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Experimental Investigation of Power Quality Disturbances Associated with Grid Integrated Wind Energy System

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Abstract—**This paper presents the experimental investigation of power quality (PQ) disturbances associated with the grid integrated wind energy generator. PQ disturbances associated with the grid synchronization and outage of doubly fed induction generator (DFIG) based wind energy generation system have been investigated in the presence of various types of loads. The voltage signal has been captured at point of common coupling (PCC) using the data acquisition system consisting of power quality analyser, laptop, and WT viewer software. The voltage signal has been analysed using MATLAB software to find the PQ disturbances. It has been observed that the PQ disturbances such as voltage fluctuations, flicker, voltage sag, voltage swell and harmonics are associated with the grid synchronization and outage of DFIG based wind energy conversion system.**

Index Terms—**Doubly fed induction generator, power quality, Stockwell's transform, utility grid, wind energy.**

I. Introduction

Recently the power plants based on the fossil fuel are not able to supply the increased demand of electricity. This has resulted in increased interruptions in the electrical supply and blackouts [1]. Therefore, possible solution is to develop renewable energy (RE) sources based power plants. Out of the different types of RE sources available, the solar energy and wind power have been promoted all over the world for generation of electrical power in the recent years. Recently, wind energy has developed rapidly in the world. Increase in the level of grid integrated wind energy increases the problems of reliability and power quality [2]. The quality of electrical power is affected by the disturbances such as notches, impulses, glitches, wave faults, momentary interruptions, voltage sag, harmonic distortions, voltage swell and flicker [3].

Signal processing and mathematical techniques are utilized for recognition of PQ disturbances. Mahela *et al.* [4] presented a detailed review of signal processing and intelligent techniques used for the detection and classification of power quality (PQ) disturbances. The effect of noise on performance of the detection and classification of PQ disturbances has also been presented. The techniques developed based on digital filters and morphological operators such as wavelet transform (WT), short-time Fourier transform (STFT), Hilbert transform (HT), wavelet packet transform (WPT), Gabor transform (GT), Stockwell transform (ST), Wigner distribution function (WDF), Gabor-Wigner transform (GWT), hybrid transform, and Hilbet-Huang transform (HHT) based methods have been commonly used for recognizing the detection of PQ disturbances [5]. An integrated method for the detection and classification of recognition of PQ disturbances using a wavelet multi-class support vector machine has been reported in [6]. A method based on combination of ensemble empirical mode decomposition (EEMD) and multi-label learning for the recognition of multiple PQ events has been reported in [7]. Mahela *et al.* [8], presented the investigation of PQ disturbances with help of an algorithm making use of Stockwell transform and Fuzzy C-means clustering (FCM).

The techniques developed and implemented on standard PQ disturbances have also been applied to analyse the PQ disturbances associated with the renewable energy (RE) penetration in to the utility grid. A number of articles are reported on the power quality problems due to various aspects of grid connected wind generators such as design of generators like synchronous or asynchronous, designs of grid side and rotor side converters of the DFIG, seasonal variations of wind speed etc. Assessment of PQ disturbances associated with the distribution systems integrated with wind energy based power generation system is detailed in [9]. Ray *et al.* [10] detailed a method for the recognition of PQ disturbances caused due to environmental characteristics in distributed power generation system. A study on the PQ disturbances and requirement of the reactive power compensation at the time of grid integration of wind power have been detailed in [11]. A study on assessment of PQ disturbances associated with the wind turbines installed in Hatay region has been elaborated in [12]. Kocatepe *et al.* [13], described a method for the measurement and analysis of PQ disturbances associated with a substation comprising of two different wind farm sites of low and high power generation rates. Investigation of PQ disturbances associated with the grid synchronization of wind generator, outage of wind generator and wind speed variation using discrete wavelet transform has been reported in [14]. A technique which can effectively classify the islanding and PQ disturbances in grid integrated distributed generation (DG) forming a hybrid power system making use of the modular probabilistic neural network and support vector machine (SVM) has been presented in [15].

