Rotor Side Converter Control of DFIG based Wind Energy Conversion System

Meera G. S
PG Scholar, Dept of EEE
Mar Baselios College of Engineering & Technology
Kerala University
Palayam, Thiruvananthapuram, Kerala

N. A Divya
Assistant Professor, Dept of EEE
Mar Baselios College of Engineering & Technology
Kerala University
Palayam, Thiruvananthapuram, Kerala

***Abstract*— Over the last ten years, the global wind energy capacity has increased rapidly and became the fastest developing renewable energy technology. But unbalances in wind energy are highly impacting the energy conversion and this problem can be overcome by using variable speed wind turbines. Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion Systems (WECS) are gaining tremendous attention nowadays. In this paper the dynamic modeling of wind turbine driven DFIG is simulated using Matlab/Simulink and the results are analyzed for various wind velocities. A stator flux oriented vector control scheme is applied to the rotor side converter in order to control the stator active and reactive power produced by the DFIG. Also an Optimal Torque Control (OTC) MPPT technique is applied in order to track optimum power from the wind turbine. Also a comparison of the stator active power with and without MPPT has been analyzed in Matlab/Simulink.**

***Keywords*—WindTurbine,Doubly-fed induction generator, Rotor-side Converter control, MPPT,OTC**

I. Introduction

In the recent years, renewable energy systems have attracted the great interest because conventional sources of energy are limited and a number of problems associated with their use, like environment pollution, large grid requirements etc. Government of the whole world is forced for the alternative energy sources such as wind power, solar energy and small hydro-electric power [1]. Among the above given choices, wind energy is a realistic way of harnessing the natural energy. Wind energy has been intensively investigated in recent years in many different countries, which resulted in several different configurations like fixed speed system with a SCIG, the variable speed system with permanent magnet synchronous generator (PMSG) and the variable speed system with a DFIG to improve the efficiency, power rating, cost benefit effectiveness etc [2].

Wind is highly variable in nature, so variable speed Doubly Fed Induction Generator based WECS offers many advantages compared to the fixed speed squirrel cage induction generators, such as reduced converter rating, cost, losses in result of that an improved efficiency, easy implementation of power factor correction, variable speed operation and four quadrants active and reactive power control capabilities . Due to variable speed operation, total energy output is much more in case of DFIG-based WECS, so capacity utilization factor is improved and cost of per unit energy is reduced [3].

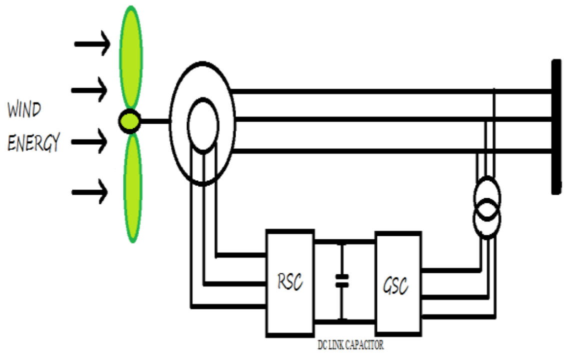

Fig.1 DFIG based WECS

A DFIG based wind energy conversion system is shown in Fig.1. Here stator of the DFIG is directly connected to the grid and the rotor is connected to the grid via a back to back PWM Voltage Source Converter (VSC). There are a lot of advantages of using DFIG in wind energy conversion system. The main advantage is the ability of generator to supply power both at lagging and leading power factors. The other advantage is the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. The main reason for the popularity of the doubly fed wind induction generators is their ability to supply power at constant voltage and frequency while the rotor speed varies. Hence DFIG became more popular in wind power applications. Again controlling the DFIG from the rotor side makes the control process more cost effective as the rotor converters have to deal with comparatively less power when connected at the rotor side than when connected at the stator side.

In this paper, a control strategy is presented for DFIG. The sub synchronous generating mode of DFIG is analyzed and a vector control is given to Rotor Side Converter (RSC), inorder to control the stator active and reactive power. A dynamic model of wind turbine driven DFIG is simulated using Matlab/Simulink. An MPPT technique is applied to the wind turbine inorder to track optimum power during subsynchronous mode . Also a comparison is made with and without MPPT and analysed the effect of stator active power.

