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CASE STUDY

Detection of Power Quality Disturbances using Phase Corrected Wavelet Transform

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Abstract Wavelet transform is very widely used for power quality analysis to detect voltage events. Although wavelet transform is an excellent tool to detect and localize the power quality disturbance events, it fails to classify them. This paper shows that phase correction to wavelet transform improves the performance of wavelet transform in identifying the power quality disturbances such as voltage sag, interruption, swell and harmonics. Phase corrected wavelet transform, commonly referred to as S-transform, has excellent time–frequency resolution characteristics and has the ability to detect the disturbance correctly even under noisy condition. This tool is applied on various voltage disturbances, generated as per IEEE Std. 1159 using MATLAB and the analysis can identify the magnitude and duration of the disturbances. The effectiveness of the S-transform is shown for multiple sag/swell condition in the presence of transients or noise. Wavelet transform is also used for analysis and results are compared with S-transform performance. Simulation results are also shown to identify both the harmonic magnitudes and phase angles using S-transform analysis. Experimental verification has been performed with transmission line model connected to linear and non-linear loads and S-transform is used to detect and classify various voltage disturbances.

Keywords S-transform · Wavelet transform · Voltage harmonics · Sag · Swell · Power quality

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Introduction

The distribution system consists of voltage sensitive critical loads which are non-linear in nature, due to the application of fast acting semiconductor switches and their specific control strategy. These non-linear loads introduce current harmonics and voltage disturbances in the utility, which affect the performance of other non-linear and linear loads at the point of common coupling. Failure of sensitive electronic loads such as data processing, process control and telecommunications equipment connected to the system has become a great concern [1, 2]. One of the important issues in power quality (PQ) problems is to detect and classify disturbance waveforms automatically in an efficient manner. To detect, solve and mitigate the PQ problem, many utilities perform PQ monitoring for their industrial and key customers.

A number of research works have been developed to classify disturbances on the electrical system using wavelet [3, 4], neural network [5, 6] and other techniques [7, 8]. Wavelet transform (WT) has the capability of extracting information from the signal in both time and frequency domain simultaneously and has been applied in the detection and classification of power quality disturbances. But it exhibits some disadvantages that it is sensitive to noise. Also, proper selection of mother wavelet and the level of decomposition are to be chosen based on the disturbance. These limitations can be overcome by applying phase correction to the mother wavelet.

The phase corrected wavelet transform (PWT) commonly referred to as S-transform (ST) is an extension of WT. A key feature of the ST is that it uniquely combines a frequency dependent resolution of the time–frequency space and absolutely referenced local phase information [9]. PWT has the ability to detect the disturbance correctly in the presence of noise. PWT analysis of time varying signal yields all of the quantifiable parameters for localization, detection and quantification of the signal. Research is being done on PQ disturbance classification using ST [9–11].

Power quality disturbances can be classified as events and variations. In this paper, PWT or ST is used to detect the most frequently occurring power quality events such as voltage sag, interruption and swell, and power quality variations such as voltage harmonics. Simulation analysis has been performed using MATLAB programming for the above mentioned voltage disturbances generated as per IEEE Std. 1159 [1]. ST analysis performed on these disturbance signals can easily identify the magnitude and duration of the disturbance. The effectiveness of the ST is shown for multiple sag/swell condition in the presence of transients or noise. WT analysis is also performed for all the cases and comparative study is presented. ST analysis results in a complex valued matrix from which the amplitude and phase information of harmonics are obtained. Performing ST analysis on the harmonic voltage waveforms, it is verified that the harmonic frequency components of the voltage are correctly extracted. Verification of the ST capability in identifying the voltage sag, swell and interruption is performed with practical voltage waveforms obtained from a transmission line model of 750 km length connected to different loads.

