DFIG based Wind Power System using PR Control Method

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Abstract - *This paper proposes an improved current control scheme for the rotor-side converter (RSC) of a doubly-fed induction generator (DFIG) wind power generation system. The control scheme consists of a proportional (P) controller and a harmonic resonant (R) regulator tuned at the grid frequency. Thus, the positive and negative sequence components of rotor current are fully regulated by the PR controller without involving the positive and negative sequence decomposition. The design and optimization of the proposed proportional-resonant (PR) controller is emphasized and investigated. To facilitate the electrical production control of the wind turbine, an independent control of the DFIG active and reactive powers is carried out. RSC is applied to control active and reactive power and a grid side converter (GSC) is adopted to control DC-link voltage. Indirect method of RSC control with the loop of power gave good performances in terms of dynamics and response to the reactive power levels. Compared with traditional control schemes based on proportional-integral (PI) current controllers, the presented control strategy effectively suppresses rotor current and reduces oscillations of DFIG power. The PR controller applied to the RSC control of a DFIG is employed in this study to improve the accuracy of the control system. One of the most important features of the resonant controller is that it is capable of sufficiently tracking the reference current, and therefore, can eliminate steady-state control variable errors at the chosen (resonant) frequencies. The PR controller applied to the RSC control of a DFIG is employed in this study to improve the accuracy of the control system. Simulation studies are carried out on a 1.5 MW wind-turbine driven DFIG system. The validity and feasibility of the proposed current controller are confirmed from the simulated results*

Key Words: Doubly-Fed Induction Generator (DFIG), Rotor Side Converter (RSC), Grid Side Converter (RSC), Proportional-Resonant(PR) controller, MATLAB/Simulink.

1. INTRODUCTION

Modern wind power technology has come a long way in the last two decades, both globally and in India. Uncertain and unpredictable behavior of wind energy, affected by the daily and seasonal climate change, can have a negative impact on the performance and stability of the system. Variable speed technologies of wind turbine allow extracting the maximum amount of wind energy by operating over a wide range of wind speeds. In the modern wind energy conversion systems (WECS), doubly fed induction generators (DFIG) have a crucial role in variable speed technology. The stator of the DFIG is directly connected to the grid, while the rotor is linked to the grid by a back-to-back converter. To facilitate the electrical production control of the wind turbine, we carry out an independent control of the DFIG active and reactive powers. The indirect method of control consists in taking into account the coupling terms and compensating them by carrying out a system includes two loops, making the possibility of rotor powers and currents control. Proportional-integral (PI) controllers have been widely used in current controllers to compensate for errors because of their simplicity and effectiveness. PI controllers have certain limitations and drawbacks when used to accurately regulate AC reference currents due to their limited bandwidth. Resonant controllers are a good option to suppress the current harmonics due to their high control gain at their resonant frequencies. Presently, resonant controllers are widely employed in power converter systems such as active power filters, photovoltaic inverters and wind turbines. Due to the infinite gain at a selected resonant frequency, this controller is capable of completely eliminating the steady-state control error at that frequency. The PR controllers are more robust in terms of response tracking and less sensitive to nonlinearity, parametric variations, and disturbances compared with the PI controllers.

2. DOUBLY FED INDUCTION GENERATOR

The DFIG is one of the machines which employ the principle of variable speed. Unlike other generators, the DFIG delivers power to the grid through both stator and rotor terminals. The stator is directly connected to the grid while the rotor is connected to the grid via power electronic converters. Wind turbines usually employ DFIG having Wound Rotor Induction Generator. The basic diagram of a DFIG is shown in Fig. 1. The stator is connected to the mains directly, as shown. The Rotor is fed through the power electronics converters present, via the slip rings. This permits the DFIG operation at various speeds depending on the changing speeds of wind. The AC/DC/AC converter is usually a PWM (Pulse Width Modulation) converter. It employs sinusoidal PWM technique for reduction of harmonics present in the system. It has two components, RSC and GSC. They are voltage source converters which employ forced commutation (IGBT) devices to generate AC voltage from a

DC source. The power in wind is extracted by the turbine and then it is converted into electrical power in the Induction Generator and sent to the grid via stator and rotor terminals. The command for the pitch angle and voltage is sent by the control system to the rotor side converter (RSC) and grid side converter (GSC) for controlling the wind turbine power, the DC link voltage and reactive power at the grid windings. RSC controls the torque and speed of the generator. It also controls the power factor at the stator terminals whereas GSC maintains the DC link voltage constant. The back to back converter arrangement sets the stage for the conversion of the varying generator frequency and voltage output to constant voltage and frequency, at par with the grid. The Gearbox is used to ensure that the maximum rotor speed occurs at the rated generator speed

