Power Quality Disturbance Detection in Grid-Connected Wind Energy System Using Wavelet and S-Transform


Abstract: S-transform and wavelet transform based approach for detection of different power quality disturbances like voltage sag, voltage swell, momentary interruption, notch and oscillatory transients in grid-connected wind power system is proposed in this paper. The voltage signal at point of common coupling is used in detection of the disturbances. The excellent time-frequency resolution characteristic of S-transform is exploited for detecting various power quality disturbances. The simulated results clearly reflect the advantages of S-transform over wavelet transform in localizing and detecting the power quality events even under noisy conditions.

Index terms: Power quality, S-transform, wavelet transform, wind energy system.

I. INTRODUCTION

Distributed generation (DG) has recently gained momentum and popularity due to market deregulation and awareness for clean environments [1]-[2]. In fact, many utilities around the world already have a significant penetration of DG in their system. But there are many issues to be seriously considered with the DG connected to utility grid and one of the main issues is power quality. Power quality disturbances occur due to the presence of power electronics based non-linear loads, unbalance in power system, computer and data processing equipments etc. at the point of common coupling (PCC). If not detected effectively, these power quality disturbances may lead to many problems to the generators and connected loads [3]. It is desired to know the sources of power system disturbances and find remedies to mitigate them. In this context, wavelet transform [4]-[5] is an attractive and effective candidate for detecting various power quality disturbances. Wavelet transform is useful in detecting and extracting disturbance features of disturbances because it is sensitive to signal irregularities but insensitive to the regular signal behavior. But the major drawback of wavelet transform is its batch processing step, which results to introduction of delay. An alternative and extension to wavelet transform is the S-transform [6]-[7], which is based on moving a varying and scalable localizing Gaussian window and is fully convertible from the time domain to two-dimensional (2-D) frequency translation domain. The S-transform has an advantage of providing multi-resolution while retaining the absolute phase of each frequency component which is useful in detecting the disturbances in presence of noise. The phase correction of the modified wavelet transform in the form of S-transform can provide significant improvement in the detection and localization of power quality disturbances. Any abrupt change occurred in the acquired signal would be effectively caught, hence increasing the reliability of detection.

II. GRID-CONNECTED WIND ENERGY CONVERSION SYSTEM (WECS)

The wind power which has been expected to be a promising alternative energy source can bring new challenges when it is connected to the power grid due to the fluctuation nature of the wind and the comparatively new types of its generators. However, to obtain secure and reliable operation, several technical issues related to power quality are required to be critically studied.

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A. Wind energy conversion system (WECS)

In general, the relationship between wind speed and mechanical power extracted from the wind can be described as [8]

\[ P_m = \frac{\rho}{2} A_n C_p (\lambda, \beta) V_r^3 \]  \hspace{1cm} (1)

where \( P_m \) is the power extracted from the wind in watts; \( \rho \) is the air density (kg/m³); \( C_p \) is the performance coefficient or power coefficient; \( \lambda \) is the tip-speed ratio \((V_r/V_s)\), \( V_r \) (m/s) is blade tip speed, and \( V_s \) (m/s) is wind speed at hub height upstream of the rotor; \( A_n = \pi R^2 \) is the area covered by the wind turbine rotor (m²), \( R \) is the radius of the rotor; and \( \beta \) is the blade pitch angle (in degrees).

The tip-speed ratio \( \lambda \) is defined as:

\[ \lambda = \frac{R \omega_r}{\omega_s} \]

where \( \omega_r = p \omega_m \omega_s \) is the electrical speed (elec. rad/s); \( p \) is the number of pole pairs of the machine; and \( \omega_m \) is the mechanical speed of the rotor (mech. rad/s). The doubly-fed induction generator (DFIG) model used as a part of the WECS is taken from [9].

III. POWER QUALITY DISTURBANCE DETECTION METHODS

A. Discrete Wavelet transforms (DWT)

In this study, the voltage signals at PCC are used as the input signals of the wavelet analysis. Haar mother wavelet, is employed since it has been demonstrated to perform well [4]-[5]. Filters of different cut-off frequencies are used to analyze the signal at different scales. The signal is passed through a series of high pass filters to analyze the high frequencies, and it is passed through a series of low pass filters to analyze the low frequencies. Hence the signal (S) is decomposed into two types of components approximation (A) and detail (D). The approximation (A) is the high scale, low-frequency component of the signal. The detail (D) is the low-scale, high-frequency components.

The first-scale decomposition of a digitized time signal is \( C_0(n) \) in terms of approximation and detailed version are given by

\[ a_0(n) = \sum_k h(k-2n) C_0(k) \text{ and} \]
\[ d_0(n) = \sum_k g(k-2n) C_0(k) \]  \hspace{1cm} (2)

where, \( h(n) \) has a low-pass filter response and \( g(n) \) has a high-pass filter response.

