Classification of Power Quality Events using Improved S-Transform

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Abstract**—The increased usage of sensitive equipment by customers led to the importance of the term Power Quality. Classification of power quality events plays an important role to have an effective mitigation. This paper represents a new approach for classification of Power Quality events using S-transform. S-transform is an improved version of wavelet transform that includes phase information as well. S-transform is used for classification of various power quality events like voltage sag, voltage swell, momentary interruption, harmonics which are simulated in MATLAB in accordance with IEEE Std. 1159. The effectiveness of the algorithm is used to identify multiple events. Phase information is also verified for various simulation cases.**

Keywords—Power Quality events, S-transform, voltage sag, swell;multiple events, phase information

I. Introduction

In recent years, there has been an increased emphasis on the quality of power that has been delivered due to the deregulation in power industry and proliferation of sensitive power electronic equipment. These non-linear loads are the major causers and also the major victims of power quality (PQ) problems. A PQ problem involves a disturbance in the voltage, current or frequency of the power signal.

In order to mitigate a PQ problem its detection and analysis plays a vital role. Most distinguished information is present in the frequency domain representation of a signal. Hence various signal processing techniques are widely used to detect the PQ events. The first tool in signal processing techniques is Fast Fourier transforms (FFT) which is the representation of amplitudes associated with various frequencies in the original waveform. Though FFT has a faster computation time, its resolution dependency on window length is a major disadvantage as indicated in [1]. Multi Resolution Analysis (MRA) techniques which resolves signal into non uniform bands have been developed to have an accurate analysis. The Wavelet Transform (WT) and Discrete wavelet Transform (DWT) which uses MRA technique is used to detect various PQ events as illustrated in [2]-[5]. WT provides a local representation of the signal by dilating and translating the mother wavelet. As indicated in [6] the DWT cannot be used to analyze the signal accurately due to the spectral leakage. The choice of mother wavelet and levels of decomposition is the major disadvantage by using WT.

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S-transform (ST) [7]-[8], an extension to wavelet transform utilizes a moving and scalable localizing Gaussian window.ST is superior to other transforms as it includes phase information of the signal as well. ST is used for identifying local spectral characteristics with the help of amplitude-frequency-time spectrum and phase-frequency-time spectrum.

II. S Transform

A. Continuous S Transform

S-transform (ST) is the phase corrected Wavelet Transform (WT). The Continuous Wavelet Transform (CWT), *W (τ , d)* of a signal *h (t)* is defined as

$$W(\tau,d) = \int_{-\infty}^{+\infty} h(t)w(t-\tau,d)dt \qquad (1)$$

w (t, d) represents the mother wavelet with dilation factor *d* that determines the width of the window and τ being the translation factor. The ST is defined as the CWT multiplied with a phase factor and is given as

$$S(\tau,f) = exp(i2\Pi f\tau).W(\tau,d) \qquad (2)$$

The mother wavelet *w (t, f)* is defined as

$$w(t,f) = \left(\frac{|f|}{\sqrt{2\pi}}\right).exp\left(\frac{-t^2f^2}{2}\right).exp(-i2\pi ft) \qquad (3)$$

Hence, from (2) ST can be given as

$$S(\tau,f) = \int_{-\infty}^{\infty} h(t).\left(\frac{|f|}{\sqrt{2\pi}}\right).exp\left(\frac{-(\tau-t)^2f^2}{2}\right).exp(-i2\pi ft)\,dt \qquad (4)$$

ST of a signal h (t) can also be obtained from Fourier spectrum H (f) of the signal as

$$S(\tau,f) = \int_{-\infty}^{\infty} \mathrm{H}(\alpha+\mathrm{f}).exp\left(\frac{-2\Pi^2\alpha^2}{\mathrm{f}^2}\right).exp(-i2\alpha ft)\,d\alpha \qquad (5)$$

B. *Discrete S Transform*

The continuous power signal can be expressed in discrete form as h (kT), k=0, 1, 2,..., N-1 where N indicates the number of samples and T is the sampling time. The Discrete Fourier Transform (DFT) of h(kT) is given as

$$H\left[\frac{n}{NT}\right] = \frac{1}{N}\sum_{k=1}^{N-1} h(kT).exp\left(\frac{-i2\Pi k}{N}\right) \quad (6)$$

where n=0, 1,2,….,N-1.

