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Analysis and Control of Grid Connected DFIG Under Sub & Super Synchronous Modes of Operation

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ABSTRACT

The most reliable system in the present scenario for effective use of the wind power is grid integrated Doubly Fed Induction Generator (DFIG). The implementation of a simple power converter arrangement in the rotor circuit for variable speeds has been proposed. Depending on wind speed, a DFIG based variable speed wind turbine is capable of operating in sub-synchronous or super-synchronous mode of operation using power electronic converters. The power flow in the rotor circuit is controlled for controlling the stator power in both the modes of operation by effecting rotor voltage through IGBT in sub-synchronous mode whereas in super-synchronous mode it is controlled by current sequence through LCI. The complete system has been modeled Using MATLAB/SIMULINK blocks and simulation study has been conducted, the operation of the proposed scheme is illustrated at different operating conditions i.e. above and below synchronous speeds.

Keywords: *Line Commutated Inverter (LCI), DFIG, power smoothing, Sinusoidal PWM Inverter.*

I. INTRODUCTION

The influence of renewable based distributed generation has been increasing intensely into the power system for last two decades [1]. A variable speed generator based wind turbine can extract more power from the wind than a fixed speed wind turbine [2]. Doubly fed induction generator (DFIG) is a popular choice for variable speed wind turbine application, as it is able to generate power at constant voltage and frequency while the rotor speed varies. A decoupled control of the real and reactive power is possible [3-4].In standalone induction generator, both the terminal voltage and frequency will vary with variation in wind speed and load and an excitation capacitor will be required. Whereas in grid connected induction generator, control of the terminal voltage and frequency under change in load and wind speed, is possible and reactive power can be supplied by the grid. The DFIG based Variable-speed wind turbines, will increase the energy output, improves the power quality and reduce mechanical stress on the wind turbine [5]. The direction of the power flow in the rotor circuit depends on the variation of the wind speed. Both the direction and magnitude of the power flow of the machine can be controlled by the power electronic converters. The control dynamics of a DFIG based variable speed wind turbine in two modes of operation and during transition period has been presented in [6]. The authors in [7] presented a simple and easy to implement configuration of DFIG in super synchronous mode with MPPT and power smoothing for wind driven applications.

In exiting literature most of the published papers on the application of DFIG for wind energy conversion systems used force commutated inverters in the rotor circuit and d-q axis control to maintain constant stator power. The proposed works presents another approach which is the power flow approach and a very simple control technique by using line commutated SCR inverter in the rotor circuit of the DFIG to explore how to obtain constant power for variable wind speeds. The inter relations among the rotor power (slip power sP_s), the air gap power P_s and the mechanical power P_m are used to analyze the DFIG based wind energy conversion system.

The rest of the proposed work is ordered as below. Section describes II Power flow in DFIG wind energy conversion system and steady state model of DFIG. In section III the operation of the open and closed loop systems of the proposed scheme employing sub-synchronous and super-synchronous modes by using power electronic converters for the grid interface has been analyzed. Section IV presents the development of simulation models of the proposed scheme along with simulation results. In section V final main observations are concluded.

II. POWER FLOW & STEADY STATE MODEL OF DFIG

A. Power flow in DFIG

DFIG can be operated in two modes of operation namely; sub-synchronous and super-synchronous modes of operation based on the synchronous speed of the rotor. The power flowing in the rotor of a doubly fed induction machine (i.e. of the wound rotor type) has three components. These are a) the electromagnetic power fetching between the stator and the rotor by the air gap which is named as the air gap power P_s; b) the mechanical power P_m fetching between the rotor and shaft; c) the slip power P_r fetching between the rotor and any external source or load (e.g. a converter) through the rotor slip-rings. These three components of rotor power are interrelated, under sub and super-synchronous modes of operation, as shown in figure.1