Phase Corrected Wavelet Transform

The continuous wavelet transform (CWT) of time varying function $h(t)$ is defined as (1)

$$W(d,\tau) = \int_{-\infty}^{\infty} h(t)w(d,t-\tau)\mathrm{d}t \tag{1}$$

The scale parameter d determines the width of the wavelet $W(d,\tau)$ and, thus controls the resolution. The phase corrected wavelet transform or S-transform can be seen as the 'phase correction' of CWT.

$$S(\tau,f) = e^{-j2\pi ft}W(d,\tau) \tag{2}$$

$W(d,\tau)$ in (2) is the CWT of $h(t)$ as in (1) but with a specific mother wavelet defined as

$$w(f,t) = \frac{|f|}{\sqrt{2\pi}}e^{-\frac{t^2f^2}{2}}e^{-j2\pi ft} \tag{3}$$

The scale parameter d is the inverse of the frequency f. Now substituting (1) and (3) in (2) gives the PWT or ST of $h(t)$ as

$$S(\tau,f) = \int_{-\infty}^{\infty} h(t)\frac{|f|}{\sqrt{2\pi}}e^{-\frac{(\tau-t)^2f^2}{2}}e^{-j2\pi ft}\mathrm{d}t \tag{4}$$

The power system disturbance signal $h(t)$ can be expressed in a discrete form as $h(kT)$ $k = 0,1, \ldots, N$, where T is the sampling time interval and N is the total sampling number. The discrete Fourier Transform of $h(kT)$ is obtained as

$$H\left[\frac{n}{NT}\right] = \frac{1}{N}\sum_{k=0}^{N-1} h(kT)e^{\left(-\frac{2\pi kn}{N}\right)} \tag{5}$$

where $n = 0,1,\ldots, N-1$.

Using (4), the ST of a discrete time series is given by (letting $\tau \rightarrow kT$ and $f \rightarrow n/NT$)

$$S\left[kT,\frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right]e^{-\frac{2\pi^2m^2}{n^2}}e^{-\frac{j2\pi mk}{N}}, n \neq 0 \tag{6}$$

where $k,m = 0,1,\ldots, N-1$ and $n = 0,1,\ldots, N-1$. For $n = 0$

$$S[kT,0] = \frac{1}{N}\sum_{m=0}^{N-1} H\left[\frac{m}{NT}\right] \tag{7}$$

Equation (7) gives the constant average of the time series into zero frequency voice, so that the averaging of the amplitude of the S-matrix over the time results in Fourier spectrum. The discrete ST can be computed quickly by taking advantage of the efficiency of the FFT and the convolution theorem. The PWT localizes the phase spectrum as well as the amplitude spectrum. PWT analysis results in a complex valued matrix. Each row of the matrix gives the frequency components of the signal analyzed at various sampling times. Each column represents the harmonic magnitude and phase of the disturbance signal at a given time or sample.

Characterization of Sag and Swell

Here, the ST and WT analysis of PQ signals such as voltage sag, swell and interruption are shown. These signals are analyzed with and without the presence of noise in the signal. The power quality signals are generated using MATLAB code, as per IEEE Std. 1159, for various percentages of sag, swell and interruption. Figure 1a shows the signal with consecutive voltage sag and swell present in the signal. This signal is simulated with various sag/swell magnitudes for 4 cycles of duration each. Here, the sampling frequency is 3.2 kHz. The disturbances introduced at different intervals are as below:

t1 to t2—30 % sag
t3 to t4—60 % sag
t5 to t6—30 % swell
t7 to t8—60 % swell

ST of the signal in Fig. 1a results in a ST-complex matrix (STC matrix) from which the magnitude of the

