Power Quality Analysis Using Modified S-Transform on ARM Processor

Sandeep Raj, T. C. Krishna Phani
Department of Electrical Engineering
IIT Patna, Bihta, India 801103
Email: {srp, chaitanya.ee10}@iitp.ac.in

Jyotirmayee Dalei
Department of Electrical and Electronics Engineering
NSIT, Bihta, Patna, India 801118
Email: jyoti_uce@yahoo.com

***Abstract*—The extensive usage of non-linear loads and electronic devices has resulted in increased vulnerability to the power quality (PQ) disturbances in the power system. Hence, the analysis of PQ disturbances becomes crucial to maintain the reliability of the distributed generation (DG). This paper presents the analysis of various disturbances like voltage swell, voltage sag, notch, flicker, spike, harmonics, momentary interruption and oscillatory transients by using a signal processing technique i.e. modified Stockwell transform (MST). The technique is employed to provide sufficient time-frequency characteristics and retain the phase information of input to detect the different PQ disturbances. Moreover, the localization of gaussian window is exploited by providing different scaling parameters which correspond to the linear phase of frequency and provides better resolution. The voltage signal is utilized for the detection of the disturbances at a point of common coupling. The time-frequency features are re-transformed into the time space (original signal) by using the inverse modified S-transform to visualize the different PQ disturbances in real-time. In this study, the methodology is implemented on commercially available ARM (Advanced RISC Machine) processor due to its features such low cost and low power consumption for real-time power quality analysis.**

Keywords*—Power Quality; Stockwell Transform; Voltage Sag; Voltage Swell; ARM9 (Advanced RISC Machine)

I. Introduction

In the last few decades, quality of power usage in modern day power systems has evolved as a great challenge for electric utilities and consumers. The widespread employment of power electronic equipment and non-linear loads have increased the demand of power and provided sufficient solutions to various issues; but have emerged as a serious threat in terms of power quality (PQ). These disturbances are a measure of deviation of frequency and amplitude of load bus current and voltage from the specified sinusoidal signal [1]–[5]. The cause of disturbance in power quality is normally caused by power line disturbances such as voltage sags/swells with or without harmonics, momentary interruption, harmonic distortion, flicker, notch, spike and transients. These disturbances cause instabilities, malfunctioning, short-lifespan and failure of electrical and electronic devices. Due to the expansion and increase in number of power grids because of different sources of electricity generation, it is necessary to limit the harmful effects caused by them, which is only possible by accurate and timely detection of power quality disturbances [1]–[7].

However, the challenge of power quality disturbances has been thoroughly studied using different signal processing techniques by various researchers. The use of various signal techniques have led the possibility of measurement and monitoring of PQ disturbances with ease. Among these various techniques, short-time fourier transform (STFT) [8]–[12] is one of the basic tool to analyze the PQ disturbances which is an extended version of fourier transform without a window. But STFT suffers from a drawback that it uses a fixed size of window for all the frequencies i.e it is limited to stationary signals only. Wavelet Transform (WT) overcome the drawback of STFT by using longer windows at low frequencies and shorter windows at higher frequencies. Rather, the characteristics of the non-stationary signals can be monitored by its use. These features can be utilized for automated detection of PQ disturbances [13]. However, the choice of sampling frequency and mother wavelet is a major factor in extraction of the wavelet features failing which leads to misleading interpretation of the input data [8]–[14]. The issue with WT, is overcome by a transform i.e stockwell transform (ST). The ST provides the local phase information and frequency dependent resolution of time-frequency space. The utilization of ST features can provide a significant improvement in the detection of PQ disturbances. However, the ST also suffers from a drawback, that it provides a redundant representation of time-frequency space and involves huge computational complexity [15]. To the knowledge of authors, no hardware realization of modified S-transform is reported. Hence, the authors have presented the hardware realization of modified-ST for the analysis of different PQ disturbances in real-time.