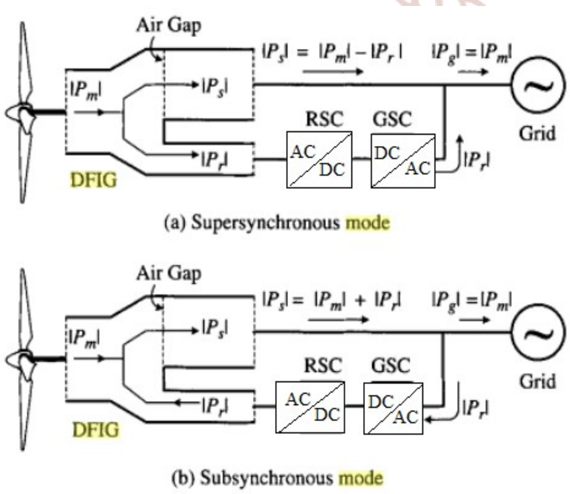


Fig.1. Power flow in DFIG wind energy conversion system

B. Steady State Model

The typical steady-state per-phase equivalent circuit can be utilized to assess the performance of doubly fed induction machine subject to the usual assumptions of a three-phase balanced supply, fixed rotor speed, and constant machine parameters. Fig.2 shows the standard per-phase equivalent circuit of DFIG in which stator frequency is used to refer the rotor circuit parameters, so at the supply frequency all machine reactance's are determined.

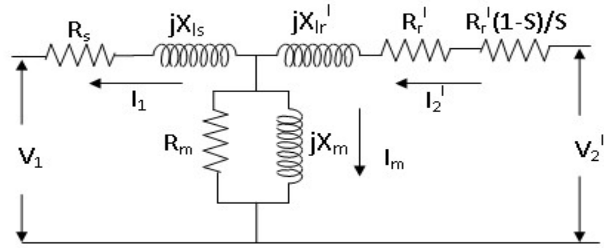


Fig.2. Per-phase equivalent circuit of a DFIG

The per unit power into the rotor circuit comes from two sources when machine is doubly-fed and

$$P_{r,\,in1} = \mathrm{Re}\,([V_2'(I_2')^*]) \quad (1)$$

$$P_{r,\,in2} = T\,(\omega_r/\omega_b) = T\,(1\text{-}S) \quad (2)$$

Where (*) denotes the complex conjugate operator. Since the machine is a generator, positive 'T 'denotes the operation of the generator.

The power lost in the rotor circuit is

$$P_{r,\,loss} = |I_2'|^2 R_r' \quad (3)$$

The power output of the circuit is

$$P_{r,\,out} = \mathrm{Re}\,[E\,(I_2')^*] \quad (4)$$

Conservation of power requires that

$$P_{r,\,in1} + P_{r,\,in2} = P_{r,\,loss} + P_{r,\,out} \quad (5)$$

So that

$$\mathrm{Re}\,[V_2'(I_2')^*] + T\,(1\text{-}S) = \mathrm{Re}\,[E\,(I_2')^*] + |I_s|^2 R_r' \quad (6)$$

Or

$$T\,(1\text{-}S) = \mathrm{Re}\,[E\,(I_2')^*] - \mathrm{Re}\,[V_2'(I_2')^*] + |I_s|^2 R_r' \quad (7)$$

But

$$\bar{E} = \frac{V_2'}{S} - I_2'\left[\frac{R_r'}{s} + j\,X_{lr}'\right] \quad (8)$$

Eq. (8) is substituting into Eq. (7),

$$T(1-S) = \mathrm{Re}\left[\left(\frac{1}{s}-1\right)V_2'(I_2')\right] + |I_2'|^2 R_r'\left(1-\frac{1}{s}\right) \quad (9)$$

Or

$$T(1-S) = \mathrm{Re}\left[\left(\frac{1-s}{s}\right)V_2'(I_2')^*\right] - |I_2'|^2 R_r'\left(\frac{1-s}{s}\right) \quad (10)$$

Cancelling out the (1-s) term

$$T = \mathrm{Re}\left[\frac{V_2'}{s}(I_2')^*\right] - |I_2'|^2 \frac{R_r'}{s} \quad (11)$$

This final equation represents the basic torque equation for a doubly fed induction generator.