This paper details the experimental investigation of PQ disturbances associated with the grid integration of wind power

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generation system based on doubly fed induction generator (DFIG). The PQ events associated with grid synchronization and outage of DFIG wind generator in the weak AC grid with various loading scenarios has been investigated using Stockwell transform. The main contribution of this research work is the experimental investigation of PQ events associated with the grid operations such as outage and synchronization of DFIG wind generator under various operating scenarios.

The organization of this paper includes six Sections. Section II describes the experimental hardware and data acquisition system and proposed methodology of PQ recognition has been detailed in the Section III. Investigations of PQ disturbances with the outage and grid synchronization of DFIG are detailed in the Sections IV and V respectively. The Section VI presents the conclusions of this research work.

II. Experimental Hardware and Data Acquisition

Experimental set up consists of a distribution utility grid, Wind power plant and various types of loads. The power system is the utility grid operating at voltage level of 400 V. The wind power plant consists of a doubly fed induction generator (DFIG) based wind energy conversion system. Technical specifications of the DFIG and wind turbine are given in the Table I. The stator of DFIG is directly connected to the utility grid through a transformer (1 kVA, 6-Y, 400/300 V). The rotor feed power to the transformer input through the AC-DC-AC converter. This converter has two voltage-sourced converters known as RSC (rotor-side converter) and (GSC) grid side converter. A dc-link capacitor is placed between these two converters as energy storage device in order to keep the voltage variations small in the dc-link voltage. The detailed study of various components of the wind energy conversion system has been reported in [16].

The single line diagram of experimental set-up along with the data acquisition system is shown in Fig. 1. An inductor having the value of 75 mH has been placed between the utility grid and the DFIG in each phase to make the AC grid weak. The system consists of the following items: Power quality analyser WT 300 fitted with the voltage transformer and current transformer, Laptop computer (64-bit operating system, 4 GB RAM, Intel(I) Core(TM)i5-3230M CPU@2.60 GHz processor), WT viewer software, Matlab software and connecting probes. PQ measurements are being carried out with outage and grid synchronization of the DFIG in the presence of various types of loads. The details of loads connected at the point of common coupling are designated by the class symbols L1 to L3 as detailed in the Table II. The DFIG is connected to the PCC using grid synchronization device (GSD). The synchronization and outage events are emulated by closing and opening the GSD.

III. Proposed Algorithm of PQ Recognition

Block diagram of proposed methodology used for investigation of PQ disturbances is illustrated in Fig. 2. Power quality disturbances have been analysed using the feature plots obtained from the S-transform based multi-resolution analysis of the voltage. The voltage signal is decomposed using S-transform to obtain S-matrix. Various feature plots are obtained from S-matrix for the analysis of power quality. These plots (ST plots) include time-frequency contour (also known as S-contour or frequency contour), sum absolute values curve, amplitude-time curve and amplitude-frequency curve. Parameters are normalized with respect to maximum values. These plots help to analyze the PQ disturbances associated with various operating events of study.

TABLE I
Technical Specifications of DFIG and Wind turbine

Parameter	**Rated value**
Voltage	400/230 V, 50 Hz
Current	2.0 A / 3.5 A
Speed	1400 / 1500 rpm
Power	0.8 kW
Power factor	0.75
Excitation voltage	130 VAC / 24 VDC
Excitation current	4 AAC / 11 ADC
Wind turbine maximum torque	6.7 Nm
Cut off frequency of wind turbine	70 Hz

TABLE II
Loading Status at PCC

S.No.	Class symbol	Type of load	Rated value
1	L1	Resistive	Y, 3-phase, 600 W per phase
2	L2	Inductive	Y, 3-phase, 0.45 H, 1.8 Ω, 330 turns per phase.
3	L3	Induction motor	6, 3-phase, 3.5 kW, 50 Hz, 415 V, 1430 rpm.

IV. Power Quality Analysis with Outage of DFIG

This section details the results related to assessment of PQ Disturbances associated with the outage of DFIG from the weak AC grid. Various S-transform based plots are used for the investigation of PQ disturbances.

