Grid Connected DFIG With Efficient Rotor Power Flow Control Under Sub & Super Synchronous Modes of Operation

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***Abstract*—To harness the wind power efficiently the most reliable system in the present era is grid connected Doubly fed induction generator (DFIG). The DFIG brings out the advantage of utilizing the turns ratio of the machine and hence the converter does not need to be rated for the machine's full rated power. 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 maintaining the stator power constant by effecting rotor voltage through IGBT in sub-synchronous mode and in the case of super-synchronous mode it is controlled by current sequence through LCI. The operation of the proposed scheme is illustrated in different operating conditions i.e. above and below synchronous speeds using computer simulations.**

***Keywords*—** DFIG, Sub&Super synchronous, Line Commutated Inverter (LCI), Sinusoidal PWM Inverter.

I. INTRODUCTION

Wind energy has become one of the most important and promising sources of renewable energy. With increased penetration of wind power into electrical grids, Doubly-Fed Induction Generator (DFIG) based wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. This has created an interest in developing suitable models for DFIG to be integrated into power system studies. 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. 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.

With this DFIG based Variable-speed wind turbines, an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. It consists of a wound rotor induction machine with slip rings, and power electronic converters between the rotor slip-rings and the grid. In this paper how we can obtain constant power for variable wind speeds under sub & super synchronous speed operation of a DFIG is investigated. The stator of DFIG is directly connected to the grid while the rotor fed at variable frequency through converter cascade (AC/DC/AC) via slip rings and brushes to allow the DFIG to operate at variable wind speeds in response to changing wind speeds. Both the stator and rotor windings are able to supply power to the grid. The direction of the power flow in the rotor circuit depends on the variation of the wind speed. The power electronic converters control both the direction and magnitude of the power flow of the machine. In sub-synchronous mode, the converter feeds the rotor windings from the grid, whereas the rotor supplies power to the grid in super-synchronous mode of operation. To ensure variable speed operation, and maintain the stator power constant both converters need to be controlled under sub- synchronous and super-synchronous modes of operation [3].

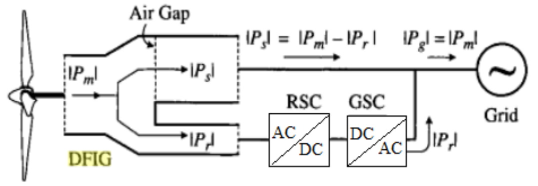
Most, if not all, of the published papers on the application of DFIG for wind energy conversion systems using force commutated inverters in the rotor circuit and d-q axis control for maintain stator power is constant. However, in this paper another approach is used which is the power flow approach and a very simple control technique by employing line commutated SCR inverter in the rotor circuit of the DFIG. In this approach 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 for analysis of DFIG based wind energy conversion system.

This paper is organized as follows. In section II Power flow in DFIG wind energy conversion system and steady state model of DFIG are described. 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 in section III. And the development of simulation models of the proposed scheme along with simulation results is presented in section IV. Finally main observations are concluded in section V.

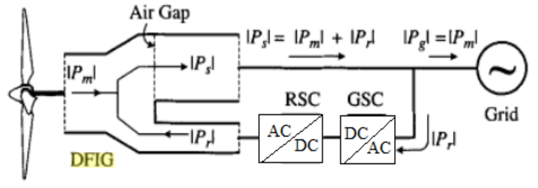
II. POWER FLOW & STEADY STATE MODEL OF DFIG

A. *Power flow in DFIG*

DFIG can be operated in two modes of operation namely; sub-synchronous and super-synchronous mode depending on the rotor speed below and above the synchronous speed. 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 transferred between the stator and the rotor through the air gap which is known as the air gap power P_s; b) the mechanical power P_m transferred between the rotor and shaft; c) the slip power P_r which is transferred 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



(a) Supersynchronous mode



(b) Subsynchronous mode

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

B. *Steady State Model*

The standard steady-state per-phase equivalent circuit can be utilized for assessing 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 illustrates the standard per-phase equivalent circuit of DFIG in which rotor circuit parameters are referred to the stator frequency, so that all machine reactances are determined at supply frequency.

