Hybrid FPGA and Neural Network Architecture for Real-Time Power Quality Monitoring

Selvin Retna Raj Thavasimuthu[1], Sai Kiran Orugant[2]
[1]Lincoln University College ;[2]Lincoln University College;
pdf.selvinthavasi@lincoln.edu.my[1], saisharma@lincoln.edu.in[2]

Abstract: The increasing integration of nonlinear loads and renewable energy sources has intensified power quality disturbances in modern electrical grids. This paper presents a hybrid FPGA and Neural Network architecture for real-time power quality monitoring with high speed and accuracy. The proposed system combines the parallel processing capability of Field-Programmable Gate Arrays (FPGAs) with the intelligent pattern recognition ability of Artificial Neural Networks (ANNs). The FPGA performs high-speed signal acquisition, preprocessing, and feature extraction from voltage and current waveforms. Extracted features are supplied to the neural network for automatic classification of power quality events. The architecture effectively identifies disturbances such as voltage sag, swell, harmonics, transients, interruptions, and flicker. Hardware acceleration significantly reduces processing latency, enabling real-time operation in smart grid environments. The neural network improves classification accuracy by learning complex nonlinear patterns from training data. The proposed design offers scalability, reliability, and low power consumption for embedded monitoring applications. Experimental evaluation demonstrates superior performance compared to conventional software-based monitoring techniques. The hybrid implementation achieves fast response times while maintaining high detection precision under varying operating conditions. The system is suitable for industrial power systems, renewable energy integration, and smart grid monitoring. The proposed architecture provides an efficient and cost-effective solution for continuous power quality assessment. Overall, the integration of FPGA hardware with neural network intelligence enhances the speed, accuracy, and reliability of real-time power quality monitoring systems.

Keywords: Modified S-Transform, Radial Basis Function Neural Network, Matlab etc.

Introduction

Power quality (PQ) disturbances are increasingly affecting modern power systems due to the widespread use of nonlinear loads, renewable energy sources, and power electronic converters. Reliable and real-time classification of PQ disturbances is essential to ensure power system stability and equipment protection. This paper presents an FPGA-based real-time PQ disturbance classification method using a Modified S-Transform (MST) for feature extraction and a Radial Basis Function Neural Network (RBFNN) for classification. The proposed MST improves time–frequency resolution while reducing computational complexity, making it suitable for hardware implementation. Discriminative features extracted from the sag, swell, interruption, harmonics, flicker, and transients, with low latency and efficient hardware utilization. Traditional PQ monitoring techniques based on software platforms often fail to meet real-time requirements because of high computational complexity and latency. Hardware-based solutions, particularly those implemented using Field Programmable Gate Arrays (FPGAs), offer high-speed parallel processing, low latency, and reconfigurability, making them suitable for real-time PQ monitoring applications

Related work

A. *T. jayasree, D. devaraj & R. sukanesh" power quality disturbance classification using s-transform and radial basis network" applied artificial intelligence, 23:680–693*

Findings: The valuation and comparison using different performance metrics for voltage sags and notches. These techniques widely used in time–frequency domain is WT, ST, and HHT, or their combination with other techniques.

B. Agudelo-Martínez, Edwin Rivas-Trujillo1 andJan Meyer" a systematic review of real-timedetection and classifcation of powerqualitydisturbances" https://doi.org/10.1186/s41601-023-00277-y.

Findings: different performance metrics of Voltage sags, voltage swells, and interruption, transient, are the most common kind of disturbance.

C. *G.N. Bonde, S.R. Paraskar, S.S. Jadhao" Review on detection and classification of underlying causes of power quality disturbances using signal processing and soft computing technique" Volume 58, Part 1, 2022, Pages 509-515.*

Findings: the valuation and comparison using different performance metrics of Voltage sags, voltage swells using PNN.