Solution of eq.11 in terms of the rotor current has been developed by Smith et. al [8]. Expanding eq. (11),

$$T = \frac{V_{2,re}'}{s}I_{2,re}' + \frac{V_{2,im}'}{s}I_{2,im}' - (I_{2,re}')^2\frac{R_r'}{s} - (I_{2,im}')^2\frac{R_r'}{s} \quad (12)$$

The phase position of the rotor voltage is generally defined as its relative phase position with respect to the stator terminal voltage V_1. Hence, $V_{2,re}'$ and $V_{2,im}'$ can be assumed to be known or specified quantities. Assuming that *T* and S are also specified, then the currents can be obtained by solving Eq. (12) by also assuming that their ratio (power factor) is specified. Other method, is instead of assuming rotor voltage is known assume the phase position of the rotor current is known to solve the eq. 12. In this case, assuming the real part of the stator current as reference,

$$I_{2,im}' = 0 \quad (13)$$

And

$$I_{2,re}' = I_2' \quad (14)$$

Eq. (12) becomes

$$T = \frac{V_{2,re}'}{s}I_2' - (I_2')^2\frac{R_r'}{s} \quad (15)$$

Which is simply a quadratic in terms of I_2' .Upon solving eq.(15).

$$I_2' = \frac{\frac{V_{2,re}'}{s} \pm \sqrt{\left(\frac{V_{2,re}'}{s}\right)^2 - 4\frac{R_r'}{s}T}}{2\frac{R_r'}{s}} \quad (16)$$

Or

$$I_2' = \frac{V_{2,re}'}{2R_r'} \pm \frac{\sqrt{(V_{2,re}')^2 - 4R_r'sT}}{2R_r'} \quad (17)$$

The voltage $V_{2,re}'$ can also be written as $V_2'\cos\Phi_2$ where Φ2 represents the phase angle of the rotor terminal voltage V_2' with respect to the rotor input current I_2'. Now the rotor current I_2' can be obtained as a function of slip for any desired torque and specified value of rotor voltage and phase.

By obtaining the rotor current from eq. (17) now it is possible to obtain the air gap voltage *E* from eq. (8). Then the stator current can be found from,

$$I_1 = I_2' - E\left(\frac{1}{R_m} + \frac{1}{jX_m}\right) \quad (18)$$

The stator voltage can be obtained by the stator loop equation

$$V_1 = E - I_1(R_s + jX_{ls}) \quad (19)$$

In general, the voltage obtained will not be same as the available terminal voltage except at specific combinations of rotor voltage and slip. Hence, emphasis is necessary to converge on the correct values which correspond to the specified stator terminal voltage.

III. OPERATION UNDER SUB AND SUPER SYNCHRONOUS MODES

Depending on wind speed, using power electronic converters a doubly fed induction generator (DFIG) based variable speed wind turbine can be operated in sub-synchronous or super-synchronous modes of operation. Traditional Wound Rotor Induction Generator (WRIG) will never obtain power at sub-synchronous mode of operation. In this mode, it generates motoring torque which can be used to control rotor voltage or current. Rotor side converter component must need to be controlled properly for proper operation of the machine under sub-synchronous and super-synchronous modes. The imposed voltage and current for the rotor circuit of the machine can be controlled by the rotor side converter. The control of imposed current is necessary for generating torque in sub-synchronous mode of operation. Whereas the control of voltage or current is necessary to utilize extra generating torque in super-synchronous mode.

During sub-synchronous mode, the speed of the rotor is less than the synchronous speed of the machine. As a result, the slip is positive (s > 0), and a motoring torque is produced. To utilize this torque, negative power (according to the positive slip) is required in the rotor circuit of the machine. This can be obtained by changing the rotor circuit injected voltage magnitude and the rotor receives power form the grid through grid side converter and DC-link. In super-synchronous mode, the rotor speed is greater than the synchronous speed of the machine and slip is negative (s< 0). To supply extra generating power to the grid through DC-link and grid side converter the rotor voltage/current sequence has to be reversed. The magnitude of the rotor current and voltage will get changed according to the wind variations.

