Power Quality Disturbance Classification based on Kalman filter and Adaptive Neural Fuzzy Inference System (ANFIS)

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Abstract. The paper introduces a new method for analyzing and classifying various Power Quality (PQ) disturbances using Kalman Filter (KF) and Adaptive Neural Fuzzy Inference System (ANFIS). The variety of distortion waveforms are simulated on the test system using MATLAB software and various input features like amplitude and slope have been used in ANFIS classifier technique inorder to classify the PQ disturbances. This is mainly achieved by implementing and training ANFIS classifier through the obtained features by KF method for disturbance classification. The results indicates that the KF based ANFIS method is clearly detected and classify the several PQ disturbance signals. The performance of the KF based ANFIS has been evaluated by comparing the results against KF based neural network and KF based fuzzy system.

1. Introduction

In the recent year, Power quality and their related issues are the main problem in the power system. It affects the entire performance of the system that result in the deviation or fluctuation of the normal voltage, current or frequency from the ideal nature. The power quality events are generally classified as voltage dips, voltage swell, outages, harmonics, sag with harmonics, swell with harmonics, notches and flickers and these are created by power line disturbances and such other factors. Wavelet transform has been applied for power quality disturbance analyzer in [1]. Multi resolution wavelets were implemented to analyze the electromagnetic nature of power system transients in [2].

A combination of Support Vector Machine and Radial Basis Function networks has been illustrated in [3] for the power quality events classification. Windowed FFT based the power quality disturbances assessment has been implemented in [4]. Wavelet multi resolution analysis and neural classifier based power quality disturbance assessment has been illustrated in [5]. Wavelet transform along with pattern recognition approach has been used to identify the short duration of power quality events in [6,7]. Analysis of various non stationary signals in the electric power system using S-transform and neural classifier is presented in [8]. Multi resolution S-transform along with fuzzy logic and pattern recognition approach for power quality disturbance assessment in [9]. S-transform based neural classifiers shows more efficient than the wavelet transform based techniques for the assessment of power quality disturbances in [10,11,12]. The binary feature matrix type of the system has been implemented using a combination of Fourier and S-transform along with a rule base has been used to
assessed the power quality events in [13]. An optimal kind of feature selection for power quality event assessment using probabilistic neural network has been presented in [14]. A representative nature of quality power vector has been discussed and derived for the various power quality analysis using adaptive neuro fuzzy interface system in [15]. Kalman filter based digital controller has been applied for the analyze and improvement the power quality events in [16]. HHT based fuzzy classifier has been presented in [17] to eliminate the noise and detect the power quality disturbances. Assessment of power quality disturbances using image processing technique along with pattern recognition has been illustrated in [18]. In this paper, a Kalman filter and Adaptive Neuro-Fuzzy Inference System (ANFIS) based power quality analyzer in which the input features are generated using Kalman Filter technique and disturbances are classified using an ANFIS is presented.

2. Proposed Technique
The proposed technique has two important stages namely input feature extraction stage and disturbance classification stage. In the input feature extraction stage, Kalman Filter technique is mainly applied for extracting the important features such as amplitude and slope. The disturbance classification stage consists of ANFIS method. Disturbance signal waveforms were simulated using Matlab software of the test system.

2.1. Feature Extraction Stage using Kalman filter
Kalman filter has been mainly applied for the purpose of the extracting the input features. Kalman filter is characterized by a set of dynamic state equations and measurement equations are shown below.

\[ X_{k+1} = \phi_k x_k + w_k \]
\[ z_k = H_k x_k + v_k \]

In power system, the measured types of signals are represent by a sum of the 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

\[ z_k = \sum_{i=1}^{n} A_k(i) \sin((i \omega_k) \Delta T + \theta_{k,i}) + v_k \]

where \( k = 1, 2, 3 \ldots N \).