II. WIND TURBINE MODELING

The possible amount of wind power, which can be harvested by a wind turbine, is limited theoretically to 58% of total power content of the wind, considering Betz limit [4-5]. The wind turbine power coefficient is typically lower than 0.45.The generalized mechanical equation of the wind turbine is given as

$$J_S \frac{dw_r}{dt} + B_s wr = T_m - T_e \quad (1)$$

In which, J_S is total inertia of the shaft, B_s is friction coefficient, T_m is the torque with wind origin and T_e is the electromagnetic torque produced by the generator. The generated torque is given by

$$T_m = \frac{P_m}{\omega_r} \quad (2)$$

P_m is the amount of mechanical power generated from the wind turbine.

$$P_m = 0.5 \rho A C_p(\lambda, \beta) V^3 \quad (3)$$

ρ is the air density, A is the swept area, Cp is the coefficient of performance, λ is the Tip speed ratio.

$$\lambda = \frac{\omega_m R}{V^3} \quad (4)$$

There are a number of approximations available for Coefficient of Performance (Cp).

$$C_p = 0.5176\left[\frac{116}{\lambda_i} - 0.4\beta - 5\right] e^{\frac{21}{\lambda t}} + 0.006795\lambda \quad (5)$$

The Cp for constant wind is 0.48. Fig.2 shows the operating characteristics of wind turbine. From cut in speed to rated speed, the machine runs below synchronous speed. During this period in order track optimum power several MPPT techniques are applied.

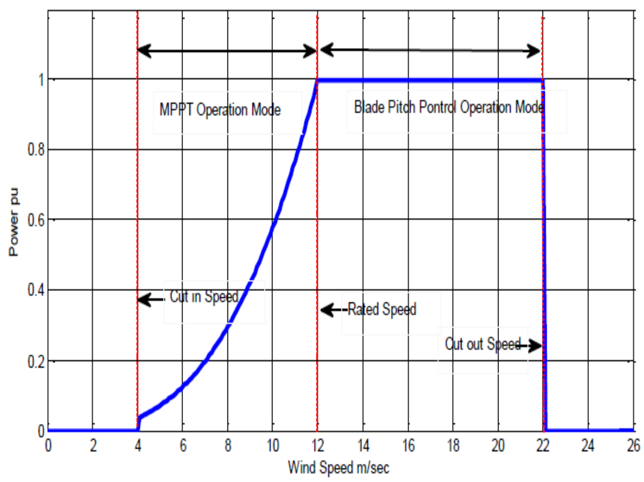

Fig. 2. Operating characteristics of Wind Turbine

III. MODELING AND ANALYSIS OF THE DOUBLY-FED INDUCTION GENERATOR

A doubly-fed induction generator is as a standard wound rotor induction generator with its stator windings directly connected to the power grid and rotor connected to the power grid through a frequency converter [6-7]. The operation of DFIG can be analyzed using the classic theory of rotating fields and well known d-q model, as well as both three-to-two and two-to-three axes transformations.

The dynamic modeling of doubly-fed induction generator in synchronously rotating reference frame de–qe involves the following equations.

$$V_{sd} = R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s \quad (6)$$

$$V_{sq} = R_s I_{sq} + \frac{d\phi_{sq}}{dt} - \omega_s \phi_{dq} \quad (7)$$

$$V_{rd} = R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \quad (8)$$

$$V_{rq} = R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \quad (9)$$

The stator and rotor fluxes can be expressed as

$$\phi_{sd} = L_s I_{sd} + M I_{rd} \quad (10)$$

$$\phi_{sq} = L_s I_{sq} + M I_{rq} \quad (11)$$

$$\phi_{rd} = L_r I_{rd} + M I_{sd} \quad (12)$$

$$\phi_{rd} = L_r I_{rq} + M I_{sd} \quad (13)$$

The electromagnetic torque is expressed as

$$T_{em} = pM\left(I_{rd} I_{sq} - I_{rq} I_{sd}\right) \quad (14)$$

The active and reactive power taken by the machine can be represented by the following equations.