The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m * \omega_r$$

$$P_s = T_{em} * \omega_s$$

For a loss-less generator, the mechanical equation is:

$$J\frac{d\omega_r}{dt} = T_m - T_{em}$$

In steady-state at fixed speed for a loss-less generator

$T_m = T_{em}$ and $p_m = P_s + P_r$

And it follows that

$$p_r = P_m - P_s = T_m\omega_r - T_{em}\omega_s = -sP_s$$

where

$$s = (\omega_s - \omega_r)/\omega_s$$

s is defined as the slip of the generator.

Generally, the absolute value of slip (s) is much lower than 1 and, therefore, P_r is only a fraction of P_s. Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and vice-versa (speed lower than synchronous speed). For super-synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to increase the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. PC_{grid} is used to generate or absorb the power P_g in order to keep the constant DC voltage as shown in Fig.3. In steady-state for a lossless AC/DC/AC converter P_g is equal to P_r and the wind turbine speed is determined by the power P_r absorbed or generated by PC_{rotor}. The generated AC voltage phase-sequence by PC_{rotor} is positive for sub-synchronous speed and negative for super synchronous speed. The product of the grid frequency and the absolute value of the slip is equal to the frequency of this voltage. PC_{rotor} and PC_{grid} have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

A dc-link capacitor is placed between the two converters, for energy storing, in order to keep the voltage

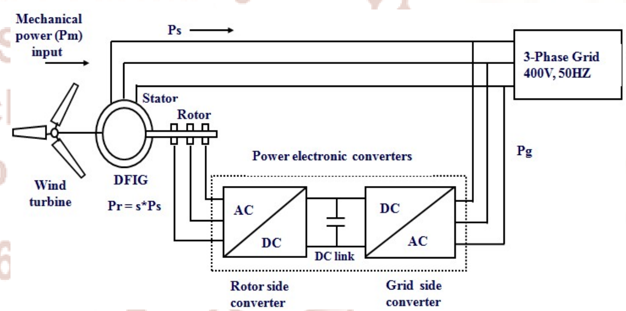


Fig.3. DFIG system with power electronic converters

variations (or ripple) in the dc-link voltage small. It is possible to control the torque or the speed of the DFIG with the machine-side converter and also the power factor at the stator terminals, while the main objective of the grid-side converter is to keep the dc-link voltage constant.

IV. SIMULATION STUDIES OF PROPOSED SCHEME

This section discusses the modeling of DFIG, power electronic converters and the simulation results of the overall scheme in both sub-synchronous and super-synchronous modes of operation.

A. Open Loop Super-Synchronous Mode

The schematic diagram for open loop super-synchronous mode of operation is shown in Fig.3.

Ratings of DFIG used in the proposed scheme are: Nominal power (P) = 2.65kW, V_{L-L} = 400V, f = 50Hz, synchronous speed (Ns) = 1000 rpm, number of poles (P) = 6 [3]. In open loop super-synchronous mode firing angle ($\alpha > 90^0$) of the line commutated inverter is varied manually to maintain the constant stator power at 2.65kW for speeds varying from 1050 rpm to 1200 rpm. As the speed varies, the power delivered to the grid by the rotor is varied but the stator power is maintained constant.

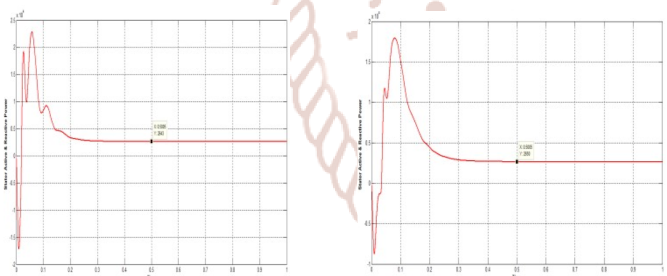
The parameters chosen for the simulation study are:

stator resistance	: 0.8285Ω
stator leakage inductance	: 3.579 mH
rotor resistance	: 0.7027Ω
rotor leakage inductance	: 3.579 mH
magnetizing inductance	: 62.64 mH

The simulation model for this mode of operation is developed and the simulation results obtained are given in Table 1.