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

For 1\(^{st}\) harmonics: \( x_1 = A_1 \cos(\theta_1) \quad x_1 = A_1 \sin(\theta_1) \)
For 2\(^{nd}\) harmonics: \( x_2 = A_2 \cos(\theta_2) \quad x_2 = A_1 \sin(\theta_2) \)

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For \( n^{th} \) harmonics: \( x_{2n-1} = A_n \cos(\theta_n) \quad x_{2n-1} = A_n \sin(\theta_n) \)

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

\[ X_{k+1} = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{2n} \end{pmatrix}_{k+1} = \begin{pmatrix} 1 & 0 & \ldots & 0 \\ 0 & 1 & \ldots & 0 \\ 0 & 0 & \ldots & 1 \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{2n} \end{pmatrix}_k + w_k \]
The measurement equation can be similarly expressed in matrix form as

\[
\begin{bmatrix}
\sin(\omega_1T) \\
\cos(\omega_1T) \\
\end{bmatrix}
\begin{bmatrix} X_1 \n X_2 \\
\end{bmatrix}
+ \begin{bmatrix} v_1 \n v_2 \\
\end{bmatrix}
= \begin{bmatrix}
\vdots \\
\vdots \\
\sin(n\omega_1T) \\
\cos(n\omega_1T) \\
\end{bmatrix}
\begin{bmatrix} X_{2n-1} \n X_{2n} \\
\end{bmatrix}
\] (7)

The system covariance matrices for \( w_k \) and \( v_k \) are written as

\[
E[w_k w_k^T] = [R_k] \quad \text{and} \quad E[v_k v_k^T] = [Q_k]
\]

The Kalman Filter execution procedure consists of various steps for time updates and measurement updates as listed below.

**Time update steps**

Project the state ahead

\[
X_{k+1} = \Phi_k x_k
\]

Project the error covariance ahead

\[
P_{k+1} = \Phi_k P_k \Phi_k^T + v_k
\] (8)

**Measurement update steps**

Compute the Kalman gain

\[
K_k = P_k^H (H_k P_k H_k^T + R_k)^{-1}
\]

Update estimate with measurement

\[
x_k = x_k^- + K_k (z_k - H_k x_k^-)
\] (9)

Update the error covariance

\[
P_k = (I - K_k H_k) P_k^-\]

Time and measurement update equations (8) & (9) are alternatively solved. The amplitudes of the fundamental frequencies and harmonic frequencies are calculated from estimated variables at any given instant \( k \) as

\[
A_{i,k} = \sqrt{\frac{X_{1,k}^2 + X_{2,k}^2}{n}}
\] (10)

\[
A_{i,k} = \sqrt{\frac{X_{2i-1,k}^2 + X_{2i,Ki}^2}{n}}
\] (11)

Slope of the signals,

\[
Slope_k = (A_{i,k} - A_{i,k-1})/\Delta T
\] (12)

### 2.2. Adaptive neuro-fuzzy inference system (ANFIS)

The Adaptive neuro-fuzzy inference system (ANFIS) is mainly used for the integration of the best features in fuzzy system and neural network. It provides a simple way to get clear definite conclusion based upon ambiguous. The sugeno type of fuzzy based system used to classify the PQ disturbance classification. Adaptive neuro-fuzzy inference system (ANFIS) is generally a multi-layer feed forward neural network in which every node performs their specific node function on the corresponding incoming signals. The fuzzy inference system has generally two inputs namely \( x \) and \( y \) and a single kind of output \( z \). In some case, the rule base has two fuzzy if-then rules of Takagi and sugeno model type.
Rule 1: If $x$ is $A_1$ (&) $y$ is $B_1$ Then $f_1 = P_1 x + Q_1 y + R_1$

Rule 2: If $x$ is $A_2$ (&) $y$ is $B_2$ Then $f_2 = P_2 x + Q_2 y + R_2$

The ANFIS architecture is a three layer feed forward network as shown in the figure 1.

Fig.1. Adaptive neuro-fuzzy inference system (ANFIS)

ANFIS uses the hybrid learning algorithm that has two-pass learning method.
➢ In the forward pass, $S_1$ is unmodified and $S_2$ is computed using least squared error (LSE) in off-line learning algorithms.
➢ In the backward pass, $S_2$ is unmodified and $S_1$ is computed using a gradient descent algorithm usually in back propagation technique.

The membership function of the FIS based on the extracted input features are shown in figure 2.