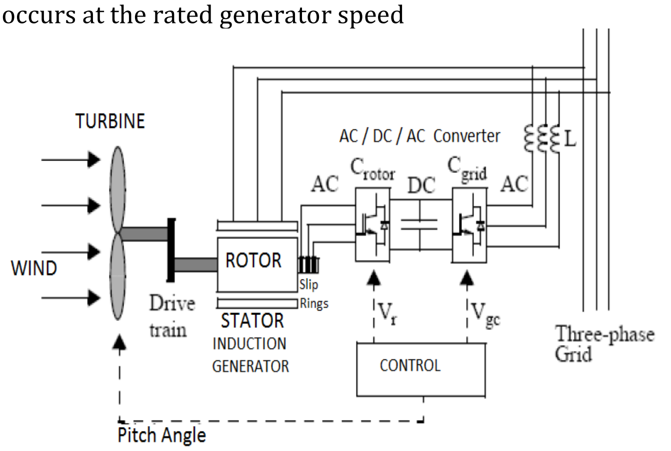

Fig - 1: DFIG system with converters, turbine and grid.

Once the speed of the rotor exceeds that of the rotating magnetic field of the stator (synchronous speed), a current is induced in rotor windings. With increase in the rotor speed, power is transferred to the stator via electromagnetic mechanism, and is then supplied to the electric grid through the stator terminals.

3. CONTROL OF DFIG

Different control methods are popular in the industry, such as scalar method (V/f), vector control, direct and indirect field oriented control, rotor and stator flux control, adaptive flux observer, stator flux orientation and field weakening control. All the said methods are complex, for reducing the complexity to choose the direct or indirect power control scheme to control the machine.

3.1 Rotor side converter control

The RSC supplies the voltage to the rotor windings of the DFIG. The purpose of the RSC is to control the rotor currents such that the rotor flux position is optimally oriented with respect to the stator flux. The RSC uses a torque controller to regulate the wind turbine output power and the voltage (or reactive power) measured at the machine stator terminals. The power is controlled in order to follow a pre-defined turbine power-speed characteristic to track the maximum power point. The actual electrical output power from the generator terminals, added to the total power losses (mechanical and electrical) is compared with the reference power obtained from the wind turbine characteristic. Usually, a PI regulator is used at the outer control loop to reduce the power error to zero. The output of this regulator is the reference rotor current i_{rq_ref} that must be injected in the rotor winding by rotor-side converter. The actual i_{rq} component of rotor current is compared with i_{rq_ref} and the error is reduced to zero by a current PI regulator at the inner control loop.

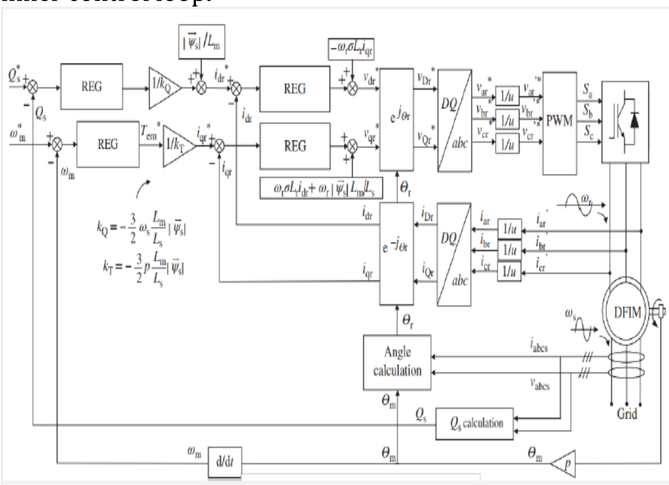

Fig - 2: Rotor side converter control scheme.

Fig. 2 shows general RSC control scheme. The output of this current controller is the voltage v_{rq} generated by the RSC. With another similarly regulated i_{rd} and v_{rd} component the required 3-phase voltages applied to the rotor winding are obtained.

3.1.1 Indirect control for RSC

To facilitate the electrical production control of the wind turbine, we carry out an independent control of the DFIG active and reactive powers. For this purpose, there are two solutions: The first method consists in neglecting the coupling terms and installing an independent regulator on each axis to control the active and reactive powers independently. This method will be called direct method because the powers regulators control directly the machine rotor voltages. The second method consists in taking into account these coupling terms and compensating them by carrying out a system includes two loops, making the possibility of rotor powers and currents control. This method is called indirect method.