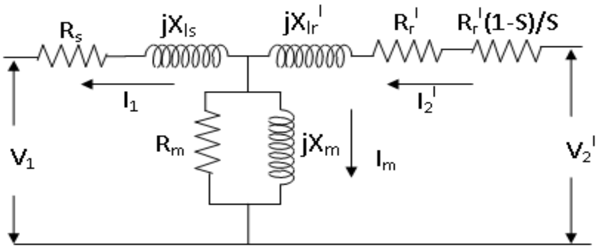


Fig.2. Per-phase equivalent circuit of a DFIG

When machine is doubly-fed, the per unit power into the rotor circuit comes from two sources

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

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

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

The power lost in the rotor circuit is

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

The power output of the circuit is

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

Conservation of power requires that

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

So that

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

Or

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

But

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

Substituting Eq. (8) into Eq.(7) ,

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

Or

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

Cancelling out the (1-s) term

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

This resulting 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 [4]. Expanding Eq. (11),

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

In general, the phase position of the rotor voltage is typically 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, Eq. (12) can be solved for the currents by also assuming that their ratio (power factor) is specified. An alternative approach to solving Eq. 12 is to assume that the phase position of the rotor current is known rather than the rotor voltage. In this case, assuming the real part of the stator current as reference,

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

And

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

Eq. (12) becomes

$$T = \frac{V'_{2,re}}{s} I_2' - (I_2')^2 \frac{R_r'}{s} \qquad (15)$$

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

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

Or

$$I_2' = \frac{V'_{2,re}}{2R_r'} \pm \frac{\sqrt{\left(V'_{2,re}\right)^2 - 4R_r' sT}}{2R_r'} \qquad (17)$$

The voltage $V'_{2,re}$ can also be written as $V_2'\cos\Phi_2$ where $\Phi2$ represents the phase angle of the rotor terminal voltage V_2' with respect to the rotor input current I_2'. Hence the rotor current I_2' can be determined as a function of slip for any desired torque and specified value of rotor voltage and phase.

Having obtained the rotor current from Eq. (17) it is now possible to obtain the air gap voltage *E* from Eq. (8). The stator current can then be found from,

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

The stator voltage can then be obtained by the stator loop equation

$$V_1 = E - I_1 (R_S + jX_{1S}) \qquad (19)$$

In general the voltage obtained will not be identical to the available terminal voltage except for specific combinations of rotor voltage and slip. Hence, iteration 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, a doubly fed induction generator (DFIG) based variable speed wind turbine is capable of operating in sub-synchronous or super-synchronous mode of operation using power electronic converters. Traditional Wound Rotor Induction Generator (WRIG) will never produce power at sub-synchronous mode of operation. In this mode, it produces motoring torque which can be utilized by controlling rotor voltage or current. The component of rotor side converter must need to be controlled properly for reliable operation of the machine under sub-synchronous and super-synchronous modes. Rotor side converter controls the imposed voltage and current for the rotor circuit of the machine. The control of imposed current is necessary for creating generating torque in sub-synchronous mode of operation. 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 machine synchronous speed. 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. These can be achieved by the changing the magnitude of the injected voltage to the rotor circuit 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 machine synchronous speed and slip is negative (s< 0). The rotor voltage/current sequence has to be reversed to supply extra generating power to the grid through DC-link and grid side converter. The magnitude of the rotor current and voltage is changing 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

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

And it follows that

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

where

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

is defined as the slip of the generator.

Generally the absolute value of slip (s) is much lower than 1 and, consequently, 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 it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to raise 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 DC voltage constant as shown in Fig.3. In steady-state for a lossless AC/DC/AC converter P_g is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by PC_{rotor}. The phase-sequence of the AC voltage generated by PC_{rotor} is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. 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.

Between the two converters, a dc-link capacitor is placed, as energy storage, in order to keep the voltage variations(or ripple) in the dc-link voltage small. With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the

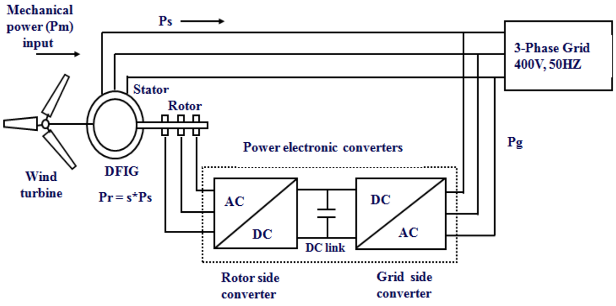


Fig.3. DFIG system with power electronic converters

stator terminals, while the main objective for 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 block schematic for open loop super-synchronous mode is shown in Fig.3. Ratings of DFIG used in the proposed scheme are: Nominal power (P) = 2.65kW, $V_{L\text{-}L}$ = 400V, f = 50Hz, synchronous speed (Ns) = 1000 rpm, number of poles (P) = 6 [7]. In open loop super-synchronous mode firing angle ($\alpha > 90^0$) of the line commutated inverter is varied manually to maintain the stator power constant at 2.65kW for speeds varying from 1050 rpm to 1200 rpm. As the speed varies, the rotor power delivered to the grid is varied but stator power is maintained constant.