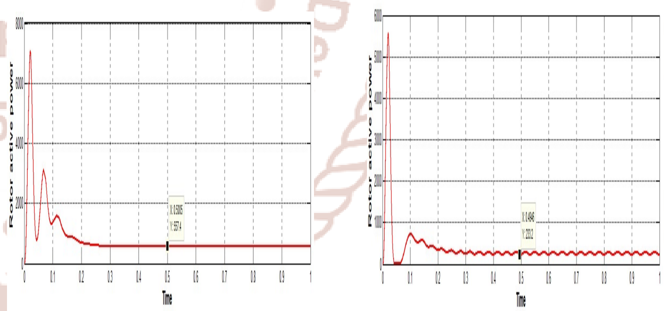
Table.1: Simulation results for open loop super-synchronous mode

Speed (N_r) in rpm	Firing angle (α) in deg.	Stator power (P_s) in watts	Rotor power (P_r) in watts	Rect. voltage in volts	LCI current (I_{act}) in amp
1200	99.87	2642	548.1	93.17	5.977
1175	98.52	2666	474.0	80.56	5.990
1150	97.18	2678	400.3	68.23	6.005
1125	95.83	2694	323.3	55.40	5.988
1100	94.49	2647	247.5	42.72	5.984
1075	93.14	2631	171.3	31.23	5.899
1050	91.83	2600	93.79	17.96	5.800



(a)Nr=1200 rpm (b) Nr=1100 rpm

Fig.4. Variation of active power delivered at the stator side



(a)Nr=1200 rpm (b) Nr=1100 rpm

Fig.5. Variation of active power delivered at the rotor side

Fig.4. shows the variation of active power of the stator for varying rotor speeds of 1200 rpm and 1100 rpm. It can be seen that the stator power is delivered to the grid and is maintained at around 2.65kW for both speeds by controlling the line commutated inverter firing angle.

Similarly, from Fig.5 shows the active power of the rotor delivered to the grid is maintained at slip times the stator power in both speeds i.e., 1200 rpm and 1100 rpm by controlling the line commutated inverter firing angle.

B. Closed Loop Super-Synchronous Mode

Fig.6. shows the simulation model of the closed loop super synchronous mode, in which the firing angle ($\alpha > 90^0$) of the line commutated inverter is varied automatically i.e., the actual DC link current, I_{act} is compared with the reference current, I_{ref} and any mismatch is used to change the firing angle α, of the inverter as follows $\alpha = (I_{ref} - I_{act})*[K_p+K_I/s]$ where K_p and K_I are the proportional and integral stage gains respectively. The optimum values for K_p and K_I have

been arrived at by trial and error method [4]. The range of mechanical torque of the wind turbine is taken into account to choose the values. This range will represent the variation in wind speed with which the system has to operate. In this proposed scheme, the P and I controller gains (K_P = 0.5 and K_I = 100) have been chosen to operate the system with rotor speed varying from 1050 rpm to 1200 rpm, to maintain the stator power constant at 2.65kW.

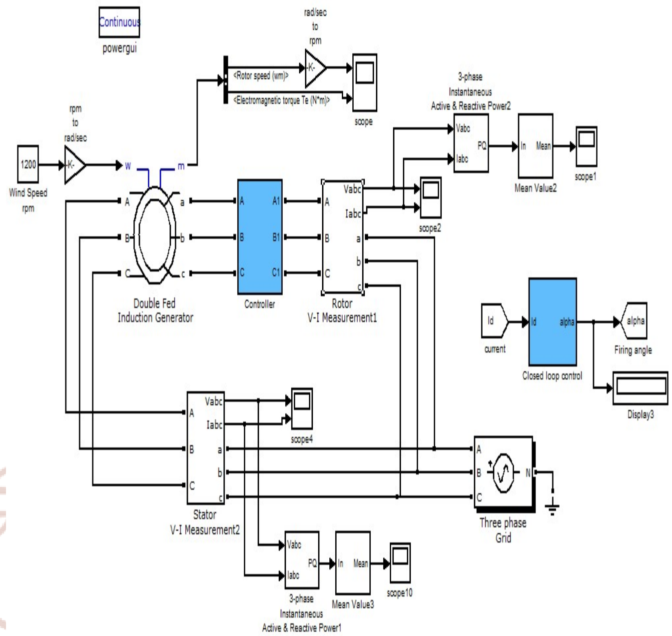
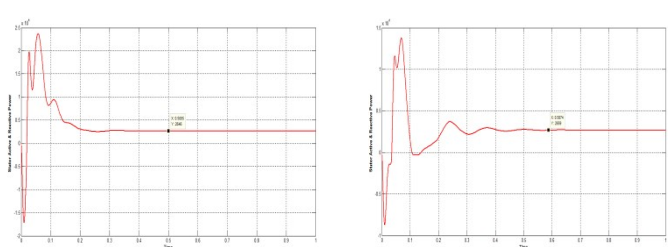


