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DFIG-BASED WIND POWER CONVERSION SYSTEM CONNECTED TO GRID

Akshay kumar
Department of electronics and communication
AKGEC Ghaziabad, INDIA.

***Abstract-* This paper presents the complete modeling and real-time simulation of wind turbine driven doubly-fed induction generator (DFIG) which feeds ac power to the utility grid. For that, two pulse width modulated voltage source converters are connected back to back between the rotor terminals and utility grid via common dc link. It is found that there are so many limitations in the conventional control techniques of DFIG. This paper presents a configuration of a DFIG-based wind Energy Conversion system (WECS) with a battery energy storage system (BESS) in the dc link with a control strategy to maintain the grid power constant. This proposed control strategy then Simulated in Matlab-Simulink. Simulation results show that the proposed strategy can enhance the performance of the DFIG**.

***Index Terms*— Doubly fed induction generator (DFIG), DC-link voltage control, vector control, wind energy conversion system (WECS).**

I. INTRODUCTION

Renewable energy including solar, wind, tidal, small Hydro, geothermal, refused derived fuel and fuel cell energies is sustainable, reusable and environmentally friendly and clean. With the increasing shortage in fossil fuels, and pollution problems renewable energy has become an important energy source. Wind energy is the fastest growing and most promising renewable energy source among them due to economically viable. In India, the total installed capacity of wind power generation is 8754 MW in the year 2008.By the end of 2012, the total installed capacity is going to be reached to 12000 MW according to ministry of new and renewable energy, India and total installed capacity of wind energy is estimated to be more than 160 GW [1-8].

During last two decades, the high penetration of wind turbines in the power system has been closely related to the advancement of the wind turbine technology and the way of how to control. Doubly-fed induction machines are receiving increasing attention for wind energy conversion system during such situation. because the main advantage of such machines is that, if the rotor current is governed applying field orientation control-carried out using commercial double sided PWM inverters, decoupled control of stator side active and reactive power results and the power processed by the power converter is only a small fraction of the total system power. So, doubly-fed induction machine with vector control is very attractive to the high performance variable speed drive and generating applications [1-4].

Presently, commercial DFIG wind turbines mainly use the technology that was developed a decade ago [11], based on the standard decoupled *d-q* vector control mechanism. This paper shows that there is a limitation in the conventional vector control approach for the grid-side converter of the DFIG wind turbine. The weakness is more evident when the converter operates beyond its linear modulation limit. This situation has also been reported recently by many studies in different applications.

This paper develops a mechanism for improved control of a DFIG wind turbine under a direct-current vector control configuration. Then, based on the proposed control structure, the integrated DFIG system control is developed, reactive power control, and grid voltage support control. A dynamic steady state simulation of WECS is essential to understand the behavior of WECS using MATLAB. A

Simulation analysis is performed and a variety of DFIG characteristics are analyzed.

II. WIND TURBINE MODELING

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the equation (1) [1-10]:

$$P_m = \frac{1}{2}\, c_p(\lambda, \beta)\rho\, Av^3 \qquad (1)$$

Where c_p is the Power Co-efficient, ρ is the air density in kg/m^3, A is the area of the turbine blades in m^2 and V is the wind velocity in m/sec. The power coefficient is defined as the power output of the wind turbine to the available power in the wind regime. This coefficient determines the "maximum power" the wind turbine can absorb from the available wind power at a given wind speed. It is a function of the tip-speed ratio (λ) and the blade pitch angle (β). The blade pitch angle can be controlled by using a "pitch-controller" and the tip-speed ratio (TSR) is given as

$$\lambda = \frac{\omega R}{v} \qquad (2)$$

Where λ is the rotational speed of the generator and R is radius of the rotor blades.

Hence, the TSR can be controlled by controlling the rotational speed of the generator. For a given wind speed, there is only one rotational speed of the generator which gives a maximum value of c_p , at a given β . This is the major principle behind "maximum-power point tracking" (MPPT) and a wind turbine needs to be designed keeping this strategy in mind.

