Modeling of wind power system in on-grid and performance analysis of the system under variant climates

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Abstract

This paper investigates modeling, design and control aspects of a grid-connected wind power system. At present scenario, the Doubly fed Induction Generator (DFIG) wind turbines are increasingly used in large wind farms due to its advantages like better control on active and reactive power, eliminates sudden change in torque and output power with respect to wind speed etc. Here DFIG is connected with the utility grid through the bus bar to share the electrical load of end users. Due to continuous variation of wind speed, the Maximum Power Point Tracking (MPPT) technique applied at the wind farm, it calculates the optimal rotational speed to extract maximum power from wind turbine. In this paper, modified MPPT control strategy has been proposed, the optimal rotational speed is determined based on the mechanical power measured. Furthermore, Stator Flux-Oriented Control (SFOC) technique has been implemented in Rotor Side Converter (RSC) to control reactive power and maintain the stator at unity power factor. The control scheme applied in Grid Side Converter (GSC) aids in maintaining constant DC bus voltage and regulate reactive power flow between win farm and electrical grid. These control strategies help to maintain unity power factor, adequate control on active and reactive power and maintain grid voltage and DC bus voltage constant regardless of the variations in environmental conditions. The effectiveness of the various control strategies applied in Wind farm are validated by theoretical analysis and verified by simulation carried out in Matlab/Simulink environment.

Keywords: Drive train; Wind turbine; Power system; MPPT; DFIG

I. Introduction

Our planet has many critical issues, the energy demand is one among them, due to the ever increase in energy usage, exhaustible non-renewable power resources, and varying climate changes. Compared with traditional energy sources, wind energy has a number of benefits such as clean and environmentally friendly energy (Burton et al. 2001). Due to increased significance on renewable energy, the wind energy sources has gained an increased attention on electrical generator design (Zou Y, Elbuluk M and Sozer Y 2010). In general, there are two ways to achieve constant speed in synchronization with a utility grid. By developing mechanical control like yaw control, blade pitch angle control. Secondly to incorporate the turbine with a generator capable of converting maximum power into electrical energy (Rashid 2017; Muller et al. 2002). Induction generators are generally preferred for both fixed and variable speed control strategies. They convert mechanical power into electrical energy, and sent to grid through RSC, GSC converters and transformer. At point of common coupling between wind farm consists of electricity meters for measurement, transformers for step up or step down of voltage and current and circuit breaker for the disconnection of the whole wind farm (Blaabjerg F and Chen Z. 2005; Hassen et al. 2001). Wind turbines blades capture the power from wind convert it to mechanical power. It is important to limit the obtained mechanical power and maintain enhanced power quality. So, Power electronic converters plays a vital role in Wind power systems. During the grid connected mode, converters helps is increasing efficiency and performance of the system (Chen Z, Guerrero JM and Blaabjerg F 2009). They help in maintaining the quality of frequency, voltage, active and reactive power control, harmonics, etc.

Over the last few years many researchers have been investigating in the integration of renewable energy systems like PV, wind, biomass etc. with the power grid and also in dynamic modelling, stability and control strategy in stand-alone and grid connected conditions. Due to extinction of non-renewable resources, and increase in electrical load demand only way is to integrate renewable energy sources like Wind farms with the utility grid. As a result, in future wind turbines may start to influence the behaviour of electrical power systems. Therefore, accurate steady state and dynamic modelling and appropriate control techniques are very essential to improve performance and efficiency of the system. Ko HS, Yoon GG, Kyung NH and Hong WP. (2008) has provided literature on detailed dynamic model on DFIG wind turbine using the dq-synchronous reference frame and control schemes on voltage source converter for reactive power control under constraints. Andreas Petersson et al (2005) has provided Experimental verification and second order model for different responses to DFIG, was very helpful in modelling of turbines under various wind speed. Due to this rapid growth on generators, it's very essential to draw and utilize the maximum power from the wind. So, usage of MPPT to extract maximum power from low to high power wind turbines is very essential. Dipesh Kumar and Kalyan Chatterjee (2016) has provided overview on different algorithms based on maximum power extraction, complexity and response speed and also highlighted merits and demerits of all MPPT algorithms, it was very helpful in choosing correct algorithm for extraction of maximum power. Hong CM, Ou TC and Lu KH (2013) proposed the MPPT controller for hybrid system consists of solar, wind power, and a diesel-engine has been proposed and provided a Matlab model design and simulation. Jogendra Singh Thongam and Mohand Ouhrouche (2011) in the book explained out the MPPT control techniques for various generators like Squirrel cage Induction Generator, Permanent Magnet Synchronous Generator (PMSG) and Doubly Fed Induction Generator based Wind energy conversion systems. Kyung-Hyun Kim et al. (2012) has proposed a new MPPT technique bases on rotor inertia power by adding proportional controller to reduce moment of inertia of the wind turbines and enhance performance of system. A comparative study on various MPPT methods such as Hill Climbing Search, Optimal Torque Control, Power Signal Feedback and Fuzzy Logic control and its behaviour of all techniques under different wind speeds are also analysed was presented by Zebraoui, O., and M. Bouzi (2018). Dida et al. (2017) proposed Hill climbing searching technique based on fuzzy logic controller and compared with conventional optimal torque control techniques and tested in Matlab environment. The report presented by Lars Henrik et al. (2017) provides survey on wind turbine generators and various power electronic circuits for wind turbines. It helps in decision making for manufactures, engineers and researchers to design generators and power electronic converters according to requirements. Iglesias et al. (2011) provided a review of the power electronics converters used in wind turbines, description on converter components and provides details and evolution about wind turbine markets. A brief description about control schemes in DFIG like stator-flux oriented vector control scheme is applied to the stator/rotor side converter control and back-to-back PWM converters are depicted by Byeon G, Park IK and Jang G. (2010) and Boutoubat M, Mokrani L and Machmoum M. (2013). A coordinated control scheme has been proposed by Anaya-Lara and N. Jenkins (2005) for controlling voltage using RSC and GSC converters and the work also impose the power quality output of wind turbine. Zhou M, Bao G and Gong Y (2011) has proposed a modified MPPT by considering the air density, wind speed and turbine parameters. The technique is analysed on 2MW PMSG wind turbine and the results are validated using Matlab platform.