Fig.6. Simulation model of the closed loop super-synchronous mode

Fig.7. shows the variation of active power of the stator for varying rotor speeds of 1200 rpm and 1100 rpm. It can be seen that the stator power is delivered to the grid and is maintained at around 2.65kW for both speeds by controlling the firing angle of line commutated inverter.

Table.2: Simulation results for closed loop super-synchronous mode

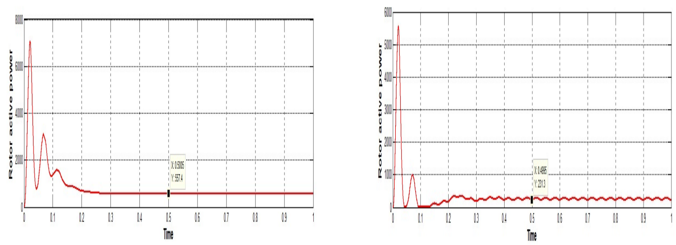
Speed(N_r) in rpm	Firing angle (α) in deg.	Stator power (P_s) in watts	Rotor power (P_r) in watts	Rect.voltage in volts	LCI current (I_{act}) in amp
1200	99.87	2653	550.1	93.17	6.000
1175	98.52	2667	474.6	80.55	5.998
1150	97.18	2679	399.1	68.00	5.991
1125	95.83	2688	324.0	55.18	6.007
1100	94.49	2687	249.8	42.63	6.050
1075	93.14	2660	176.1	30.58	6.010
1050	91.83	2650	99.5	17.57	6.020



(a)Nr=1200 rpm (b) Nr=1100 rpm

Fig.7. Variation of active power delivered at the stator side

Similarly Fig.8.shows the variation of the active power of the rotor delivered to the grid is maintained at slip times the stator power for both speeds i.e., 1200 rpm and 1100 rpm by controlling the firing angle of line commutated inverter.



(a)Nr=1200 rpm (b) Nr=1100 rpm

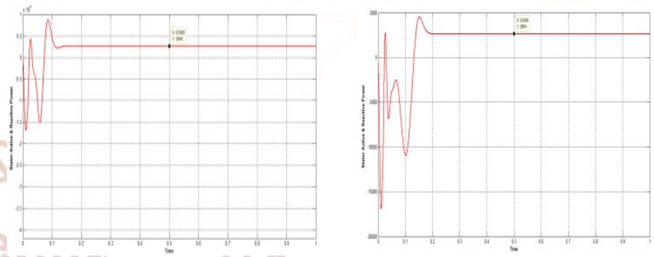
Fig.8. variation of active power delivered at the rotor side

C. Open Loop Sub-Synchronous Mode

In open loop sub-synchronous mode, modulation index of the sinusoidal pulse width modulation inverter is varied manually to maintain the stator power constant at 2.65kW for speeds varying from 800 rpm to 950 rpm. As the speed varies, the rotor power absorbed from the grid is varied but stator power is maintained constant.

The simulation model for this mode of operation is developed and the simulation results obtained are given in Table.3.

Fig.9 shows the variation of active power of the stator for varying rotor speeds of 800 rpm and 900 rpm. It can be seen that the stator power delivered to the grid is maintained at 2.65kW for both speeds by controlling the modulation index of the sinusoidal PWM inverter.

