BEHAVIOUR OF VECTOR CONTROLLED DFIG BASED LOW VOLTAGE WECS AT VARIOUS WIND SPEEDS

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ABSTRACT

The ever-increasing demand of Electricity necessitates the establishment of new generating stations. Shrinkage of Fossil Fuel and strict environmental regulations enforce us to explore various alternative options of generation. Wind power is becoming more attractive due to its mature and clean aspects. DFIG based WECS are becoming popular as these systems offer high controllability, allow maximum power extraction and individual control of active and reactive power components using back to back power converters of reduced rating. In this paper, the behaviour of WECS with vector controlled DFIG; feeding ac power to distribution system is studied under varying wind velocity conditions. The stator of DFIG is connected directly to the grid while the rotor is fed to the grid through two voltage source converters connected back to back with a common DC link. The system is simulated for better power quality and the system is capable of harnessing maximum power at various wind velocities. The system is simulated in MATLAB Simulink environment.

KEYWORDS: *DFIG, WECS, Vector Control and Induction Generator*

I. INTRODUCTION

Wind energy have attracted the world wide attention due to the shrinkage and soaring prices of fossil fuels. With no dependency on fossil fuels and environmental friendliness, the wind energy is playing a major role as an attractive alternative source of energy. Wind energy is considered as most suitable alternative source of electromagnetic energy conversion due to its mature and clean aspects. Wind energy is the most promising and infact world's largest renewable energy resource among the all alternatives available with the prediction of annual growth rate of 15.5% per year for new annual installations up to the end of 2015. Cumulative installed capacity worldwide by the end of year 2010 reached 199,520 MW and around 24000 new wind turbines were erected across more than 50 different countries [1]. The energy demand in India is ever increasing and expected to grow at an annual rate of 6% over the next 10 years. In India, the total installed capacity of wind power generation was 8754 MW in the year 2008. By the end of 2012, the total installed capacity is expected to reach 12 GW according to the Ministry of new and renewable energy in India. The installation of wind turbines in power system has grown rapidly in last 20 years. Present growth rates and worldwide policies indicate that this development will continue [2].
WECS can be built as constant speed system in which the electrical generating machine is operated at constant speed inspite of having variable wind speeds or it can run as variable speed system in which the machine is operating at varying speeds. The machine speed varies in accordance to the wind speed in varying speed WECS. Squirrel cage induction generators (SCIG) were used in fixed speed WECS during initial stage of WECS development. In case of such fixed speed WECS, the energy conversion efficiency is found to be very low. In order to improve the energy conversion efficiency, the

technology has shifted from fixed speed to variable speed WECS. Variable speed WECS have the advantages of low stress, improved quality, better efficiency, low power and torque pulsations. Amongst various methods to achieve variable speed operation, the wind turbine with doubly fed induction generator (DFIG) is widely used. Variable speed operation with permanent magnet generator necessitate the use of converters for full power while in case of DFIG based WECS, converters have to handle only the slip power which is a small fraction of the system power. In this case the speed of the generator is varied within a certain range below and above the synchronous speed.

To harness maximum amount of wind energy under varying wind velocity conditions, Doubly Fed Induction Generator (DFIG) seems to be one of the promising options. Fixed speed generation schemes, when compared with variable speed wind generators, have both advantages as well as disadvantages. Presently fixed speed SCIGs are used in several wind energy conversion systems (WECS) effectively and efficiently, due to qualities like robustness, low cost, low maintenance and simplicity when they are directly connected to grid [4]. The fixed speed system has no ability to vary the rotor speed therefore it has low efficiency of wind power conversion and no ability to provide reactive power support. For the variable speed generators the key advantage is its ability to extract maximum electric power at various wind speed via rotor speed adjustment. A grid connected DFIG is an interesting option with a growing market demand and presently research is active on the various control aspects of variable speed constant frequency WECS. DFIG systems offer high controllability, allow maximum power extraction and individual control of active and reactive power components is possible using back to back power converters of reduced rating [4].

