The Study of Voltage Sag Detection by Improved S-transform

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***Abstract*—Nowadays, Short Time Fourier Transform (STFT), Wavelet Transform (WT) and S-transform are applied for signal processing and power quality disturbance detection. But S-transform, Using localizing scalable Gaussian window called generalized S-transform, provides the best time-frequency resolution and is suitable for analysis and detection of power quality disturbance under noisy conditions. According to the operation of scalable window in S-transform, the mother wavelet function is suggested for improved S-transform as a scalable window. It is Important to specify the best mother wavelet function for accurate detection of power quality disturbance. In this paper, simulations have been performed to evaluate the effectiveness of five selective mother wavelet functions for detection of the voltage sag by the improved S-transform.**

Keywords- power quality; Voltage sag; S-transform(ST); time-frequency resolution.

I. INTRODUCTION

In recent years, recognition and detection of Power Quality Disturbance (PQD) has become a growing concern in the power quality studies. Due to the importance of detecting these disturbances in the power network, signal processing and filtering are done for achieving better representation of actual waveforms and filtering unnecessary parts such as noise. A signal can be expressed as a combination of the infinite series of sinus and cosine waveforms using Fourier Transform, but the major drawback of the Fourier expansion is that it has only frequency resolution and no time resolution [1].

To overcome this drawback, Short Time Fourier Transform (STFT) is utilized for detecting and characterizing the power quality disturbance in time-frequency domain [2]. STFT has the constraint of using fixed width window which causes limitations for concurrent analysis of high frequency and low frequency non-stationary signals [3].

Wavelet Transform (WT) represents both time and frequency information of the disturbances and is used as a useful method for presentation of time-frequency features for analyzing transient disturbances [4]. The major disadvantages of WT are complexity of the calculations, sensitivity to noise and dependence of its accuracy to the selected wavelet base function [5]. S-transform has proposed in [6,7] for time-frequency analysis of time series which is an improvement idea of WT and STFT with the superior characteristics to them. S-transform also has the limitation of using the fixed width window which decreases its capability [5]. The Generalized S-Transform (GST) is introduced in [4] in order to overcome this restriction and is used in [8] for power quality disturbance analysis. The method of GST avoids the restriction of S-transform by utilizing dilated and translated versions of Gaussian window [3].

As a proposal, the mother wavelet functions can be used instead of the scalable Gaussian window such that the best function can be identified for time-frequency signal processing and power quality disturbance identification.

In this paper, five mother wavelet functions including Shannon, Mexican Hat, Morlet, Haar and Gaussian are evaluated in order to overcome the restrictions of the S-transform. The best function is determined for time-frequency analysis of the voltage sag and simulation results verify the effectiveness of these functions.

II. S-TRANSFORM AND WINDOW FUNCTION

A. The Wavelet Transform and Mother Wavelet

Against the Fourier Transform (FT), The WT is very suitable for analyzing non-stationary signals and can represent proper time and frequency characteristics. Wavelet function is an oscillatory function with zero mean which rapidly decreases to zero and is the main component for the WT.

The most important section in the wavelet analysis is selection of proper wavelet function named mother wavelet. Translated and dilated version of mother wavelet is used for analyzing the signal by WT [9]. All the daughter wavelets are produced Using a basic mother wavelet $\psi(t)$. The continuous wavelet transform (CWT) is defined as:

$$CWT_h^{\psi}(\tau,s)=\frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty}h(t)\ \psi^*\left(\frac{t-\tau}{s}\right)dt \qquad (1)$$

Where s and τ, are scale and translation factors, respectively. The $s^{-1/2}$ factor is used in order to normalize the energy between different scales. The discrete wavelet

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transform (DWT) can be written by using s and τ as follows in order to implement CWT on digital systems [10].

$$s = a_0^j \ , \ \tau = k a_0^j b_0 \tag{2}$$

Where j and k are discrete scale and shift parameters, respectively, with conditions of $a_0>1$, $b_0\neq 0$. Assuming $a_0=2$ and $b_0=1$, the CWT formula can be written as:

$$DWT_h^{\psi}(j,k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{+\infty} h(t)\ \psi^*\left(2^j t - k\right) dt \tag{3}$$

Different resolutions are achieved by using different wavelet basic functions with different characteristics. There is a considerable issue about selection of the mother wavelet function which generates the best resolution for detection of the voltage sag events.