A. Without Any Load at PCC

Outage of DFIG from weak AC grid without any type of load at PCC is performed in the 3rd cycle. Various S-transform based plots of voltage are shown in Fig. 3. High magnitude peaks in the amplitude curve and sum absolute values curve as well as high magnitude contour in the frequency contour indicate the presence of impulsive transient (IT). Continuous finite values in the frequency-amplitude curve of Fig. 3 (v) also indicate the presence of IT. Low magnitude voltage sag is also observed in the amplitude curve of Fig. 3 (iii). Harmonics have been increased after the outage as indicated in the sum absolute value curve and frequency contour of voltage in Fig. 3 (iv) and (ii) respectively. Transient components are also indicated by the sudden increase in amplitude of the frequency-amplitude curve after 0.35 normalized frequencies.

B. Induction Motor is Connected at PCC

Outage of DFIG from weak AC grid in the presence of induction motor load at PCC is performed in the 5th cycle.

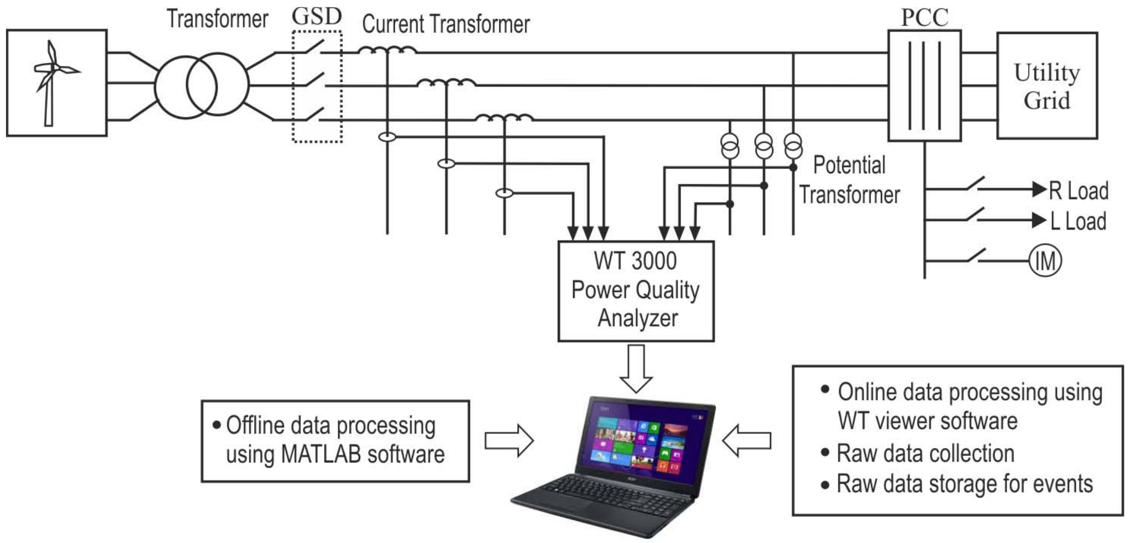

Fig. 1. Schematic diagram of power quality measurement system

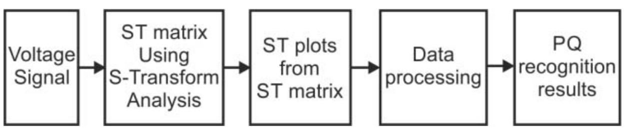

Fig. 2. Block scheme of PQ recognition

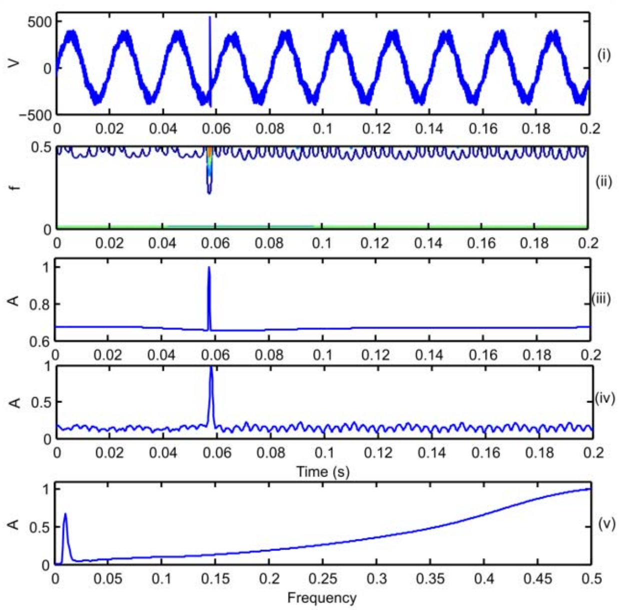

Fig. 3. The S-transform based plots for outage of DFIG from AC grid in the absence of load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