Although, the generalized s-transform suffers from a drawback that it provides poor energy concentration in the time-frequency domain. Its time resolution at lower frequency and frequency resolution at higher frequency yields degraded performance. This study utilizes the property of stockwell transform (ST) and exploits the localization of the gaussian window for the analysis of various power quality disturbances. Moreover, the proposed methodology is implemented on the commercially available low-cost ARM9 processor to study different PQ disturbances. The real-time input signals are generated in the arbitrary function generator (AFG 3252) which is provided as input to the ARM microcontroller for extracting the time-frequency (i.e modified ST) features. Again for the study, the original input signal is recovered by using the inverse of the modified S-transform. The various kinds of PQ disturbances is monitored on digital storage oscilloscope (DSO) by interfacing a external digital-to-analog converter (DAC) to the ARM9 microcontroller in the laboratory setup.

978-1-5090-2541-1/16/$31.00 © 2016 IEEE

The rest of the paper is structured as follows. Section II presents the detailed theory of modified stockwell transform. Section III presents the complexity analysis of proposed methodology while Section IV presents the experiment on hardware platform results and its discussion. Finally, Section V concludes the article.

II. Modified Stockwell Transform

This section presents a detailed description of the theory of modified stockwell transform which is used in this work for the analysis of different PQ disturbances.

A. Stockwell Transform

The field of time-frequency analysis has gained significant attention with the development of the short time fourier transform (STFT). The STFT localizes time-frequency representation of a time series input by using a window function. The window localizes the time and the fourier transform to localize the frequency. Though, the STFT has poor time-frequency resolution due to the fixed width of the window. The wavelet transform (WT) has the advantage over STFT that uses a basis function which dilates and contracts with frequency. However, the WT does not retain the absolute phase information and the time scale plots provided by WT is complex. It is necessary to modify the phase of mother wavelet to have the information contained in phase in the time-series input. The CWT (τ, d) of a function $a(t)$ is defined as

$$W(\tau,d)=\int_{-\infty}^{\infty}a(t)w(t-\tau,d)dt \quad (1)$$

where $w(\tau,d)$ is a scaled replica of the mother wavelet, and d is the dilation parameter that determines the width and controls the resolution. The s-transform can be obtained by multiplying the CWT with a phase factor.

$$S(\tau,f)=e^{i2\pi ft}W(t-\tau,d)dt \quad (2)$$

The features of STFT and WT are combined for an efficient time-frequency representation developed by Stockwell [9], which is known as the S-transform. It can be seen as a frequency dependent STFT or a phase corrected wavelet transform. The continuous s-transform for an input signal $a(t)$ is defined as the product of fourier transform (FT) of input signal $a(t)$ and the gaussian window is represented as:

$$S(\tau,f)=\frac{|f|}{2\pi}\int_{-\infty}^{\infty}a(t)e^{-\frac{(t-\tau)^2.f^2}{2}}e^{i2\pi ft}dt \quad (3)$$

where the width of the Gaussian window is given by

$$\sigma(f)=T=\frac{1}{|f|} \quad (4)$$

The s-transform localizes the real and the imaginary components of the spectrum independently, localizing the phase spectrum as well as the amplitude spectrum. This is referred to as absolutely referenced phase information. The ST produces a time-frequency representation instead of the time scale representation developed by the WT. The S-transform is a method of spectral localization.

McFadden et al. [16] and later Pinnegar and Mansinha [17] developed a generalized S-transform by introducing a parameter β into the window function to have a greater control where the width varies with frequency as:

$$\sigma(f)=\frac{1}{|f|*|\beta|} \quad (5)$$

Hence, the generalized S-transform is given by:

$$S(\tau,f,\beta)=\frac{|f|*\beta}{\sqrt{2\pi}}\int_{-\infty}^{\infty}a(t)e^{\frac{-(t-\tau)^2f^2\beta^2}{2}}e^{-j2\pi ft}dt \quad (6)$$

where the window can be given by:

$$\omega(\tau-t,f,\beta)=\frac{|f|*\beta}{\sqrt{2\pi}}e^{\frac{-(t-\tau)^2f^2\beta^2}{2}} \quad (7)$$

where τ is a parameter that controls the position of the generalized window ω on the time axis. For the Gaussian window the parameter β controls the width of the window.