B. *The S-transform*

S-transform is proposed as an extension of WT or STFT with the characteristics of superior to WT and STFT [11]. Since, WT has the disadvantages of dependence on the base function, complexity of the calculations, and sensitivity to the environment noise, S-transform can be used to overcome these disadvantages. S-transform provides a frequency dependent resolution which is in direct relationship with the Fourier spectrum. Because of the fixed time-frequency window of S-transform, the method of generalized S-transform is proposed based on the localizing scalable Gaussian window [12]. But, there is another choice instead of using Gaussian window such as mother wavelet function. The selected mother wavelet function is used as scalable window in the improved S-transform and then all the windows are the translated and dilated versions of the main mother wavelet function. The S-transform of a time series h(t) is defined as:

$$S(\tau, f) = \int_{-\infty}^{+\infty} h(t)\ w(\tau - t, f)\ e^{-i2\pi f t} dt \tag{4}$$

Where t and τ are time and f is the frequency parameters. In fact, the S-transform definition is equivalent to the Fourier transform formula of product of signal and mother wavelet window as follows:

$$S(\tau, f) = FT\{h(t) w(\tau - t, f)\} \tag{5}$$

As a result, we have a matrix of Fourier transform of the signal multiplied to the dilated and translated versions of mother wavelet function window, and this matrix represents the improved S-transform coefficients. In each row, we have a set of vectors, anyone related to an specific amount of dilation and translation, so that each element in each vector corresponds to an specific frequency value.

In this paper, the S-transform with mother wavelet window is used in order to detect the voltage sag events and five mother wavelet functions, Shannon, Mexican Hat, Morlet, Haar and Gaussian, are evaluated according to the Figures 1 to 3.

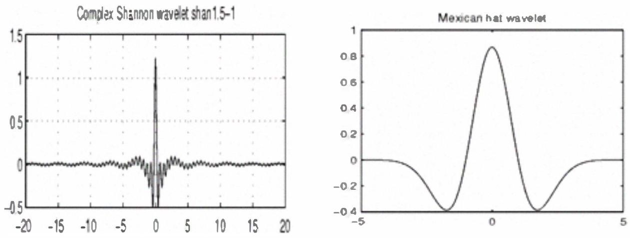


Figure 1. Shannon and Mexican Hat wavelet functions

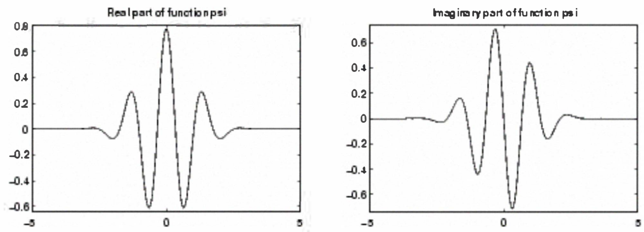


Figure 2. Gaussian wavelet functions (Real & Imaginary)

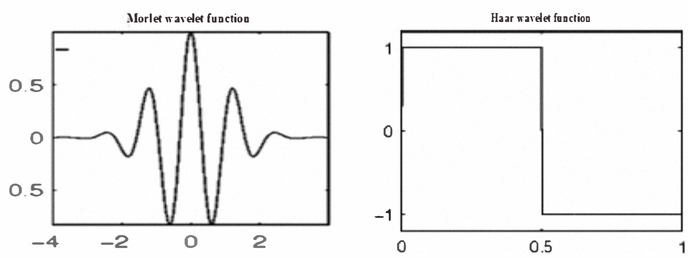


Figure 3. Morlet and Haar wavelet functions

III. ANALYSIS AND DISCUSSION OF VOLTAGE SAG EVENT

A. *Signals for Simulation*

In this paper, voltage sag disturbance detection is studied in the improved S-transform analysis, which is as follows:

- Sinusoidal

$$y(t) = \sin \omega_0 t \tag{6}$$

- Voltage sag

$$y(t) = \{1 - a[u(t - t_1) - u(t - t_2)]\} \times \{\sin \omega_0 t + [u(t - t_3) - u(t - t_4)]\} \tag{7}$$

These signals are simulated using MATLAB 7.10 with 1KHz sampling frequency .

B. *Analysis and Disscussion*

Two kinds of analysis have been performed to study the application of the improved S-Transform for detection of the voltage sag events. The first analysis provides visual inspection of the improved S-Transform contour plots and the second analysis provides the features described according to the Table I. These features consist of the standard mathematical indices such as maximum values, minimum values, standard deviation values and mean values of the improved S-transform coefficients [13].

TABLE I. FEACHURES SELECTED FOR DETECTION OF VOLTAGE SAG

Features	Description
F1	Maximum value of the S-transform coefficient
F2	Minimum value of the S-transform coefficient
F3	Mean value of the S-transform coefficient
F4	Standard deviation of the S-transform coefficient

Figure 4 depicts the results of the first analysis.

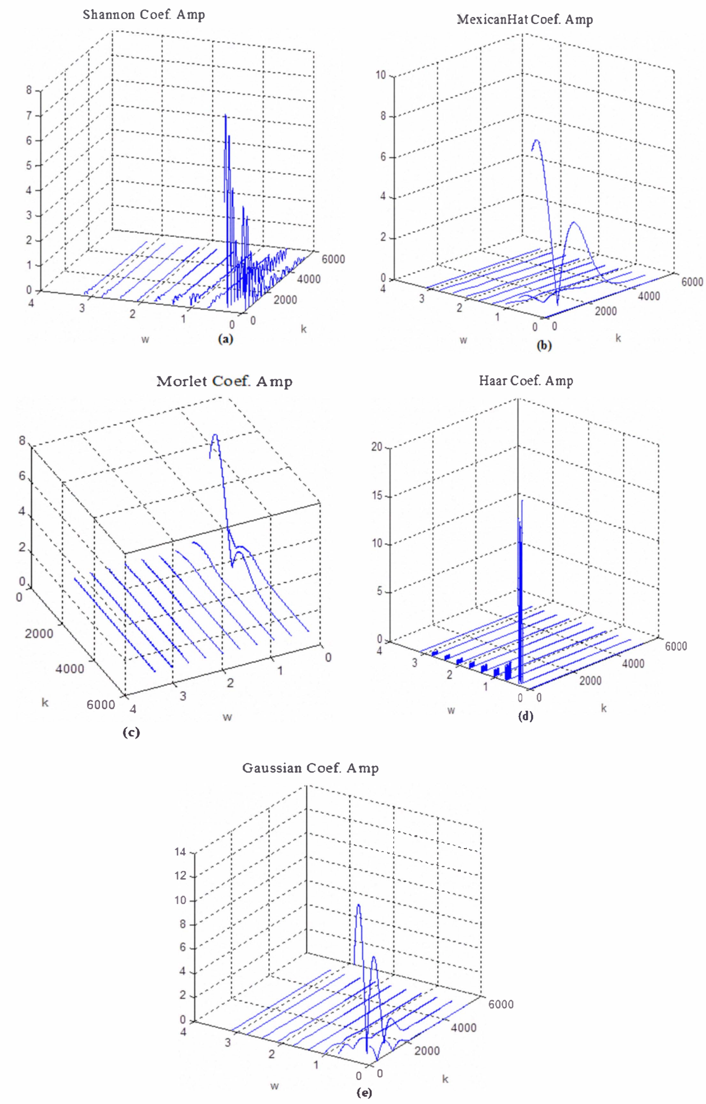
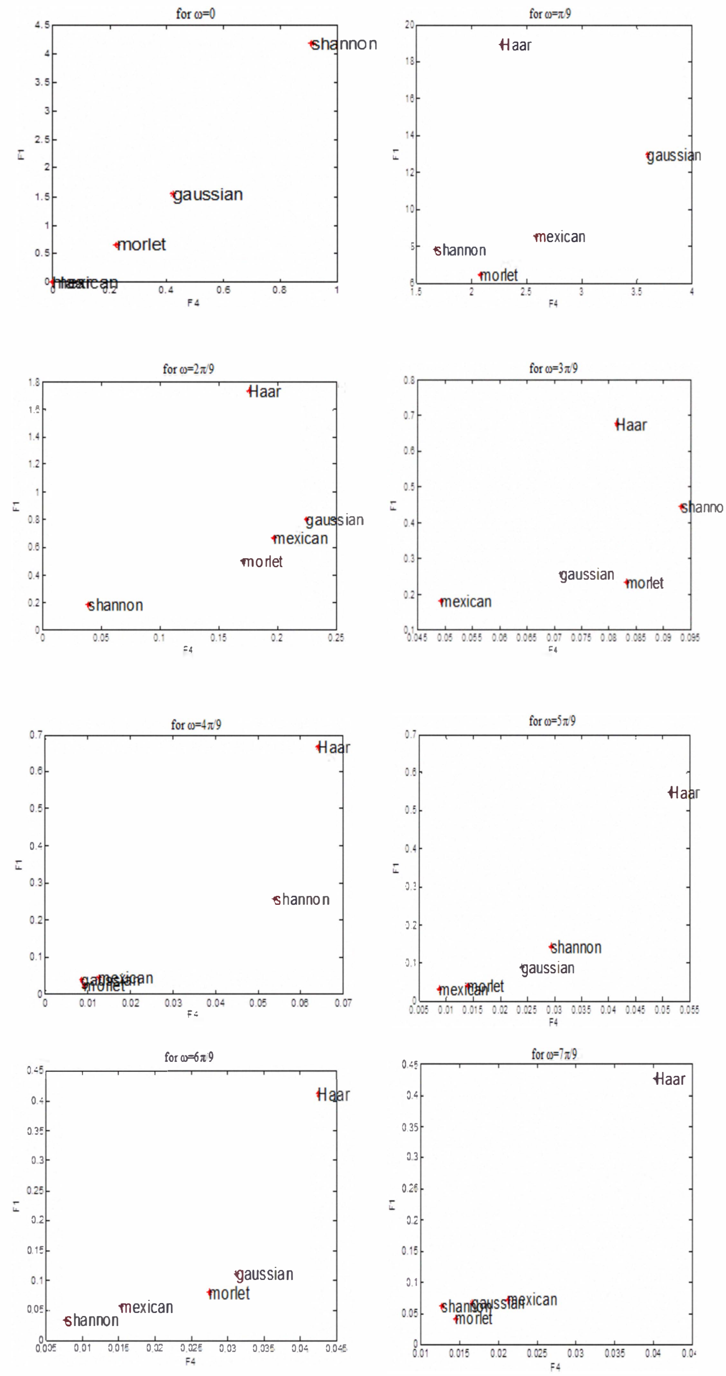


Figure 4. 3-dimensional S-transform coefficients representation for (a) Shannon basic function (b) Mexican Hat basic function (c) Morlet basic function (d) Haar basic function (e) Gaussian basic function

the results show that all the selective mother wavelet functions used as scalable windows in the improved S-transform are capable of detecting the voltage sag events.