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

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

Where *d* and *q* subscripts stand for the *d*-axis and *q*-axis components, *r* and *s* subscripts stand for rotor and stator, *V* stands for the constant grid voltage ϕ stands for flux, *R* stands for resistance, *I* stands for current, ω stands for the utility frequency, *p* stands for the number of pole pairs, ω_r stands for the rotational speed of the generator rotor,

IV. BACK TO BACK CONVERTER

A DFIG consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid/load and the rotor windings connected to a back-to-back partially rated (20–30% rating)power converter. This allows DIFG to operate at a variety of speeds in response to changing wind speed. The back-to-back converter is a bi-directional power converter consisting of two conventional pulse width modulation (PWM) voltage source converters and a common DC bus employing a DC link capacitor. Both stator and rotor are able to supply the power, but the direction of active power flow through the rotor circuit is dependent on the wind speed and accordingly the generator speed. Below the synchronous speed, the active power flows from the grid to the rotor side and the rotor side converter (RSC) acts as voltage source inverter while grid side converter (GSC) acts as a rectifier. Due to the bi-directional power flow ability of the converter, the DFIG may operate as a generator or motor in both sub synchronously (0<slip<1) and super synchronously (slip<0).The higher the slip, the larger the electrical power, which is either absorbed or delivered through the rotor.

V. CONTROL SCHEME

A lot of research has been undergone in order to decouple the active and reactive power. Vector control scheme [8] is one of the most effective scheme for decoupled control of active and reactive power, which was first proposed by F. Blaschke.Various type of controllers are used like P-I controller, fuzzy logic controllers, sliding mode controller etc in the vector control scheme for the control of active and reactive power. P-I controller is the most primitive and highly used controller in power applications for its simplicity and easy applicability As the stator winding of DFIG is connected directly to the infinite grid, the magnitude and frequency of stator voltage can be approximately considered to be constant[9]. So DFIG usually adopts stator flux linkage oriented control strategy. DFIG based WECS needs control of Voltage source converter to achieve variable speed operation.

A. Rotor Side Converter Control

A vector control is applied to rotor side converter in order to control the stator active and reactive power. The direct axis loop is used to control reactive power where as the quadrature axis is for active power control [10]. A stator flux oriented vector control is applied to the rotor side converter [11]. The block diagram of the RSC controller is shown in Fig.3. The direct axis loop is used to control reactive power where as the quadrature axis is for active power control.

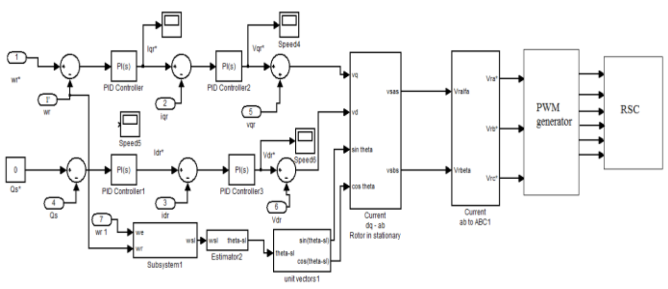

Fig.3 Rotor side converter control

The equations related to this scheme is

$$V_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_{sl} \sigma L_r i_{qr} \qquad (17)$$

$$V_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} - \omega_{sl} \left(\sigma L_r i_{dr} + L_o i_{ms} \right) \qquad (18)$$

VI. MAXIMUM POWER POINT TRACKING TECHNIQUES

Maximum Power variation with rotation speed of DFIG is predefined for each wind turbine. So for MPPT the control system should follow the tracking characteristic curve (TCC) of the wind turbine. Each wind turbine has TCC similar to the one shown in the figure. Due to the nature of the wind that is instantaneously changing, it is essential to include a controller that is able to track maximum peak regardless of any wind speed [12].

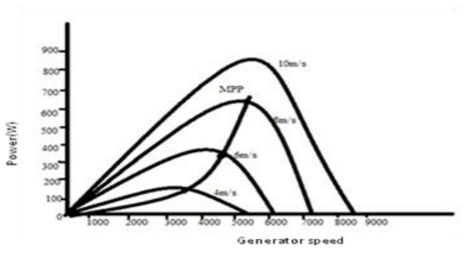

Fig. 4. Tracking Characteristic Curve

Several MPPT algorithms have been proposed [13] among this two methods in descried in [14] and [15] are best solution due to their adaptive tracking and self tuning capability. In [16] have compared some of the available MPPT algorithms for wind energy system. In [17] reviews the fundamentals of the available MPPT algorithms for wind energy system and compared three selected MPPT techniques and concluded that Optimal Torque Control method is simple, fast and more efficient.