This research work focuses the performance and response analysis of grid integrated wind farm by applying proposed MPPT algorithm and also analyses the control schemes applied on RSC and GSC converters. The effectiveness of the MPPT algorithm and various control strategies applied in Wind farm are validated by theoretical analysis and verified by Matlab simulation. In this paper section II briefs, out the overview of the proposed system configuration and the control schemes incorporated with the system to improve performance and efficiency. The mechanical modelling of and characteristics of wind turbine are described under section III. Additionally, the power and torque characteristics of wind turbine examined provides comprehensive understanding on the mechanical model of turbine under various wind velocities. The proposed MPPT algorithm applied in the paper is analysed under section IV. It clears out the difference between the conventional algorithm and the proposed algorithm. Modelling of Rotor side converter and Grid side converter and the control schemes applied to the converters are explained in section V and VI. Simulation results of all sections are delivered in section VII. The simulation results have proven the effectiveness of the MPPT technique in extraction the maximum power from the aerodynamic section and robustness of control strategies under varying environmental conditions. Finally, in section VIII the conclusion of research work is discussed.

II. System Configuration

A typical configuration of a DFIG–based wind turbine is shown schematically in Fig. 1. The power system consisting of wind farm of 9 MW rating placed at different locations. The wind farm is integrated with bus bar to inject the generated power. In general, DFIG wind turbines make use of a wound rotor induction generator, where the rotor winding is fed through AC/DC/AC converter and stator windings are straight connected to the bus bar. Rotor side and Grid side converters are two main units of AC/DC/AC converter. They are voltage source converters and the IGBT switches are controlled by forced commutation technique and convert AC to DC voltage. A capacitor connected between acts as DC bus. Slip rings of DFIG is connected with Rotor side converter, it links DC voltage with Grid side converter. This configuration is called Back to Back configuration. SFOC technique applied to RSC controls the wind turbine output power and the voltage measured at the point of common coupling. The controller adapted to GSC tends to maintain the DC bus voltage and control reactive power flow between utility grid and wins station. On the other hand, a modified MPPT technique based on mechanical power measurement is implemented to capture the maximum power from wind farm during variation of the wind speed. In addition, the wind farm is interconnected with the PCC-bus through 575 V/25 KV Δ/Y transformer. The power system is controlled to operate at unity power factor, and the injected active power is transmitted to the electrical grid through 30 Km transmission lines and 25 KV/120 KV Y/Δ transformer.

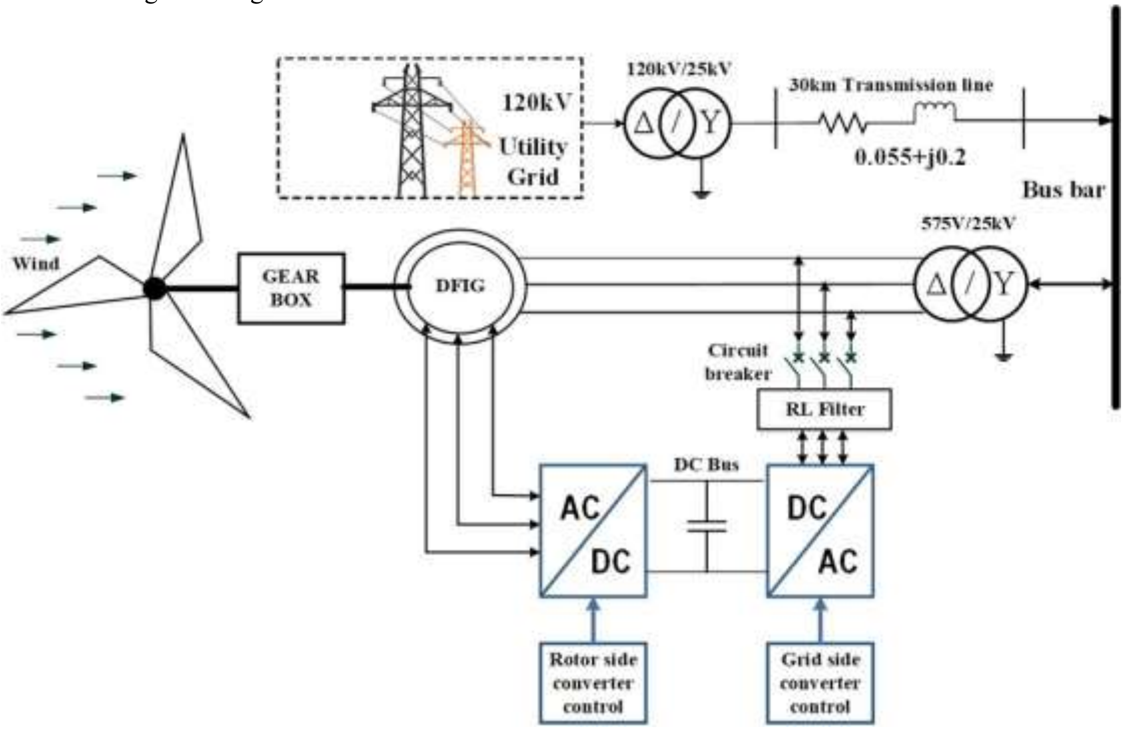

Fig. 1 Schematic diagram of wind turbine

III. Wind energy conversion system

The principle of wind turbines in power generation is to convert the kinetic energy present in air into mechanical power. Selection of number of blades for turbine and choosing the windy area for turbine erection plays a vital role in wind energy conversion system (Ashok Kumar L, S. Sumathi, and P. Surekha2015). The kinetic energy of wind E_W and extracted power P_w is expressed in equation (1) and (2).