Fig.2. Adaptive neuro-fuzzy inference system (ANFIS)
3. Classification stage
In order to classify the several PQ disturbances, the extracted features through Kalman filter namely amplitude and slope are given as inputs to the Adaptive neuro-fuzzy inference system (ANFIS). The ANFIS technique is very useful for the analysis and classification of several kind of PQ disturbance.

4. Simulation and Test results
Tested data were simulated through the Matlab software on the test system for different types of disturbances The single line diagram and Matlab simulation block diagram of the test system model are shown in figure 3 and figure 4.
Seven classes of single PQ disturbances, namely pure sine (normal), sag, swell, surge, outage, harmonics, notch, flicker and Two classes of combined PQ disturbances, namely sag with harmonics, swell with harmonics were considered.

In the following case studies, the classifications of power quality disturbances are presented.

- **Single types of PQ events**
  The Simulation waveform for the various kinds of single power quality events such as sinewave, voltage dips, voltage swell, voltage surge. Outages, harmonics, voltage spike, flicker and notch are shown in the figure 5(a) to 5(h).

Kalman filter technique is implemented to extract the two input features such as amplitude and slope from the various types of single power quality disturbances.
Fig. 6(a) Extraction of amplitude from pure sine
Fig. 6(b) Extraction of slope from pure sine

Fig. 7(a) Extraction of amplitude from sag
Fig. 7(b) Extraction of slope from sag

Fig. 8(a) Extraction of amplitude from swell
Fig. 8(b) Extraction of slope from swell

Fig. 9(a) Extraction of amplitude from surge
Fig. 9(b) Extraction of slope from surge

Fig. 10(a) Extraction of amplitude from outages
Fig. 10(b) Extraction of slope from outages
- Combined types of PQ events

The Simulation waveform for the two kinds of combined power quality disturbances like sag with harmonics and swell with harmonics are shown in the figure 14(a) to 16(i).

Figure-14 Sag with harmonics  
Figure-15 Swell with harmonics

Kalman filter technique is implemented to extract the two input features such as amplitude and slope from the various kinds of combined power quality disturbances.
Fig. 16(a) Extraction of amplitude from Sag with harmonics  
Fig. 16(b) Extraction of slope from Sag with harmonics  

Fig. 17(a) Extraction of amplitude from Swell with harmonics  
Fig. 17(b) Extraction of slope from Swell with harmonics

ANFIS model has been developed using MATLAB software and it has been applied to classify the disturbances from the extracted input features. Figure 18(a) shows the performance evaluation in terms of graphical nature of the testing and validation data.

Fig. 18(a) graphical representation of the testing data

Figure 18(b) shows the membership function of the extracted input features inorder to classify the power quality disturbances.
Fig. 18(b) shows the membership function of the extracted input features

The classification performance of the proposed method has been demonstrated through Table 3 and Figure 19.

| Sno | Types of PQ disturbances | Percentage of Accuracy | Input Features | Kalman filter based Adaptive Neuro-Fuzzy Inference System |
|-----|---------------------------|------------------------|----------------|----------------------------------------------------------|
| 1   | Pure Sine wave            | 100                    | 100            |
| 2   | Voltage Sag               | 100                    | 100            |
| 3   | Voltage Swell             | 100                    | 99             |
| 4   | Voltage Surge             | 100                    | 98             |
| 5   | Outages                   | 100                    | 98             |
| 6   | Harmonics                 | 100                    | 98             |
| 7   | Sag with Harmonics        | 100                    | 99             |
| 8   | Swell with Harmonics      | 100                    | 97             |
| 10  | Notch                     | 100                    | 98             |
|     | Overall accuracy          |                        |                | 98.7                                                     |
5. Conclusion
In this paper, a new classification method based on Kalman filter and Adaptive Neuro-Fuzzy Inference System (ANFIS) is implemented for the classification of different power quality disturbances. The disturbance waveforms were simulated using Matlab software on the test system and the combined disturbances are inclusive of sag with harmonics and swell with harmonics also. The extracted features such as standard deviation and variance were obtained using kalman filter. The ANFIS method has been used to analyzing and classifying the disturbances. It has been shows that the seven type single disturbances and two type of combined disturbances were classified accurately by the proposed technique.

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