From (5), ST of a discrete signal can be obtained by considering f→$\frac{n}{NT}$ and τ→jT as

$$S\left[jT,\frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right].G(m,n).exp\left(\frac{-i2\Pi mj}{N}\right) \quad (7)$$

where $(m,n) = exp(-2\Pi^2 m^2/n^2)$, n≠0 and j,m =0,1,….,N-1for all n=1,2,…,N-1.For n=0

$$S[jT,0] = \frac{1}{N}\sum_{m=0}^{N-1} h\left(\frac{m}{NT}\right) \quad (8)$$

The ST is a complex matrix from which amplitude and phase can be obtained as $\left|S\left[jT,\frac{n}{NT}\right]\right|$ and $angle\left(S\left[jT,\frac{n}{NT}\right]\right)$.

C. *Implementation*

The discrete S Transform of a signal can be obtained using the following steps.

i) Compute FFT of signal h (k) using FFT software routine.
ii) Compute S [jT, 0] as per the equation (8).
iii) Calculate w=$\sum_m \frac{2*pi*m}{n}$ for all n=1 to ns/2, m=1 to N, Where ns represents sampling frequency.
iv) Calculate G=$e^{-\frac{w^2}{2}}$ for all n=1 to ns/2.
v) Shift spectrum H[m] to H [m+n], where m=1 to N and n=1 to ns/2.
vi) Compute inverse Fourier transform of the product of H [m+n] and G to obtain S-transform matrix.

The ST matrix is a complex 2-D matrix with columns indicating the time and rows indicating the frequencies. Each column represents the harmonic order amplitudes and phases present at that time and each row represents the frequency components at various sampling instances.

III. VALIDATION OF S-TRANSFORM

This section shows the validation of ST for various PQ events such as sag, swell, harmonics and momentary interruption. The PQ events are simulated in MATLAB environment according to the IEEE Std.1159.

A. *Voltage Sag*

Voltage Sag occurs during a fault or switching heavy load. During the sag condition the voltage drops by 10 to 90 percent of the rated voltage. Fig.1 shows sag of 20 percent in a voltage signal and its ST amplitude-time contour. The amplitude-time contour obtained from ST analysis accurately detects the voltage sag at 0.4 sec.

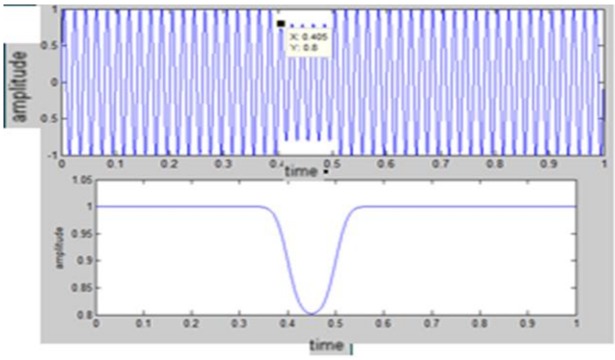


Fig. 1. ST analysis of a voltage Sag

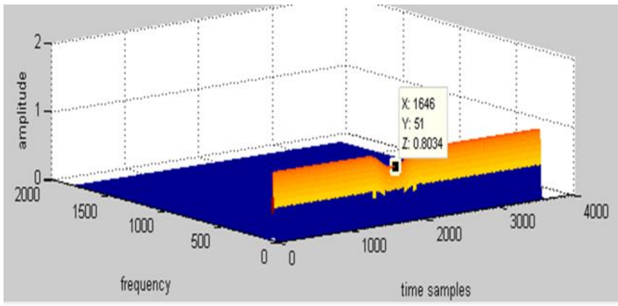


Fig. 2. Amplitude-Time-Frequency plot using ST analysis of a voltage Sag

B. *Voltage Swell*

Voltage Swell indicates an increase in voltage by 10 to 90 percent of the rated voltage.Fig.3 shows a swell of 20 percent in a voltage signal and its ST amplitude-time contour. The amplitude-time-frequency contour is represented in Fig.4. From Fig.3. and Fig.4. it is evident that the event voltage swell is accurately detected using ST based analysis.