Rotor voltage equations in dq reference frame are,

$$V_{rd} = R_r i_{rd} + \sigma\, L_r \frac{di_{rd}}{dt} - \omega_r\, \sigma\, L_r\, i_{rq} + \frac{M\, V_s}{L_s}$$

$$V_{rq} = R_r i_{rq} + \sigma\, L_r \frac{di_{rq}}{dt} + \omega_r\, \sigma\, L_r\, i_{rd} + \frac{g\, M\, V_s}{L_s}$$

Where, $\sigma = 1 - \frac{M^2}{L_s L_r}$ is leakage factor and g is the slip

Stator currents can be expressed as,

$$i_{sd} = -\frac{M}{L_s} i_{rd} + \frac{V_s}{L_s \omega_s}$$

$$i_{sq} = -\frac{M}{L_s} i_{rq}$$

Finally we deduce the following expression of P_s and Q_s as,

$$P_s = -\frac{M}{L_s} V_s i_{rq}$$

$$Q_s = -\frac{M}{L_s} V_s i_{rd} + \frac{V_s{}^2}{L_s \omega_s}$$

The indirect method consists in reproducing, in opposite direction, the block diagram of the system to be controlled. We build a block diagram allowing thus, expressing the voltages according to the powers. We end up then to a model which corresponds to that same of the machine but in opposite direction. The indirect control will contain therefore, all the elements showed in the DFIG block diagram. According to equation of P_s and Q_s, active and reactive power can be controlled via rotor currents. That is why we call this approach as indirect method.

The current references can be deduced as follows,

$$i_{rq\_ref} = \left(-\frac{L_s}{M V_s}\right) P_{s\_ref}$$

$$i_{rd\_ref} = \left(-\frac{L_s}{M V_s}\right) \left(Q_{s\_ref} - \frac{V_s{}^2}{L_s \omega_s}\right)$$

And expressions for rotor voltages used are,

$$V_{rd} = R_r i_{rd} + \left(L_r - \frac{M^2}{V_s}\right) \frac{di_{rd}}{dt} - s\,\omega_s \left(L_r - \frac{M^2}{V_s}\right) i_{rq}$$

$$V_{rq} = R_r i_{rq} + \left(L_r - \frac{M^2}{V_s}\right) \frac{di_{rq}}{dt} + s\,\omega_s \left(L_r - \frac{M^2}{V_s}\right) i_{rd} + g \frac{M V_s}{L_s}$$

3.1.2 Control with loop of power

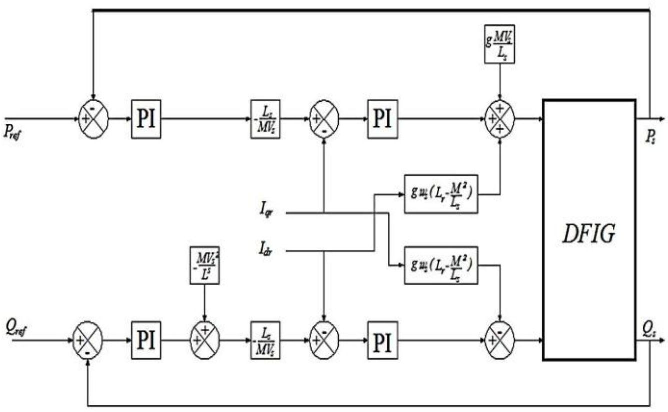

Fig - 3: Block diagram of indirect control with the power loop [8].

So as to improve the indirect control, we will incorporate an additional regulation loop at the powers in the goal to eliminate the static error while maintaining the system dynamics. Block diagram presented in Fig. 3, where we distinguish two regulation loop functions for each axis, one controlling the current and the other power.

3.2 Grid side converter control

The aim of the grid side control is to maintain DC link voltage at a constant level irrespective of the rotor power and guarantees unity power factor operation in rotor circuit. Fig. 4 shows the grid side converter control scheme. At any instance, the power exported by the GSC is determined by the state of the DC- link voltage. The grid-side converter controller monitors the DC- link voltage. If the DC- link voltage rises, the grid-side converter can export more real power by increasing the load angle in order that the DC- link voltage moves back towards it nominal value. If more power is being exported by the GSC than is currently being generated by the RSC, the DC link voltage will fall below its nominal value.