$$E_w = \frac{1}{2} m_w v_w^2 \quad (1)$$

$$P_w = \frac{1}{2} \rho A v_w^3 \quad (2)$$

In this section, the mechanical modelling of the wind turbine and its characteristics are examined. The maximum wind turbine power (P_{Tmax}) captured by the turbine is performance coefficient (C_p) times the wind power is expressed in equation (3)

$$P_{Tmax} = P_w C_p = \frac{1}{2}\rho \frac{\pi R^5 \omega_m^3}{\lambda^3} C_p = K_{opt}\omega_m^3 \quad (3)$$

where $K_{opt} = \frac{1}{2}\rho\frac{\pi R^5}{\lambda^3}C_p$

where ρ - density of air (in Kgm^{-3}), R - radius of rotor blade (in m), v_w - wind velocity (in ms^{-1}), λ and λ_{opt} - tip speed ratio (TSR) and ω_m - angular speed of rotor (in rad s^{-1}).
The performance coefficient (C_p) is obtained from the equation (4)

$$C_P(\lambda,\beta)= C_1\left(\frac{C_2}{\lambda_i}-C_3\beta-C_4\right)e^{\frac{C_5}{\lambda_i}}+C_6\lambda \tag{4}$$

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.008\,\beta}-\frac{0.035}{\beta^3+1}$$

and the values of constants are C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, and C_6=0.0068. These constants are obtained from the aerodynamic data. The tip speed ratio is defined as the ratio between the radius of wind turbine R and blade tip speed ω_t to the wind speed V given in equation (5).

$$\lambda=\frac{\omega_t R}{V} \tag{5}$$

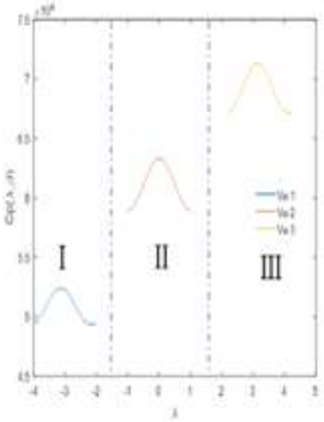

Fig.2 TSR vs Performance coefficient for different wind velocity

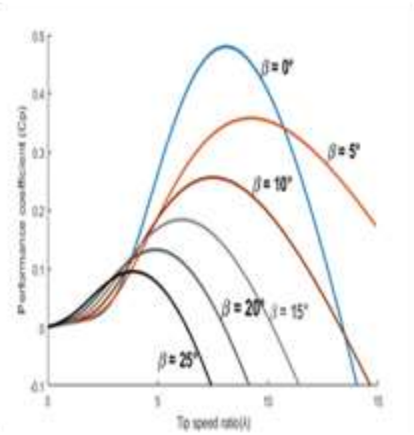

Fig. 3 TSR vs Performance coefficient for different pitch angles

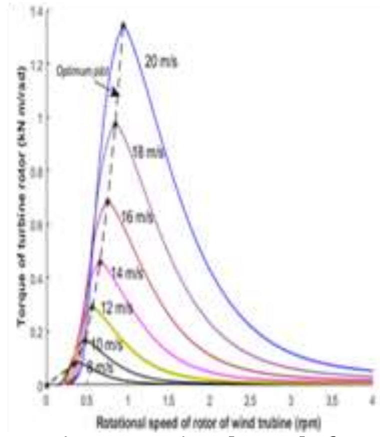

Fig. 4 Rotational speed of rotor vs torque of turbine for different wind velocity

The power extracted and wind speed are directly proportional to each other. At rated wind speed, turbine delivers rated power. (Abdulhamed Hwas and Reza Katebi 2012) Control system is required to deliver constant power at pre-set limits. Once wind exceeds cut off speed the turbine is shut down. Fig.2 demonstrates the performance coefficient (C_p) vs TSR (λ) for various pitch wind speeds, Fig.3 plots variations of TSR (vs) Cp under different pitch angles and Fig 4 demonstrates variation of rotor turbine torque vs rotational speed under different wind speeds.