III. DOUBLY FED INDUCTION GENERATOR

The wind turbine and the doubly-fed induction generator (WTDFIG) are shown in the fig.1 called the Wind Turbine and the Doubly-Fed Induction Generator System. The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). Crotor and C_{grid} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.

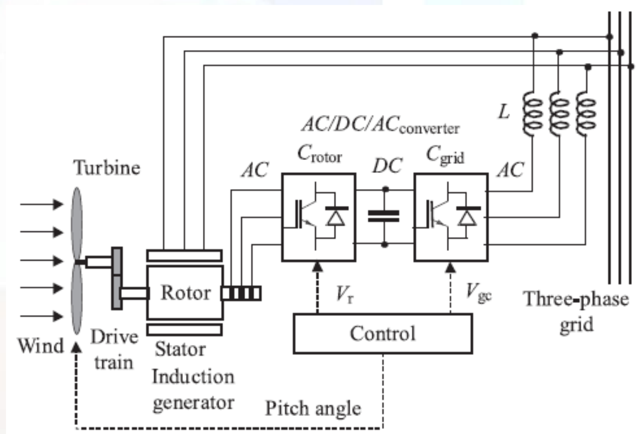

Fig.1. The Wind Turbine and the Doubly-Fed Induction Generator System.

IV. OPERATING PRINCIPLE OF THE WIND TURBINE DOUBLY-FED INDUCTION GENERATOR

The power flow, illustrated in the fig.2 called the Power Flow, is used to describe the operating principle. In this figure the followings parameters are used:

P_m	Mechanical power captured by the wind turbine and transmitted to the rotor
P_s	Stator electrical power output
P_r	Rotor electrical power output
P_{gc}	C_{grid} electrical power output
Q_s	Stator reactive power output

Q_r Rotor reactive power output

Q_{gc} C_{grid} reactive power output

T_m Mechanical torque applied to rotor

T_{em} Electromagnetic torque applied to the rotor by the generator

ω_r Rotational speed of rotor

ω_s Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.

J Combined rotor and wind turbine inertia coefficient.

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

$$P_m = T_m \omega_r \tag{3}$$

$$P_s = T_{em} \omega_s \tag{4}$$

For a loss less generator the mechanical equation is

$$J \frac{d\omega_r}{dt} = T_m - T_{em} \tag{5}$$

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

$$T_m = T_{em} \;\&\; P_m = P_s + P_r \tag{6}$$

It follows that:

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

$$= - T_m \left(\frac{\omega_s - \omega_r}{\omega_s}\right) \omega_s = - s\, T_m \omega_s$$
$$= - s\, P_s \tag{7}$$

where s is defined as the slip of the generator:

$$s = \left(\frac{\omega_s - \omega_r}{\omega_s}\right) \tag{8}$$

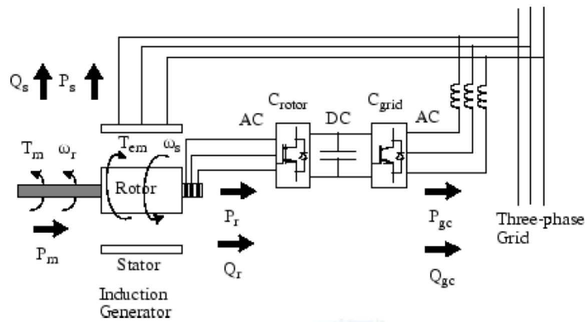

Fig.2. The Power Flow

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of Ps. Since Tm 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 rise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a loss less AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}. The power control will be explained below.

The phase-sequence of the AC voltage generated by C_{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.

C_{rotor} and C_{grid} have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

V. ROTOR CONTROL SYSTEM

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. An example of such a characteristic is illustrated in the fig.3 called Turbine Characteristics and Tracking Characteristic, by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line, the speed of point B must be greater than the speed of point A. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 pu) and the speed of the point D must be greater than the speed of point C. Beyond point D the reference power is a constant equal to one per unit (1 pu).

