Constant Power Generation of DFIG based Wind Energy System using Battery Energy Storage System

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Abstract- **Wind energy conversion using Doubly Fed Induction Generator is one of the most important types of renewable energy generations. Wind farm power output has large fluctuations due to sudden wind speed changes. The proposed topology includes a Battery Energy Storage System (BESS) in the dc link to reduce the power fluctuations on the grid due to the varying nature and unpredictability of wind. The power fed to the grid is always leveled, resulting in an efficient and reliable source of electrical power to the grid. In order to decouple the active and reactive powers generated by the machine, stator-flux oriented vector control is applied. High performance control of power can be achieved by the proposed scheme, since it facilitates the decoupled control of active and reactive power. The proposed strategy is simulated in MATLAB-SIMULINK under different wind speeds. Placing a BESS in the dc link of a DFIG-based wind energy conversion system, proves to be a satisfactory implementation in terms of maintaining a constant power at the grid.**

Index Terms:- Doubly Fed Induction generator (DFIG), Stator Flux Oriented Reference Frame, Battery Energy Storage System (BESS)

I. INTRODUCTION

The energy demand is increasing day by day with high population growth and economic development in the world. Fossil fuel sources like oil, coal, etc. are now become costly and cause serious pollution to the environment. The use of renewable sources for electric power generation has experienced a huge face lift since the past decade. The average temperature around the world is increasing every year because of greenhouse emissions. Wind energy generation coming under renewable energy source, is a feasible solution to energy shortage. It is the fastest growing source of electrical energy in the world today due to the increasing awareness of the environmental problems together with the rapid increase in the fuel cost and the power demand.

Power extracted from wind can be described in terms of air density, wind speed, rotor radius and turbine efficiency.

$$P_m = \frac{1}{2}\rho\pi R^2 C_p V_w^3 \tag{1}$$

Where ρ is the density of air, C_p is the Power Coefficient, and V_w is the wind speed.

II. DOUBLY FED INDUCTION GENERATOR (DFIG)

In DFIG the stator winding is directly connected to the grid and the rotor winding is connected to grid through the rotor-side VSC and GSC. This type of machine is equipped with two identical VSC. These converters typically employ IGBT in their design. The AC excitation is supplied through both the grid-side VSC and the rotor- side VSC. The grid side VSC is connected to the ac network. The rotor side converter is connected to the rotor windings. The grid side VSC and the stator winding of the DFIG are connected to the ac grid. The VSC allow a wide range of variable speed operation of the Wound Rotor Induction Machine (WRIM). The converters are placed in the rotor side so they have a rating of approximately 30% of the generator rating. The capacitor connected to the DC-link acts as a constant DC voltage source, an energy storage device and a source of reactive power. The control system generates the commands which are intended to control the rotor side VSC and control the grid side VSC (to control the electrical power). In turn, the rotor-side VSC controls the power of the wind turbine, and the grid-side VSC controls the dc-bus voltage and the reactive power at the grid terminals. The applied rotor voltage can be varied in both magnitude and phase by the converter controller, which controls the rotor currents. A typical arrangement of a DFIG is shown in fig. 1.

At synchronous speed, the magnetic field of the rotor rotates at the same speed as the stator magnetic field. The DFIG then essentially operates as asynchronous machine with DC current in the rotor windings meaning no active power will be generated in the rotor windings and therefore all active power from the DFIG machine will flow from the stator to the grid. When the wind speed increases, the speed of the rotor increases above synchronous speed, resulting in a negative slip and super synchronous operation. In this operation, power flows to the grid from both the stator windings and the rotor windings. As the wind speed decreases rotor speed decreases and the machine operates in sub- synchronous mode with positive slip. Rotor absorbs active power from the grid essentially borrowing power for rotor winding excitation. Hence as a generator DFIG, power with constant voltage and constant frequency through stator, while rotor is supplied through a static power converter at variable voltage and variable frequency. The rotor circuit may absorb or deliver electric power.

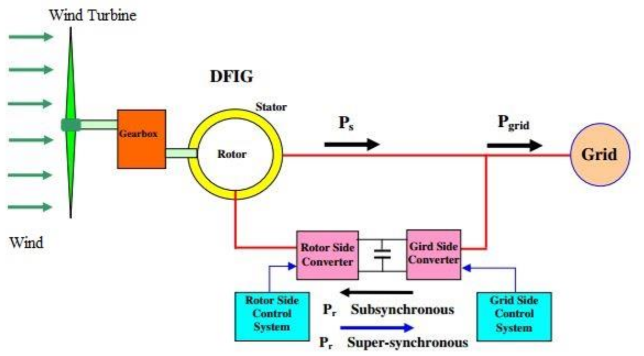

Fig. 1. Basic configuration of a DFIG wind turbine

III. CONTROL OF DOUBLY FED INDUCTION GENERATORS

Rotor Side Converter (RSC) is used to control the torque production of the DFIG through direct control of rotor currents. RSC does this by applying a voltage to the rotor windings that corresponds to the desired current. Controlling the rotor currents controls the slip and so the speed of the machine. RSC will operate at varying frequencies corresponding to the variable rotor speed requirements based on wind speed.