This paper presents a WECS using DFIG at both sub-synchronous and super-synchronous ranges of speed. The back to back connected converter cascade inserted in the rotor side is able to control the power flow and the control strategy ensures that maximum power is extracted at a given wind velocity. The control strategy employed also ensures better power quality at the grid interface, low voltage ride through capability, dynamic power factor correction and reactive power control. The system model proposed in this paper is developed in MATLAB simulink environment.

The paper is organized as follows: Section I presents an introduction along with objectives of the present work followed by system configuration described in Section II. The simulation model developed in MATLAB/Simulink is detailed in Section III and the results obtained from this model are explained in Section IV. The conclusions drawn from these results obtained under various operating conditions are summarized in Section V.

II. SYSTEM DESCRIPTION

The system consists of a wind turbine coupled to a DFIG through a gearbox. The stator terminals of the DFIG are directly connected to the grid whereas the rotor is connected through a back-to-back connected voltage source converter and coupling inductor as given in Fig 1.

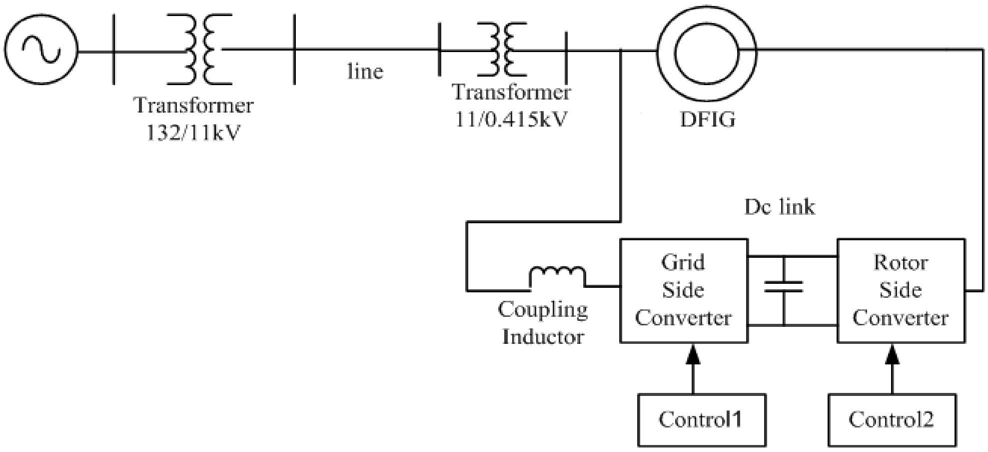


Fig. 1. Block diagram of WECS using DFIG

The coupling inductor is connected at the grid side for filtering the high frequency ripples due to switching of the converter devices. The converters are designed to handle the slip power over a limited speed range. The supply side converter keeps the DC link voltage constant. A vector control strategy (control 1) is used with reference frame oriented with the supply voltage vector which independently controls the active and reactive power flow between supply side converter and supply. The system can be operated in both, sub-synchronous and super-synchronous speeds because the rotor is capable of supplying as well as consuming the slip power. Induction machine is controlled (control 2) by orienting d-axis of synchronously rotating d-q axis frame along the stator flux vector position.

2.1. Optimal Operating Point Tracking

Wind turbine is a non-linear system whose output depends on various parameters such as wind velocity, dimensions of the wind turbine and tip speed ratio. The power extracted (P_{wt}) by a wind turbine is

$$P_{wt} = 0.5\, C_p\, (\lambda, \beta)\, \rho\, A\, v^3 \quad (1)$$

Where v is the wind speed, ρ is the air density, A is the area swept by the blades and C_p is the wind power coefficient. C_p; a function of pitch angle (β) and tip speed ratio (λ) denotes power extraction efficiency. Tip Speed Ratio (TSR) is given by R Ω_l / v where R is turbine radius; Ω_l is the speed of wind turbine. Thus, power captured by the wind turbine mainly depends on TSR when β is fixed. The power conversion efficiency has a well determined maximum C_{pmax} for a specific tip speed ratio λ_{opt}. The optimal control of active power in a variable-speed fixed-pitch WECS can therefore be easily achieved, if λ is controlled for attaining the C_{pmax} corresponding to a given wind velocity. From equation (1) and expression for λ, it follows that

$$P_{wt} = 0.5\, C_p(\lambda)\, \rho\, \pi\, R^2\, v^3 = 0.5\, \{C_p(\lambda) / \lambda^3\}\, \rho\, \pi\, R^5\, \Omega_l^3 \quad (2)$$