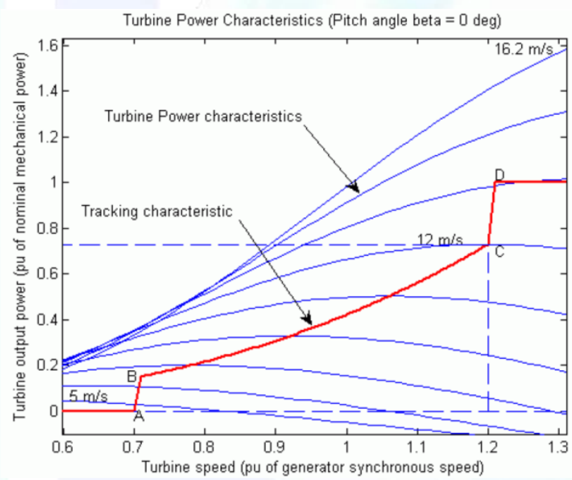

Fig.3. Turbine Characteristics and Tracking Characteristic

The generic power control loop is illustrated in the fig.4 and fig.5 called Rotor-Side Converter Control System. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current I_{qr}_ref that must be injected in the rotor by converter C_{rotor}. This is the current component that produces the electromagnetic torque T_{em}. The actual I_{qr} component of positive-sequence current is compared to $_{Iqr\_ref}$ and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage V_{qr} generated by C_{rotor}. The current regulator is assisted by feed forward terms which predict V_{qr}.

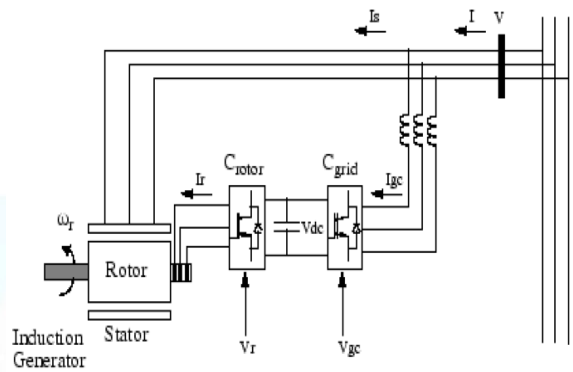

Fig.4. Rotor-Side Converter Control System

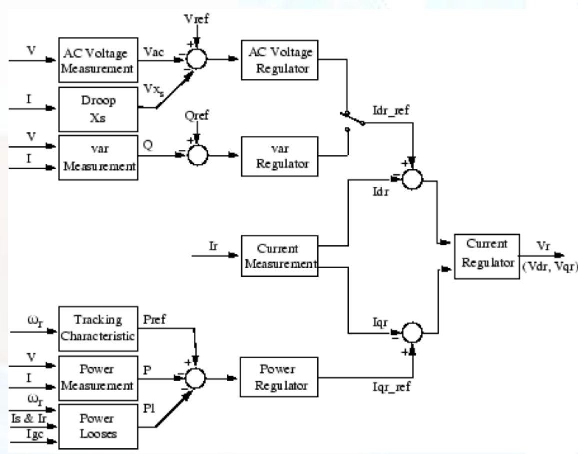

Fig.5. Block diagram of Rotor-Side Converter Control System

The voltage or the reactive power at grid terminals is controlled by the reactive current flowing in the converter C_{rotor}. The generic control loop is illustrated in the fig.5 called Rotor-Side Converter Control System. When the wind turbine is operated in voltage regulation mode, it implements the following V-I characteristic shown in fig .6..