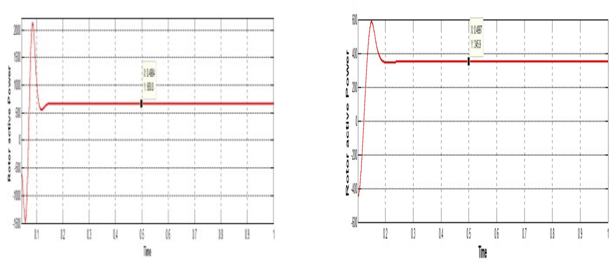


(a)Nr=800 rpm (b) Nr=900 rpm

Fig.9. Variation of active power delivered at the stator side

Table.3: Simulation results for open loop sub-synchronous mode

Speed (N_r) in rpm	Modula--tion index (m)	Stator power (P_s) in watts	Rotor power (P_r) in watts	Rotor freq (f_r) in Hz	Rotor voltage (RMS) in volts
800	0.2500	2648	651.1	10.0	85.62
825	0.2195	2650	574.6	8.75	74.96
850	0.1893	2650	498.0	7.50	64.99
875	0.1594	2650	421.5	6.25	54.86
900	0.1299	2652	345.8	5.00	44.73
925	0.1008	2655	270.1	3.75	34.79
950	0.0720	2647	193.6	2.50	24.88



(a)Nr=800 rpm (b) Nr=900 rpm

Fig.10. Variation of active power absorbed from the grid at the rotor side

Fig.10 shows the variation of active power of the rotor absorbed from the grid is maintained at slip times the stator power for both speeds i.e., 800 rpm and 900 rpm by controlling the modulation index of the sinusoidal PWM inverter.

D. Closed Loop Sub-Synchronous Mode

In closed loop sub-synchronous mode, the modulation index of the sinusoidal pulse width modulation inverter is varied automatically i.e., the actual rotor voltage, V_2 is compared with the reference voltage, $V_{2\,ref} = s*V_1$ and any mismatch is used to change the modulation index m, of the inverter as follows. $m = (V_2 - V_2\,ref) *[K_p+K_I/S]$.

The optimum values for K_p and K_I have been arrived at by trial and error method. The values have been chosen taking into account the range of mechanical torque of the wind turbine. This range will represent the variation in wind speed with which the system has to operate. In the proposed scheme, the P and I controller gains ($K_P = 0.05$ and $K_I = 2.38$) have been chosen for operating the system with rotor speed varying from 800 rpm to 900 rpm, to maintain the stator power constant at 2.65kW, though the rotor power absorbed from the grid is varied.

The simulation model for this mode of operation is developed and is shown in Fig.11. The simulation results obtained are given in Table.4

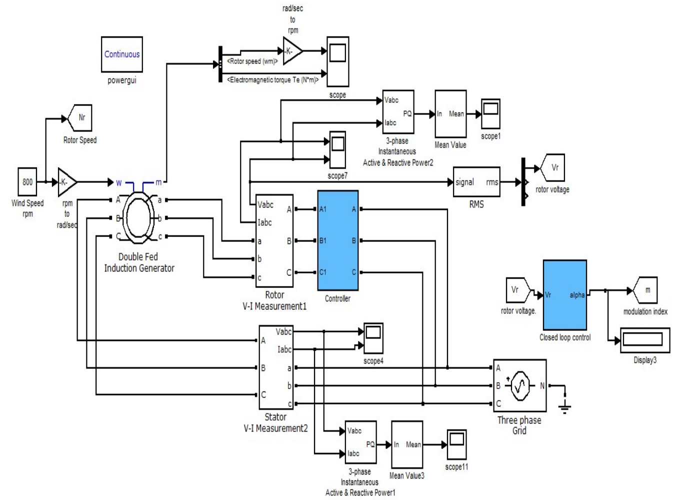
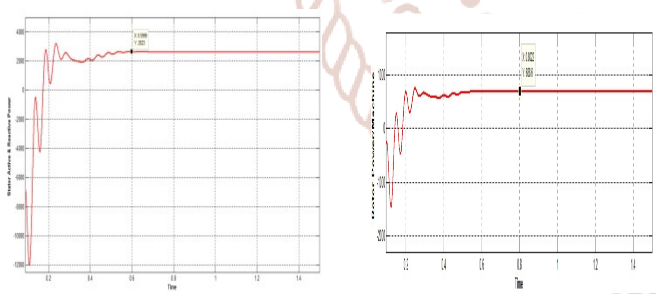


