Classification of Power Quality Disturbances using Hyperbolic S-Transform

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Abstract— **This paper is presented for the detection of power quality disturbances using Hyperbolic S transform (HS-transform) signal processing technique. Different power system events such as voltage sag, voltage swell and oscillatory transients are simulated and processed by the HS transform technique to generate S matrix. The value of energy and standard deviation for the samples of the power system events for the classification are obtained using the S matrix. Also this paper is dealt with the merits and demerits of the proposed signal processing technique. The test results show that the MMT is having more compatibility for identifying events.**

Keywords- Power quality, Voltage sag, Voltage swell, Oscillatory transients, HS transform, Parseval's theorem.

I. INTRODUCTION

The power quality disturbances can be classified into steady state variations and events. The steady state variations are small deviations from the desired voltage and current values. Voltage fluctuations, harmonic distortion and unbalancing voltage and current are some of the steady state variations. A significant sudden change of wave shape or deviation of voltage or current from the desired value is termed as power quality event. The common power quality events are voltage sag, voltage swell, interruptions and transients.

The needful of extracting specific information from the raw data which is power system voltage and current waveforms are analysed through signal processing techniques. The collection of data through signal processing techniques from simulation models are dictated in [1]. The analysis of power quality broadly divided into the problem of classification, identification and characterization. A large volume of data is being collected and analysed with the advancement of measurement technology. It is highly importance for the automation. Signal processing is therefore called upon for identification, classification and characterization. And also the techniques used vary depending on the characteristics of the phenomenon. Generally power system consists of alternating current; Root Mean Square (RMS) quantity is most commonly used measure for voltage magnitude. This may be the periodic waveform, it is often taken as a rough estimate of the non-periodic or time varying voltage variations which includes voltage dips, swells and interruptions are characterized and classified using RMS[2]. When more explicit is needed such as evaluating in disturbance propagation, time frequency decomposition methods are necessary.

DFT is a convenient way of visualization stationary and periodic signal from its frequency content view point. It is also applied to non stationary signals but with added windowing to focus on certain period of time. This is called Short Time Fourier Transform (STFT) allowing some tracing of the magnitude variations. Harmonic distortions are typically handled in this manner but the constraints placed on the frequency resolution makes it difficult to extend STFT to the analysis of inter harmonics. In fast voltage transients the peak magnitudes and rise times are required to be determined accurately. For oscillatory transients pre dominant frequency has to be derived before computing its magnitude.

Discrete Fourier Transform (DFT) is often used even though these waveforms are not periodic and last for less than one fundamental cycle since it is often necessary to determine their spectra content. The information obtained after identification, classification and characterization stored for future references. The steps undertaken in the signal processing techniques compression, processing and threshold operation are carried out to reduce the amount of data stored.

In literature, there are several signal processing techniques like Fourier Transform, STFT, S-Transform, wavelet transform and wavelet packet transform are used for examining the power quality events such as Swell, Sag and transients. Fourier Transform and Short-Time Fourier Transform can be used only a fixed window width which is inadequate for the analysis of the transient non-stationary signals [3]. In reference various electric power quality disturbances are analysed using wavelet transform in time-scale domain[4]. A complex wavelet network is used for power quality disturbances[5]. In the paper authors utilized various mother wavelet functions to identify the voltage sag[6]. In another method wavelet packet transform is used for power quality disturbances[7]. In modern spectrum and harmonic analysis, DFT is used to monitor and assess the recorded data. DFT is not successful in transient signal tracking, because it must perform only in a fixed length window. The DFT method gives magnitude and phase angle of different frequency components of a periodic and stationary voltage or current waveform. Rectangular sampling windows of 10 cycles width in 50Hz power system is used and grouping of output bins of DFT analysis is done to compute the voltage and current waveform harmonic distortion. However DFT analysis only provides information in the frequency domain with a resolution that depends on the width of the time window. It doesn't give any time information about the signal provided [8].

As an extension of the wavelet transform and Fourier transform, the S-transform introduced by Stockwell et al [9] has good time frequency analysing ability. The S-transform has distinctive advantages compared to the wavelet transform and Fourier transform. The result of the S-transform signal is a complex matrix in which the values are the amplitude and the phase. The S-transform is an invertible time frequency spectral localization technique that combines the elements of the wavelet transforms and STFT. The S-transform uses an analysis window, whose width decreases with the frequency providing a frequency dependent resolution. This transform may be seen as a continuous wavelet transform with phase correction. It produces a constant relative bandwidth analysis like wavelets, while it maintains a direct link with the Fourier spectrum.

