VSS) then (output is SAG WITH HARMONICS).
20) If (Amplitude is LA) and (Slope is VSS) then (output is SWELL WITH HARMONICS).
21) If (Amplitude is VLA) and (Slope is VSS) then (output is NORMAL).
22) If (Amplitude is VLA) and (Slope is SS) then (output is SWELL).
23) If (Amplitude is VLA) and (Slope is NS) then (output is HARMONICS).
24) If (Amplitude is VLA) and (Slope is VLS) then (output is FLICKER).
25) If (Amplitude is VLA) and (Slope is VLS) then (output is NOTCH).

III. CLASSIFICATION STAGE

In this stage, features extracted through the Kalman filter are applied as inputs to the fuzzy expert system in order to classify various power quality disturbances. Fuzzy logic with 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 power quality disturbances and
- Block-3 Identification of disturbances

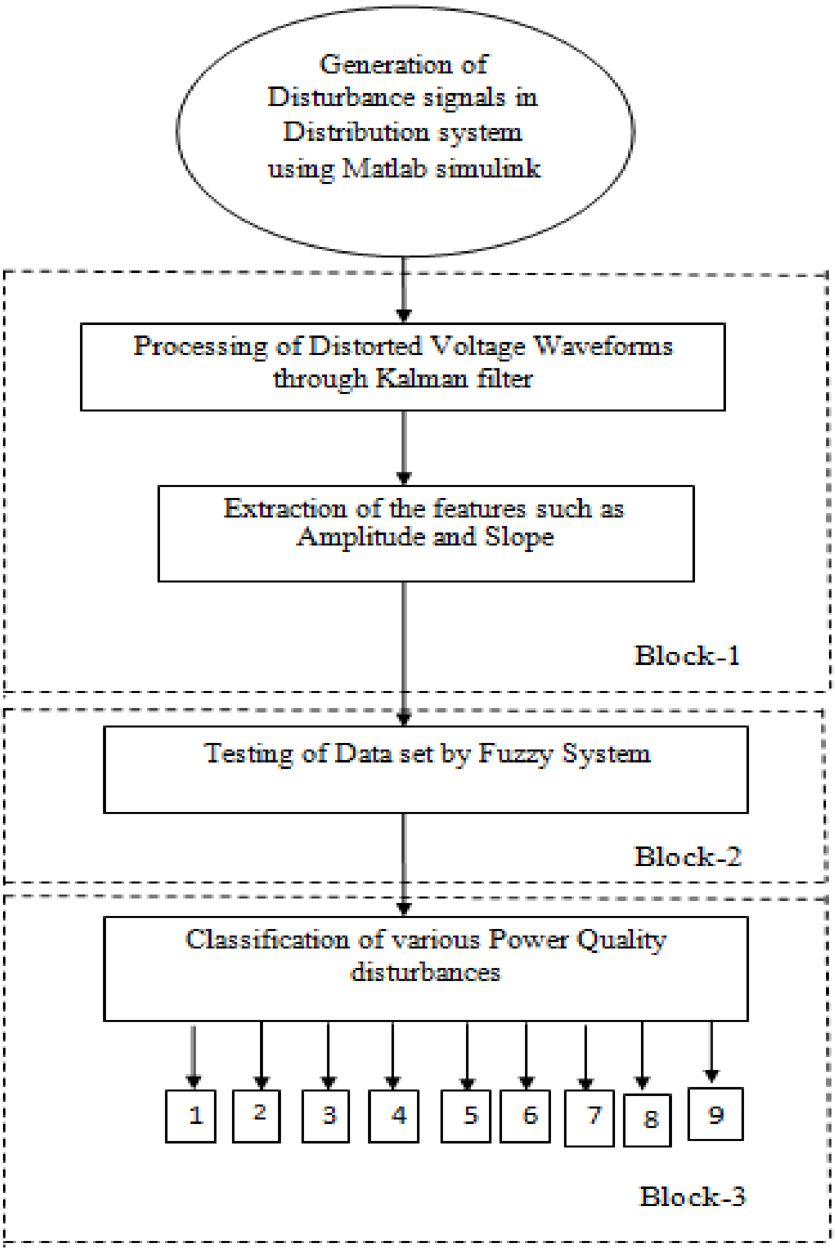


Figure 4.Flowchart for the Classification of Power Quality disturbances

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Test data were simulated using Matlab simulink model for various classes of disturbances. Nine different types of power quality disturbances, namely pure sine (normal), sag, swell, outage, harmonics, sag with harmonic, swell with harmonic, notch and flicker were generated and they were almost close to the real time signals. The Matlab simulation block diagram of the test system are shown in figure 5. These input signals were then applied to the fuzzy expert system to get an accurate classification of disturbances.