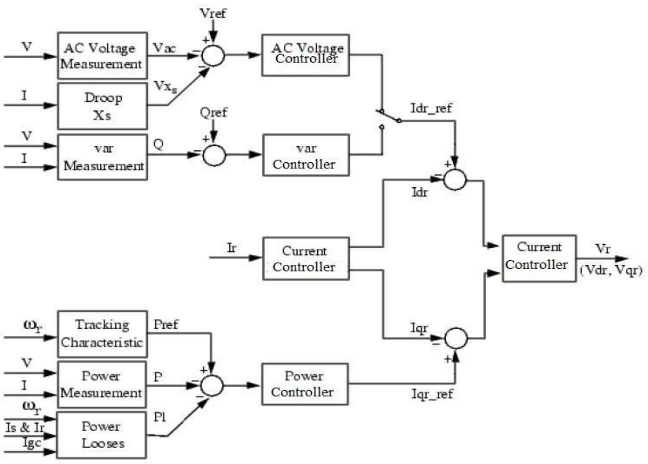

Fig.2. Rotor Side Converter Control

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 as shown in fig. 2. 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 is compared to I_{qr_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}. The voltage at grid terminals is controlled by the reactive power generated or absorbed by the converter C_{rotor}. The reactive power is exchanged between C_{rotor} and the grid, through the generator. In the exchange process the generator absorbs reactive power to supply its mutual and leakage inductances. The excess of reactive power is sent to the grid or to C_{rotor}.

The Grid Side Converter (GSC) is used to regulate the voltage of the DC bus capacitor. This controller consists of:

1. A measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage V_{dc}.
2. An outer regulation loop consisting of a DC voltage Regulator.
3. 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 as shown in fig. 3

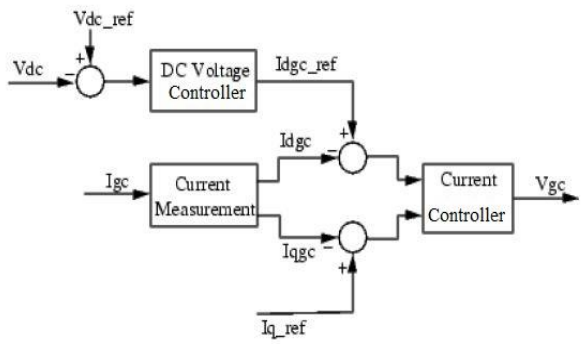

Fig.3. Grid Side Converter Control

IV STATOR FLUX ORIENTATION CONTROL

Vector Control stems from decoupled flux-current and torque-current control in AC drives. It resembles the principle of decoupled control of excitation and armature current in DC brush machines. When the DFIG is connected to the power grid, active and reactive powers are close-loop controlled, and they produce the reference flux and torque currents in vector control.

Consider the DFIG space phasor model in synchronous coordinates:

$$I_S R_S + V_S = -\frac{d\psi_S}{dt} - jw_1\psi_S;\quad \psi_S = L_S I_S + L_m I_r \qquad (2)$$

$$I_r R_r + V_r = -\frac{d\psi_r}{dt} - j(w_1 - w_r)\psi_r;\quad \psi_r = L_r I_r + L_m I_s \qquad (3)$$

Aligning the system of co-ordinates to stator flux as in fig. 4 seems most useful, as at least for power grid operation, ψ_s is almost constant, because the stator voltages are constant in amplitude, frequency, and phase:

ISSN: 2278-0181

$$\psi_s = \psi_d \quad (4)$$
$$\psi_q = 0 \quad (5)$$
$$\frac{d}{dt}\psi_q = 0 \quad (6)$$

$$P = \frac{3}{2}\omega_1 \psi_d \frac{L_m I_{qr}}{L_s} \quad (7)$$
$$Q = \frac{3}{2}\omega_1 \frac{\psi_d}{L_s}(\psi_d - L_m I_{dr}) \quad (8)$$

Equation shows that under stator flux orientation (vector) control, the active power delivered (or absorbed) by the stator may be controlled through the rotor current I_{qr}, while the reactive power may be controlled through the rotor current I_{dr}.Both powers depend heavily on stator flux and frequency .This constitutes the basis for vector control of P and Q, by controlling the rotor currents I_{dr} and I_{qr} in synchronous co-ordinates.