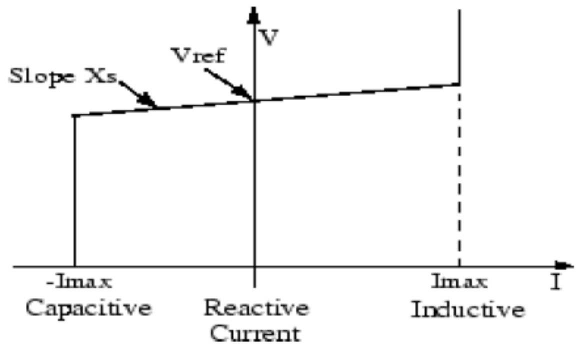

Fig.6. Wind Turbine V-I Characteristic

As long as the reactive current stays within the maximum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage V_{ref}. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure called Wind Turbine V-I Characteristic. In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{ref} + X_s.I \qquad (9)$$

Where

V	Positive sequence voltage (pu)
I	Reactive current (pu/P_{nom}) (I > 0 indicates an inductive current)
Xs	Slope or droop reactance (pu/P_{nom})
P_{nom}	Three-phase nominal power of the converter specified in the block dialog box.

When the wind turbine is operated in var regulation mode the reactive power at grid terminals is kept constant by a var regulator.

The output of the voltage regulator or the var regulator is the reference d-axis current I_{dr_ref} that must be injected in the rotor by converter C_{rotor}. The same current regulator as for the power control is used to regulate the actual I_{dr} component of positive-sequence current to its reference value. The output of this regulator is the d-axis voltage V_{dr} generated by C_{rotor}. The current regulator is assisted by feed forward terms which predict V_{dr}. V_{dr} and V_{qr} are respectively the d-axis and q-axis of the voltage V_r.

VI. GRID CONTROL SYSTEM

The converter C_{grid} is used to regulate the voltage of the DC bus capacitor. In addition, this model allows using C_{grid} converter to generate or absorb reactive power. The control system, illustrated in the fig.7 called Grid-Side Converter Control System, consists of:

- Measurement systems measuring the d and q components of AC positive-sequence currents to be controlled as well as the DC voltage V_{dc}.
- An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current I_{dgc_ref} for the current regulator (I_{dgc} = current in phase with grid voltage which controls active power flow).
- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C_{grid} (V_{gc}) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_{q_ref} reference. The current regulator is assisted by feed forward terms which predict the C_{grid} output voltage.

The magnitude of the reference grid converter current I_{gc_ref} is equal to $\sqrt{Idgc\_ref^2 + Iq\_ref^2}$. The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When I_{dgc_ref} and I_{q_ref} are such that the magnitude is higher than this maximum value the I_{q_ref} component is reduced in order to bring back the magnitude to its maximum value.

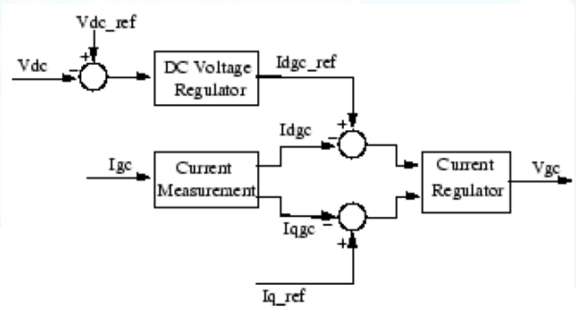

Fig.7. Grid-Side Converter Control System

VII. PITCH ANGLE CONTROL SYSTEM

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. The control system is illustrated in the following fig.8.

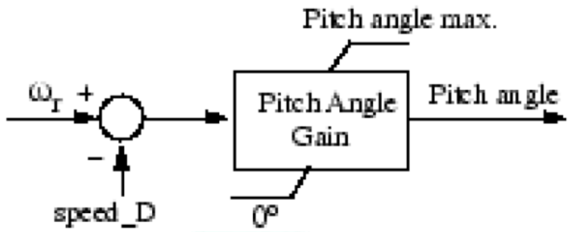

Fig.8. Pitch Control System

VIII. MATHEMATICAL MODELING OF DFIG

A simplified mathematical model would help in efficient analysis of the behavior of any complex system, under different operating conditions and control strategies. For a DFIG, the most common way of deriving a mathematical model is in terms of direct and quadrature axes (*dq* axes) quantities in a frame which rotates synchronously with the stator flux vector. An equivalent circuit for the DFIG in the synchronous reference frame [14] is represented in Fig.9.