B. Modified S-Transform

Various scaling rule is utilized for the gaussian window in the modified s-transform. The scaling function γ is exploited which corresponds to a linear function of frequency.

$$\gamma(f)=\eta f+b \quad (8)$$

where 'η' is the slope and 'b' is the intercept. The resolution in time and in frequency depends on both of these parameters. The suitable values of 'η' and 'b' are determined empirically based on trial and error. The modified S-transform becomes

$$S(\tau,f,\eta,b)=\int_{-\infty}^{\infty}a(t)\omega(t-\tau,f,\eta,b)e^{-j2\pi ft}dt \quad (9)$$

where ω denotes the window function of the modified s-transform is given by

$$\omega(t-\tau,f,\eta,b)=\frac{|f|}{\sqrt{2\pi}(\eta f+b)}e^{\frac{-(t-\tau)^2f^2}{2(\eta f+b)^2}} \quad (10)$$

Using equations (9) and (10),

$$S(\tau,f,\eta,b)=\int_{-\infty}^{\infty}a(t)\frac{|f|}{\sqrt{2\pi}(\eta f+b)}e^{\frac{-(t-\tau)^2f^2}{2(\eta f+b)^2}}e^{-j2\pi ft}dt \quad (11)$$

The modified s-transform also satisfies the normalization condition for s-transform windows and hence is invertible.

$$\int_{-\infty}^{\infty}\frac{|f|}{\sqrt{2\pi}(\eta f+b)}e^{\frac{-(t-\tau)^2f^2}{2(\eta f+b)^2}}e^{-j2\pi ft}d\tau \quad (12)$$

The parameters are the number of periods of the fourier sinusoids that can be contained within one standard deviation (σ) of the gaussian window. The factor ω controls the time resolution i.e. the event onset and offset time and frequency smearing. If ω is too small the gaussian window retains very few cycles of the sinusoid which results in poor frequency resolution at lower frequencies. If ω is too high the window retains more sinusoids within it and as a result the time resolution degrades at high frequencies. Thus, it is suggested that the value of ω should be suitably chosen for better energy distribution in the time-frequency plane. The typical range of 'η' is 0.25-0.5 and 'b' is 0.5-3. The value of η and b is selected depending on the nature and type of signal under study.

Fig. 1 shows the power quality monitoring system for the power system model (i.e single line diagram shown) considered in this work. The voltage sensors receives the voltage signal and sends to the embedded computing system i.e ARM microcontroller for its processing. In the processing, modified S-transform is used to study the disturbances and reconstructed for their analysis on the displaying device.

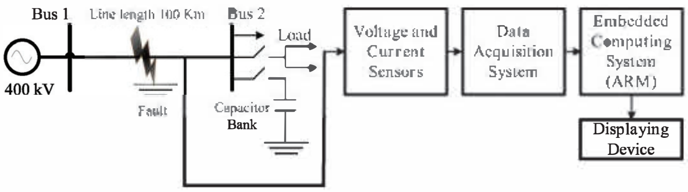


Fig. 1. PQ Monitoring System for the power system model

III. Complexity Estimation

However, it is essential to estimate the complexity of modified-ST prior to its implementation. The two types of complexities are estimated for the possible implementation of stockwell transform. The first include the time complexity which is the time taken for the execution of the methodology while memory consumption is second which denotes the memory required by the features on the hardware for processing.

The memory consumption for ST can be estimated as follows:

1) The storage of input time series 'x' and its FFT requires 2N + 2N. However, the storage of ST output requires $2N^2$.
2) The storage of gaussian function and its FFT requires $2N^2 + 2N^2$.
3) The storage of product of time series FFT and Gaussian FFT requires $2N^2$ more.
4) The calculation of FFT and IFFT requires $4N$.

The total memory required for calculation of ST is approximately of order $12N^2 + 8N$.

Memory Consumption for implementing IST:

1) The storage of input ST and output y requires $2N^2 + 2N$.
2) The average value of ST is calculated and stored it in 'y', so there is no more memory required.