IV. Maximum Power Tracking

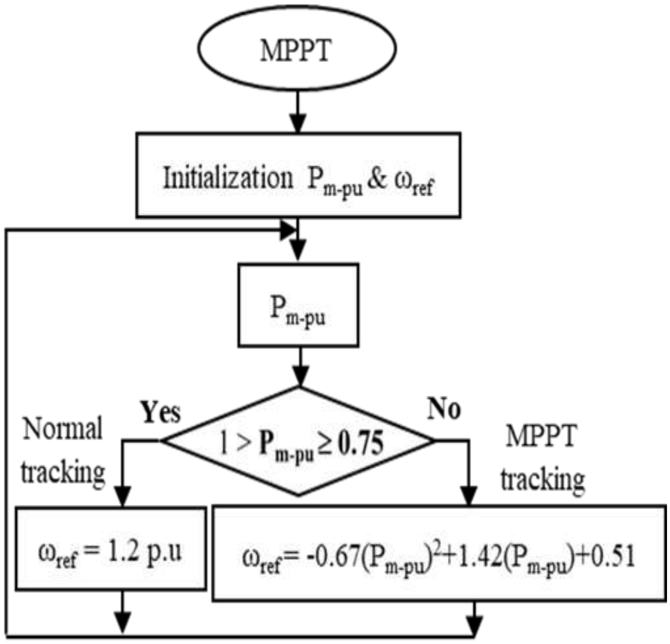

Fig 5. Flow chart of MPPT of wind turbine system

In general, the MPPT techniques applied for Wind system are based on wind speed and wind turbine characteristics. In the techniques performance of the system is reduced due to delay or absence of accuracy in sensor. But the proposed MPPT technique makes use of optimum rotational speed of the rotor to extract the maximum amount of power under varying wind conditions. The flow chart of the proposed MPPT model is illustrated in Fig 5. Initially the mechanical power (Pm-pu) and optimal rotational speed are given into the controller. Secondly the MPPT controller calculates actual mechanical power to calculate optimum rotational speed. If mechanical power is more than 0.75 p.u then optimum rotational speed is normally 1.2 p.u, meanwhile if mechanical power is lesser than 0.75 p.u, then optimum rotational speed is calculated according to equation (6).

$$\omega_{ref} = \begin{cases} 1.2 & 1 \geq P_{m\text{-}pu} \geq 0.75 \\ -0.67(P_{m\text{-}pu})^2+1.42\left(P_{m\text{-}pu}\right)+0.51\ P_{m\text{-}pu} & <0.75 \end{cases} \quad (6)$$

V. Rotor Side Converter Controller

RSC of wind turbine is to capture the maximum power from a wind turbine and control the injected reactive power by the DFIG to keep the stator at unity power factor. The stator flux-oriented control (SFOC) technique has been followed to achieve the controller system, with stator flux (ψ_s) oriented along synchronously rotating d-axis ($\psi_s = \psi_{ds}$) thus, $\psi_{qs} = 0$. The q axis and d axis of stator and rotor voltage can be calculated using equations (7)(8)(9) and (10). The flux linkage in q and d axis of stator and rotor are calculate using equations (11) (12) (13) and (14). The active and reactive power of stator and rotor can be calculated using equations (15) (16) (17) and (18). Finally, the electromagnetic torque produced can be calculated using equation (19).

$$V_{qs} = r_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega\psi_{ds} \quad (7)$$

$$V_{ds} = r_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega\psi_{qs} \quad (8)$$

$$V_{qr} = r_r I_{qr} + \frac{d}{dt}\psi_{qr} + (\omega-\omega_r)\psi_{dr} \quad (9)$$

$$V_{dr} = r_r I_{dr} + \frac{d}{dt}\psi_{dr} + (\omega-\omega_r)\psi_{qr} \quad (10)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad (11)$$

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (12)$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \quad (13)$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \quad (14)$$

$$P_s = \frac{3}{2}(V_{qs}I_{qs} + V_{ds}I_{ds}) \quad (15)$$

$$Q_s = \frac{3}{2}(-V_{ds}I_{qs} + V_{qs}I_{ds}) \quad (16)$$

$$P_r = \frac{3}{2}(V_{qr}I_{qr} + V_{dr}I_{dr}) \quad (17)$$

$$Q_r = \frac{3}{2}(-V_{dr}I_{qr} + V_{qr}I_{dr}) \quad (18)$$

$$T_e = \frac{3P}{2}\left(\psi_{ds}I_{qs} - \psi_{qs}I_{ds}\right) \quad (19)$$

Fig.6 shows the control scheme for the RSC of DFIG. The maximum power from the wind turbine under the different wind speed is calculated from the q-axis component of current. The reference rotor current iqr* is obtained from the MPPT controller. The control signal is compared with the iqr then the difference is applied to the current regulator to produce rotor reference voltage (Vqr*). In the same way the d-axis component is utilized to control the injected reactive power from DFIG and the rotor reference current idr* is generated from the reactive power control loop. The reactive reference power (Qs*) is set to zero to keep the stator of DFIG at unity power factor. The idr* is compared with idr and the error is fed to the current regulator to generate the Vdr*.

VI. Grid Side Converter Controller

The main objective of GSC is to maintain the DC-bus voltage constant and control the exchanged reactive power with the electrical grid. The d-q axis components for GSC voltage in synchronous reference frame are as shown in equation (17) and (18). The d-q synchronous reference frame is employed to implement the decoupled control system for the GSC, with d-axis of grid voltage is aligned with grid voltage vector (V_d=V_g) thus, V_q = 0. Therefore, the active power (P_g) and the DC-Bus voltage can be controlled by (i_d) while reactive power (Q_g) can be adjusted by (i_q) as given in equation (19, 20).