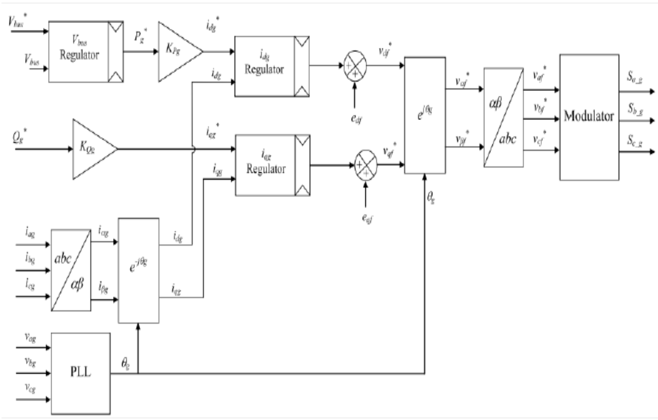

Fig - 4: Grid side converter control scheme.

3.3 Comparison of PI and PR Controller

PR Controllers have significant advantage over PI controllers in terms of regulating ac input quantities at tuning frequencies. PI Controllers provide high gain over DC signals and need to have a very high bandwidth for accurately regulating ac signals. However, PI controllers are basically low pass filters hence they do provide a lag in case of regulating ac quantities. Moreover, it is not always possible to provide a very high bandwidth for PI controllers if switching frequency is not very high. PR controllers are tuned to provide a very high gain or an infinite gain at the tuning frequency. PR controllers are very good at regulating a time varying ac periodic signal of fixed frequency. PR controllers have the disadvantage that if the input quantity to the controller has a frequency other than the tuning frequency of the PR controller, then the controller will provide a much lower gain and will not be able to regulate the reference signal.

A sample Bode plot of PI controller and a PR controller tuned at 50 Hz is shown in figure. The parameters are assumed as follows, K_p=25, K_i=K_r=1000.

$$G_{PI} = K_P + \frac{K_i}{s} \text{ and } G_{PR} = K_P + \frac{K_r\ s}{s^2+\omega^2}$$

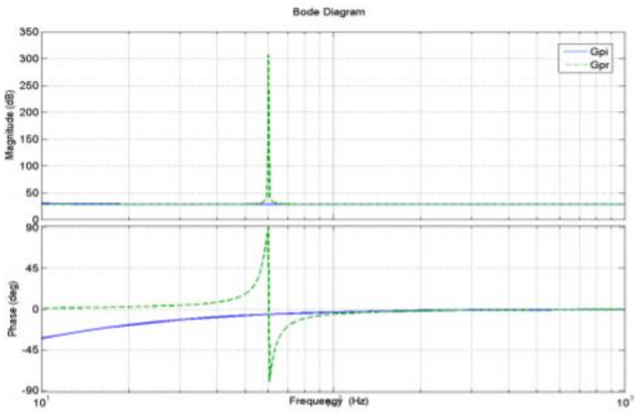

Fig - 5: Bode plot of PI and PR controllers.

It can be observed from figure that PR controller is giving a very high gain at 50 Hz but at all other frequencies it is giving the same gain as PI controller. Hence it can be concluded that PI controller is capable enough for providing sufficient gain to ac input quantity of frequency 50 Hz. However, PR controller does provide a very high gain to ac input quantity of tuning frequency.

4. PROPOSED SYSTEM MODELLING IN MATLAB/SIMULINK

The development of simulations of the complete model (turbine and DFIG) using indirect control method with power loop under MATLAB/Simulink/SimPowerSystems environment.

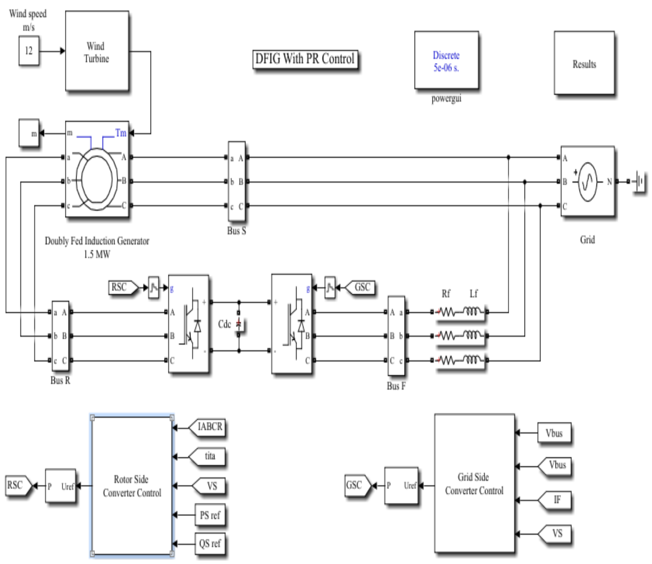

Fig - 6: Wind powered DFIG model with RSC and GSC control in MATLAB/Simulink.