Time complexity of ST:

1) The calculation of FFT of an input signal 'x' takes $\Theta(NlogN)$.
2) FFT of gaussian is calculated directly. Product of FFT of time series while the FFT of gaussian function requires $\Theta 2N^2$.
3) The IFFT of the product of gaussian function and FFT requires $\Theta(N * (NlogN))$.

Therefore, the total time complexity becomes of the order of $(N^2 * logN) + (2N^2) + (NlogN)$. While, IST involves N times average of N items which is of order N. The IFFT of obtained average is of order $NlogN$. Hence, the total complexity of the method becomes $\Theta(N + 1)logN$.

IV. Systems for simulation and Results

Power quality analysis represents various kinds of electrical disturbances such as voltage sags, voltage swells, harmonic distortions, flickers, notch, spike, oscillatory transients, and momentary interruptions, etc. These power quality disturbances are analyzed and detected performed on the EHV line [11] by using the time-frequency localization property of the modified S-transform. For each type of the PQ disturbance, 1024 number of sample index are considered for their detection and analysis in simulation as well as in hardware realization.

A. Simulation Results

The experiments are performed on the MATLAB software [R2012a; Version 7.14.0.739 installed on Windows 7 platform, 3.33GHz, i5 CPU] package and accordingly the parameters are calculated for analysis of different PQ disturbances.

Fig. 2 shows the pure sinusoidal waveform which is free from any kind of disturbances and its modified s-transform analysis.

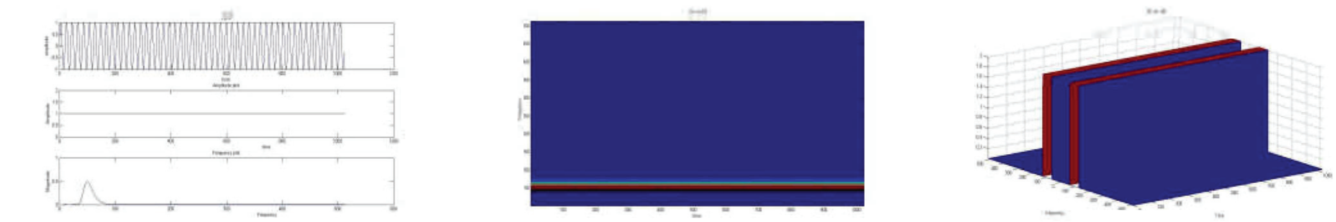
A voltage sag occurs when the root-mean-square (rms) voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute. Whereas, a swell is defined as an increase between 1.1 and 1.8 pu in rms voltage or current at the power frequency for duration from 0.5 cycle to 1 min. Swells are usually associated with system fault conditions. Fig. 3 and Fig. 4 shows the different graphical plots analysis for voltage sag and swell signals. In these plots amplitude versus frequency and magnitude versus frequency along with the 3-dimensional contour is plotted.

The term flicker may be defined as variations range from 0.1% to 7% of nominal voltage with frequencies less than 25 Hz. Subsequently, the most important effect of this power quality problem is the variation in light output of various lighting sources. The Momentary outages are defined as zero voltage events lasting for less than five minutes, are measured via MAIFI [Momentary Average Interruption Frequency Index]. Spikes are fast, short duration electrical transients in voltage (voltage spikes), current (current spikes), or transferred energy (energy spikes) in an electrical circuit. Harmonic voltages and currents in an electric power system are a result of non-linear electric loads. Whereas, the harmonic frequencies in the power grid are a frequent cause of power quality problems.

Since, this study focuses on the hardware implementation of the modified S-transform and due to space constraint restriction, the simulation results are presented for only sine, sag and swell signals. While all the different power quality disturbances analyzed in hardware are presented in Fig. 6 for visualization which is discussed in the next subsection.