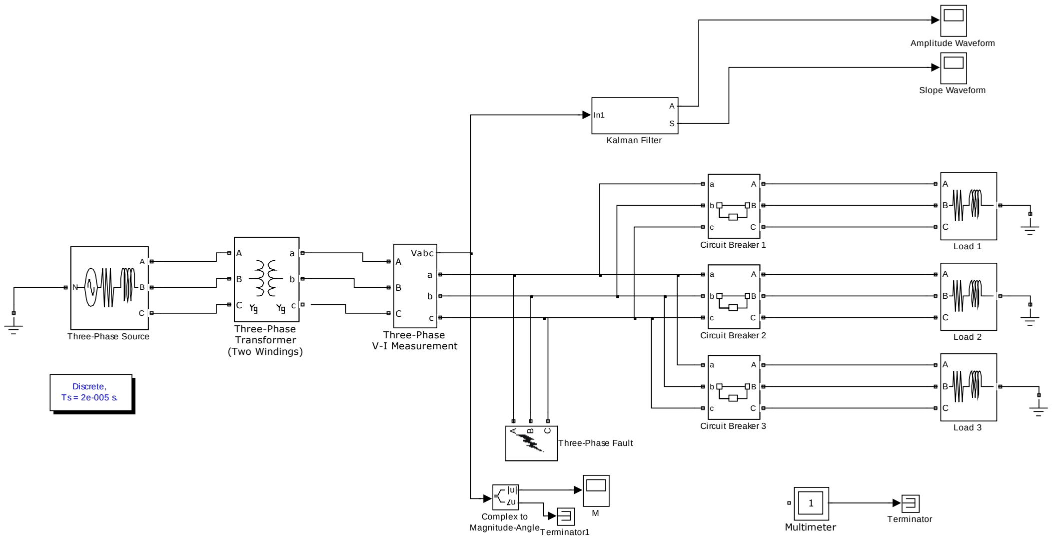


Figure 5. Matlab simulation block diagram for the test system model

The following are the case studies presented to highlight the suitability of the application of the proposed method.

1) **Pure sine wave** is a normal voltage signal of amplitude 1 V at the frequency 50 Hz as shown in the figure 6(a).The amplitude and slope outputs of the Kalman filter are shown in figures 6(b) and 6(c). The fuzzy output of the pure sine wave is shown in the figure 6(d).

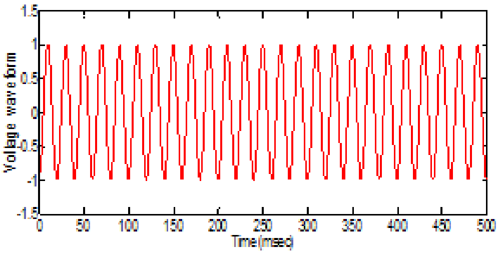


Figure 6(a)

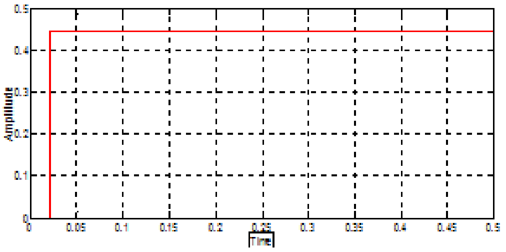


Figure 6(b)

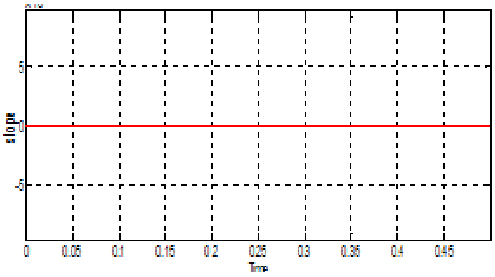


Figure 6(c)