The next higher scale decomposition is based on \( a_0(n) \) instead of \( C_0(n) \). At each scale, the number of the DWT coefficients of the resulting signals (e.g. \( a_1(n) \) & \( d_1(n) \)) is half of the decomposed signal (e.g. \( C_0(n) \)).

B. Modified Wavelet Transform: S–Transform

It is well known that information is contained in the phase of the spectrum, as well as in the amplitude. In order to utilize the information contained in the phase of the continuous wavelet transform (CWT), it is necessary to modify the phase of the mother wavelet. The S–transform \( W(\tau,a) \) of a function \( h(t) \) is defined as

\[ W(\tau,a) = \int_{-\infty}^{\infty} h(t) \text{exp}(-i\omega t) dt \]  \hspace{1cm} (3)

where \( W(\tau,a) \) is a scaled replica of the fundamental mother wavelet; the dilation determines the width of the wavelet and this controls the resolution. The S–transform is obtained by multiplying the CWT with a phase factor as:

\[ S(\tau,f) = \text{exp}(i2\pi f \tau) \cdot W(\tau,a) \]  \hspace{1cm} (4)

where the mother wavelet for this particular case is defined as

\[ \omega(t,f) = \left( \frac{|f|}{\sqrt{2\pi}} \right) \cdot \text{exp} \left( -\frac{r^2 f^2}{2} \right) \cdot \text{exp} \left( -i 2\pi ft \right) \]  \hspace{1cm} (5)

In the equation just shown, the dilation factor is the inverse of the frequency. Thus, the final form of the continuous S–transform is obtained as

\[ S(\tau,f) = \int_{-\infty}^{\infty} h(t) \left( \frac{|f|}{\sqrt{2\pi}} \right) \cdot \text{exp} \left( -\frac{(r-t)^2 f^2}{2} \right) \cdot \text{exp} \left( -i 2\pi ft \right) dt \]  \hspace{1cm} (6)

and the width of the Gaussian window is :

\[ \sigma(f) = T = \frac{1}{|f|} \]  \hspace{1cm} (7)

IV. SIMULATED RESULTS AND DISCUSSIONS

This section presents the performance of above discussed techniques for power quality disturbance detection in grid-connected wind power system under various operating scenarios. The various operating scenarios of disturbances are created for study in MATLAB/SIMULINK. The parameters of the components used for simulation are given in the appendix. The voltage signal is captured from the PCC. The voltage signal is then passed through Haar as mother wavelet and S–transform to detect the disturbances. In the simulation part, the extracted voltage signal (original signal) is taken for 2000 samples while the corresponding approximate and detail wavelet coefficients are taken for 1000 samples ,i.e., half the samples of that of the extracted signal. Hence as shown in the graphical results, the detection instants are observed at half of the samples of
extracted voltage signal. Fig. 2 shows the extracted voltage signal with notch and its S-transform contour is shown in Fig.3. The corresponding approximate and detail coefficients at every sample obtained by wavelet transform using Haar as mother wavelet is shown in Fig.4. Then the detection of voltage notch under 20 dB noise conditions is shown in Fig.5, 6 & 7 respectively which clearly reflects the advantages of S-transform while Haar wavelet fails to localize the disturbance. Similar observations were seen in Fig. 8, 9 & 10 and Fig.11, 12 & 13 for voltage swell scenario under normal and 20 dB noise conditions respectively. It can be seen that S-transform contours clearly detecting and localizing the disturbance instants signal under both without and with noise conditions while wavelet transform fails under noise conditions. Exactly similar observations can be analyzed with other disturbances like voltage sag, momentary interruptions and oscillatory transients whose results are not presented due to page limitations.

Fig. 2 Voltage signal with notch.
Fig. 3 S-transform contour.
Fig. 4 Detection by Haar mother wavelet transforms.
Fig. 5 Voltage signal with notch and 20 dB noise.
Fig. 6 S-transform contour with 20 dB noise.

Fig. 7 Detection by Haar wavelet transforms with noise.
Fig. 8 Voltage signal with swell.
Fig. 9 S-transform contour.
Fig. 10 Detection by haar mother wavelet transforms.
Fig. 11 Voltage signal with swell & 20 dB noise.
This paper has considered the study on detection of power quality disturbances in grid-connected wind energy conversion system using wavelet and S-transform techniques under various scenarios. The variation in voltage signal is observed through wavelet and S-transform under different scenarios. The contours of S-transform suggested not only the detection of power quality events, but also its classification on the type of disturbances. The simulated results clearly show the advantages of S-transform as comparison to wavelet transform in detecting and localizing the disturbances even under 20 dB noise conditions.

VI. APPENDIX

<table>
<thead>
<tr>
<th>TABLE I: RATING OF THE GRID-CONNECTED WIND SYSTEM</th>
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<tbody>
<tr>
<td>Wind energy conversion system</td>
</tr>
<tr>
<td>Active power: 1 MW, rated</td>
</tr>
<tr>
<td>speed: 12 m/s, rated</td>
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<tr>
<td>voltage 575V, frequency</td>
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<td>:50Hz</td>
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VII. REFERENCES