In this paper, power quality events such as sag, swell and transients are distinguished using HS-transform and then the energy and standard deviations are calculated using Parseval's theorem for the classification purpose.

II. NOTATION

g_f	Forward taper parameter
g_b	Backward taper parameter
τ	Controls the position of Gaussian window on the t-axis in HS –transform; translation parameter
cD	Detail co-efficient
cA	Approximation co-efficient
$\psi_{i,j}$	Function of wavelet expansions
s	Scale parameter
S	S- Transform
T	Sampling interval
$h(t)$	Time series of the signal
W_{gs}	Generalized window
p	Phase factor
w_{ky}	Hyperbolic function
w_{hy}	Hyperbolic window function
N_g	Total number of samples
λ^2_{hy}	Hyperbolic window

III. METHODOLOGY OF THE PROPOSED WORK

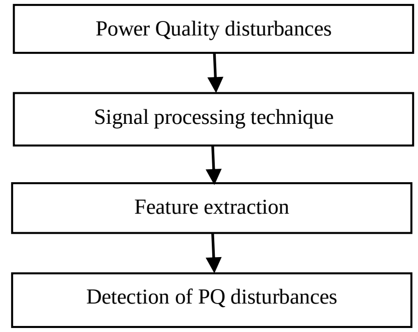

Figure 1. Methodology of the proposed work

Fig. 1. shows the methodology of the proposed system organized in following steps.

1) Generation of power quality events such as voltage swell, voltage sag and oscillatory transients from power system model using MATLAB/SIMULINK software.
2) Data obtained from the events are processed to signal processing techniques such as HS-transform and wavelet transform.
3) Feature extraction is done on the processed events of HS transform. HS transform produce energy matrix from S matrix. The average of these energy values over frequency gives a vector of energy values for all instances of time. Also STD values from S matrix produced frequency contours for the corresponding instances.
4) Detection of power quality disturbances are based on obtained energy values from processed signals.

IV. INTRODUCTION TO HS TRANSFORM

The wavelet transform decomposes a signal from high to low frequency bands through an iterative procedure. This procedure performs well for high frequency transients but not so well for low- frequency components. This task is very difficult as it increases the decomposition level's leading to computation burden. Therefore, a better suitable signal processing technique has been found to recognize the voltage signal patterns from a distribution system. The limitations of wavelet transform were overcome by HS-transform, which is actually a time-frequency transform. It combines continuous wavelet transform and STFT. The S-transform is a STFT in that it provides time as frequency information[10]. S-transform is an extension of continuous wavelet transform in that it uses a variable window whose width varies inversely with frequency content of the signal[11]. The output of HS-transform is S-matrix whose columns are the time at which samples are taken from the signal. Thus, each column represents the real spectrum at one point in time. The S transform has two parts namely

1. The slow varying envelope (the Gaussian function) that localizes in time.

2. The oscillatory exponential kernel that selects the frequency being localized.

HS-transform which produces frequency contours and using Parseval's theorem features such as energy and standard deviation are calculated from S-matrix. An extensive simulation analysis was performed using MATLAB/SIMULINK and HS-transform is implemented using MATLAB (M-File) environment. Advantage of the proposed HS algorithm is its accuracy in representing the signals in the pattern recognition form, which reduces the computation burden and handle the signals with polluted noise [12].

V. TRANSIENT ANALYSIS BASED ON HYPERBOLIC S TRANSFORM

The expression of the original signal is defined as

$$\mathbf{S}(\tau,\mathbf{f}) = \int_{-\alpha}^{+\alpha} \mathbf{h}(\mathbf{t}) \left\{ \frac{|\mathbf{f}|}{\sqrt{2\pi}} \exp\left\{ \frac{\mathbf{f}^2(\tau-\mathbf{t})}{2} \times \exp(-2\pi \mathbf{f t}) \right\} \mathbf{dt} \right. \quad (1)$$

In equation (1), S-denotes the S-transform of h(t), which is actual voltage signal varying with time frequency is denoted by f, and the quantity τ is a parameter which controls the position of Gaussian window on the time-axis.