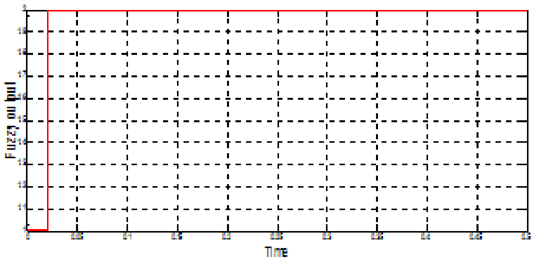
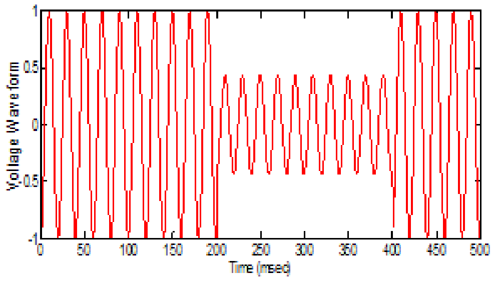


Figure 6(d)

2) **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 as shown in the figure 7(a). The input features extracted using kalman filter from the disturbance signals are shown in figures 7(b), and 7(c). The fuzzy output of the voltage sag disturbance signal is shown in the figure 7(d).



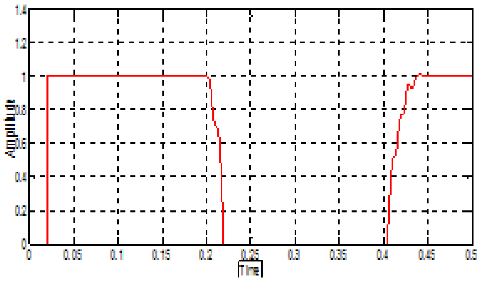
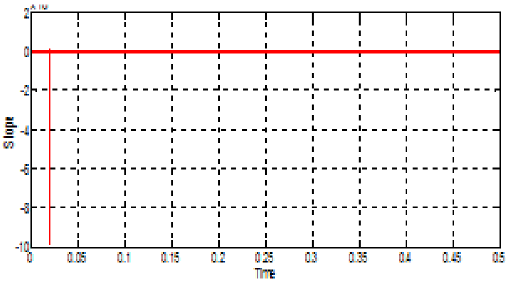


Figure 7(a)

Figure 7(b)



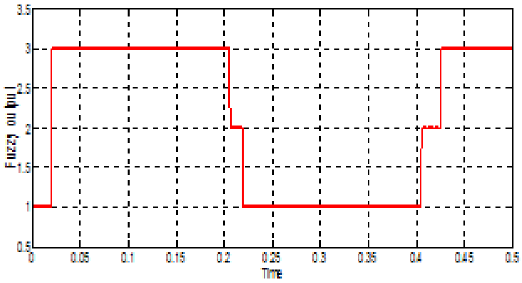
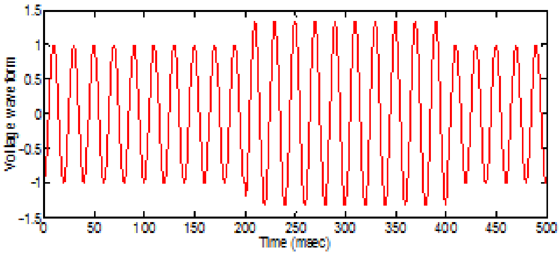


Figure 7(c)

Figure 7(d)

3) **Voltage swell** causes the rise of 10-90% of the system voltage. The duration of the swell disturbance is 0.2 to 0.4 cycles in 1 min as shown in figure 8(a) and their corresponding features extracted from the kalman disturbance signal are shown in the figures 8(b) and 8(c). The fuzzy output of the voltage swell disturbance signal is shown in the figure 8(d).



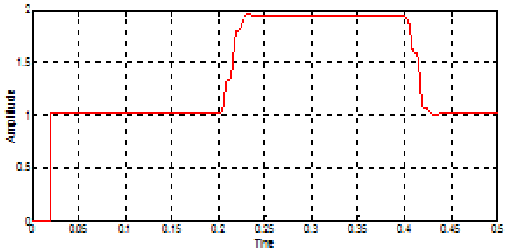
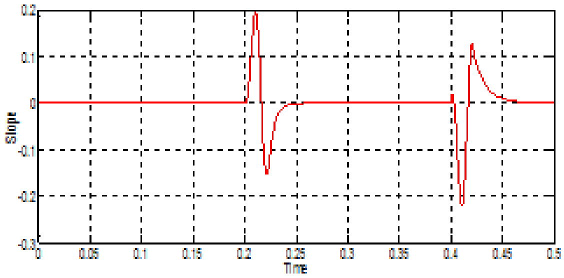