The second analysis has been performed based on the extracted features according to the Table I. The Fourier series coefficients of different translated versions of the signal multiplied by the mother wavelet function used as a scalable window in the first scale have been calculated in order to obtain the maximum values, mean values, and standard deviation values. This analysis evaluates and compares the individual performance of the five mother wavelet functions used as scalable windows in the improved S-transform for detection of voltage sag.

In order to realize the individual performance of the five selective mother wavelet functions used as scalable windows in the improved S-transform, the diagram of F1 versus F4 is shown in Figure 5 for all of the mother wavelet functions at different frequencies in the range of $[0,\pi]$ (rad/s) and the frequency step is $\pi/9$.



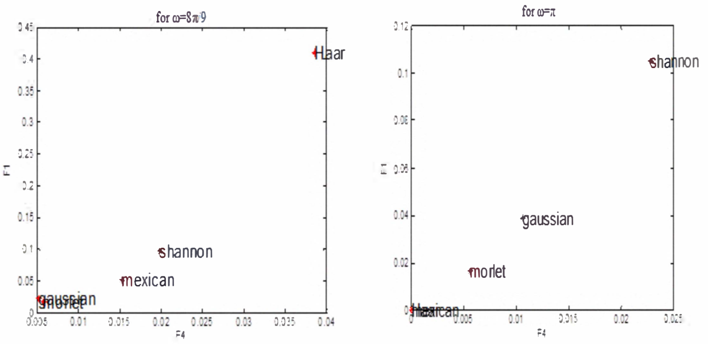


Figure 5. Diagram of F1 versus F4
for all of the mother wavelet functions at different frequencies in the range of [0,π]

According to the figures depicted above, the best wavelet mother function used as a scalable window in the improved S-transform is chosen by the biggest value of F1, by considering the variation of F4 in interval of [0,1]. Table II shows the results of wavelet mother functions ranking at different frequencies.

TABLE II. RANKING OF WAVELET MOTHER FUNCTIONS IN PROVIDING BIGGER AMPLITUDE FOR IMPROVED S-TRANSFORM COEFFICIENTS

Freq.	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
0	Shannon	Gaussian	Morlet	Haar&Mexican	Haar&Mexican
π/9	Haar	Gaussian	Mexican	Shannon	Morlet
2π/9	Haar	Gaussian	Mexican	Morlet	Shannon
3π/9	Haar	Shannon	Gaussian	Morlet	Mexican
4π/9	Haar	Shannon	Mexican	Gaussian	Morlet
5π/9	Haar	Shannon	Gaussian	Morlet	Mexican
6π/9	Haar	Gaussian	Morlet	Mexican	Shannon
7π/9	Haar	Mexican	Gaussian	Shannon	Morlet
8π/9	Haar	Shannon	Mexican	Gaussian	Morlet
π	Shannon	Gaussian	Morlet	Haar&Mexican	Haar&Mexican

The results show that the Haar wavelet is the best indicator of the voltage sag event, generating bigger amplitudes for improved S-transform coefficients. The Shannon, Gaussian, Mexican Hat, and Morlet wavelets are in the next places for their capability in the voltage sag detection, respectively.

IV. CONCLUSION

In this paper, the performance of the improved S-transform in detection of voltage sag has been presented. According to the performed studies, the selection of the mother wavelet functions provides variable width windows and is important in detection of the voltage sag. The improved S-transform with mother wavelet functions used as scalable windows gives acceptable resolutions of the contours and high coefficients magnitudes during the voltage sag events.

It can be seen in the second analysis, multiplying the complex part, $e^{j\omega t}$, by the wavelet mother functions, plays an important role in increasing the amplitude of the coefficients in different dilations, translations, and frequencies. specially, in ω=π/9, the amplitude of the coefficients are so higher than the traditional wavelet transform (ω=0). This means that in this frequency the signal and wavelet mother function have an excellent correlation, compared to other frequency ranges, especially at ω=0 which represents the traditional wavelet transform.

Based on the features extracted from the improved S-transform, the Haar Wavelet function provides the highest level of accuracy in detection of the voltage sag events.

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