The expressions related to this model are as

$$v_{qds} = r_s i_{qds} + j\omega_e \psi_{qds} + \frac{d}{dt}(\psi_{qds}) \quad (10)$$

$$v_{qdr} = r_s i_{qdr} + js\omega_e \psi_{qdr} + \frac{d}{dt}(\psi_{qdr}) \quad (11)$$

$$\psi_{qds} = L_s i_{qds} + L_m i_{qdr} \quad (12)$$

$$\psi_{qdr} = L_r i_{qdr} + L_m i_{qds} \quad (13)$$

$$T_e = \frac{3}{2}\frac{p}{2} R_e \, [j\psi_{qds}.\overline{\iota_{qds}}] = \frac{3}{2}\frac{p}{2} R_e \, [j\psi_{qdr}.\overline{\iota_{qdr}}] \quad (14)$$

Where $\overline{\iota_{qds}}$ and $\overline{\iota_{qdr}}$ are the complex conjugates of the stator-current and rotor-current space vectors and stator and rotor inductances are defined as

$$L_s = L_{ls} + L_m \quad (15)$$

and $$L_r = L_{lr} + L_m \quad (16)$$

The complex torque equation of (14) can be resolved in reference *d-q* leading to

$$T_e = \frac{3}{2}\frac{p}{2} R_e \, [\psi_{ds}.i_{qs} - \psi_{qs}.i_{ds}] = \frac{3}{2}\frac{p}{2} R_e \, [\psi_{dr}.i_{qr} - \psi_{qr}.i_{dr}] \quad (17)$$

The stator side active and reactive powers are given as

$$P_s = \frac{3}{2} R_e \, [v_{qds}.\overline{\iota_{qds}}] = \frac{3}{2} R_e \, [v_{qs} i_{qs} + v_{ds} i_{ds}] \quad (18)$$

$$Q_s = \frac{3}{2} Im \, [v_{qds}.\overline{\iota_{qds}}] = \frac{3}{2} [v_{qs} i_{ds} - v_{ds} i_{qs}] \quad (19)$$

considering that

$$\overline{\iota_{qds}} = \frac{1}{L_s}\overline{\psi_{qds}} - \frac{L_m}{L_s}\overline{\iota_{qdr}} \quad (20)$$

The active and reactive power equations are modified as[14]

$$P_s = \frac{3}{2}\{\frac{1}{L_s}(v_{qs}\psi_{qs} - v_{ds}\psi_{ds}) - \frac{L_m}{L_s}(v_{qs} i_{qr} + v_{ds} i_{dr})\} \quad (21)$$

$$Q_s = \frac{3}{2}\{\frac{1}{L_s}(v_{qs}\psi_{qs} + v_{ds}\psi_{ds}) - \frac{L_m}{L_s}(v_{qs} i_{dr} - v_{ds} i_{qr})\} \quad (22)$$

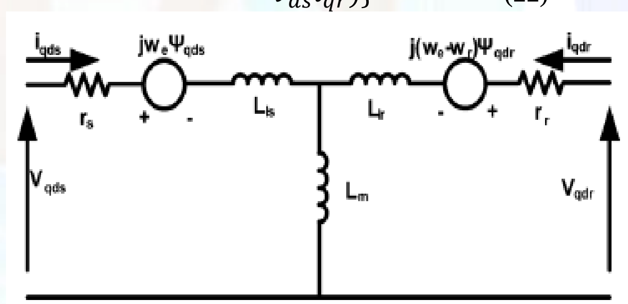

Fig..9. Complex synchronous equivalent of a DFIG

Thus, the magnitudes of stator currents govern the active and reactive powers of the stator, and these currents depend on the rotor currents. Thus, the active and reactive powers can be controlled by appropriately controlling the rotor currents (i_{qr} and i_{dr}) in WECS.

XI. MATLAB-BASED MODELING

The model of WECS with BESS shown in Fig. 1 is developed in the MATLAB-SIMULINK shown in fig.10 and results are presented to demonstrate its behavior at different wind speeds.