Figure 8(a)

Figure 8(b)



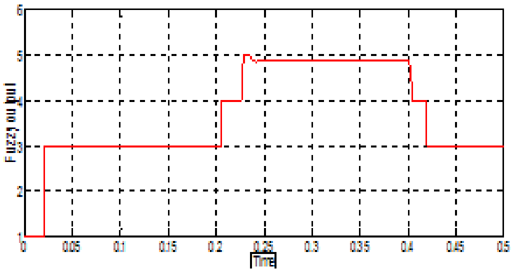


Figure 8(c)

Figure 8(d)

4) **Outages** may be seen as a loss of voltage on the system for the duration of 0.5 cycles to 1min as shown in the figure 9 (a) and the corresponding features are shown in the figures 9(b) and 9(c). The fuzzy output of outages is shown in the figure 9(d).

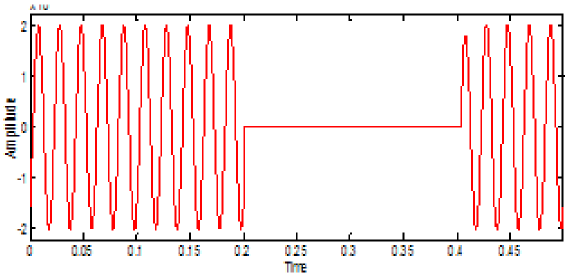


Figure 9(a)

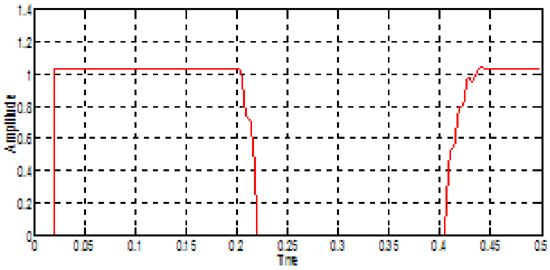


Figure 9(b)

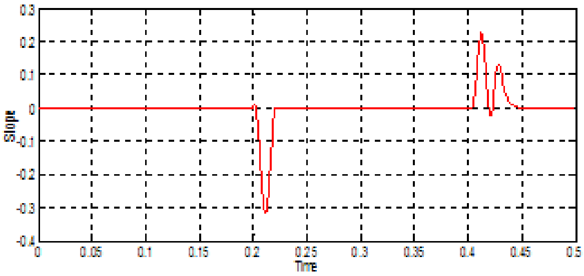


Figure 9(c)

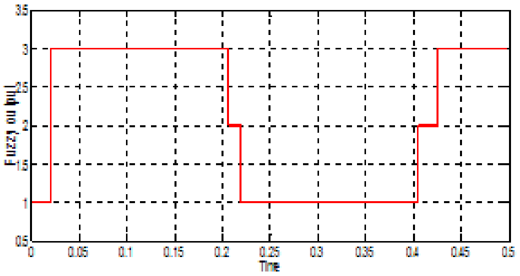


Figure 9(d)

5) **Harmonics** are generated by connecting a non linear load to the system for 10 cycles. Figure 10(a) shows the distortion of voltage waveform and the corresponding Kalman filter outputs are given in the figures 10(b) and 10(c). The fuzzy output of the harmonic disturbance signal is shown in the figure 10(d).

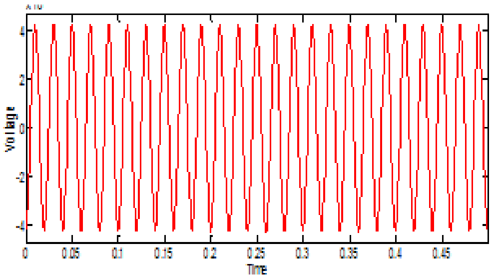


Figure 10(a)

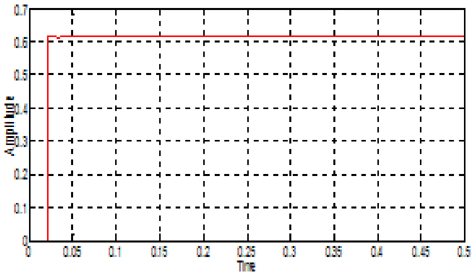


Figure 10(b)