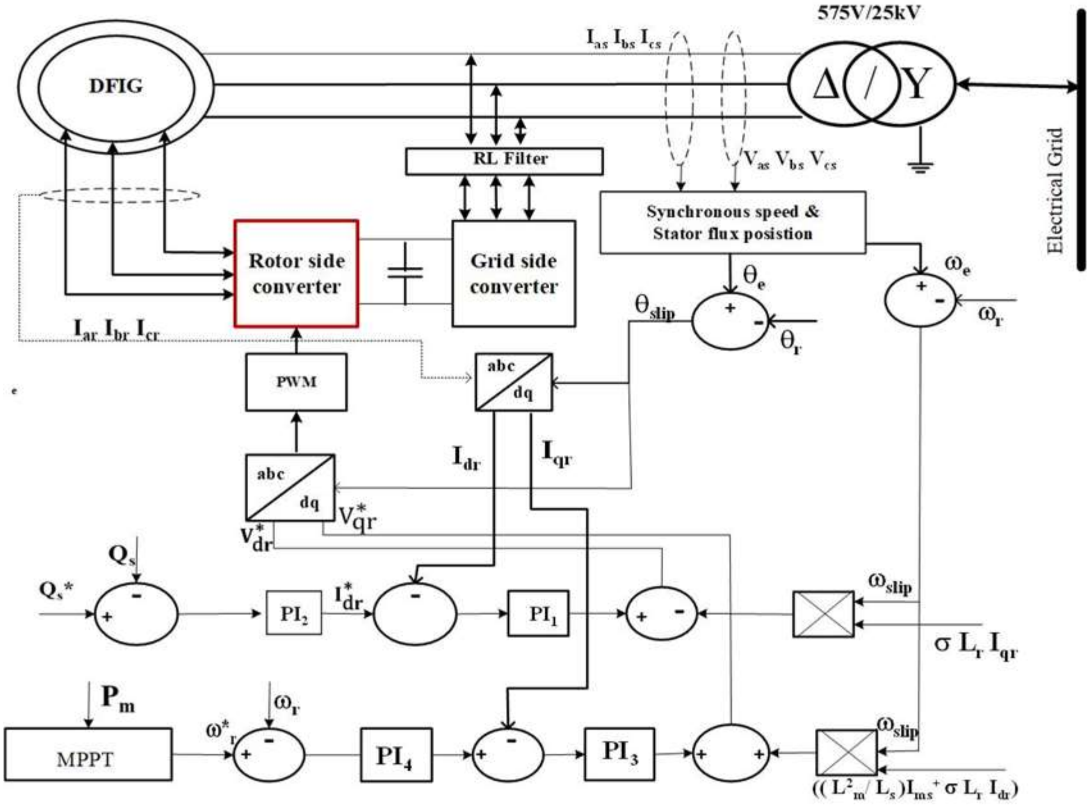

Fig. 6 Control scheme for RSC of DFIG

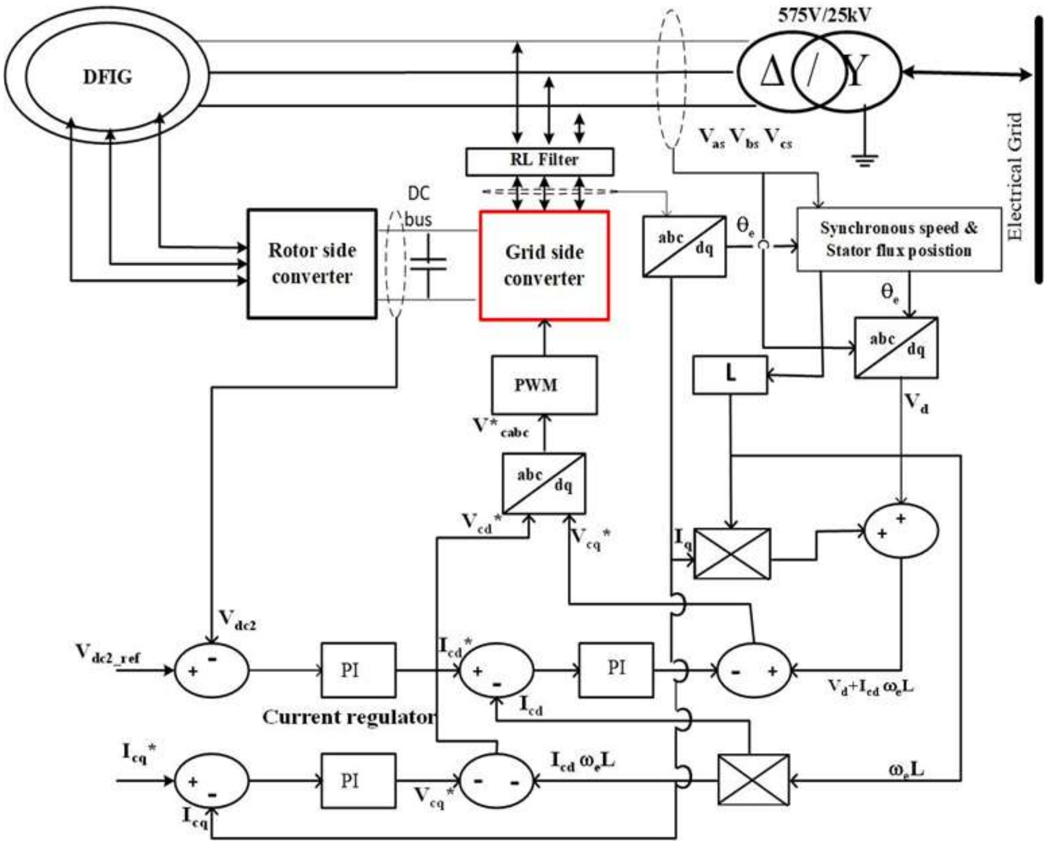

Fig. 7 Control scheme for GSC of DFIG

$$P_g = \frac{3}{2} V_d i_d \text{ and } Q_g = -\frac{3}{2} V_d i_q \quad (19)$$

$$c\,\frac{dV_{dc2}}{dt} = \frac{3m}{4\sqrt{2}}\, i_d - i_{or} \quad (20)$$

The control scheme for GSC is depicted in Fig. 7. The d-axis current component (i_d) is utilized to keep the DC-bus voltage constant, while the q-axis current component (i_q) is utilized to regulate exchanged reactive power with the electrical grid. The reference DC-bus voltage ($V_{dc2\text{-}ref}$) is compared with an actual value (V_{dc2}), and the error is passed through PI-controller to create the d-axis of reference grid current (id*). The difference between the d-axis of reference grid current (id*) and the d-axis of measured grid current (id) is passed through the current regulator to create the d-axis of reference GSC voltage (V_{d1}*).On the other hand, the q-axis of reference grid current (i_q*) is set to zero to maintain the DFIG at unity power factor. The q-axis of reference grid current (i_q*) is compared with the q-axis of measured grid current (i_q) and the difference is applied to the current regulator to create the q-axis of reference GSC voltage (V_{q1}*). The d-q axis components of reference GSC voltage in the synchronous reference frame can be expressed using equation (21)(22).

$$V_{d1}^* = -V'_d + \omega_e L i_q + V_d \quad (21)$$

$$V_{q1}^* = -V'_q - \omega_e L i_d \quad (22)$$

VII. Results and Discussion