Figs. 11, 12, and 13 show the performance of the proposed configuration of a DFIG-based WECS at sub-synchronous speed, super-synchronous speed, and during transition i.e., at synchronous speed, respectively. The waveforms for stator voltage , grid current, grid side converter current, rotor side converter current , stator current, rotor speed , dc link voltage , reactive power, grid power, and battery power are presented for different wind speeds. The convention for the battery power is chosen as to be negative if the battery discharges any power to the grid and positive if power is stored in the battery.

In all three cases, the value of the grid power is maintained to be constant at 0.75 MW by the modified grid power control strategy. However, this is maintained by either charging or discharging the battery in the corresponding region of operation. The reactive power is maintained at a stable value of zero, demonstrating a unity power factor operation. The analysis has been performed at variable wind speeds and the grid power is maintained to be constant at the reference value. The reference grid power can be chosen to be the average power supplied by the total period of operation. Hence, the grid power reference is chosen to be 0.75 MW as calculated and satisfactory results are obtained as shown in Figs. 11–13.

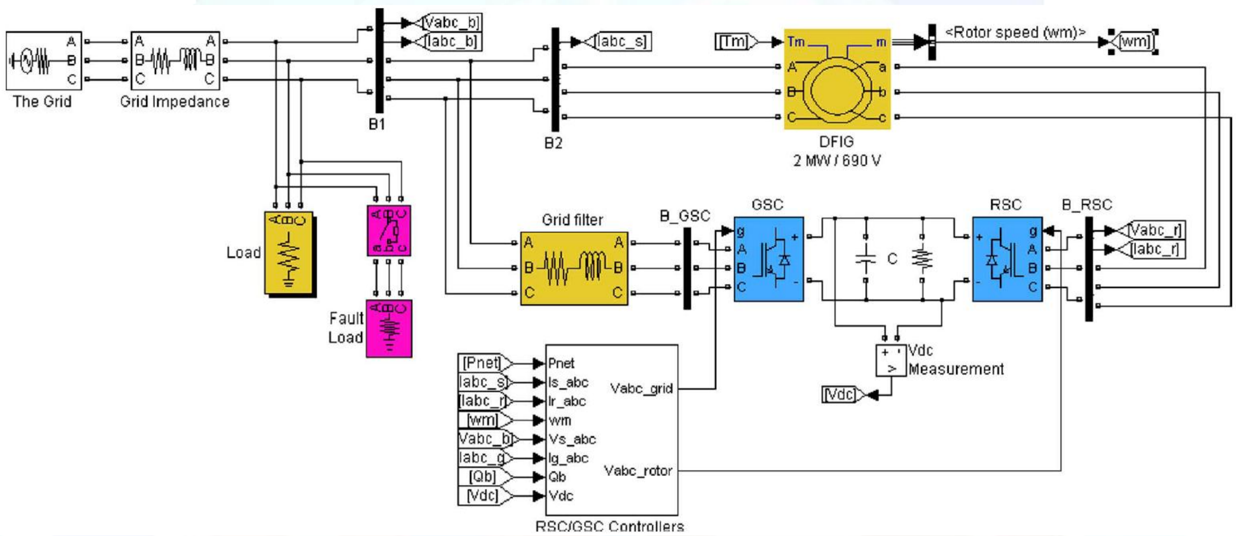

Fig.10. GSC and RSC control of DFIG wind turbine in Sim-Power Systems

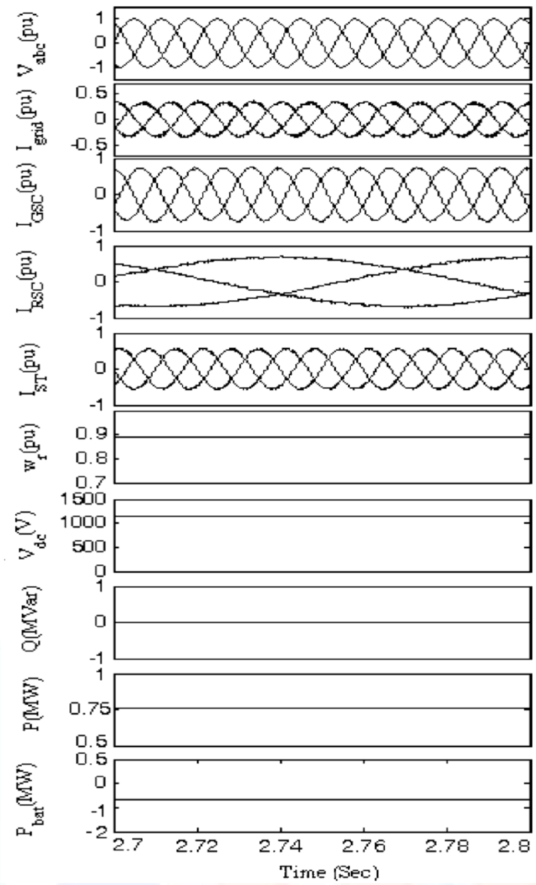