The corresponding torque equation can be written as

$$T_{wt} = P_{wt}/\, \Omega_l = K\, \Omega_l^2 \quad (3)$$

$$\text{Where } K = 0.5\, \{C_p(\lambda) / \lambda^3\}\, \rho\, \pi\, R^5 \quad (4)$$

So, by the above equations it can be seen that for a particular TSR, the power extracted by the turbine is maximum for a given wind velocity. By keeping the static operating point of the turbine around the optimal regimes characteristic (ORC), one can ensure an optimal steady-state operation, i.e., the captured power is the maximum available from the wind [5].

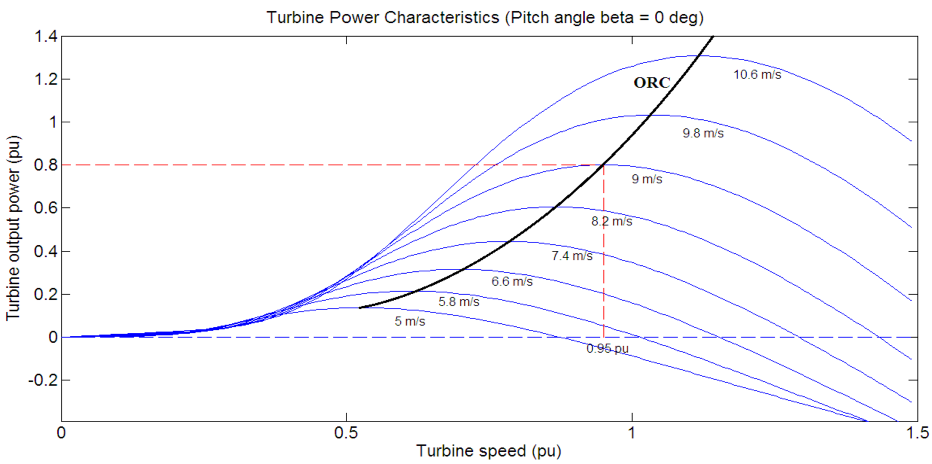


Fig. 2. Optimal regime characteristics for wind turbine power versus speed

This is equivalent to maintaining the tip speed ratio at its optimal value λ_{opt} and can be achieved by operating the turbine at a variable speed, corresponding to the wind speed. In this work, the generator torque is adjusted according to ORC to achieve the optimal power operation at a particular wind speed. The torque control is achieved by the vector control of DFIG via rotor side converter control.

2.2. Grid Side Converter Control

The grid side converter is responsible for maintaining a constant DC link voltage regardless of the direction of rotor power flow. A vector control approach is used with a reference frame oriented along the grid voltage vector, whereby independent control of active and reactive power is achieved [6]. The DC link voltage is regulated through I_d – the direct axis component of current, whereas the quadrature axis component I_q is responsible for the transfer of reactive power. In this work, the system is operated such that unity power factor is achieved. The reactive power reference therefore is considered equal to zero i.e. $Q_{ref} = 0$. Fig. 3 presents the control of DC link voltage through the grid-side converter.