Key Contribution

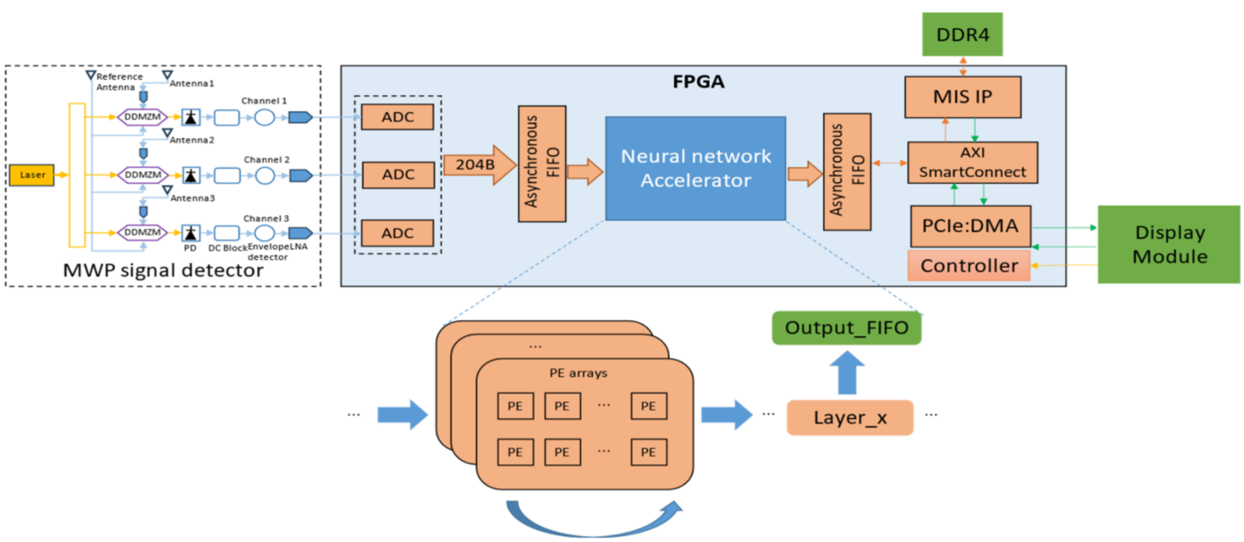

Fig: Modified S-Transform suitable for FPGA

Time–frequency analysis techniques play a crucial role in PQ disturbance analysis. Commonly used methods include the Short-Time Fourier Transform (STFT), Wavelet Transform (WT), and S-Transform (ST). Among these, the S-Transform provides frequency-dependent resolution and absolute phase information, which is advantageous for analyzing nonstationary PQ signals. However, the conventional S-Transform requires extensive computation, limiting its real-time hardware implementation.

Artificial intelligence techniques, particularly neural networks, have been widely applied for PQ disturbance classification. Radial Basis Function Neural Networks (RBFNNs) are well suited for real-time applications due to their simple structure, fast training, and strong generalization capability.

This paper proposes an FPGA-based real-time PQ disturbance classification system using a Modified S-Transform for feature extraction and an RBF neural network for classification. The main contributions of this work are summarized as follows:

1. Development of a computationally efficient Modified S-Transform suitable for FPGA implementation.
2. Extraction of effective time–frequency features for PQ disturbance characterization.
3. Hardware implementation of an RBFNN classifier for real-time PQ disturbance classification.