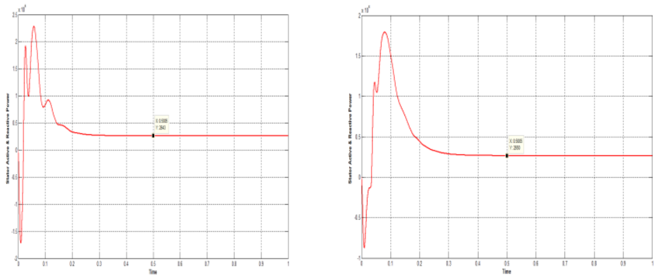
The parameters chosen for the simulation study are :

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 4.1 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

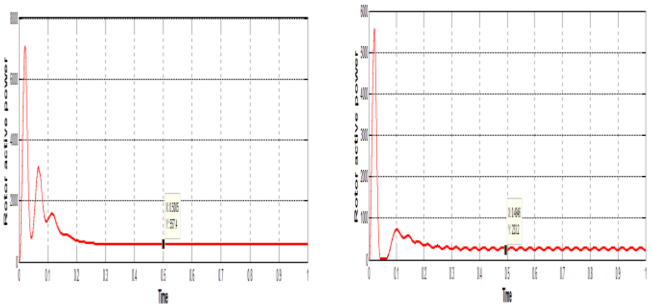


(a)Nr=1200 rpm (b) Nr=1100 rpm

Fig. 4.1 Variation of active power delivered at the stator side

Fig. 4.1 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.

Similarly from Fig. 4.2 we observe that the rotor power 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 firing angle of line commutated inverter.



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

Fig. 4.2 Variation of active power delivered at the rotor side

B. *Closed Loop Super-Synchronous Mode*

Fig. 4.3 shows 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 [6]. 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 = 0.5 and K_I = 100) have been chosen for operating the system with rotor speed varying from 1050 rpm to 1200 rpm, to maintain the stator power constant at 2.65kW.

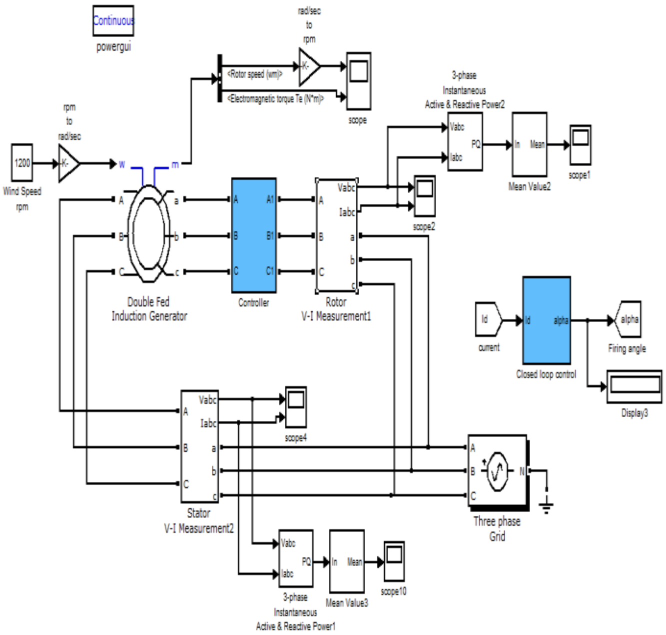


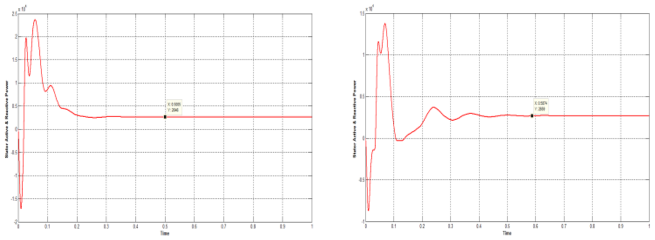
Fig. 4.3 Simulation model of the closed loop super-synchronous mode

The simulation model for this mode of operation is developed and is shown in Fig. 4.3. The simulation results obtained are given in Table 4.2.

Table 4.2 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

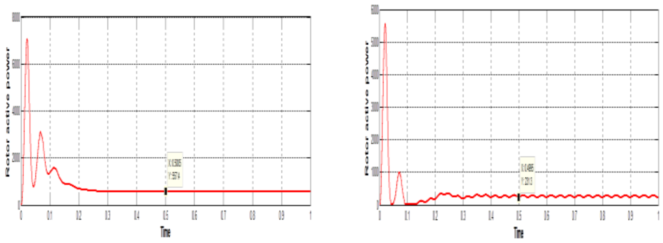
Fig. 4.4 shows the variation of active power of the stator for varying rotor speeds of 1200 rpm and 1100 rpm. It can be seen that the stator power is delivered to the grid and is maintained at around 2.65kW for both speeds by controlling the firing angle of line commutated inverter.