A. Optimal Torque Control Method

Maintaining the operation of wind turbine at the λopt ensures that the maximum exploitation of the available wind energy to be converted into mechanical energy [18].

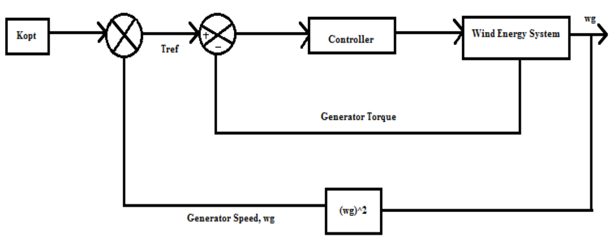

Fig. 5 Optimal Torque Controller

The principle of this method is to adjust the DFIG torque according to a maximum power reference torque of the wind turbine at a given wind speed.

$$T_{mopt} = \frac{1}{2}\rho\pi R^5 \frac{C_{p\max}}{\lambda_{opt}^3}\omega_m^2 \qquad (19)$$

It is a torque control based method the optimum torque is given as the reference torque for the controller connected to the wind turbine.

VII. SIMULATION RESULTS AND DISCUSSION

The response of the DFIG system is simulated for the case of step changes in the wind speed as shown in Fig.6.

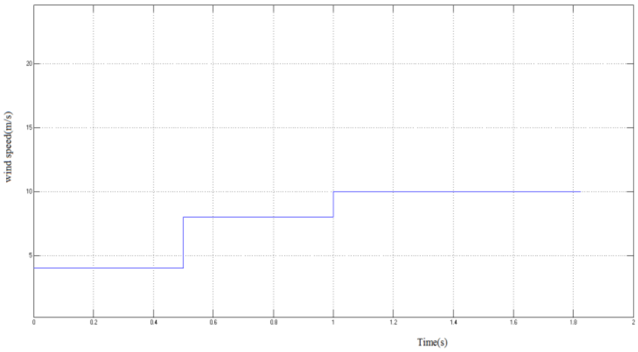

Fig.6.Variable wind speed

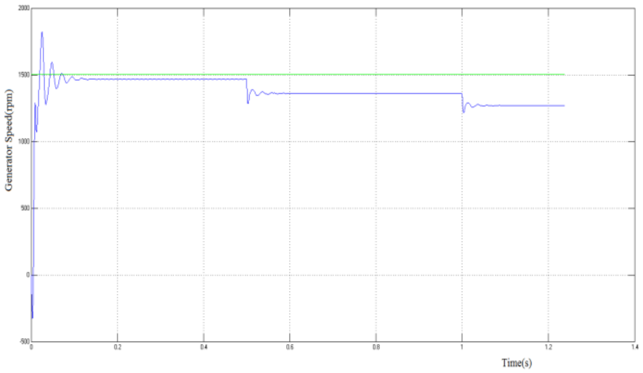

Fig.7.Generator speed

The variation of wind speed at 0, 0.5 and 1 sec is shown in fig.6. From 0 to 0.5 wind speed is 4m/s, from 0.5 to 1 it is 8m/s and beyond 1 it is 10m/s.