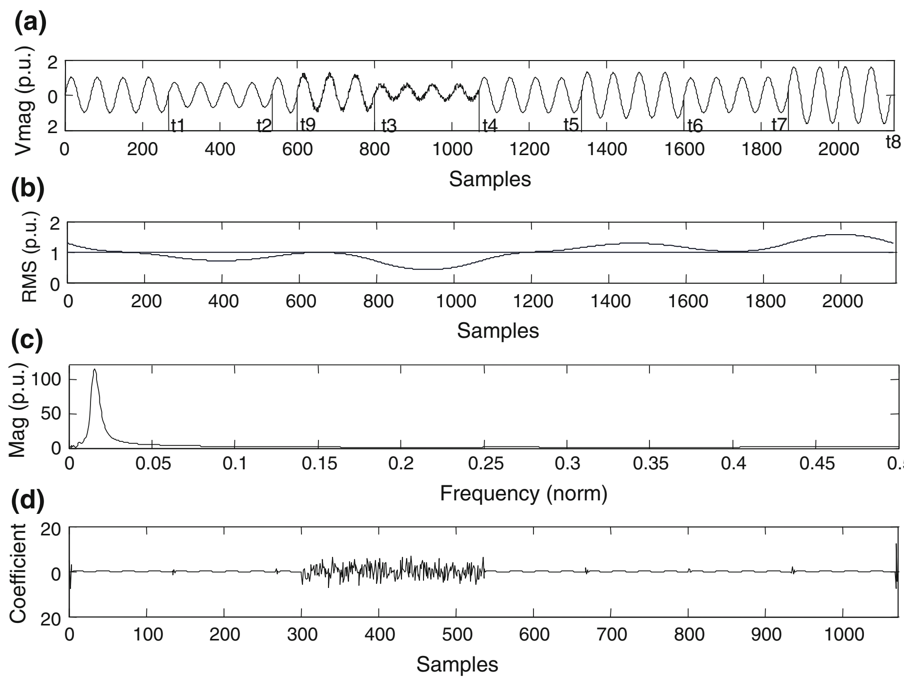

Fig. 1 ST and WT analysis of consecutive voltage sag and swell with noise

signal is extracted. Figure 1b shows the plot of rms value (in per unit) of the signal versus samples. The rms values are obtained from STC matrix by identifying the maximum amplitudes of the signal at every sample using (8).

$$\left| S\left[kT, \frac{n}{NT}\right] \right| \tag{8}$$

The peak values in the rms plot indicate the magnitude of voltage during disturbance. Figure 1c is the curve of normalized frequency versus the magnitude of the frequency components. Normalized frequency (f_n) is given by (9)

$$f_n = n\frac{f_0}{f_s}, \quad n = 1, 2, 3, \ldots \tag{9}$$

where f_0 is the fundamental frequency (50 Hz) and f_s, the Sampling frequency (3.2 kHz). Hence, the peak for fundamental frequency occurs at $f_n = 0.015$.

Figure 1d shows the level 1 detailed coefficient at every sample obtained by performing WT using db6 wavelet. The spikes occur at the instants of sudden deviation/change in the signal magnitude. The magnitude of the coefficients gives the magnitude of change in the signal. Noise is introduced in the signal of Fig. 1a for about seven cycles from t9 to t4. Figure 1b, c show the effectiveness of the ST in identifying the disturbances. Figure 1d shows that WT coefficients are very high for the duration t9 to t4 when the signal contains noise or transients. WT coefficients cannot differentiate the instants of start and end of sag/swell in the signal and the noise present in the signal. Hence, ST is having edge over the WT in detecting a disturbance under noisy condition. It has ability to detect the occurrence of disturbance correctly in the presence of noise.

Figure 2 shows the RMS plots for different levels of sag, swell and interruption calculated from the STC matrix for each case. ST gives directly the rms value of the signal at each sample or time. Thus by comparing with the reference RMS value, the disturbances such as sag, swell and interruption are easily identified. RMS plots in Fig. 2 are also used to characterize the voltage events by evaluating magnitude and duration of sag/swell. But when WT is used, analysis has to be performed at more than one level using multi-resolution analysis and suitable techniques [3, 4] are to be applied. Also, the accuracy of WT analysis is dependent on the choice of mother wavelet.