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

Fig. 4.4 Variation of active power delivered at the stator side

Similarly from Fig. 4.5 we observe that the rotor power 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

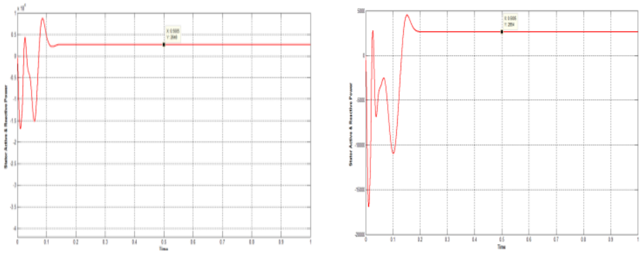
Fig. 4.5 Variation of active power delivered at the rotor side

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 4.3.

Fig. 4.6 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.

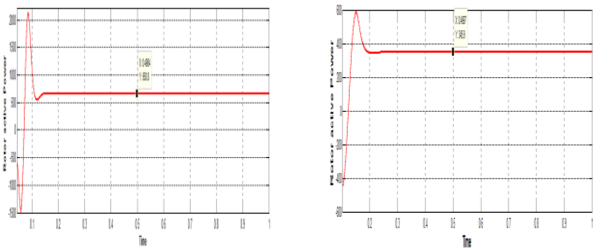


(a)Nr=800 rpm (b) Nr=900 rpm

Fig. 4.6 Variation of active power delivered at the stator side

Table 4.3 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. 4.7 Variation of active power absorbed from the grid at the rotor side

Similarly from Fig. 4.7 we observe that the rotor power 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. 4.8. The simulation results obtained are given in Table 4.4

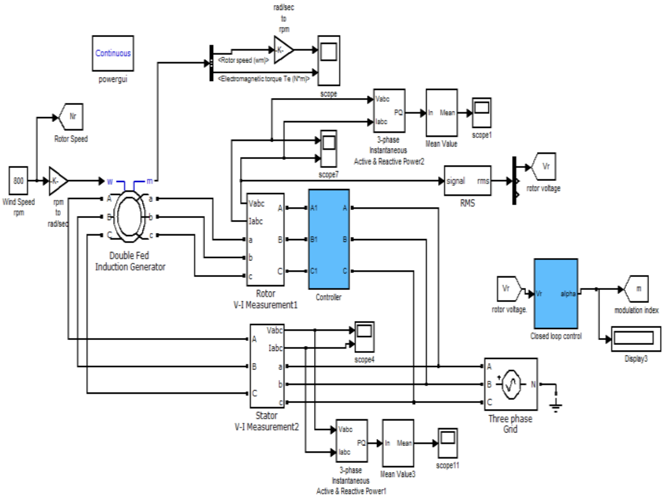
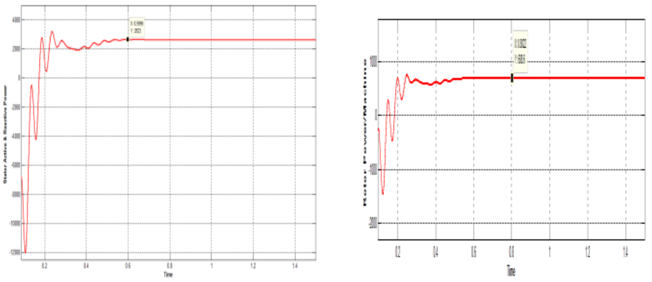


Fig. 4.8 Block diagram for closed loop sub-synchronous mode

Table 4.4 Simulation results for closed 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 (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. 4.9 Variation of active power for N_r = 800 rpm

Fig. 4.9 (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 from Fig. 4.9 (b), we observe that the rotor power absorbed from the grid is maintained at slip times the stator power.

V. CONCLUSION

In this paper the operation of a double-fed wound-rotor induction machine, coupled to a wind turbine, as a generator at different speeds is investigated. A very simple and easy to implement configurations of DFIG for wind driven applications have been demonstrated. The power flow in the rotor circuit has been controlled for maintaining the stator power constant in both sub & super-synchronous modes of operation.

The simulation results depict the smooth control of active power fed to the grid with variation in rotor speed of the DFIG. Such a system allows the utilization of wind power in different operating conditions i.e. above and below synchronous speeds, thus leading to higher power harvesting and consequently higher efficiency of wind energy conversion system.

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