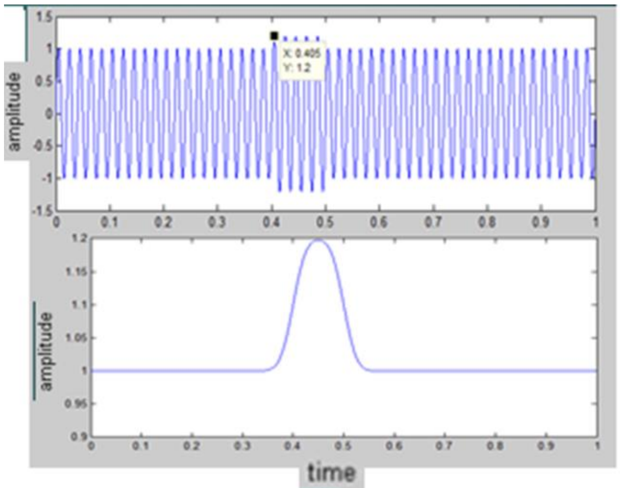


Fig. 3. ST analysis of a voltage Swell

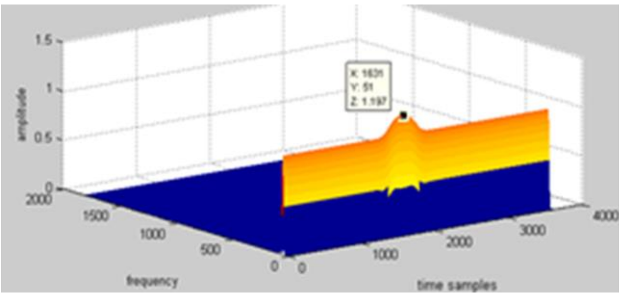


Fig. 4. Amplitude-Time-Frequency plot using ST analysis of a voltage Swell

C. *Momentary Interruption*

A momentary interruption indicates a disturbance that drops the voltage by 90 to 100 percent of the rated voltage that last for 0.5 cycle to 1 minute. Fig.5 indicates an interruption in a voltage signal at 0.4 sec for a duration of 0.1 sec. Fig.6 represents the frequency contour which indicates momentary interruption at the time sample corresponding to 0.4 sec.

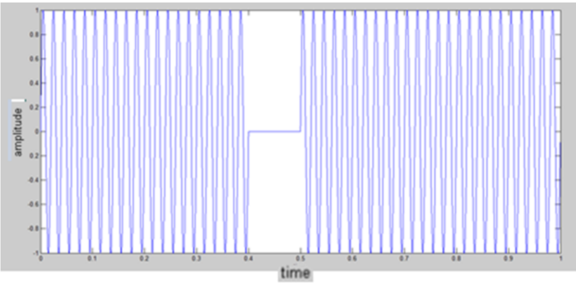


Fig. 5. Momentary Interruption

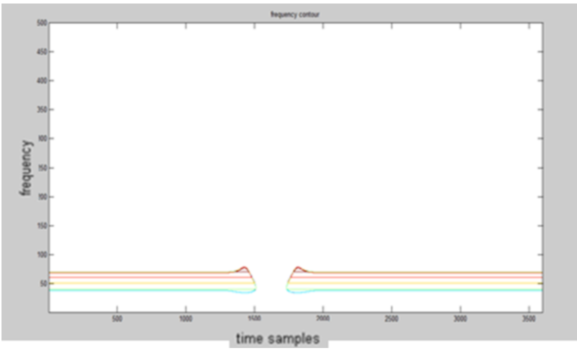


Fig. 6. Frequency Contour

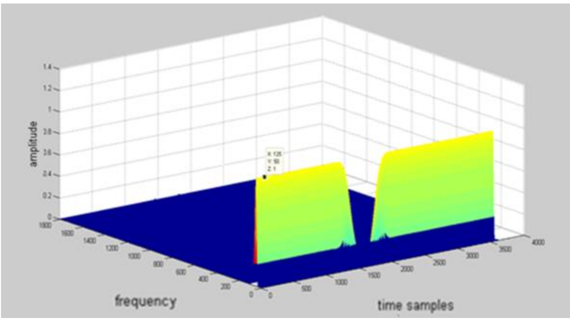


Fig. 7. Amplitude-Time-Frequency plot using ST analysis of a voltage interruption

D. *Harmonics*

The presence of frequency components that are multiples of a fundamental frequency is termed as harmonics which are evident due to the presence of non-linear loads in the system. A signal with fundamental, 50Hz and 0.3pu of 3rd harmonic, 150Hz is simulated as shown in Fig.8. The frequency contour is indicated in Fig. 9. which represents the presence of 50 Hz and 150 Hz.