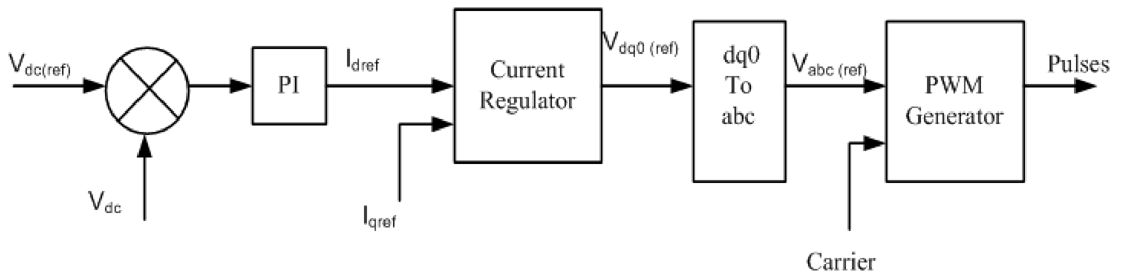


Fig. 3. Block diagram of Grid Side Converter (GSC) control

The active and reactive power flows are

$$P = (V_d I_d + V_q I_q) \quad (5)$$

And

$$Q = (V_d I_q + V_q I_d) \quad (6)$$

Where, V_d, V_q, I_d and I_q are the direct and quadrature axis components of voltages and currents respectively. Aligning the d-axis of the reference frame along the stator voltage position, V_q becomes zero. Since the amplitude of the supply voltage is constant, V_d is constant. So according to Eqns. (5) and (6) the active and reactive power will be proportional to I_d and I_q, respectively.

2.3. Rotor Side Converter Control

Author The rotor side converter controls the active and reactive powers injected by the stator of the DFIG to the grid. Its control configuration is shown in Fig. 4. Vector control of the machine is achieved in synchronously rotating reference frame. The d-axis is aligned with the stator flux vector position, which sets the q-axis stator flux to zero, i.e., $\Phi_{sq} = 0$.
Therefore, torque T is given by,

$$T = - (3/2)\, P\, (L_m/L_s)\, \Phi_{sd}\, I_{rq} \quad (7)$$

where, P is the number of pole pairs, L_m and L_s are the magnetizing and stator inductances, Φ_{sq} and Φ_{sd} are the q-axis and d-axis stator fluxes respectively, I_{rq} is the q-axis rotor current. Thus, I_{rq} controls the electromagnetic torque, that is active power; and I_{rd} controls the reactive power.

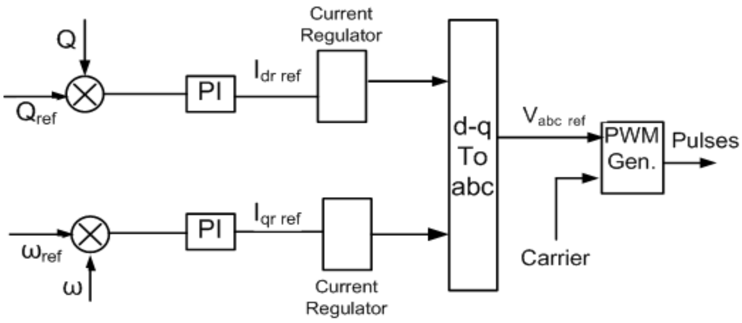


Fig. 4. Block diagram for Rotor Side Converter (RSC) control

The stator flux is determined as follows:

$$\Phi_{sd} = \int (V_{sd} - R_s I_{sd})\, dt \quad (8)$$

$$\Phi_{sq} = \int (V_{sq} - R_s I_{sq})\, dt \quad (9)$$

The stator flux angle is calculated as follows

$$\theta_s = \tan\text{-}1(\Phi_{sq}/\Phi_{sd}) \quad (10)$$

Where, θ_s represents the stator flux position [6]. The error in rotor speed ω_r is processed by a PI controller to yield the torque reference (T_{ref}).