The typical DFIG configuration, illustrated in Fig. 6 consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back power converter. Parameters used in the simulation are represented in Table 1.

Table - 1: Simulation parameters and ratings

Parameter	**Rating**
DFIG parameters	
Power rating, P	1.5 MW
Grid frequency	50 Hz
Grid voltage	690 V
Stator resistance, R_s	2.57 mΩ
Rotor resistance, R_r	2.88 mΩ
Stator inductance, Ls	2.547 mH
Rotor inductance, Lr	2.547 mH
Magnetizing inductance, L_M=M	2.5 mH
Pole pairs, p	2
Rated speed, N	1500 rpm
Grid parameters	
Grid filter resistance (R_f)	0.025 mΩ
Grid filter inductance (L_f)	0.3 mH
Turbine parameters	
Rated wind speed	12 m/sec
Rated turbine power	1.5 MW
Wind turbine inertia constant H (s)	4.32
Shaft spring constant (pu of Nominal mechanical torque/rad)	1.11
Shaft mutual damping (pu of nominal mechanical torque/pu dw)	1.5
Shaft base speed (rad/s)	188.5
Turbine initial speed (pu of base speed)	1
Initial output torque (pu of nominal mechanical torque)	0.83

Fig. 7 shows modeling of the wind turbine.

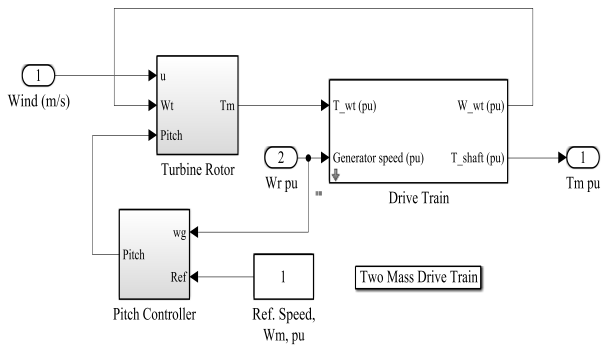

Fig - 7: MATLAB/Simulink based wind turbine model.

The maximum power collected by turbine blades is,

$$P_{max} = \frac{1}{2}\ \rho\ \pi\ R^2\ V_w{}^3$$

Where, P_{max}: Maximum power (Watts), ρ: Air density, about 1225 kg/m^3, V_w: Wind speed (m/sec), S: Surface swept by the propeller (m^3) and R: Radius of turbine (m).

Turbine output power characteristics of 1.5 MW turbine vs turbine speed (pitch angle β = 0^0) at different wind speeds is shown in Fig. 8.

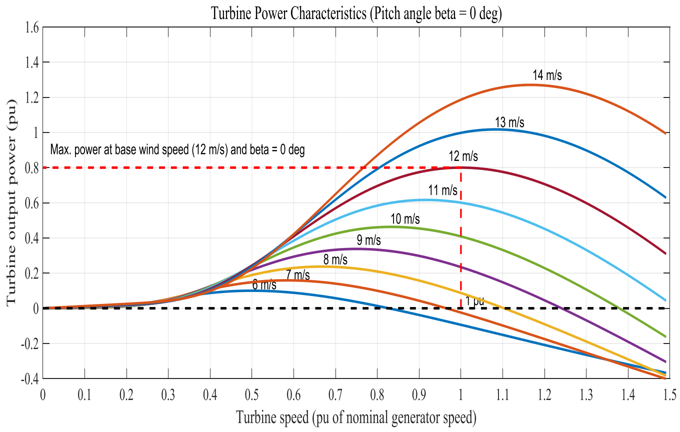

Fig - 8: Power characteristics of 1.5 MW turbine (pitch angle β = 0^0).