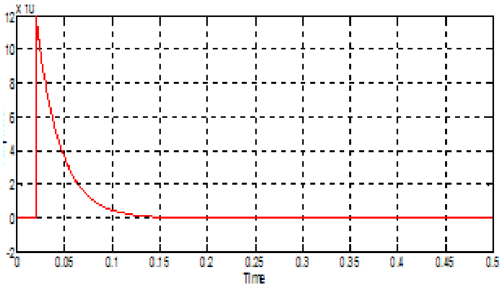


Figure 10(c)

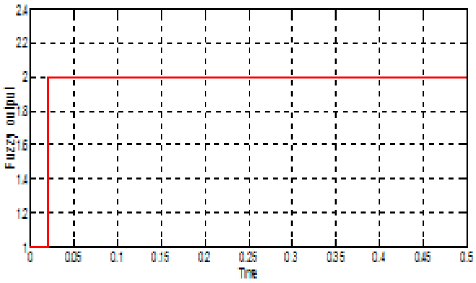


Figure 10(d)

6) **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 11(a). The amplitude and slope outputs of the kalman filter for this type of disturbances are shown in the figures 11(b) and 11(c). The fuzzy output of this disturbance signal is shown in the figure 11(d).

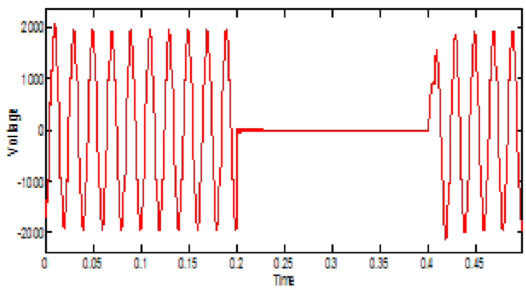


Figure 11(a)

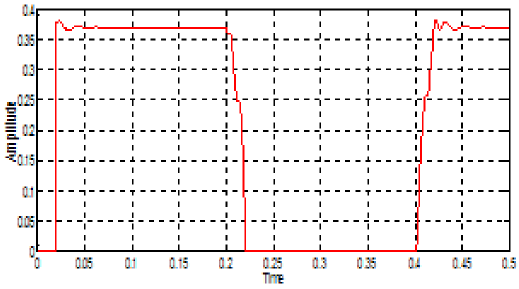


Figure 11(b)

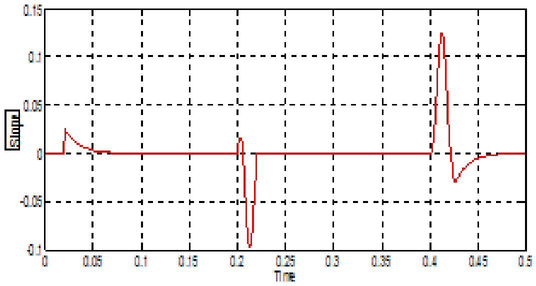


Figure 11(c)

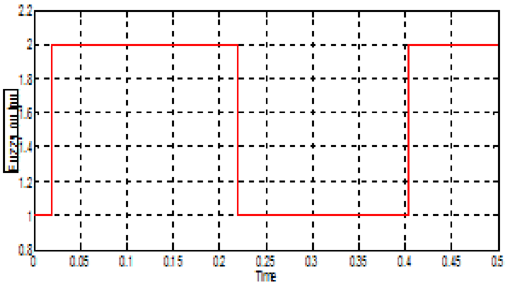


Figure 11(d)

7) **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 12(a) and the corresponding kalman filter outputs are given in the figures 12(b) and 12(c). The fuzzy output of this disturbance signal is shown in the figure 12(d).

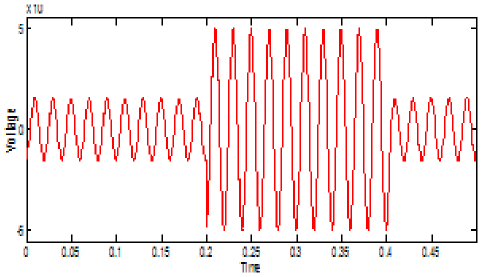


Figure 12(a)