Various S-transform based plots are shown in Fig. 4. Decrease in magnitude of amplitude curve as shown in Fig. 4 (iii) indicate the voltage sag. Low magnitude voltage variations are depicted by the continuous variations of sum absolute valued curve shown in Fig. 4 (iv). A low magnitude impulsive transient is confirmed by the projected contour in the frequency contour, peak available in the sum absolute value curve and continuous finite value of the amplitude frequency contour as shown in Figs. 4 (ii), (iv) and (v) respectively. Low magnitude peak other than fundamental in the frequency-amplitude curve indicate the presence of harmonics. Harmonics are also observed on the surface of sum absolute value curve. High magnitude transients are also detected by the finite value with high magnitude after 0.35 normalized frequency in the frequency amplitude curve of Fig. 4 (v).

C. Inductive Load is Connected at PCC

Outage of DFIG from weak AC grid in the presence of inductive load at PCC is performed in 4th cycle. Various S-transform based plots are shown in Fig. 5. A low magnitude voltage sag is observed as shown in amplitude curve of Fig. 5 (iii). High magnitude peaks in the amplitude curve and sum absolute value curve as well as high magnitude contour in the frequency contour indicate IT. Continuous finite value in frequency-amplitude curve of Fig. 5 (v) also indicates the presence of IT. Low magnitude voltage variations are also observed on the surface of sum absolute values curve. Low magnitude peaks other than fundamental in frequency amplitude curve indicate the presence of harmonics and oscillatory transient (OT). The isolated contours in the frequency contour also indicates OT. Harmonics are also observed on the sum absolute value curve. High magnitude transients are also detected by the finite value with high magnitude after 0.35 normalized frequency in the frequency amplitude curve of Fig. 5 (v).

D. Resistive Load is Connected at PCC

Outage of DFIG from weak AC grid in the presence of resistive load at PCC is performed in 5th cycle. Various S-transform based plots of voltage and current signals are provided in Fig. 6. A low magnitude voltage sag is detected in amplitude

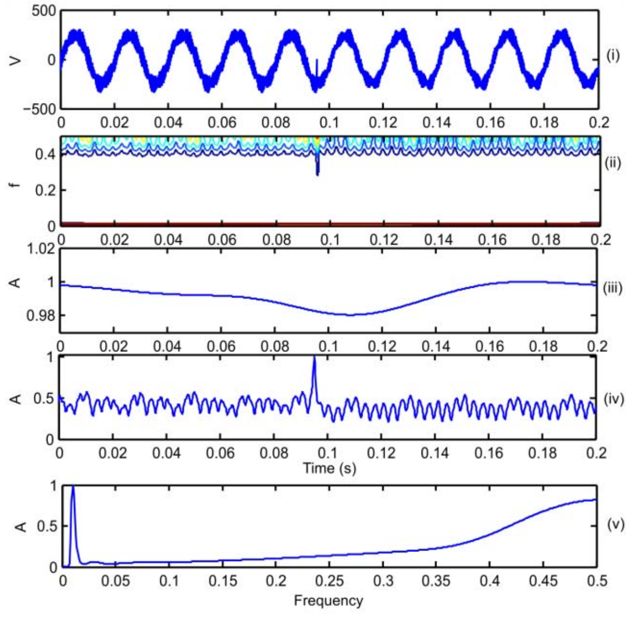

Fig. 4. The S-transform based plots for outage of DFIG from AC grid in the presence of induction motor load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