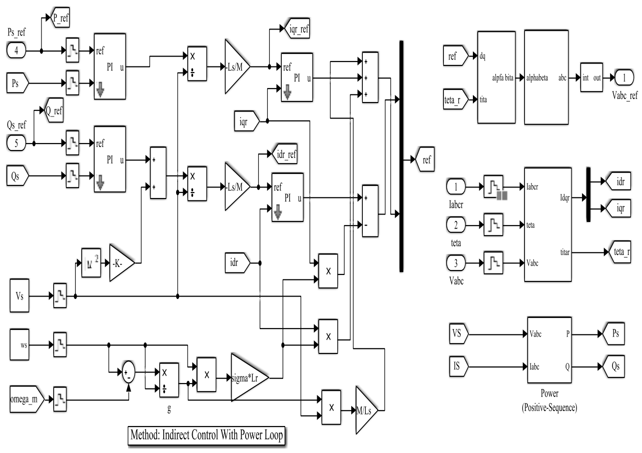

Fig - 9: RSC control of DFIG in MATLAB/Simulink.

Fig. 9 shows the indirect control of the active and reactive powers. The main function of RSC is to achieve decoupled control of active and reactive power. In the first stage, the desired P_{s_ref} and Q_{s_ref} determine the reference stator currents, which allow calculating the components of the reference rotor voltage, as well as the control by PWM technique realised for the inverter control which feeds the rotor through a converter. For guarantee a drive of the DFIG around its speed of synchronism by carrying out a speed regulation. The second stage is devoted to the rotor current controller. The rotor currents of DFIG are sensed and transformed to d, q reference frame by using Park transformation. The q-axis component of the rotor current controls the active power while the d-axis component controls the reactive power. These controllers are used to control the active and reactive power output independently, as shown in Fig. 9, and these controls are organized in two loops, with two controllers in each control loop.

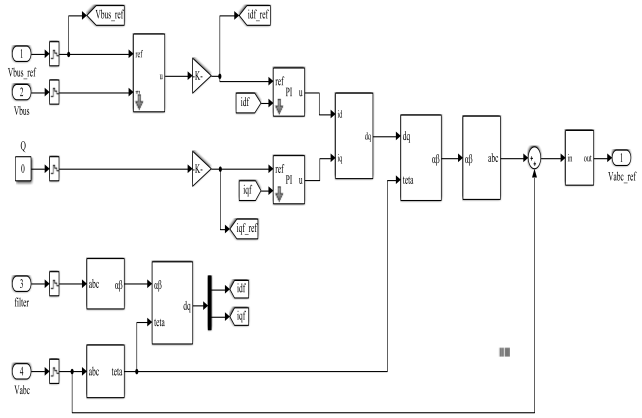

Fig - 10: GSC control of DFIG in MATLAB/Simulink.

GSC control shown in Fig. 10 has two roles, maintaining the constant DC voltage regardless of the magnitude and direction of the rotor energy flow. This command performs functions to control currents flowing in the RL filter and DC bus voltage control.

This diagram represents the external voltage regulation loop. By forcing the reference voltage value, the current value as specified in the internal regulation loop of the current flowing through the filter is obtained in the d-q axis at the output. In order to obtain a unit power factor, the reactive power reference is kept at 0.

5. COMPARISON OF RESULTS WITH PI AND PR CONTROLLER

The test investigated to compare the PI and PR controls with indirect control with power loop. In this case of study the response of rotor speed, torque, active power, reactive power, direct and quadrature axis rotor current, system voltage, system current, rotor current, DC bus voltage and direct and quadrature axis stator current is observed as shown in following figures. The dynamic simulation is not affected by wind profile because it is considered constant during the fault period, for average wind speed of 12 m/s.

The reference tracking by applying stator active (-0.75, -1.5, -1.0 MW) and reactive power steps (-1.5, 0, 0.75 MVAR) to the DFIG, while the machine's speed is maintained nearly constant at 1500 rpm (157 rad/s). The machine is considered as working over ideal conditions (no perturbations and no parameters variations). The performance of the PI control scheme shows more settling time (1 sec) as verified from our simulation results. However, comparatively the proposed PR controller, provide a better dynamic response and less settling time

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(0.5 sec). Furthermore, the references of powers are correctly tracked and DC voltage is maintained at 1200 V.