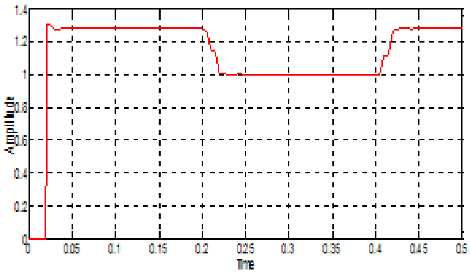


Figure 12(b)

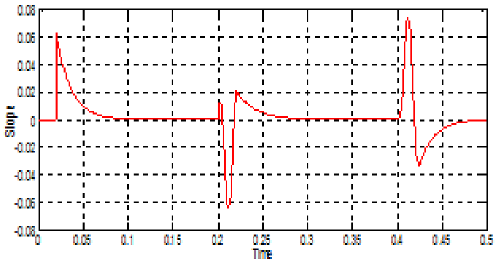


Figure 12(c)

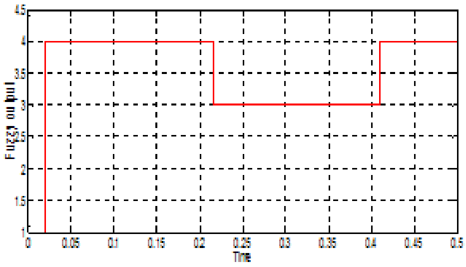


Figure 12(d)

8) **Flicker** disturbance is caused by a continuous and rapid variation of the system load The waveform of flicker is shown in the figure 13(a). The amplitude and slope outputs of kalman filter for flicker waveform are shown in the figures 13(b) and 13(c). Fuzzy output of the flicker disturbance signal is shown in the figure 13(d).

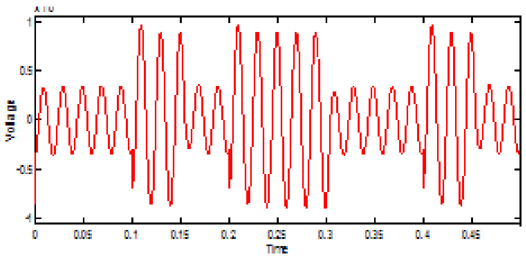


Figure 13(a)

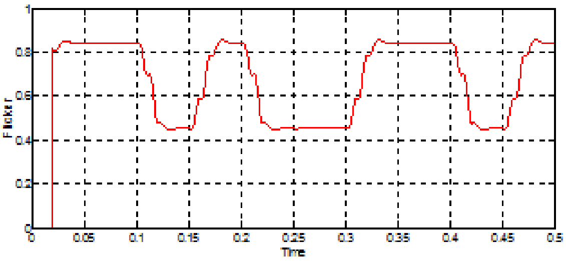


Figure 13(b)

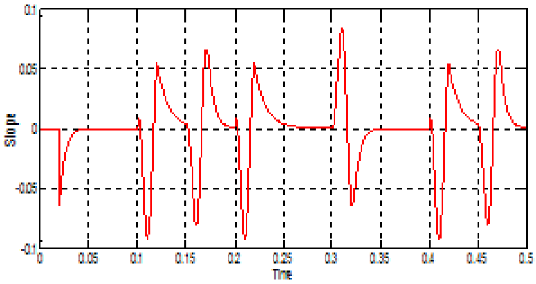


Figure 13(c)

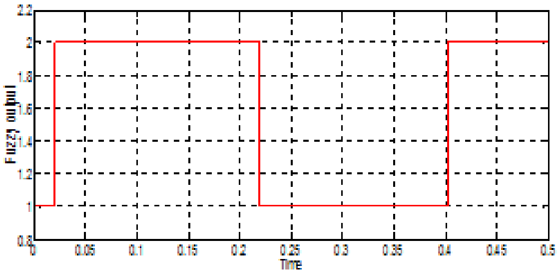


Figure 13(d)

9) **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 14(a) and its corresponding features are given in the figures 14(b) and 14(c). The fuzzy output of the notch disturbance signal is shown in the figure 14(d).