Validation of the proposed method through simulation and FPGA-based experiments

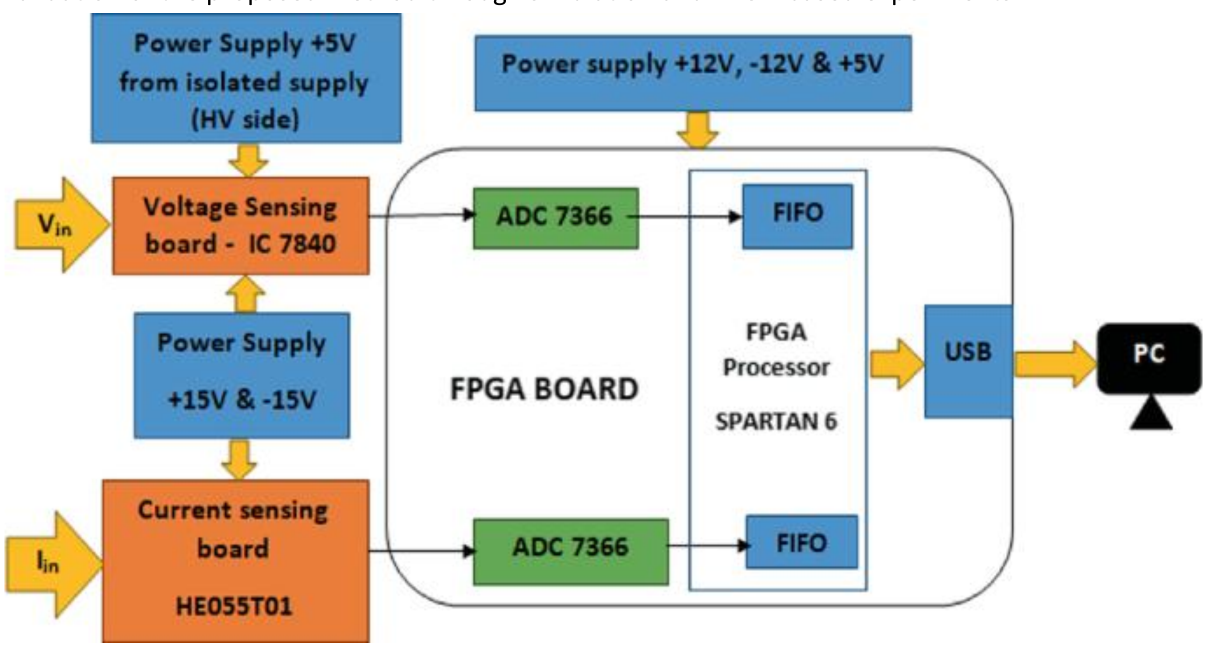

Fig: simulation and FPGA-based experiments

Method, Experiments and Results

Wavelet analysis is a type of time-frequency approach employing wavelets, which are limited-energy and average-zero functions, described as $\int_{-\infty}^{\infty} \psi(t)dt = 0$ .In wavelet analysis, a particular wavelet called as mother wavelet is initially chosen as the basis function. The mother wavelet is then generated in dilated and translated forms, where $\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\frac{(t-b)}{a}$.

The scale parameter *a* indicates dilation whereas the translation parameter *b* is used to alter translation. The location of the wavelet function as it is moved through the signal is related to the translation parameter which in turn matches the time information. The scale parameter is equal to frequency information and is specified as 1/frequency|. Scaling causes a signal to either dilate or compress. Small scales compress the signal and give general information about it, whereas large scales widen the signal and reveal hidden values. Disturbance Detection in the presence of Noise:
Input signals are added with Additive Gaussian noise and the DWT is applied.