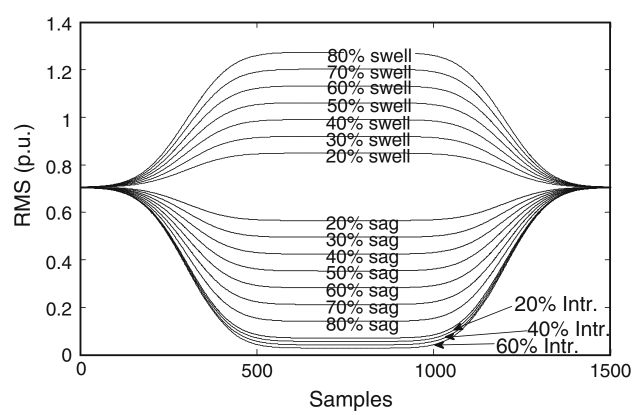

Fig. 2 RMS plots obtained from phase corrected wavelet transform for different levels of sag, swell and interruptions

Extraction of Harmonics

Harmonics analysis of the distorted voltage signal is performed using ST analysis. Voltages signal considered for analysis is generated using MATLAB code containing predefined value of harmonic signal combined with the fundamental value. The sampling frequency is 2 kHz. ST analysis can extract the information of these harmonics along with magnitude and phase angle. Figure 3a consists of 1 pu of fundamental signal with (1/3) pu of third harmonic with a phase difference of 50°. S-transform analysis of Fig. 3a is performed and RMS plot shown in Fig. 3b is obtained for fundamental component. Figure 3c is the normalized frequency curve obtained from STC matrix and shows that the peak values occur at dominant frequencies. The X and Y values here indicate the normalized frequency and rms value (in pu) respectively at the dominant frequencies.

The phase angles of all the frequency contents at a particular time can be obtained from STC matrix. Figure 3d shows the curves of normalized frequency versus phase angle calculated from STC matrix at all rows of a column using (10). Hence ST has the feature of extracting phase information of the signal harmonics.

$$\tan^{-1}\left\{\frac{\mathrm{Imag}S\left[jT,\frac{n}{NT}\right]}{\mathrm{Real}S\left[jT,\frac{n}{NT}\right]}\right\} \tag{10}$$

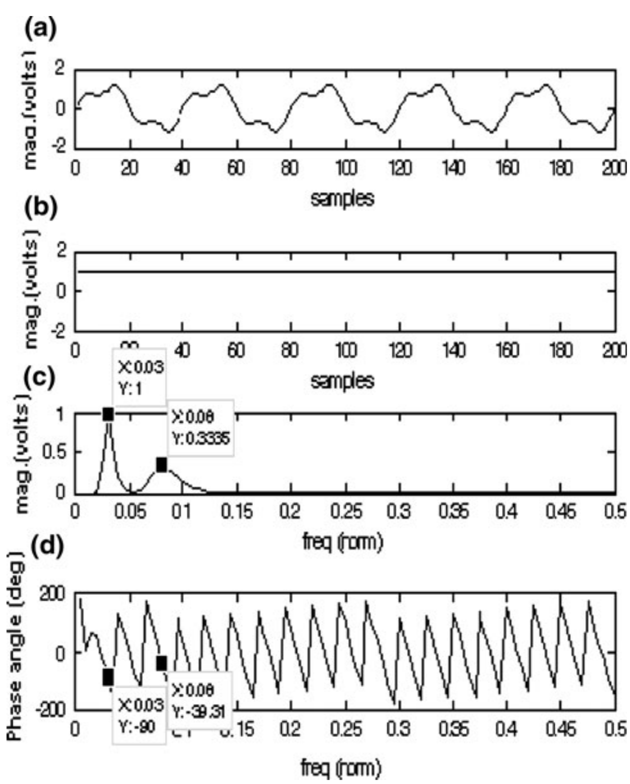

Fig. 3 Voltage with fundamental and 3rd harmonic with phase shift

The X and Y in Fig. 3d indicate the normalized frequency and phase angles, respectively at the frequencies corresponding to the peak value frequencies of Fig. 3c. Table 1 shows the simulation results of the different cases for which ST was used to extract the information of harmonics. From Table 1, it is clear that the harmonics (magnitude and phase) present in the simulated signal and the harmonics detected from ST exactly match. Hence, using STC matrix the details of the harmonics present in the signal can be correctly extracted.