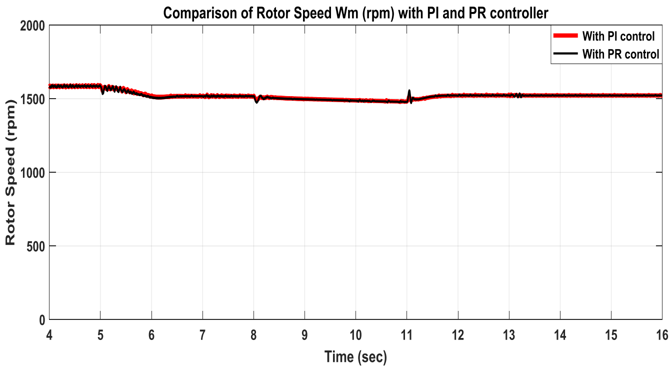

Fig - 11: Comparison of Rotor Speed ω_m (rpm).

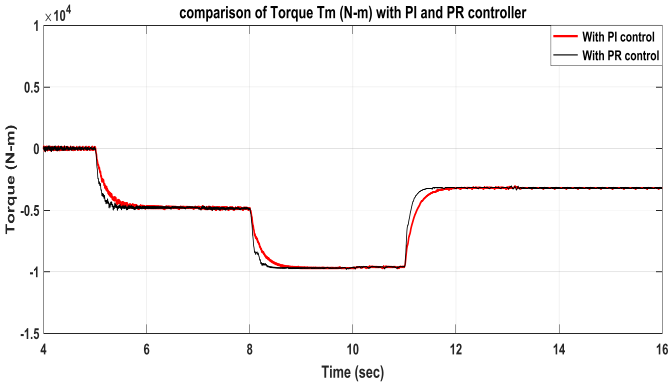

Fig - 12: Comparison of Torque T_m (N-m).

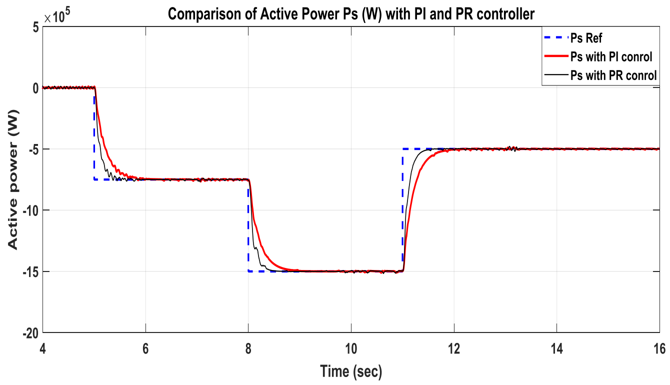

Fig - 13: Comparison of Active power P_s (W).

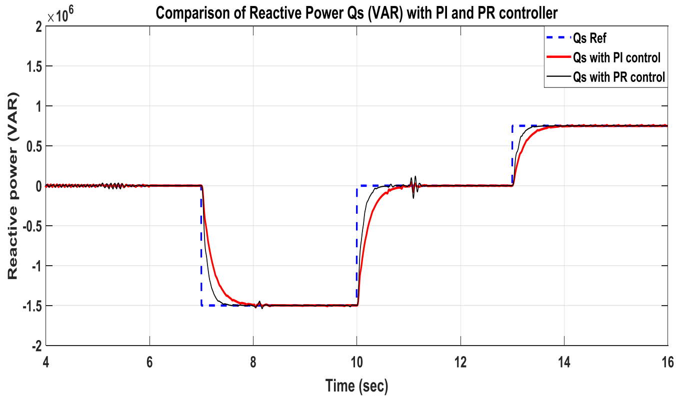

Fig - 14: Comparison of Reactive power Q_s (VAR).

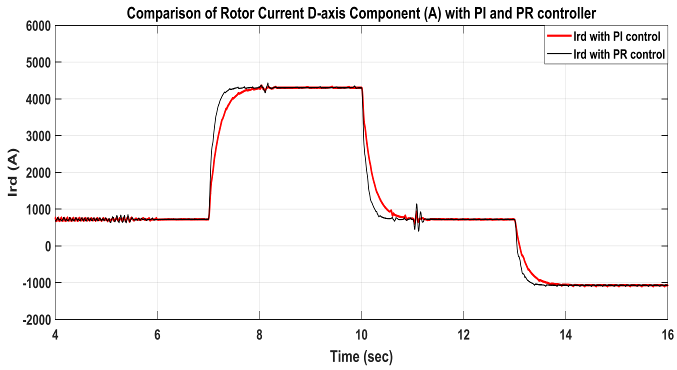

Fig - 15: Comparison of rotor current d-axis component.