Fig.11. Performance of a DFIG-based WECS with a BESS at sub-synchronous speed (wind speed =8 m/s, rotor speed = 0.9 p.u.).

X. CONCLUSION

This paper has presented the modeling and simulation of doubly-fed induction generator driven by a wind turbine with a BESS in the dc link which feeds constant power to the utility grid. The power flow control in the DFIG can be obtained by connecting two back to back PWM converters between rotor and utility grid. The PWM rectifier model and PWM inverter model has been described and these two converters provides bi-directional power flow with reduced power rating.

It is observed that DFIG driven by wind turbine with a BESS shows satisfactory performance under different wind speed conditions. In "over generation" if utility fails to maintain the grid power constant, the consumers are to be paid in return to absorb the excess power, which means that consumers loose both energy and money. The proposed control strategy mitigates this problem by maintain the grid power constant under different wind speeds. The main disadvantage of this control strategy is using a high rating of BESS. Compared to conventional control strategy, this DFIG driven by wind Turbine with a BESS in the dc link is more stable and shows better performance.

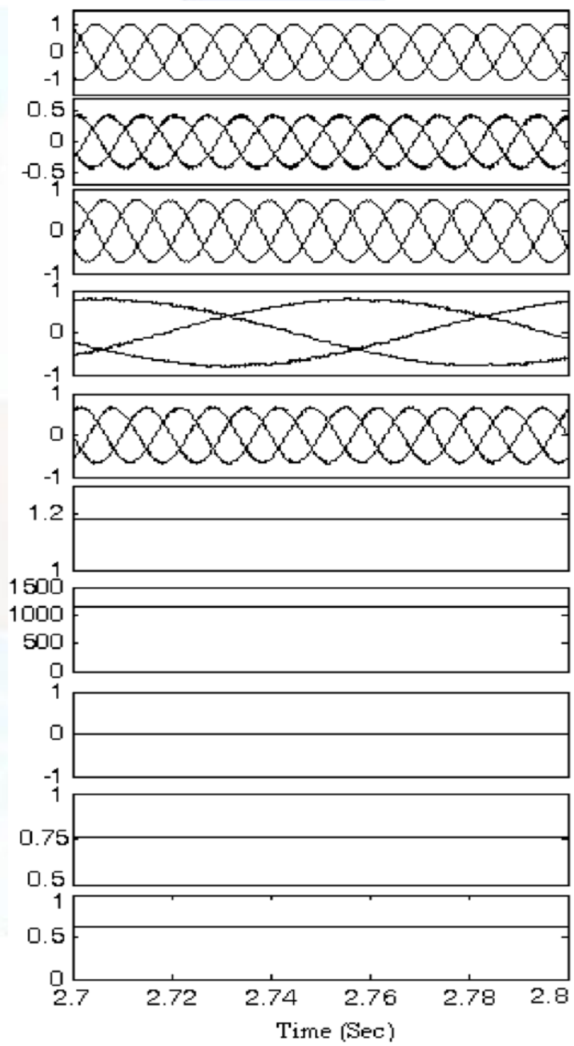

Fig. 12. Performance of a DFIG-based WECS with a BESS at super-synchronous speed (wind speed = 12 m/s, rotor speed = 1.2 p.u.).