The generalized S-transform is obtained from the original S-transform by replacing the Gaussian window with a generalized window, the expression is given by,

$$Wgs(\tau - t, f, p) = \frac{|f|}{\sqrt{2\pi}\, p} \exp \frac{[-f^2(\tau-t)]}{2p^2} dt \quad (2)$$

$$S(\tau, f, p) = \int_{-\alpha}^{\alpha} h(t).w(\tau - t, f, p) e^{(-2\pi i f t)} dt \quad (3)$$

In this paper transients signals are presented using amplitude of S(τ,f) using equation (3) and h(t) is the time series of the signal to be analyzed, w(τ-t,f,p) is the window function and $\mathbf{e}^{(-2\pi \mathbf{ift})}$ is the phase factor. τ is the parameter which controls the position of the window on the t axis, Wgs is an generalized window and f is frequency of signal p denotes a set of parameter that govern the shape of window 'w'. The hyperbolic S-transform is obtained by using hyperbolic window in the place of w in equation (3).

The hyperbolic window can be expressed mathematically as follows:

$$W_{ky} = \frac{2|f|}{\sqrt{2\pi}(g_f + g_b)} X \exp\left\{ \frac{-f^2\left[\chi(\tau - t, \{g_f + g_b, \lambda^2 hy\})\right]^2}{2} \right\} \quad (4)$$

In the above equation (4) , we have used the g_f as forward taper parameter its value is 50 and g_b as backward taper parameters its value is 150 we have considered and λ_{hy}^2 is $(1/16)^2$ Where

$$X(\tau - t, \{g_f, g_b, \lambda^2 hy\}) = \left(\frac{g_b + g_f}{2 g_b g_f}\right)(\tau - t - \xi) + \left(\frac{g_b - g_f}{2 g_b g_f}\right)\sqrt{(\tau - t - \xi)^2 + \lambda^2 hy} \quad (5)$$

In the above expression 0< g_f < g_b and ξ is an translation parameter which is defined as

$$\xi = \sqrt{\frac{(g_b - g_f)^2 \lambda_{hy}^2}{4.gb.gf}} \quad (6)$$

The translation by ξ ensures that the peak of Wky to occur at $\tau - t = 0$. The equation [4,5,6] are taken from reference [13]. In equation [4,5,6] gf is the forward taper parameter and gb is the backward taper parameter.

These two parameters determine the shape of hyperbolic window. Since event initiation, time is more important than event termination. We use 0 < gf < gb this makes the window asymmetric with slower taper in backward direction and sharper taper in forward direction. This asymmetry is needed since, if its window is symmetry then time resolution is good and frequency resolution is poor. Hence, w used asymmetric window to get good time and frequency resolution during event initiation at the expense of resolution during event termination. In (5), X is a hyperbolic in (τ-t) and depends on gf, gb and positive curvature parameter λhy which have units of time. The translation factor ξ is used to make the peak of Wky (hyperbolic window) to occur at $\tau - t = 0$. In (7) and (8), the radicals denote positive square root. Where τ is the sampling interval, which is in practical applications where capture signals are in discrete form the discrete version of S-transform technique is obtained by making f equals to n/NT and τ equal to KT

$$s\left[KT, \frac{n}{KT}\right] = \sum_{m=0}^{N-1} h\left[\frac{m+n}{NT}\right].G(m,n)\exp\left(\frac{2\pi i n K}{N}\right) \quad (7)$$

where, n is the total number of samples; H [m+n /NT] is Fourier transform of analyzing signals; G (m, n) is Fourier transform of hyperbolic window; K, M are discrete time indices, n is discrete frequency index k,m,n varies 0 to N-1.

VI. APPLICATION OF PARSEVAL'S THEOREM TO HS TRANSFORM FOR DATA COLLECTION

The Parseval's theorem states that the energy of signal i(t) remains the same, whether it is calculated in the signal domain or in the transformed domain.

$$E_{signal} \frac{1}{T}\int_0^T |i(t)|^2 \, dt = \sum_n^N |i(t)|^2 \quad (8)$$

where T and N are the time period and length of the signal i(t). The Fourier transform of the signal is i(t)2 . Using equation (8), the energy is retrieved from the S-matrix output and the corresponding STD is calculated for the voltage supply of sag, voltage supply of swell and oscillatory transients[14]. Once the signal is extracted it is processed to HS-transform to obtain relevant features for identifying the type of event.