Experimental Analysis of Power Quality Event Detection

Earlier, it is shown that ST could identify the disturbance correctly in the presence of noise and also that ST could identify the harmonics. Hence, ST is best suitable for PQ event identification in real time applications. Here, STC matrix construction is performed for the load voltage of 750 km transmission line model. The block diagram of the prototype is shown in Fig. 4a. The system consists of transmission line model with 12 pi-sections, with each section having L = 11.63 mH and C = 1.54 μF as line constants. A variable three phase supply voltage (0 V–400 V, 50 Hz) is used. The receiving end of the transmission line is connected to four resistive loads of rating 2.5 kW, 10 A and a controlled rectifier as nonlinear load. Experimentation is performed for different percentages of voltage sag and swell by varying load and supply voltage.

Interruption in the voltage is introduced by opening the mains switch (CB1). The analog voltage signal is stored in a Tektronix make TDS 3032B, 300 MHz digital oscilloscope. The load voltage waveform for R-phase stored in oscilloscope for sag is shown in Fig. 4b. The sampling frequency of the oscilloscope is 25 kHz with 500 samples per cycle. This is down sampled to 5 kHz and STC matrix is found by ST or PWT.

The RMS plot and frequency spectrum are plotted as shown in Fig. 4c, d respectively. Due to the presence of nonlinear load, small amount of harmonics are introduced which are extracted by the ST. WT applied to the voltage waveform of Fig. 4b resulted into the level 1 coefficient shown in Fig. 4e. Here the coefficients are continuously varying and WT fails to differentiate the instances of sag start and end with the noise. Table 2 details the experiment result of ST analysis performed for some of the voltage disturbances. The magnitudes of voltage disturbances calculated from ST are matching with the measured value. This is major advantage with PWT or ST, as compared to WT, that it can detect the voltage disturbances based on RMS calculation and also provide harmonic information even in the presence of noise.

Table 1 Simulation result of ST analysis of voltage harmonics

Signal	Simulated signal frequency components			ST solution of frequency components			Phase different (°)
	Freq (Hz)	Mag (pu)	Phase (°)	Norm (freq)	Mag (pu)	Phase (°)	
1	50	1.00	0	0.03	1.00	−90	In phase
	150	0.33	0	0.08	0.3335	−89.99	
2	50	1.00	0	0.03	1.00	−90	50.69
	150	0.33	50	0.08	0.3335	−39.31	
3	50	1.00	0	0.03	1.00	−90	50.7
	250	0.20	50	0.13	0.2142	−39.3	
4	50	1.00	0	0.03	1.00	−90	In phase
	150	0.33	0	0.08	0.3335	−89.99	
	250	0.20	0	0.13	0.2142	−88.82	