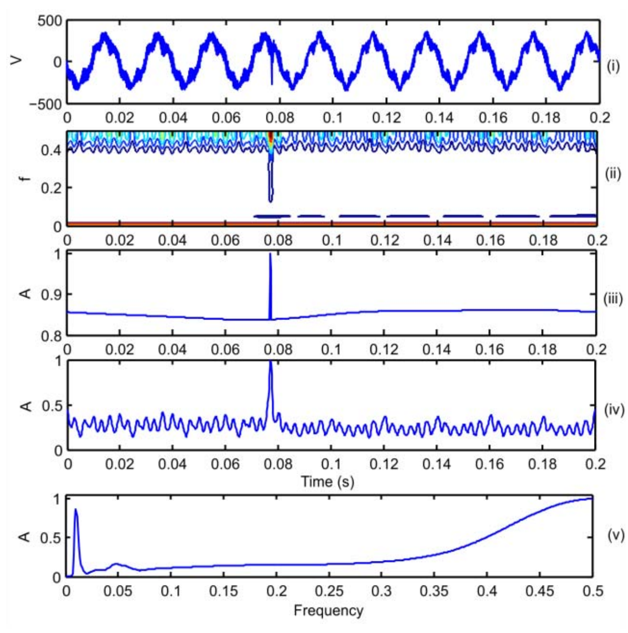

Fig. 5. The S-transform based plots for outage of DFIG from AC grid in the presence of inductive load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

curve of Fig. 6 (iii). It is observed that low magnitude voltage variations appear due to outage. Sum absolute value curve of Fig.9 (iv), detects low magnitude harmonics. High magnitude transients are detected by finite value with high magnitude after 0.35 normalized frequency in frequency amplitude curve of Fig. 6 (v).

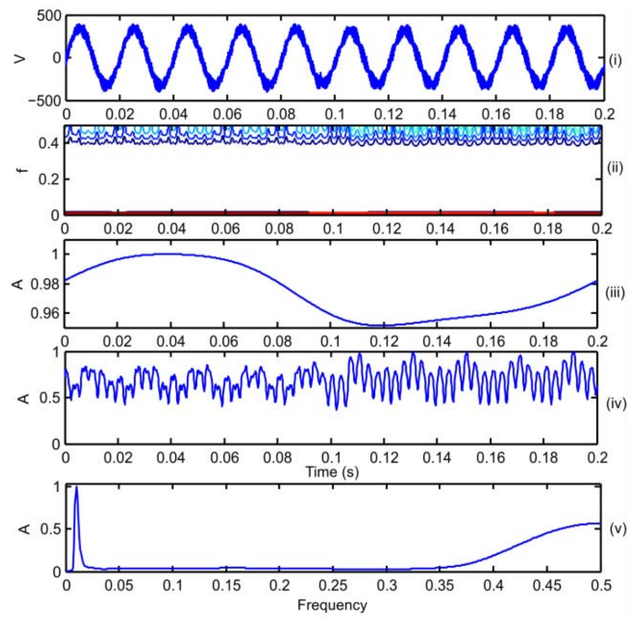

Fig. 6. The S-transform based plots for outage of DFIG from AC grid in the presence of resistive load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

V. Power Quality Analysis with Grid Synchronization of DFIG

This section details the results related to assessment of PQ disturbances associated with synchronization of DFIG to weak AC grid. DFIG is synchronized to the utility grid and then active and reactive powers of the RSC and GSC are controlled so that the power can be injected into the utility network. The investigation of power quality disturbances associated with this power injection stage have been illustrated in the case studies related to synchronization. Various *S*-transform based plots are used for the investigation of PQ disturbances.

A. Without Any Load at PCC

Various S-transform based plots of voltage during grid synchronization of DFIG in the absence of load at PCC are shown in Fig. 7. Continuous spikes available on surface of the sum absolute value curve and amplitude curve of Fig. 7 (iv) and (iii) respectively indicate the harmonics. Variations in magnitude of amplitude curve of Fig. 7 (iii) indicates the voltage fluctuations. Hence, voltage flicker is detected. In Fig. 7 (ii), the upper contour of frequency contour also indicates the harmonics. Finite value of frequency amplitude curve between normalized frequencies 0.35 to 0.5 in the Fig. 7 (v) indicate the harmonics in voltage.