III. Modelling and Simulation

The system described above is modelled in MATLAB/simulink environment. The stator of the DFIG is connected to the distribution system of 415 V, 50 Hz. Wound rotor induction machine is of 24 KW, 415V, 50Hz rating with R_s = 0.01114 pu, R_r = 0.0122 pu, L_s = 0.05295 pu, L_r = 0.05295 pu, L_m = 2.006 pu and Stator/rotor turns ratio = 1.7. Two voltage fed PWM converters with a common DC bus are placed in the rotor circuit providing the rotor side control and grid side control respectively. The DC link voltage is maintained at 600 V. The system is operated at wind speeds of 8.5m/sec, 9.5 m/sec and 10.5 m/sec. Initially the wind speed is assumed to be 8.5 m/sec and later at t=2 s and t=4 sec, the wind speed is changed to 9.5 and 10.5 m/s respectively, yielding sub-synchronous operation in the beginning and then near-synchronous and super-synchronous speeds of the generator subsequently. Change in wind speed is effected, when system reaches steady state for each of the previous wind speeds. The speed of the wind turbine increases to the value dictated by the reference speed, which is set by the wind-turbine characteristics for achieving maximum power. The difference between the reference speed and actual speed of the generator is fed to the PI controller which yields the reference torque or indirectly I_{qref} for the rotor side converter. The reference for the d-axis current is governed by the reactive power requirement. These reference currents are then compared with actual d-q axis rotor currents and the difference is passed through another PI controller to yield refrence d-q voltages, which are further transformed to 3-phase voltages V_{abc} using inverse park transformation. The resulting three phase voltages serve as reference voltages to generate firing pulses for PWM converter. A standard sinusoidal PWM converter is used to generate firing signals for the 6 devices in the converter where each of the phase voltage is compared with high frequency triangular wave to determine the firing pulse patterns.

The GSC is operated in such a way to keep the DC voltage on the capacitor constant, therefore the real power demands of the RSC is met through the GSC control (or by controlling d-axis rotor current of GSC). A feedback controller is used in which the error between the desired and the reference d and q-axis currents is passed through a PI controller to generate V_d and V_q. These are converted into three-phase voltages, which serve as the modulating waves for the conventional sinusoidal PWM converter. In the present work, the q-axis current reference is set to zero in order to achieve unity power factor operation.

IV. RESULTS AND DISCUSSIONS

The model described above is simulated in MATLAB/simulink environment for different wind velocities to check if the system can successfully function in both sub-synchronous as well as super-synchronous speeds. Fig. 5 shows the active power taken by the load connected at the point of common coupling. The load is taken as pure resistive and is maintained constant throughout the simulation work. Fig. 6 shows the variation in generator speed with the change in wind speed. It is very clear that the generator speed is adjusted such that maximum power can be harnessed at a given wind velocity. At 10.5 m/sec of wind velocity, the generator speed is 1.17 pu indicating super synchronous operation. At 9.5 and 8.5 m/sec of wind velocities, the speed of the machines are at 1.03 pu and 0.92 pu respectively indicating near synchronous and sub-synchronous operations respectively.