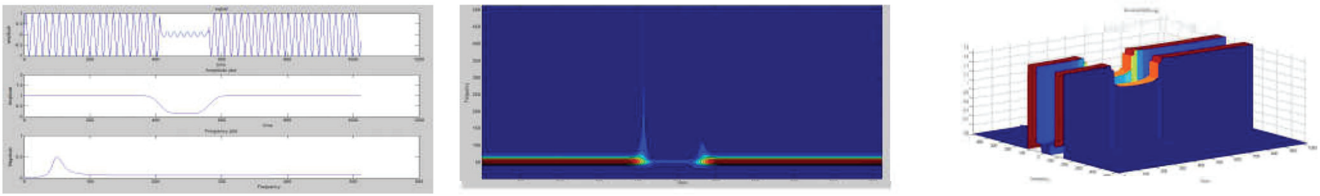
B. Hardware Implementation

Now-a-days, many hardware platforms such as low, middle and high range programmable microcontrollers as well as re-



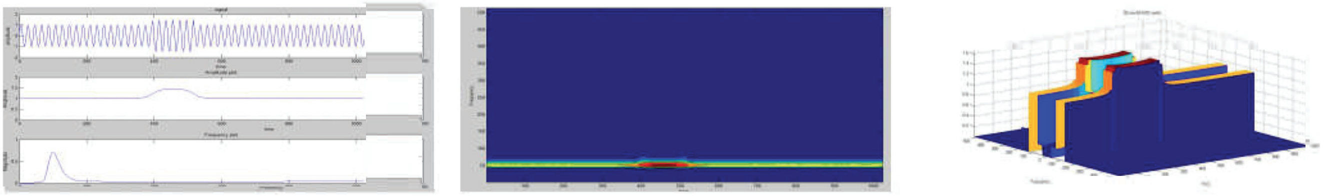
(a) Graphical plots analysis for sinusoidal signal (b) Time-frequency representation for sine signal (c) 3D-Contour plot for Sine signal MST

Fig. 2. Graphical plots analysis for the undisturbed sinusoidal signal



(a) Graphical plots analysis for voltage sag (b) Time-frequency representation for voltage sag signal (c) 3D-Contour plot for sag signal

Fig. 3. Graphical plots analysis for voltage sag



(a) Graphical plots analysis for voltage swell (b) Time-frequency representation for voltage swell (c) 3D-Contour plot for swell

Fig. 4. Graphical plots analysis for voltage swell

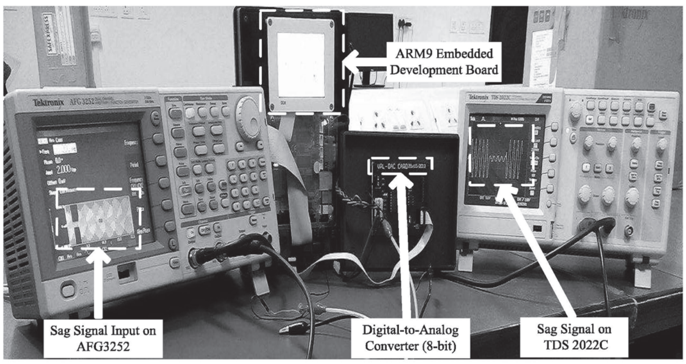
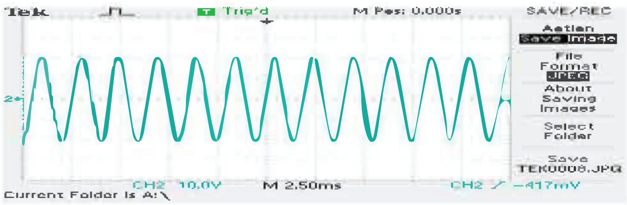


Fig. 5. Laboratory experimental setup

configurable CPLD and FPGAs are available for real-time implementation of digital signal processing algorithms. However, ARM based embedded systems have dominated the modern technology recently. Its low power, simple, elegant, faster time to market and fully static design is particularly suitable for the implementation of the signal processing algorithms. The commercially available customized ARM9 board (i.e which includes Samsung S3C2440 processor, 32-bit data bus, 5V regulated supply) is used for the analysis of different power quality disturbances.