Fig.11. Block diagram for closed loop sub-synchronous mode

Table.4: Simulation results for closed loop sub-synchronous mode

Speed (N_r) in rpm	Modulation index (m)	Stator power (P_s) in watts	Rotor power (P_r) in watts	Rotor freq (fr) in Hz	Rotor voltage in volts
800	0.2497	2610	641.7	10.0	85.5
825	0.2187	2560	554.6	8.75	75.0
850	0.1894	2652	498.5	7.50	64.9
875	0.1603	2748	437.7	6.25	55.0
900	0.1320	2690	318.0	5.00	44.7



(a) Delivered to the grid (b) Absorbed from the grid

Fig.12. Variation of active power for N_r = 800 rpm

Fig.12.(a) shows the variation of active power of the stator for speed of 800 rpm. It can be seen that the stator power is delivered to the grid and is maintained at 2.65kW by controlling the modulation index of the sinusoidal PWM inverter. Similarly Fig.12.(b) shows the variation in active power of the rotor absorbed from the grid is maintained at slip times the stator power.

CONCLUSION

A very simple and easy to implement configuration of DFIG for wind driven applications in both sub & super-synchronous modes of operation has been presented. The simulation results in power smoothing mode for variable wind speeds are presented. The analysis of the DFIG in feeding the required power to the grid with the variation in rotor speed is carried out. The simulation results represent the smooth control of active power fed to the grid with variation in rotor speed of the DFIG. Such a system permits to use the wind power in different operating conditions i.e. above and below synchronous speeds that leading to the higher power harvest and therefore higher efficiency of wind energy conversion system.

REFERENCES

1) A. Miller, E. Muljadi, and D. Zinger, “A Variable Speed Wind Turbine Power Control”, IEEE Trans. on Energy Conversion, Vol. 12, No. 2, June 1997, pp. 181-186.
2) S. Müller, M. Deicke, and R. W. De Doncker, “Doubly fed induction generator system for wind turbines“, IEEE Industry Applications Magazine, pp. 26-33, May/June, 2002.
3) D. J. Atkinson, R. A. Lakin, and R. Jones, “A vector-controlled doubly-fed induction generator for a variable-speed wind turbine application,” Trans. Inst. Meas. Contr., vol. 19, no. 1, 1997, pp. 2–12.
4) R. Peña, J. C. Clare, and G. M. Asher, “Doubly Fed Induction Generator using back-to-back PWM converters and its application to variable speed wind-energy generation,” Proc. Inst. Elect. Eng., Elect. Power Appl., vol.143, no. 3, pp. 231–241, May 1996.
5) T.A.Lipo University of Wisconsin Madison WI USA, “A Super synchronous Doubly Fed Induction Generator Option for Wind Turbine Applications” IEEE Conference proceedings, 24-26 June 2009, pages 1-5.
6) M. Aktarujjaman, M.. E.Haque, K. M.Muttaqi, M. Negnevitsky, and G.Ledwich, sch.of.Eng., Univ.of Tasmania, Hobart, TAS, “Control Dynamics of a Doubly Fed Induction Generator Under Sub and Super-Synchronous Modes of Operation” IEEE Conference Proceedings, 20-24 July 2008, pages 1-9
7) D. R. Binu Ben Jose, N. Ammasai Gounden and R. Sri Naga Ramesh “A unified power electronic controller for wind driven grid connected wound rotor induction generator using line commutated inverter” Frontiers in Energy March 2013, Volume-7, Issue-1, pp.39–48.
8) A.C. Smith, R. Todd, M. Barnes and P.J. Tavner, "Improved Energy Conversion for Doubly Fed Wind Generators", IEEE Trans. on Ind. Applications, Vol. 42, No.6, Nov./Dec. 2006, pp. 1421-1428.