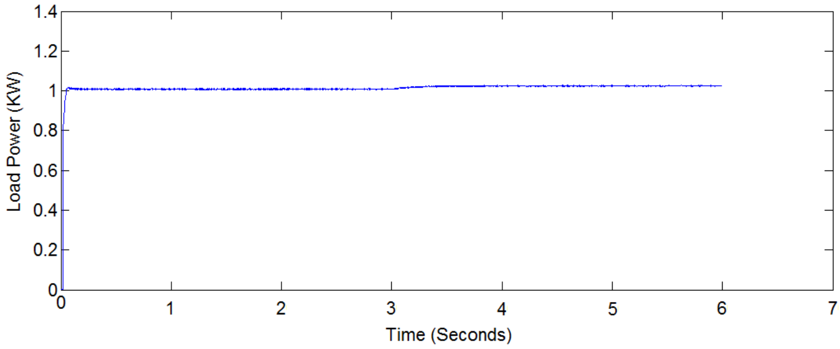


Fig. 5. Load connected at PCC v/s time

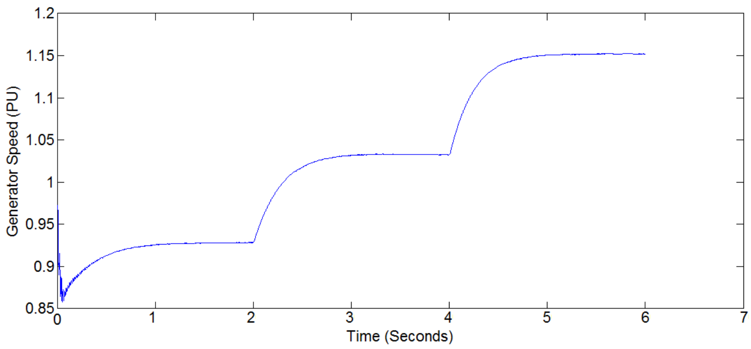


Fig. 6. Variation in generator speed v/s time

Fig. 7 shows the variation of stator power at various wind speeds. It is observed that the magnitude of real power supplied by the stator is changing with the change in wind speed. The stator real power is 16kW, 20kW and 24 kW at 8.5 m/s, 9.5 m/s and 10.5 m/s of wind speeds respectively. The direction is unchanged indicating that the real power always flows from the machine to the grid under generator mode operation of wound rotor induction machine irrespective of the wind speed.

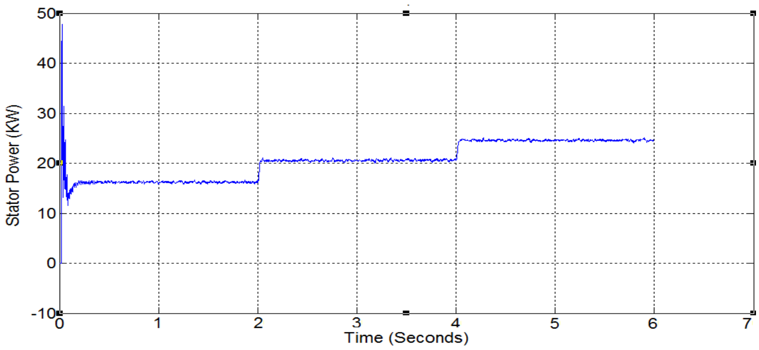
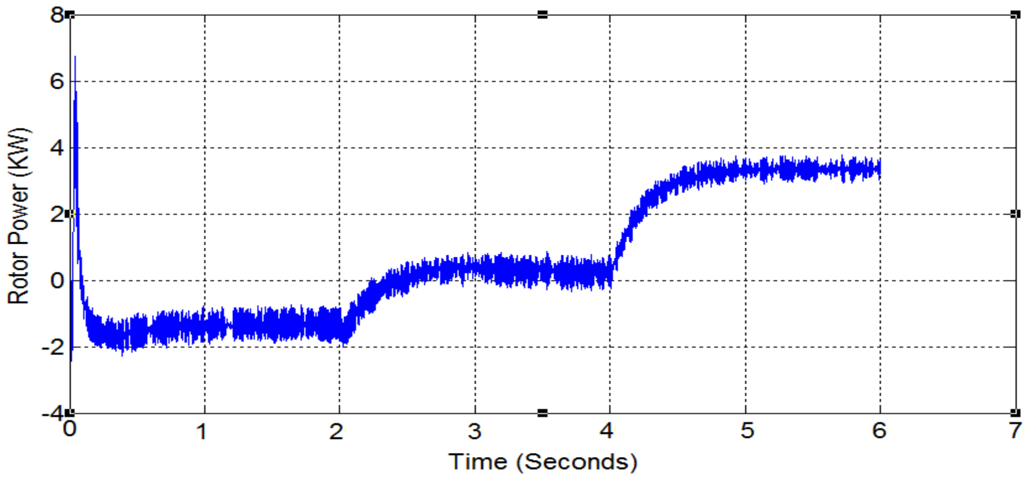


Fig. 7. Variation of stator power for various wind speeds.

Fig. 8 indicates the real and reactive powers of the rotor circuit. As expected, during super-synchronous operation of the generator, the slip power is 3 KW which flows out of the rotor. When the wind speed is reduced to 9.5 the machine is working at near synchronous speed and at this speed the rotor is neither consuming nor supplying the power. On further reduction of wind speed to 8.5 m/sec, the machine starts working in sub-synchronous zone making the slip power negative 2 KW indicating that the rotor is drawing 2 KW power from the grid . The reactive power does not change its sign indicating that as long as I_d of the RSC and I_q of the GSC are not changed, it will not affect the reactive power irrespective of the wind-velocity variations.