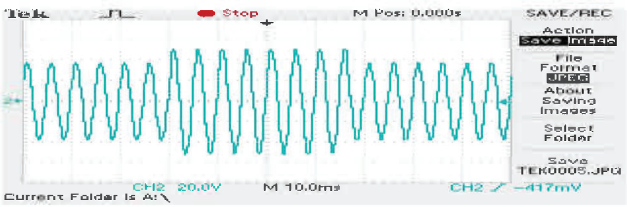
The ARM9 processor core at 400MHz operating frequency is used that offers five stage pipelining with an instruction latency of 2.5 nanoseconds and instruction throughput of 400 MIPS. The methodology i.e modified S-transform is developed using Cpp programming language in the Linux environment. Fig. 5 presents the laboratory experimental setup where the sag signal is reconstructed and displayed on DSO.

Initially, a series of various types of PQ disturbances are generated in text file and transferred in Arbitrary Function Generator (AFG 3252) using Arb Express Application Software to generate corresponding real-time disturbance signals. In the AFG3252, the input signal is amplified and sent to embedded computing system i.e ARM processor for its direct processing by the ADC. The ADC samples the input signals at a rate of 1Hz. The time-frequency features of different PQ disturbances by implementing modified-ST are reconstructed in order to visualize the reconstructed PQ disturbances on digital storage oscilloscope (TDS2022) which is done by using inverse modified s-transform. For this purpose, a digital-to-analog converter (DAC) has been interfaced with the customized ARM development board. The various reconstructed PQ disturbances obtained by implementing the aforesaid methodology is depicted in Fig. 6. Hence, it can be concluded from this study that the proposed implementation on ARM9 processor facilitates automated identification or analysis of different PQ disturbances for real-time applications.

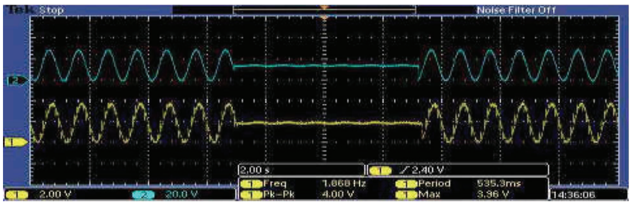


(a) Voltage sine Signal

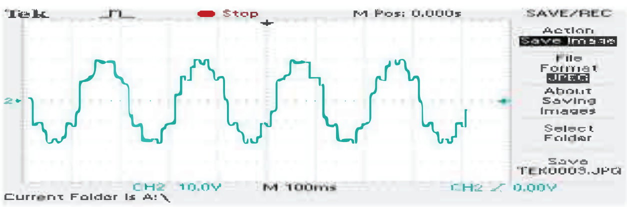
(b) Voltage Sag Signal



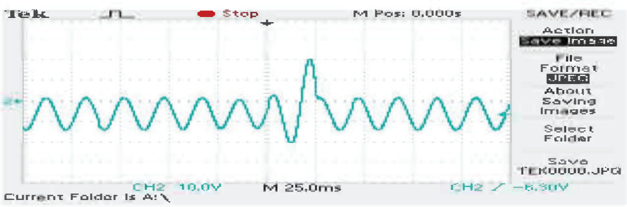
(c) Voltage Swell Signal



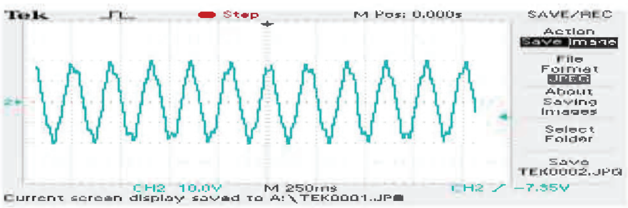
(d) Voltage interrupt Signal



(e) Voltage Harmonics Signal



(f) Voltage flicker signal



(g) Voltage oscillatory transient signal

Fig. 6: Hardware Results of different PQ disturbances on DSO

V. Conclusion

This study presents the hardware realization of the methodology based on modified s-transform for the analysis of various types of power quality disturbances. The use of modified s-transform provides an improved energy concentration of the s-transform. The introduction of additional parameter in the window facilitates the variation with frequency that modulates the kernel of s-transform efficiently with increase in frequency. However, due to huge complexity of the methodology it has not been possible for the real-time analysis on the desired hardware platform i.e ARM processor. The future scope of this work is to integrate the classification tools with the stockwell transform for the automatic classification of PQ disturbances and facilitating the development of PQ monitoring systems.