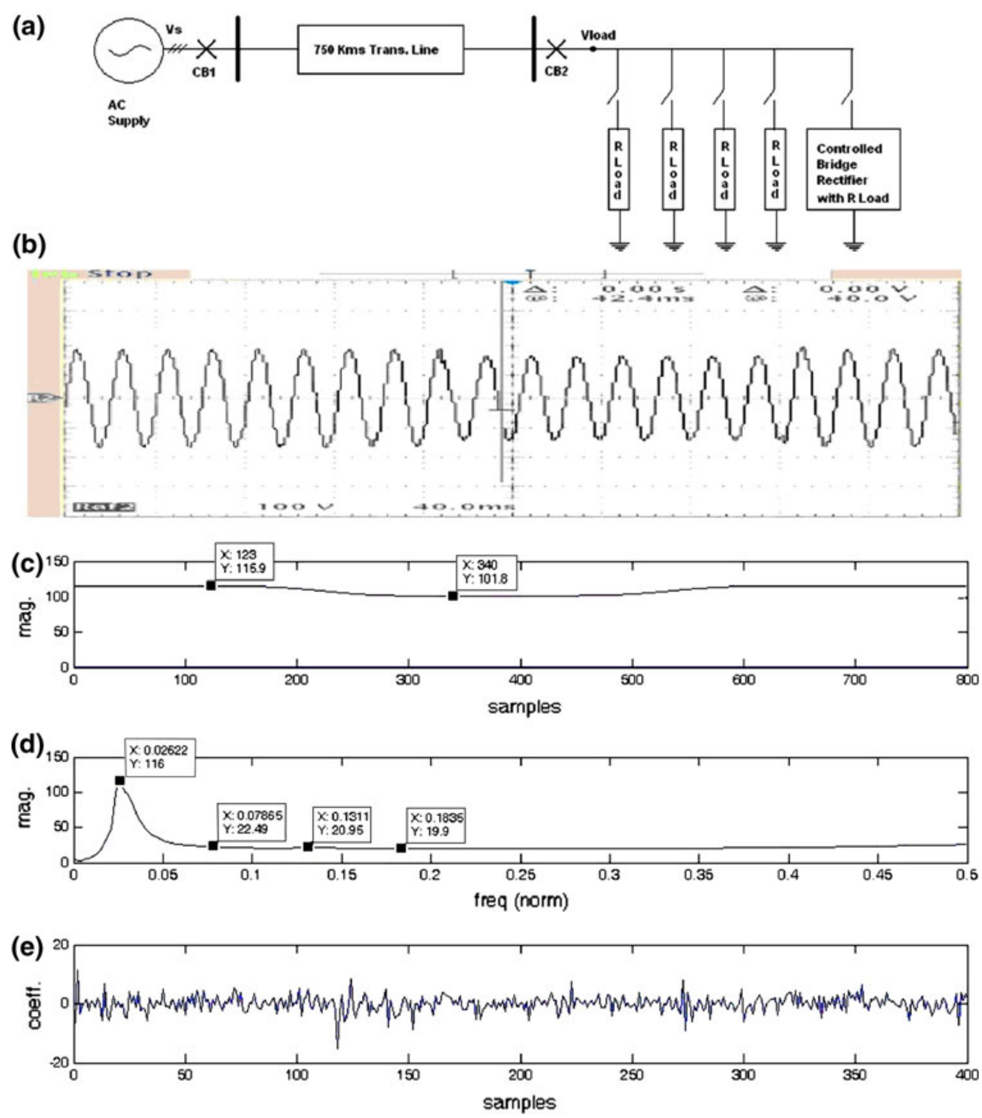

Fig. 4 **a** Block diagram of transmission model with loads, **b** load voltage waveform obtained from experimental setup for voltage sag condition, **c** RMS plot from ST analysis and **d** frequency spectrum from ST analysis and **e** WT coefficients

Table 2 Experimental results of ST for Sag/Swell and interruption identification

Disturbance type	Voltage recorded (rms)			Voltage calculated by ST analysis (rms)		
	Normal condition (V)	Under disturbance (V)	Disturbance magnitude (%)	Under normal condition (V)	Voltage under disturbance (V)	Disturbance magnitude (%)
Sag 1	133	116	12.30	132.8	116.2	12.50
Sag 2	116	102	12.07	115.7	102.8	11.15
Sag 3	102	90	11.76	103.2	91.38	11.45
Sag 4	133	92	30.83	133.0	91.04	31.55
Swell 1	90	134	48.89	91.82	133.8	45.72
Swell 2	90	102	13.33	91.46	104.5	14.26
Swell 3	80	90	12.50	80.81	90.91	12.50
Swell 4	80	102	27.50	80.27	103.0	28.32
Interruption	133	0	100.0	132.6	0	100.0

Conclusions

This paper has introduced S-transform or the phase corrected wavelet transform for detection of PQ events such as voltage sag, swell, interruption and PQ variations such as harmonics. ST analysis performed on these disturbances can easily identify the magnitude and duration of the disturbance. It is verified that ST technique is suitable to identify the voltage sag/swell in the presence of transients or noise. Wavelet transform is sensitive to noise and cannot detect the disturbances correctly in the presence of noise. Also detection of events by wavelet transform is affected by the choice of mother wavelet. Finally ST features are validated for the voltage disturbances obtained from the experimental analysis on a transmission line model connected with various linear and nonlinear loads.

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