The wind power system shown in Fig. 1 is modelled and simulated using Matlab software to evaluate the effectiveness of the MPPT techniques and control strategy during variation of the environmental conditions. The simulation of wind power system is done with different wind speeds such as 10, 12 and 15 m/s. The variable speeds are fed in the aerodynamic section of the system with fast changes in the speed as shown in fig 8 and 9. The DC link voltage between the RSC and GSC obtained in the simulation is as shown in fig 10. The voltage is remains constant as expected for the optimal function of the wind power system. The voltage and current fed into the grid are as shown in fig 11 and fig 12. The voltage is nearly 25 kV, all the three phases are maintaining their amplitude, frequency and phase as that of the expected parameters for a grid. The frequency of the voltage and current are 60 Hz as shown in the insect diagrams of the graphs. The voltage and current generated in the DFIG is fed to the grid through stator windings as well as rotor through RSC and GSC. The fig 13 and fig 14 show the wave form of direct stator voltage and stator current applied to the transformer. The graphs of three phases are having sinusoidal in nature with same amplitude, frequency and phase as expected for the grid. The active and reactive power developed in the DFIG are as shown in the fig 15. The expected active power in this research is 9 MW is maintained constant within few seconds. In the beginning there is a sudden peak in the power due to the supply from the grid to initialize the generation. As expected, the reactive power is very close to zero. Similarly, the voltage and current fed into the grid at the point of common coupling analysed and the waveforms are as shown in Fig 16. The waveforms are distortion less and provide good power quality to the end users.