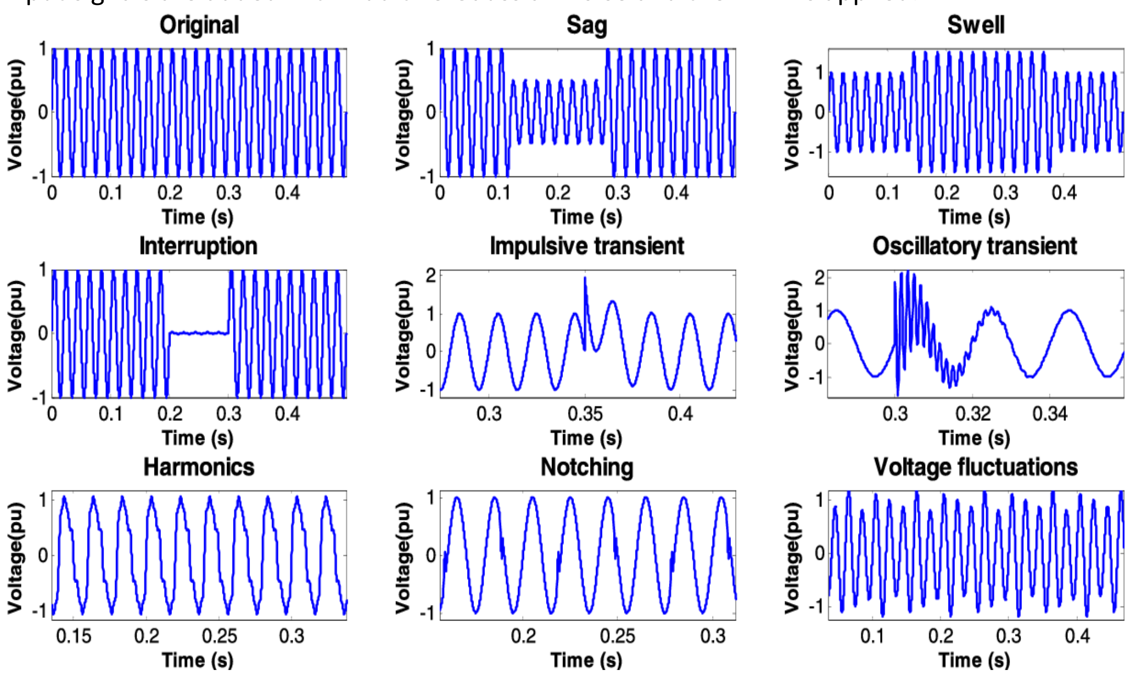

Fig: The S-Transform is a time–frequency analysis technique

The S-Transform is a time–frequency analysis technique that combines the advantages of STFT and WT. The continuous S-Transform of a signal x(t) is defined as:

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t)\frac{|f|}{\sqrt{2\pi}} \exp\left(-\frac{(t-\tau)^2 f^2}{2}\right) e^{-j2\pi f t} dt$$

Although the S-Transform provides excellent time–frequency localization, its high computational complexity makes it unsuitable for real-time FPGA implementation.

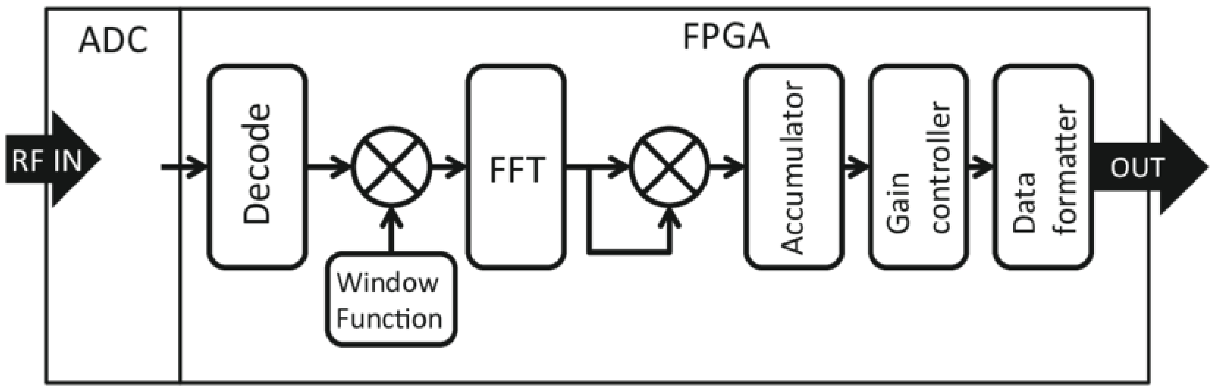

Fig4: FPGA-based real-time power quality disturbance

The S – Transform of the power quality disturbance signals are found out and subsequently, the ST-Matrix, S–Transform contour and S – Transform 3D plots are obtained. The program for computing S-Transform is written in MATLAB. The results are displayed in this section. Figure 5.2 shows the voltage swell signal, its S-Transform, S-Transform contour and S – Transform 3D plots. Features such as mean, median, energy and variance are calculated for all the power quality disturbances from the ST matrix. As shown in Figure, the values of all the features are different for each disturbance. The presence of voltage transient disturbance is represented by the presence of contours in all the sub bands. Here it shows the clear information of the signal chances