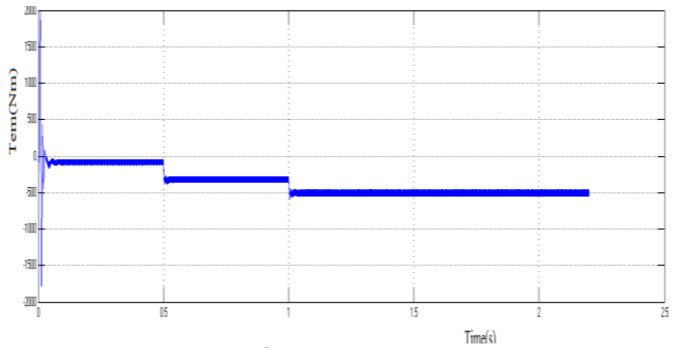

Fig.8 Electromagnetic Torque

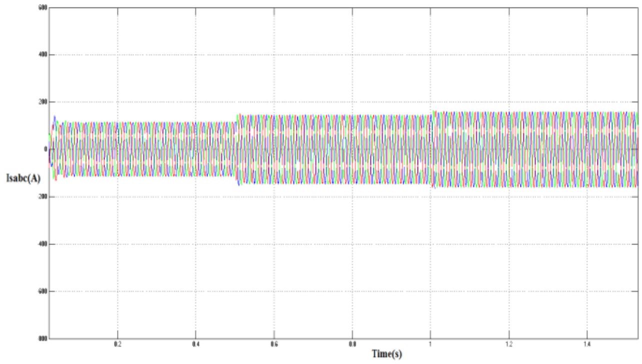

Fig.9 Stator current

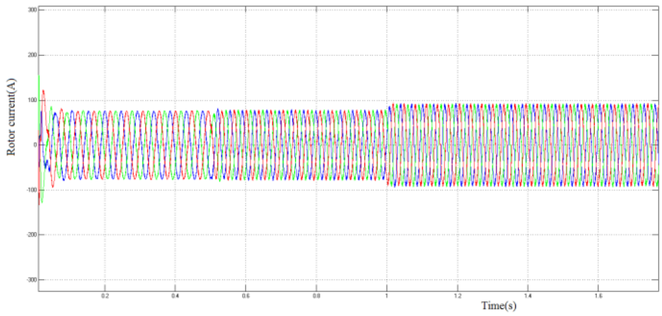

Fig.10 Rotor current

After the cut in speed the turbine starts generating power. When the wind speed increases the generator speed also increases[19-20]. When the wind speed is less than the rated speed rotor rotates at a speed less than the synchronous speed i.e. sub synchronous generating mode. Fig.7 shows the sub synchronous generating mode of DFIG for variable wind speed. Fig.8 shows that when wind speed increases the torque increases and as it is a generator the torque is negative.

As the wind speed increases stator current and rotor current increases. The simulation results are shown in Fig.9 and Fig.10. Also when the speed of the generator rotor is less than the synchronous speed, the corresponding slip will be positive as shown in Fig.11.

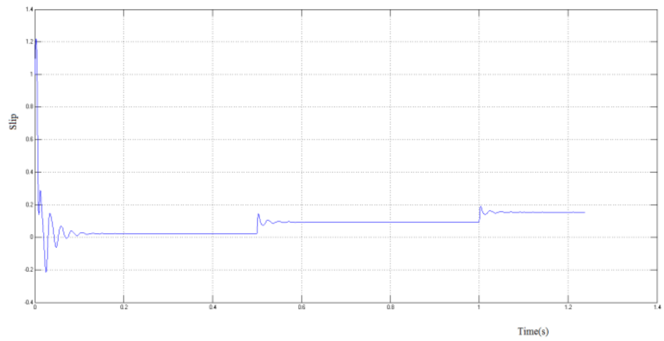

Fig.11. Slip

Fig.12 shows the stator active power. A vector control is given to the rotor side converter. The stator active and reactive power is controlled by controlling the rotor side converter. By controlling the RSC using vector control the active power increases with increase in wind speed and the reactive power is controlled in order to improve the power factor at the stator. Below the synchronous speed, power is generated by the stator only. The reactive power required by the machine is generated by the rotor converter.

The simulation results of controlled active and reactive power is shown in the Fig. 12 and 13. Here when wind speed increases the active power increases and the reactive power remains almost zero.