Fig. 9 shows the variation of total power supplied by the DFIG at various wind speeds and the results confirm that the total power is the sum of stator power and rotor power at all the wind speeds. At sub synchronous speed it is 14 KW which is the sum of stator power (16 KW) and rotor power (-2 KW), near synchronous speed it is equal to the stator power (20 KW) and at super synchronous speed it is 27 KW (Sum of 24 KW from stator and 3 KW from rotor). Out of the total power, 1KW is consumed by load (Fig.5) and remaining power (13KW, 19KW and 26 KW respectively) is supplied to the grid (Fig. 12).



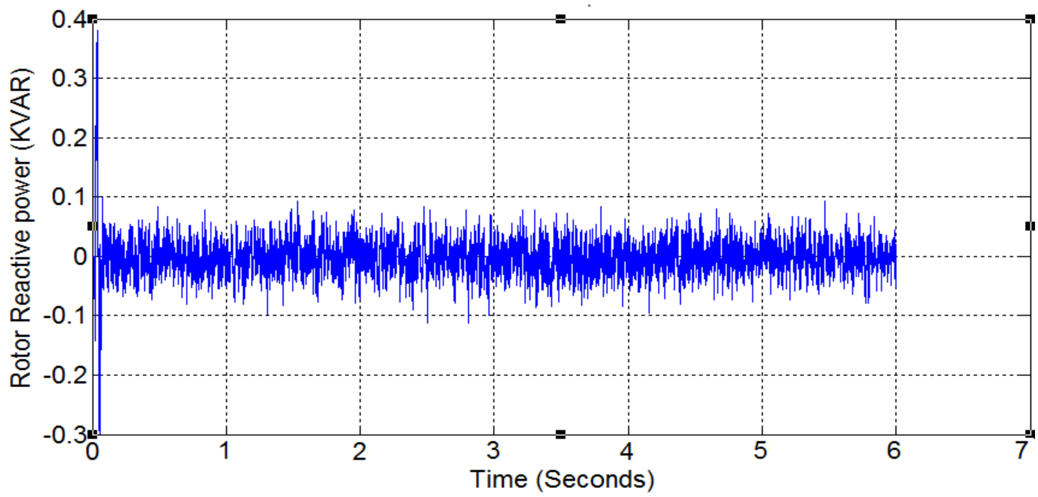


Fig. 8. Variation of rotor real and reactive power for various wind speeds.

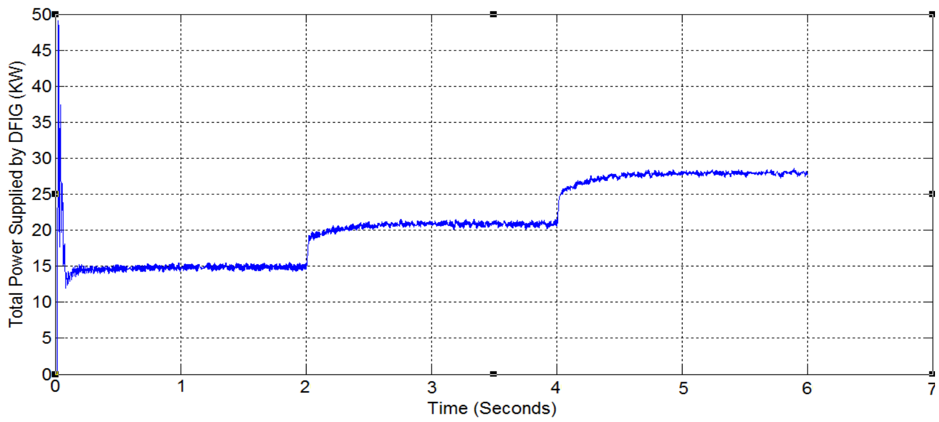


Fig. 9. Variations in total power supplied by DFIG for various wind speeds

The voltage at the PCC is sinusoidal as shown in Fig. 10, whereas the currents are not perfectly sinusoidal (Fig.11); the current is distorted because of the converter operation.