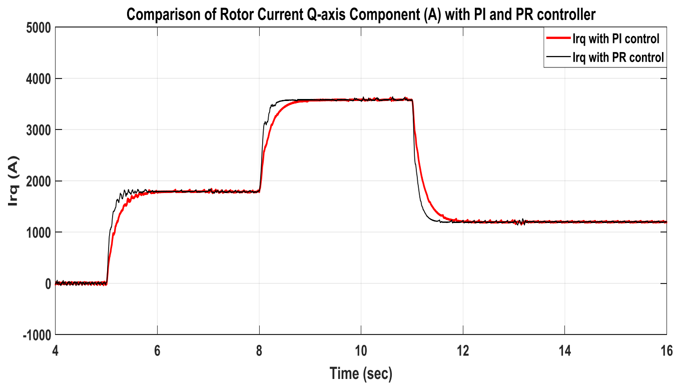

Fig - 16: Comparison of rotor current q-axis component.

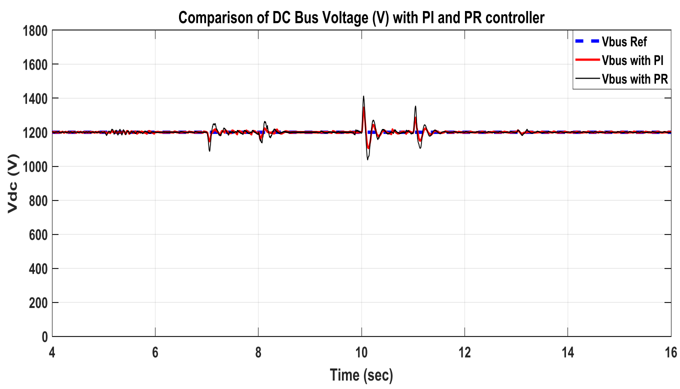

Fig - 17: Comparison of DC bus voltage (V_{dc}).

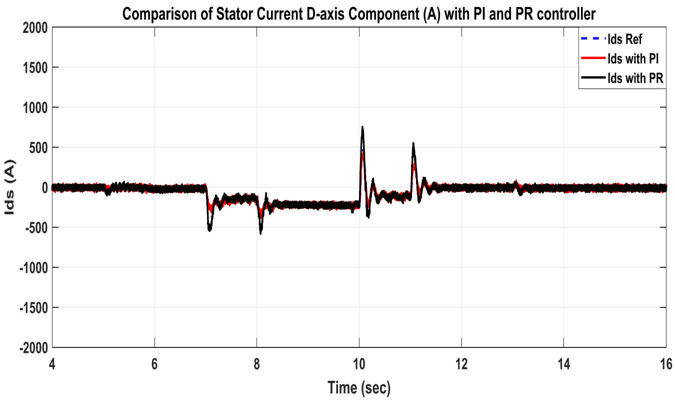

Fig - 18: Comparison of Stator current d-axis component.

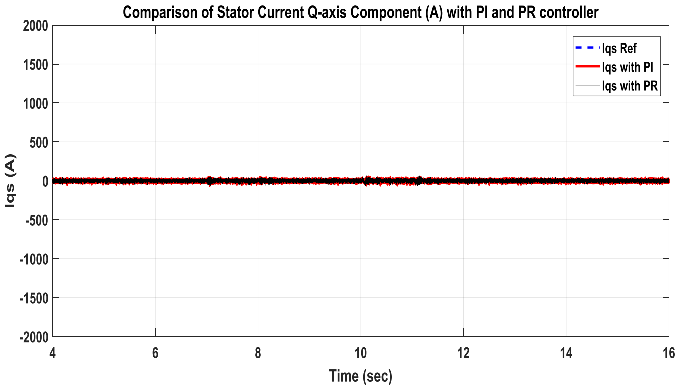

Fig - 19: Comparison of Stator current q-axis component.

6. CONCLUSION

This paper presents the modeling and simulation of a wind turbine using DFIG under MATLAB/Simulink. An approach has been proposed to control the active and reactive power for a wind power conversion system equipped by a DFIG and connected to the grid. Firstly an analytical model of wind turbine was presented and power coefficient characteristics were investigated. Furthermore, a mathematical model of wind farm was built with enhanced RSC and GSC control using PI and PR controller. Due to a perfect tuning of the PR controller, results were very prominent in terms of stability of the rotor speed. The performance of the PI control scheme shows sensitivity, large oscillations, and slow convergence as verified from our simulation results. However, comparatively the proposed PR controller, provide a better dynamic response, less sensitivity, fast convergence, less oscillation and robust.

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