The feature extraction of the energy and the STD of the HS-transform contour are obtained as

Energy a = (S-matrix a) ^ 2 (9)

S-matrix a = S-matrix of phase a and

STD a = STD (abs (S-matrix a)) (10)

VII. SIMULATION RESULTS

A. *Power system model studied for voltage swell*

The equivalent circuit of the SIMULINK model for obtaining voltage swell is given in Figure 4a and simulation model is developed.

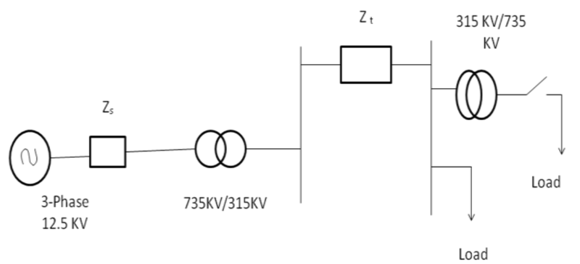

Figure 2. Equivalent circuit for generation of swell

Figure 2 shows the supply voltage of the voltage swell obtained due to energization of three phase RLC series load connected at the secondary of the transformer 2. It is observed in the voltage signal between 0.02s to 0.1s there is a voltage rise. Figure 4 shows processed voltage signal after HS transform which produce patterns of voltage swell, then Parseval's theorem computes the energy matrix from S-matrix to obtain energy and standard deviation values for data collection are given in the Table.1.

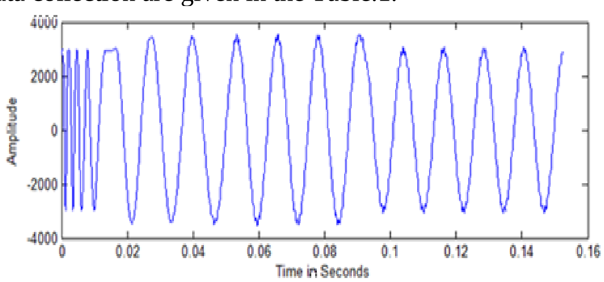

Figure 3. Voltage waveform with swell

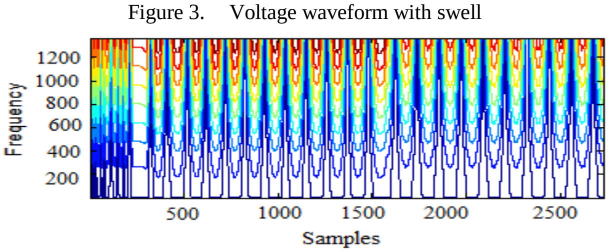

Figure 4. Amplitudes of HS –transform for voltage Swell

B. *Power system model studied for voltage sag*

Equivalent circuit for generation of voltage sag is given in Figure.5 and corresponding simulink model is developed for generating voltage sag.