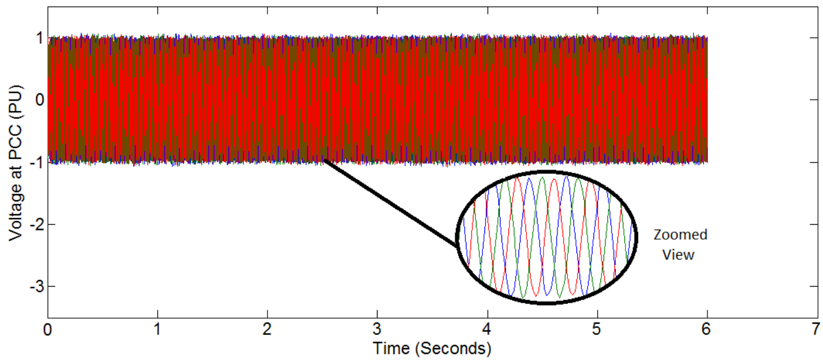


Fig. 10. Voltage at the point of common coupling

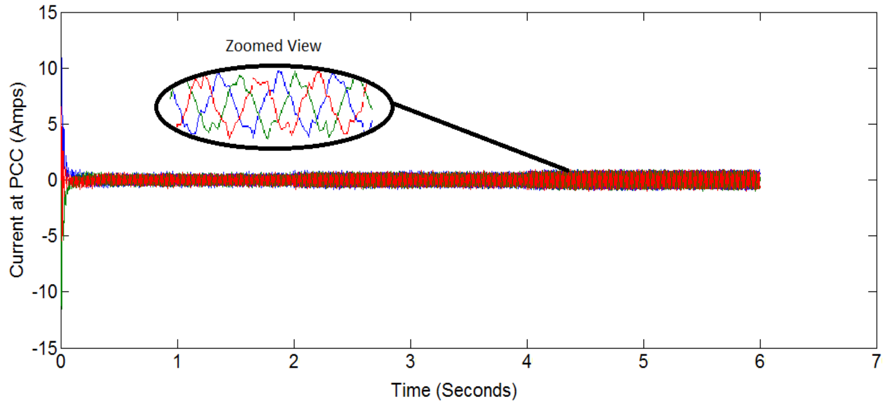


Fig. 11. Current at the point of common coupling

It is also observed that the distortion of the stator current is increasing with the decrease in the wind speed. It can be realized that more power quality problems are encountered at low wind speeds.

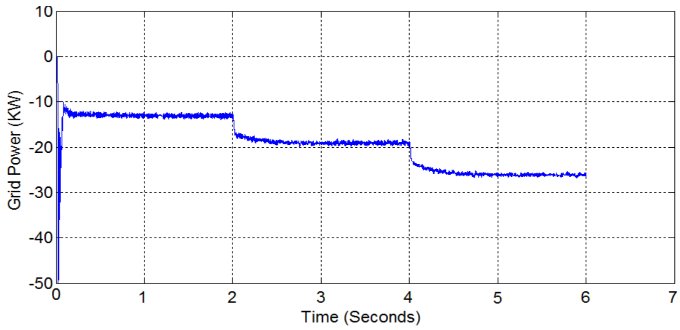


Fig. 12. Variation of power supplied to grid for various wind speeds

V. CONCLUSIONS

This paper has presented the analysis of a grid connected WECS using DFIG under varying wind velocity conditions. The system model is developed in MATLAB/simulink environment. Wind turbine characteristics are embedded into the model in order to extract maximum possible power from the wind according to the wind velocity and tip-speed ratio. The bidirectional power flow control in the DFIG has been obtained by inserting a pair of back-to-back connected voltage source converters between rotor and the utility grid. The complete sets of waveforms indicate that the DFIG functions successfully in both super-synchronous as well as sub-synchronous modes of operation with the appropriate directions of power flow from the stator and the rotor. The rotor side controls work properly maintaining the power balance simultaneously allowing for maximum power being harnessed at a given wind velocity. In all, this paper presents a power analysis of DFIG based grid connected WECS at varying speeds in MATLAB/simulink environment.

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