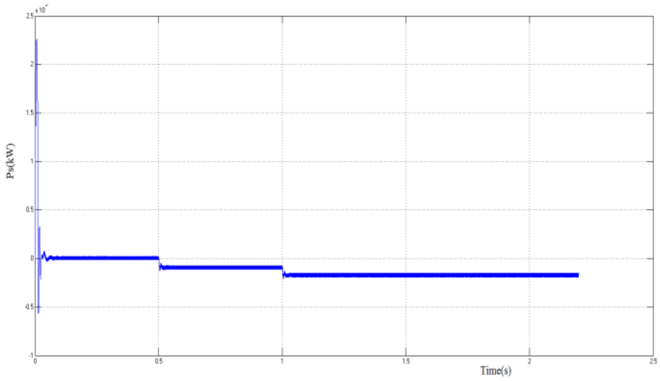

Fig.12 Ps without MPPT

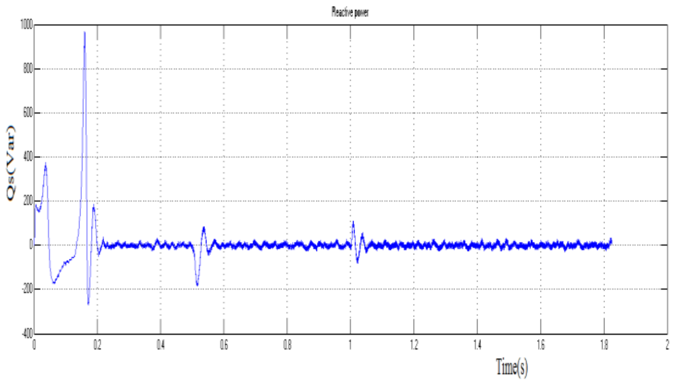

Fig.13 Reactive power

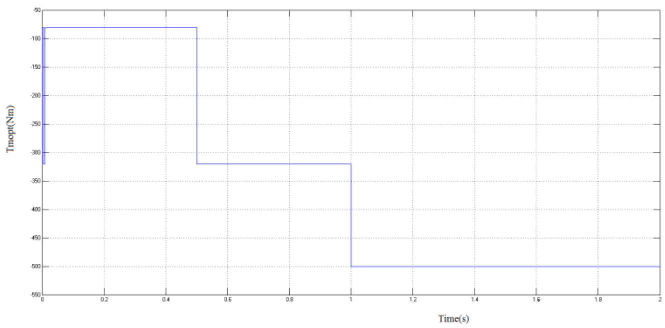

Fig.14 Optimum mechanical torque from wind turbine

When a maximum power point tracking technique is applied to the wind turbine. Therefore optimum power will flow from stator to grid during sub synchronous speed. Fig.14 shows the optimum mechanical torque from wind turbine.

The stator active power with MPPT is shown in the Fig.15. Also the rotor active power in Fig.16 shows that active power flows to the rotor from grid.

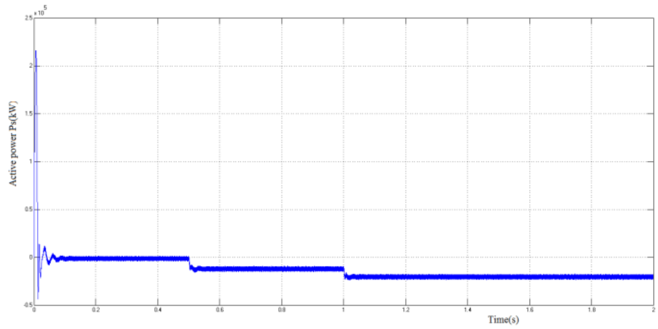

Fig.15.Ps with MPPT

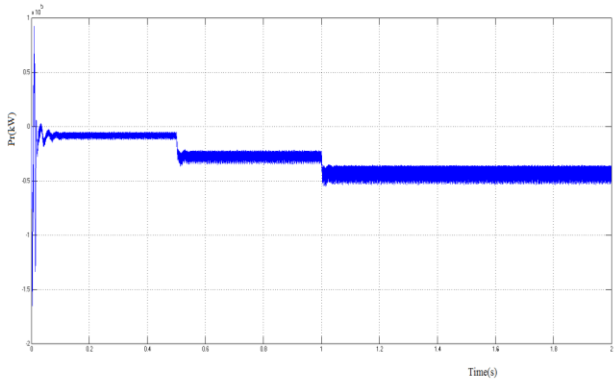

Fig.16 Rotor active power

A comparison of stator active power is made with and without MPPT controller. Using OTC the active power flow from stator to grid has been improved. Table.1 shows the comparison of active power with and without MPPT. The table shows that when the wind speed is 4, 6 and 8m/s the active power Ps without MPPT is 0.8, 7.25 and 15kW. When an Optimal Torque Control MPPT technique is enabled the active power flow from stator to grid is improved.

Table 1: Comparison of stator active power

Time(s)	Wind speed(m/s)	Ps without MPPT	Ps with MPPT
0	4	0.8kW	1kW
0.5	8	7.25kW	10kW
1	10	15kW	18kW

VIII.CONCLUSION

In this paper dynamic model of wind turbine driven DFIG is simulated using Matlab/Simulink and the simulation results for various wind velocities are analyzed. A vector control is applied to rotor side converter in order to control the stator active and reactive power. Also Optimal Torque Control MPPT technique is applied to the wind turbine in order to transfer optimum power from stator to grid during sub synchronous mode. A comparison is made and concluded that using OTC the active power flow from stator to grid has been improved.

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