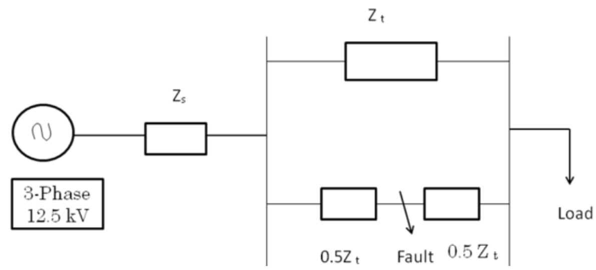

Figure 5. Equivalent circuit for generation of sag

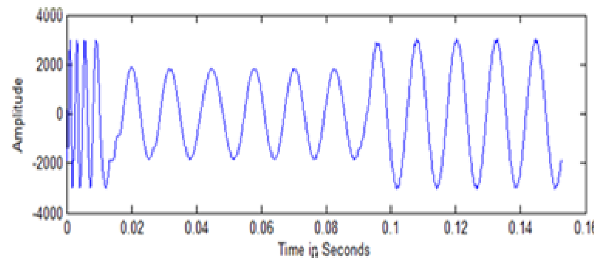

Figure 6. Voltage waveform with sag

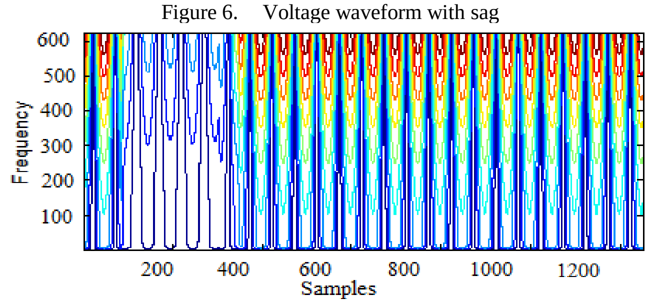

Figure 7. Amplitudes of HS-transform for voltage sag

The voltage sag is generated by introducing a fault through a breaker on the transmission line of the model. Figure5b shows the supply voltage with voltage sag obtained from simulink model due to energization of three phase breaker at 0.05s. Figure7 shows the voltage sag after HS transform. It is clearly observed that contours are bright for the duration of sag and contours are dark for supply voltage and the corresponding energy values for the duration of sag are given in the Table. 1.

C. Power System model for oscillatory transients

The equivalent circuit for generation of oscillatory transients is given in Figure 7. And simulink model is developed for capture of transients. Occurrence of transients is captured after energization of capacitor at the secondary of the transformer. Oscillatory phase voltages due to transients are obtained by voltage moment of the load side.

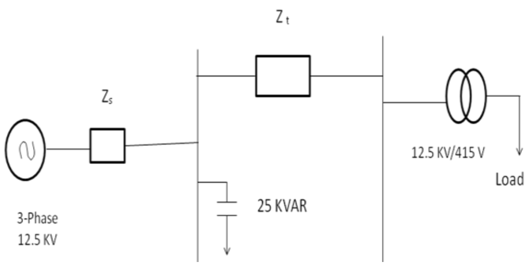

Figure 8. Equivalent circuit for generation of transients

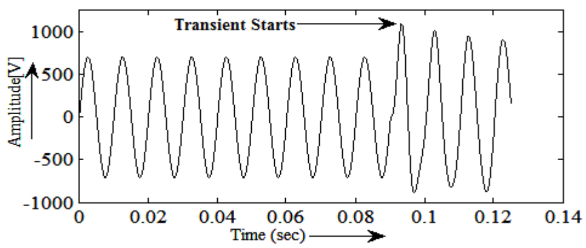

Figure 9. Voltage waveform with transient

Figure 8 shows the generation of transient signal. Figure.6c shows the amplitude of HS-transform for the full window. The oscillatory transient voltage shown in Figure.6c is processed to HS-transform which produces S-Matrix. Using Parseval's theorem, energy and STD are calculated for the duration of transients for 0.09 to 0.12 sec. Table.1 gives the computed energy values of power quality disturbances Using this values it can be easily discriminated from other events like harmonic, sag and swell. The average values of energy and STD is used to distinguish between the different PQ disturbances by setting a proper threshold value for each of the disturbances.

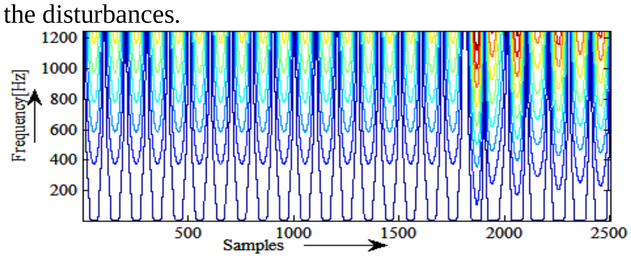

Figure 10. Detection of transient signal for full window using HS-transform

TABLE I. ENERGY VALUES OF POWER QUALITY DISTURBANCES

Power quality events		HS transform	
		Energy	Standard deviation
Oscillatory Transient	Phase A	2.50E+06	317.5250
	Phase B	2.58E+06	334.3081
	Phase C	2.58E+06	326.6780
Voltage Swell	Phase A	2.4159e+006	126.0312
	Phase B	6.5903e+006	201.9883
	Phase C	8.8947e+006	239.1745
Voltage Sag	Phase A	4.5876e+008	3.548e+003
	Phase B	4.6246e+008	3.531e+003
	Phase C	4.4869e+008	3.507e+003

VIII. CONCLUSION

This paper gives a study of HS transform signal processing technique on detection of PQ disturbances using S-transform under various power system events. The study was carried out with extraction of voltage signals using different power system models. The detail coefficients have similar variation for all the power system events obtained in HS transform. From the results it is found that the hyperbolic S transform gives a faster and reliable determination of power quality disturbances.

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