References

[1] J. Arrillaga and N. R. Watson, "Power system quality assessment," *John Wiley & Sons*, 2000.

[2] S. Santoso, E. Powers, and W. Grady, "Power quality disturbance data compression using wavelet transform methods," *IEEE Trans. Power Deliv.*, vol. 12, no. 2, pp. 1250–1257, 1997.

[3] A. Elmitwaly, S. Farhai, M. Kandil, S. Abdelkadar, and M. Elkateb, "Proposed wavelet neurofuzzy combined system for power quality violations detection and diagnosis,," *IEE Proc. Gener. Transm. Distrib.*, vol. 148, no. 1, pp. 15–20, 2001.

[4] M. J. B. Reddy and D. Mohanta, "A wavelet-neuro-fuzzy combined approach for digital relaying of transmission line faults," *Electr. Power Compon. Syst.*, vol. 35, no. 12, pp. 1385–1407, 2007.

[5] R. Mahanty and D. Gupta, "An improved method of digital relaying of transmission lines," *Electr. Power Compon. Syst.*, vol. 32, no. 10, pp. 1013–1042, 2004.

[6] S. K. Meher and A. K. Pradhan, "Fuzzy classifiers for power quality events analysis," *Electric Power Systems Research*, vol. 80, no. 1, pp. 71–76, 2010.

[7] P. Ray, N. Kishor, and S. Mohanty, "Islanding and power quality disturbance detection in grid-connected hybrid power system using wavelet and s-transform," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1082–1094, Sept. 2012.

[8] R. Stockwell, "S-transform analysis of gravity wave activity from a small scale network of airglow imagers," *Ph.D. thesis, Faculty of Graduate Studies, University of Western Ontario London ON*, 1999.

[9] R. Stockwell, L. Mansinha, and R. Lowe, "Localization of the complex spectrum: The s-transform," *IEEE Trans. Signal Process.*, vol. 44, no. 4, pp. 998–1001, Apr. 1996.

[10] R. Stockwell, L. Mansinha, R. Lowe, M. Eramian, and R. Schincariol, "Local s spectrum analysis of 1-d and 2-d data," *Phys. Earth Planet. Inter.*, vol. 103, no. 3, pp. 329–336, 1997.

[11] P. Dash, K. Panigrahi, and G. Panda, "Power quality analysis using s-transform," *IEEE Trans. Power Deliv.*, vol. 18, no. 2, pp. 406–411, Apr. 2003.

[12] R. Stockwell, "A basis for efficient representation of the s-transform," *Digital Signal Process.*, Vol. 17, no. 1, Jan. 2007, pp. 371-393.

[13] M. J. B. Reddy, D. Mohanta, and B. Karan, "Power system disturbance recognition using wavelet and s-transform techniques," *Int. J. Emerg. Electric Power Syst.*, vol. 1, no. 2, pp. 1–14, Nov. 2004.

[14] "Arm-based arrhythmia beat monitoring system," *Microprocessors and Microsystems (Elsevier)*, vol. 39, no. 7, pp. 504 – 511, 2015.

[15] S. Raj, K. C. Ray, and O. Shankar, "Cardiac arrhythmia beat classification using dost and pso tuned svm," Computer Methods and Programs in Biomedicine, vol. 136, pp. 163 – 177, 2016.

[16] C. J. G. McFadden P. D. and F. L. M., "Decomposition of gear vibration signals by the generalized s-transform, mechanical systems and signal processing",, vol. 13, no. 5, pp. 691–707, 1999.

[17] R. P. C. and L. Mansinha, "The s-transform with windows of arbitrary and varying shape", Geophysics, vol. 68, no. 1, pp. 381–385, Jan. 2003.