APPENDIX

A. Parameters of the Wind Turbine

Parameters	Value
Rated Power	1500kw
Cut-in Wind speed	4m/s
Rated Wind speed	14m/s
Cut-out Wind	20m/s
No. of Blades	3
Rotor Diameter	82m
Swept Area	5281m^2

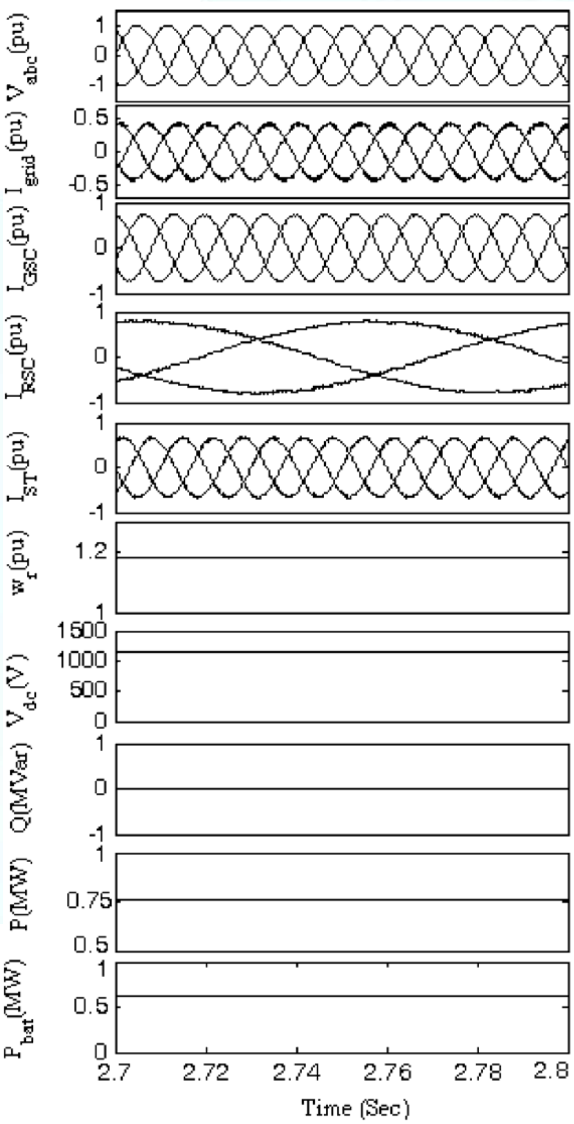

Fig. 13. Performance of a DFIG-based WECS with a BESS at super-synchronous speed (wind speed = 10 m/s, rotor speed = 1 p.u.).

B. Parameters of the Battery

Parameters	Value
Battery Nominal Voltage	1200v
Internal resistance	10000Ω
Internal capacitor	675000F
Battery Series Resistance	0.00094Ω

C. Parameters of the DFIG

Parameter	Value
Rated Power(MW)	1.5
Stator Voltage(V)/Frequency(Hz)	575/50
Stator/Rotor turns	0.38
Pole numbers	4
Stator Resisitance(pu)	0.00706
Rotor Resistance(pu)	0.005
Stator leakage Inductance(pu)	0.171
Rotor leakage Inductance(pu)	0.156
Magnetizing Inductance(pu)	2.9
Lumped Inertia constant(s)	5.04

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Akshay Kumar was born in Ghaziabad, India, in 1988. He received the B. Tech (Electrical and Electronics) degree from Ideal Institute of Technology, Ghaziabad (affiliated to UPTU, Uttar Pradesh), in 2009 and, currently pursuing his M. Tech (Electrical Power and Energy Systems) from Ajay Kumar Garg Engineering College, Ghaziabad (affiliated to MTU, Uttar Pradesh). He worked in Industry and he has also teaching experience of more than 1 and half year in Engineering College.