B. Induction Motor is Connected at PCC

Various S-transform based plots of voltage signals during grid synchronization of DFIG in the presence of induction motor load at PCC is shown in Fig. 8. Continuous spikes

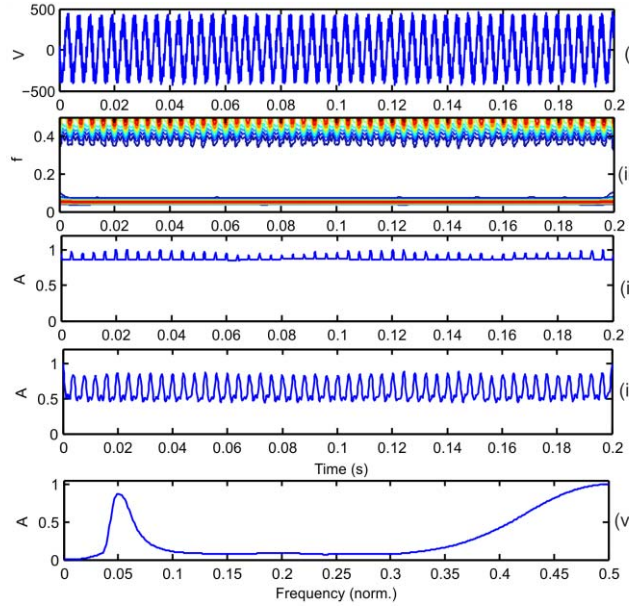

Fig. 7. The S-transform based plots for synchronization of DFIG to weak AC grid in the absence of load at PCC (i) voltage signal (ii) frequency contour (iii) Amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

available on surface of sum absolute value curve and amplitude curve of Fig. 8 (iv) indicate the harmonics. In Fig. 8 (ii), the upper contour of the frequency contour also indicates the harmonics. Variations in magnitude of amplitude curve of Fig. 8 (iii) indicates the voltage fluctuations which is the source of flicker. Finite value of the frequency amplitude curve between the normalized frequency 0.35 to 0.5 in the Fig. 8 (v) indicate the harmonics.

C. Inductive Load is Connected at PCC

Various S-transform based plots of voltage signals during grid synchronization of DFIG are shown in Fig. 9. Continuous spikes available on the surface of sum absolute value curve and amplitude curve of Fig. 9 (iv) indicate the harmonics. Upper contour of frequency contour of Fig. 9 (ii) also indicates the harmonics. Finite value of frequency amplitude curve between normalized frequencies 0.35 to 0.5 in Fig. 9 (v) indicate the transients.

D. Resistive Load is Connected at PCC

Various S-transform based plots of voltage signals during grid synchronization of DFIG in the presence of resistive load at PCC are shown in Fig. 10. Continuous spikes available on surface of sum absolute value curve and amplitude curve indicate the harmonics. In Fig. 10 (ii), the upper contour of the frequency contour also indicates the harmonics. Finite value of frequency amplitude curve between normalized frequency 0.35 to 0.5 in the Fig. 10 (v) indicate the presence of high frequency transients.

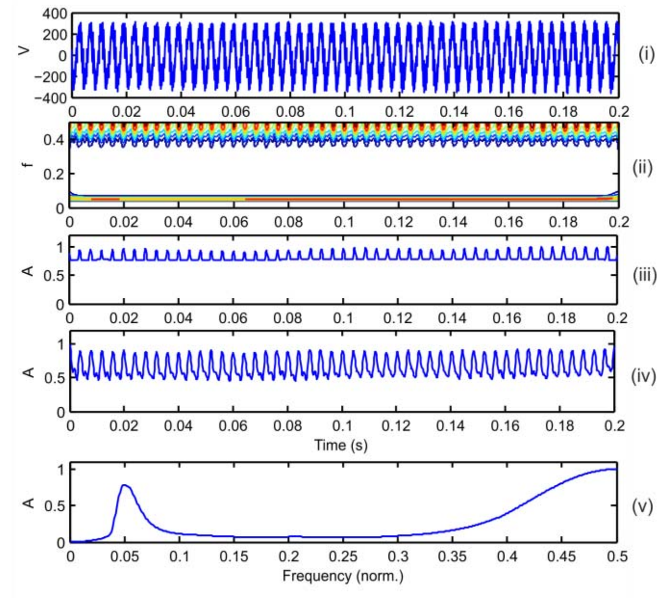

Fig. 8. The S-transform based plots for synchronization of DFIG to weak AC grid in the presence of induction motor load at PCC (i) voltage signal (ii) Frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