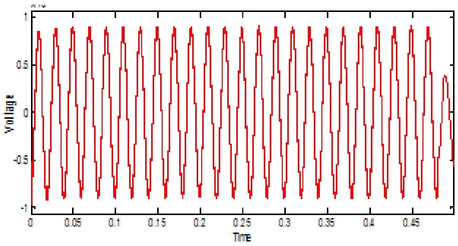


Figure 14(a)

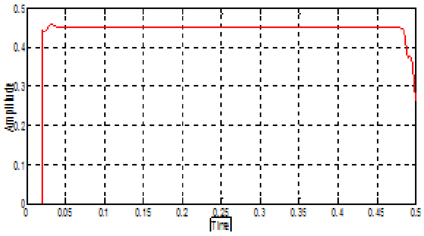


Figure 14(b)

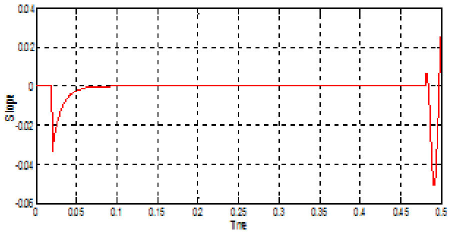


Figure 14(c)

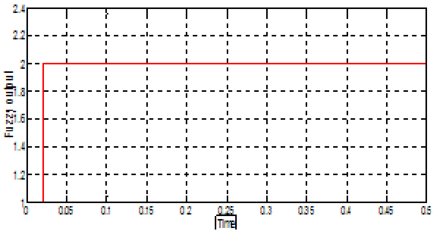


Figure 14(d)

Table 1.Classification Accuracy

Sno	Types of PQ disturbances	Percentage of Accuracy	
		Input Features	Kalman filter based fuzzy system
1	Pure Sine wave	100	100
2	Voltage Sag	100	100
3	Voltage Swell	100	98
4	Outages	100	96

5	Harmonics	100	100
6	Sag with Harmonics	100	98
7	Swell with Harmonics	100	96
8	Flicker	100	96
9	Notch	100	96
Overall accuracy			97.78

The classification performance of the proposed method has been demonstrated through Table 1 and Figure 15.

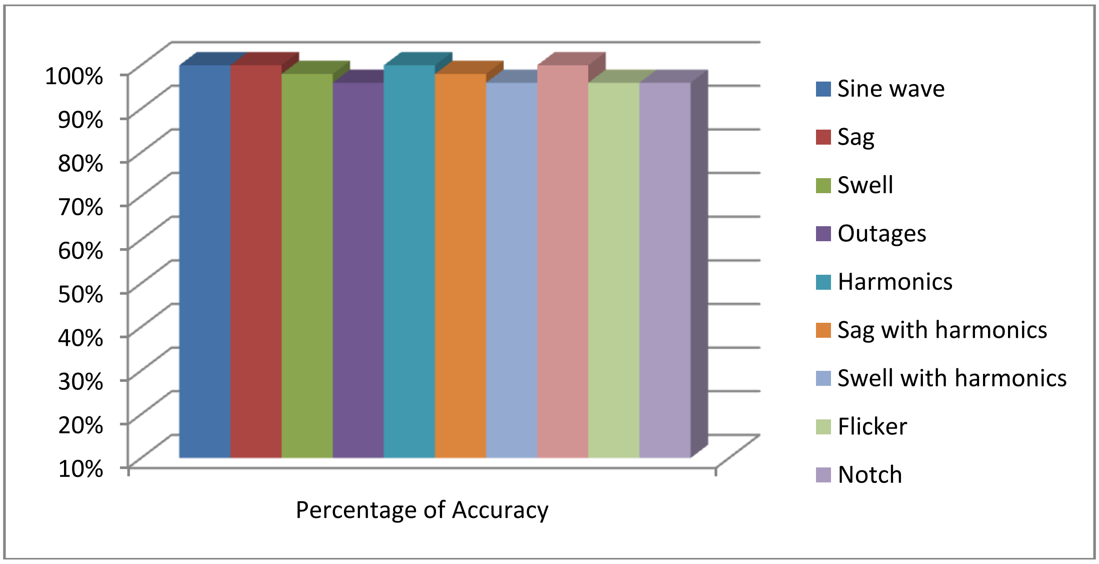


Figure 15. Bar diagram for the percentage of accuracy of the proposed method

V. CONCLUSION

In this paper, a new method for the power quality disturbances classification in the distribution system using the kalman filter technique has been proposed. The disturbance waveforms were generated through Matlab simulink on the test system and input features such as amplitude and slope were extracted through Kalman filter. Fuzzy expert system has been applied for assessed the various power quality disturbances. It has also been found that all the nine disturbances were classified accurately by the proposed method. The result shows that the proposed system can be applied effectively on real life systems for power quality disturbance classification.

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