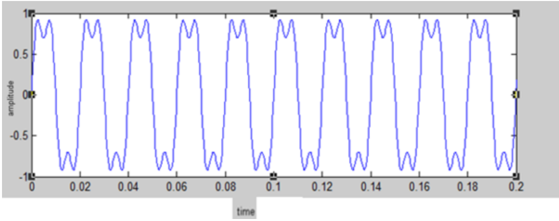


Fig. 8. Voltage Signal with fundamental and third harmonic component

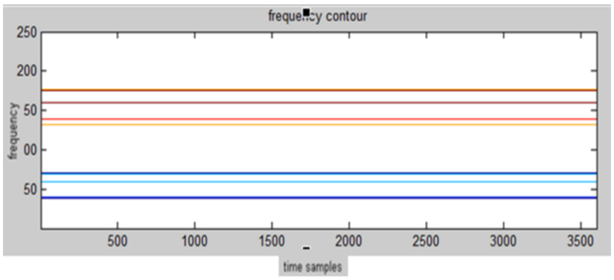


Fig. 9. Frequency Contour

E. *Multiple Events*

In the present case the effectiveness of ST is determined for multiple events. Fig.10 indicates a voltage signal with fundamental and third harmonic components with swell and sag at 0.4sec,0.8 sec respectively. Fig. 11 reresents the amplitude-time-frequency contour.

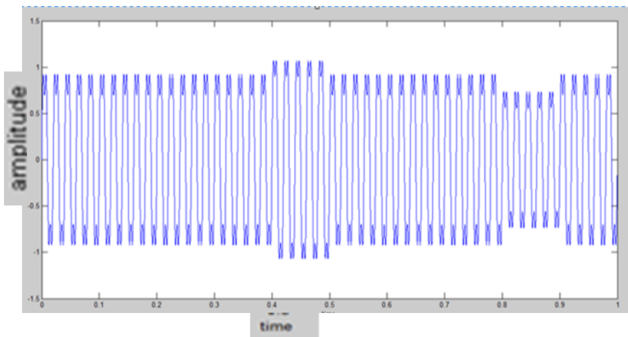
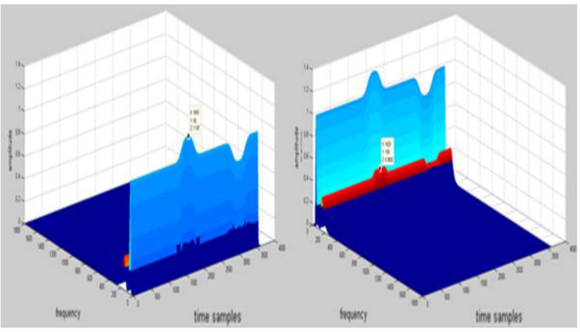


Fig. 10. Voltage Signal with swell and sag in the presence of fundamental and third harmonic component

Fig.11(a) indicates the front view of amplitude-time-frequency contour indicating the presence of 50 Hz component for the entire duration and Fig.11(b) indicates the back view of amplitude-time-frequency contour indicating the presence of 150 Hz for the entire duration.



(a) (b)

Fig. 11. Amplitude-Time-Frequency plot using ST analysis for multiple events (a) Front View (b) Back View

F. Phase Information

The significant feature of ST is that it includes phase information as well. A voltage signal with fundamental and third harmonic component is simulated with variation in phase of the components in each case and the effectiveness of the ST has been studied. Table I gives the validation of ST for phase information.

TABLE I. VALIDATION OF ST FOR PHASE INFORMATION

Case	Frequency Components (Hz)	Actual Phase Difference (deg)	Simulated Phase Difference (deg)
1	50	0	0.0000
	150		
2	50	30	30.0246
	150		
3	50	60	60.0148
	150		
4	50	-30	-29.9744
	150		
5	50	-60	-59.9852
	150		

IV. CONCLUSION

The S-transform is an effective tool in classifying various PQ events. It has a very good time and frequency resolution. The PQ events such as voltage sag, swell, momentary interruption, harmonics which are simulated are accurately identified using S-transform. The major feature of S-transform includes the identification of multiple events as well. S-transform accurately determines the phase information for the simulated cases. The amplitude-time-frequency plot indicates local spectrum as well as global spectrum.

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