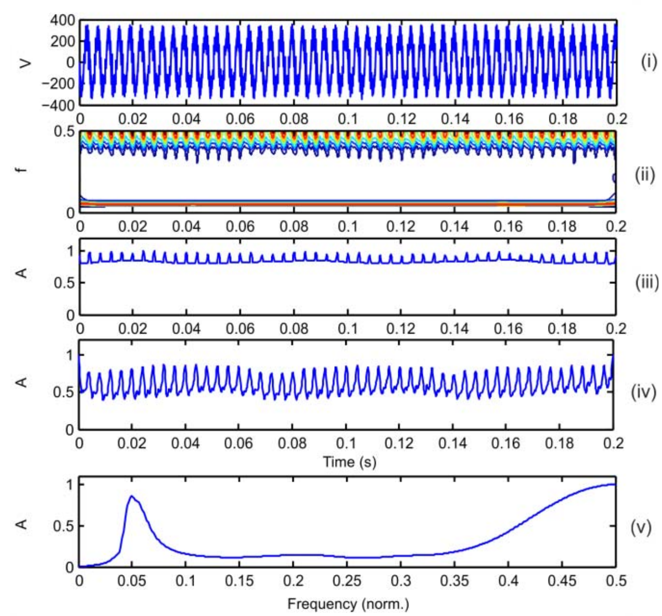

Fig. 9. The S-transform based plots for synchronization of DFIG to weak AC grid in the presence of inductive load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

VI. CONCLUSIONS

In this paper experimental investigations of PQ disturbances associated with grid connected DFIG based wind energy generation system have has been presented. Assessment of the PQ disturbances associated with grid synchronization and

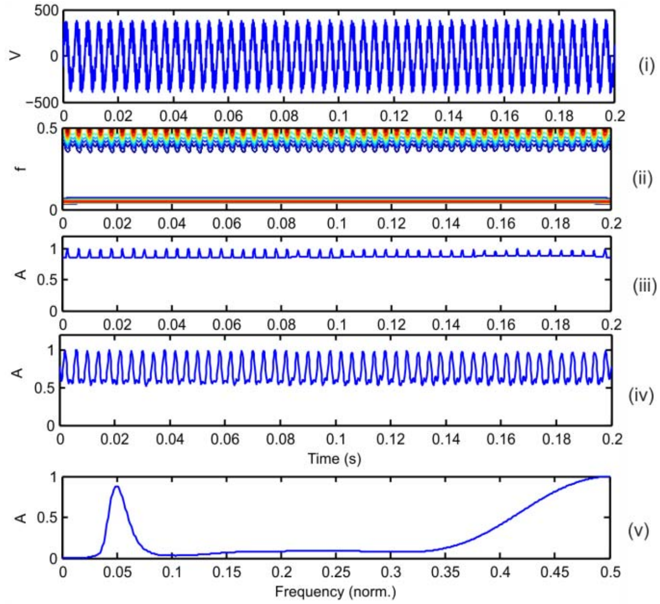

Fig. 10. The S-transform based plots for synchronization of DFIG to weak AC grid in the presence of resistive load at PCC (i) voltage signal (ii) frequency contour (iii) amplitude curve (iv) sum absolute value curve (v) frequency-amplitude curve

outage of DFIG in the presence of inductive load, induction motor load and resistive load at the PCC has been carried out. The PQ disturbances without load at PCC have also been investigated. Voltage signals captured at PCC have been decomposed using the S-transform and S-transform based plots such as frequency contour, amplitude curve, sum absolute value curve and amplitude-frequency curve have been obtained. The analysis of these plots helps to detect the PQ disturbance. It has been observed that the PQ disturbances like harmonics, impulsive transient, voltage sag, flicker and voltage swell are associated with the outage and grid synchronization of wind power generation system utilizing the DFIG based integrated to weak utility grid.

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