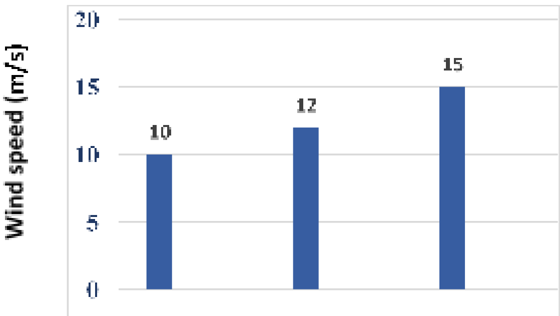

Fig.8 Wind speed profile

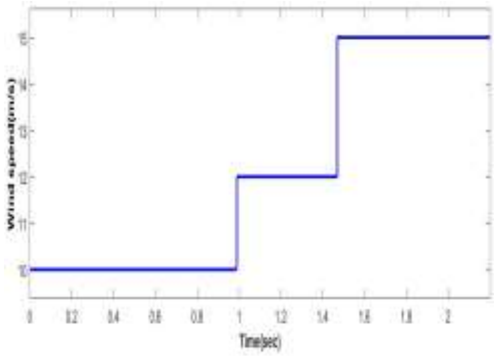

Fig.9 Variable wind speed to turbine

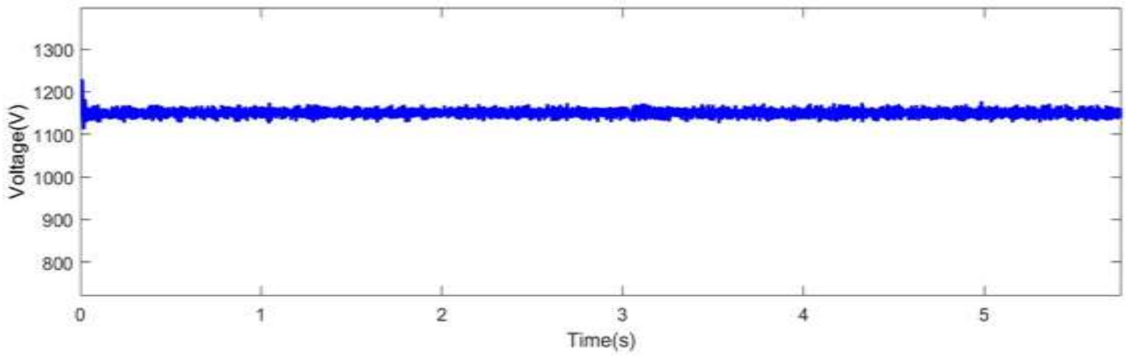

Fig 10. Figure DC bus voltage

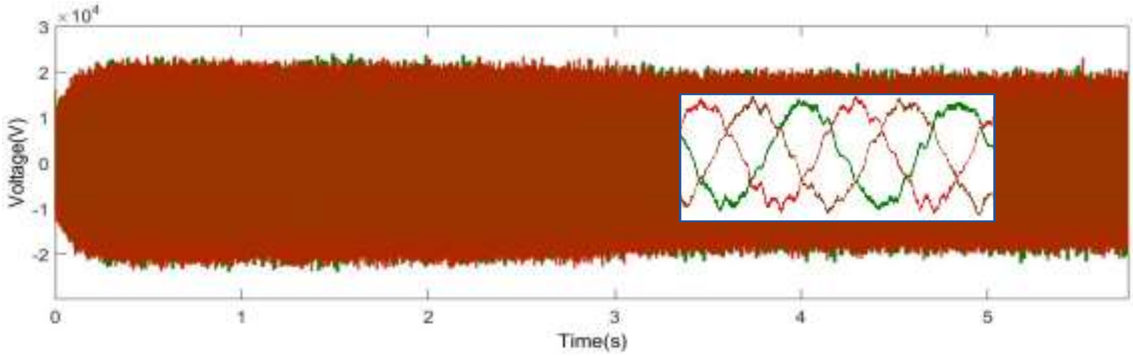

Figure 11 Grid voltage

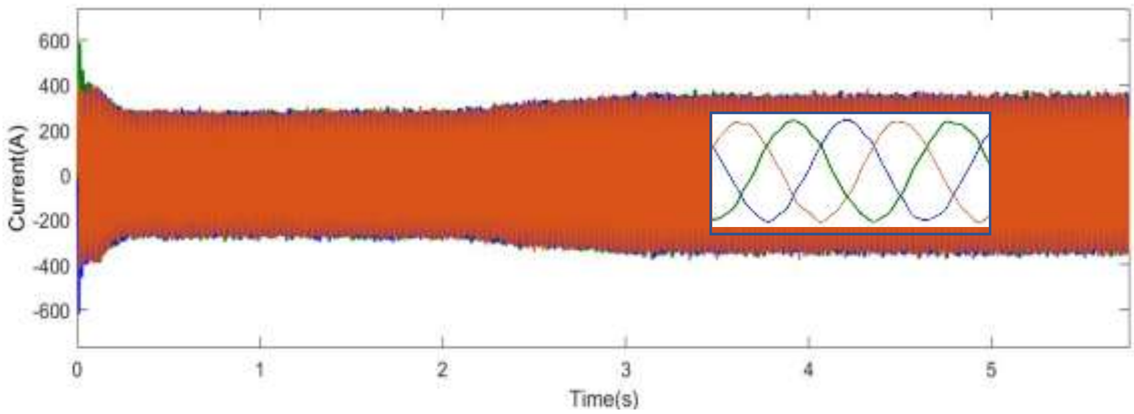

Figure 12 Grid current

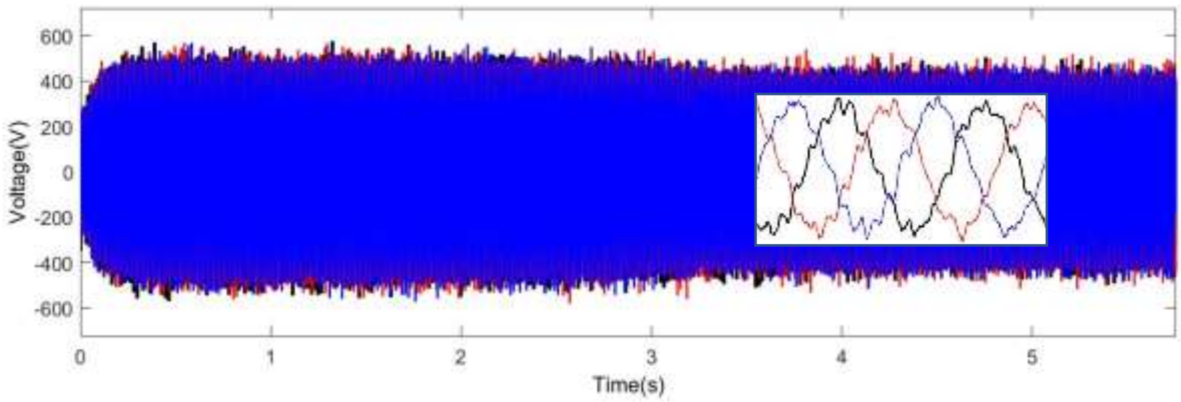

Figure 13 Direct stator voltage

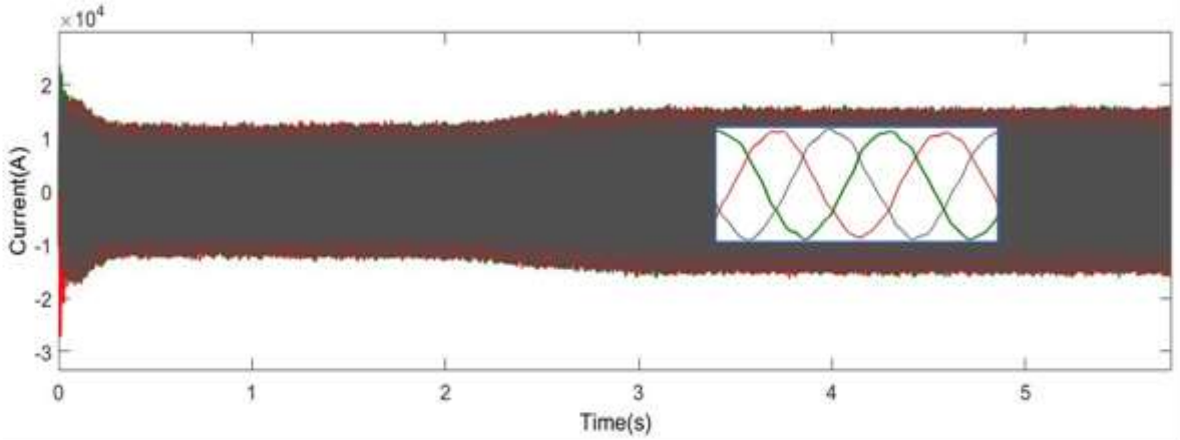

Figure 14 Direct stator current

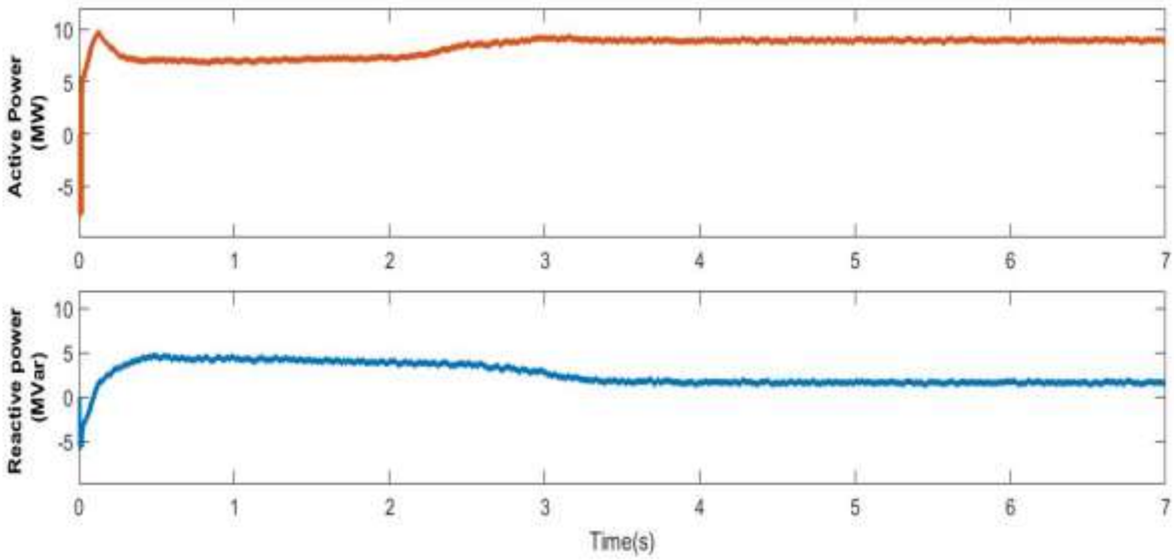

Figure 11 Active and Reactive power of DFIG

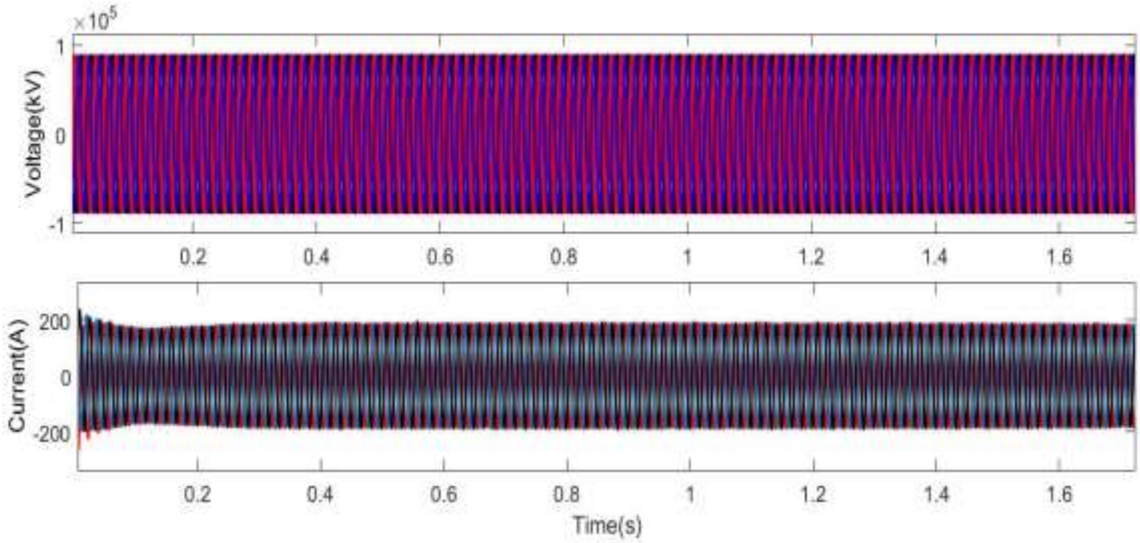

Figure 12 Voltage and current at the point of common coupling

VIII. Conclusion

In this paper a detailed investigation is made on dynamic modelling, design and control strategy of a grid connected wind power system. The wind farm is of 9MW rating integrated with 120 kV utility grid through point of common coupling and active power and other electrical ratings are measured at the bus bar. Various characteristics of wind turbine analysed helps to understand the response of wind turbine parameters to wind variations. The MPPT algorithm extracted from mechanical power is studied and analysed in the proposed system. And further mathematical modelling of Rotor side converter and Grid side converter are completely studied and simulated. The simulation results have proven the validity of the control strategies applied the converter in maintaining the unity power factor, adequate control on active and reactive power and maintain grid voltage and DC bus voltage constant regardless of the variations in environmental conditions

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