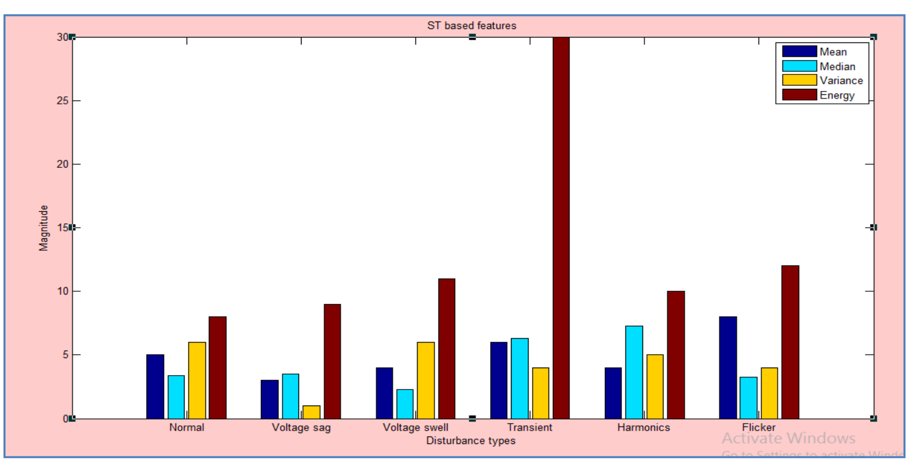

Fig: S–Transform contour

Conclusions

An FPGA-based real-time power quality disturbance classification system using a Modified S-Transform and an RBF neural network has been presented in this paper. The Modified S-Transform effectively extracts discriminative time–frequency features with reduced computational complexity, while the RBFNN provides fast and accurate classification. Experimental results demonstrate high accuracy, low latency, and efficient FPGA resource utilization. The proposed system is suitable for real-time PQ monitoring in smart grid applications. Future work will focus on extending the method to multi-phase systems and incorporating adaptive learning mechanisms.

.

References

1.International Journal of Electrical and Electronic Engineering and Tele-Communications, vol. 8, no. 1, pp. 45-50.

2. Bhuiyan, SM, Khan, J & Murphy, G 2018, ‘WPD for detecting disturbances in presence of noise in smart grid for PQ monitoring’, IEEE Trans Ind Appl, vol. 54, no. 1, pp. 702-711.

3. Biswal, M & Dash, PK 2013, ‘Measurement and classification of simultaneous power signal patterns with an s-transform variant and fuzzy decision tree’, Industrial Informatics, IEEE Transactions, vol. 9, no. 4, pp. 1819-1827.

4. Cai, D, Li, K, He, S, Li, Y & Luo, Y 2018, ‘A highly accurate and fast power quality disturbances classification based on dictionary learning sparse decomposition’, Transactions of the Institute of Measurement and Control, vol. 41, no. 1, pp. 145-155.

5. Huang, J, Jiang, Z, Rylands, L & Negnevitsky, M 2017, ‘SVM-based PQ disturbance recognition system’, IET Generation, Transmission and Distribution, vol. 12, no. 2, pp. 328-334.

6. Huang, N, Xu, D, Liu, X & Lin, L 2012, ‘Power quality disturbances classification based on S-transform and probabilistic neural network’,

7.Abisha, S & Jayasree, T 2019, ‘Application of image processing techniques and artificial neural network for detection of diseases on brinjal leaf’, IETE Journal of Research, vol. 68, no. 3, pp. 2246-2258.

8. Achlerkar, PD, Samantaray, SR & Manikandan, M S 2018, ‘Variational mode decomposition and decision tree based detection and

classification of power quality disturbances in grid-connected distributed generation system’, IEEE Transactions on Smart Grid, vol. 9, no. 4, pp. 3122-3132.