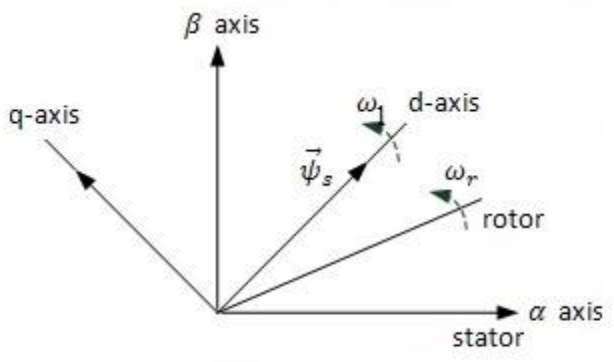

Fig. 4. Stator Flux Oriented Reference Frame

The source side converter is connected to power grid eventually via a step-up transformer in some embodiments. At the maximum slip, rotor voltage equals the stator voltage. In general, the source –side voltage converter uses a power filter to reduce current harmonics flow into the power source. Neglecting the harmonics due to switching in the converter and the machine losses and converter losses, the active power balance equation is as follows:

$$V_{dc} I_{dc} = \frac{3}{2} V_d I_d = P_r \,;\; V_q = 0 \quad (9)$$

But, with the PWM depth, m_1,as known

$$V_d = \frac{m_1}{2\sqrt{2}} V_{dc} \quad (10)$$

It is evident that DC link voltage V_{dc} may be controlled through I_d control. The reactive power from (to) the source Q_r is

$$Q_r = \frac{3}{2}\left(V_d I_q - V_q I_d\right)$$
$$= \frac{3}{2} V_d I_q \quad since\ V_q = 0 \quad (11)$$

Consequently, the reactive power from the power source to (from) the source side converter may be controlled through I_q. In general, the reactive power from power source through the source side converter is set to zero ($I_q = 0$) to ensure unity power factor operation.

V DESIGN OF BATTERY ENERGY STORAGE SYSTEM

The battery energy storage system is connected to the DC bus of the back-to-back power converters of the doubly-fed induction generator through a bi-directional DC/DC power converter. In the new system, the rotor-side converter is used to manage the active power and reactive power from the stator terminals independently; while the stator-side converter is applied to manage the active power and reactive power from the stator-side converter independently. The battery converter helps to keep the DC bus voltage constant regardless of the magnitude and direction of the rotor and stator powers. The design of a suitable rating of the BESS is very necessary for satisfactory operation of the proposed configuration of Wind Energy Conversion System (WECS). At higher wind speeds, power output of the WECS is higher as compared to the average power and therefore, the extra power is stored in the battery. At the lower wind speeds, the power is drawn from the battery to maintain the average power fed to the grid. Thus it is ensured that the power fed to the grid is always leveled resulting in an efficient and reliable source of electrical power to the grid. The MATLAB based modeling of the battery is done using the Thevenin's equivalent of it as shown in fig.5. Since the battery is an energy storage unit, its energy is represented in kWh. When a capacitor is used to model a battery unit, the capacitance can be determined from

$$C_b = \frac{(kWh) \times 3600 \times 10^3}{0.5\left(V_{ocmax}^2 - V_{ocmin}^2\right)} \quad (12)$$

Where V_{ocmin} and V_{ocmax} are the minimum and maximum open circuit voltage of the battery under fully discharged and charged conditions.

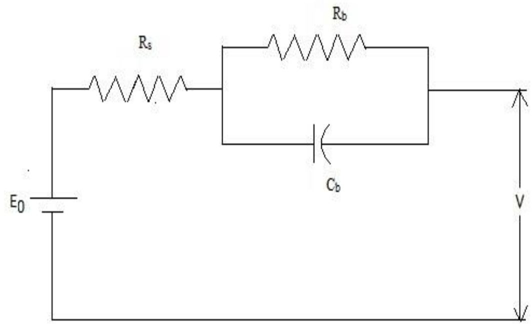

Fig. 5. Thevenin's Equivalent of BESS

In the Thevenin's equivalent model of battery, R_s is the equivalent resistance (external +internal) of parallel/series combination of a battery, which is usually a small value. The parallel circuit of R_b and C_b is used to describe the stored energy and voltage during charging or discharging. R_b in parallel with C_b represents self-discharging of the battery. Since the self-discharging current of the battery is small, the resistance R_b is large.

Table I Battery Parameters

Parameters	Value
Rating	120 kWh
Battery voltage	1200 V
Battery series resistance	0.00094 Ω
Internal capacitance	640 F
Internal Resistance	10000 Ω

VI RESULTS AND DISCUSSION

The model of WECS with BESS is developed in MATLAB-SIMULINK as in fig. 6 and results are presented to demonstrate its behavior at different wind speeds. BESS is placed in between these two converters. Synchronous Reference Frame method is used for reference signal generation.

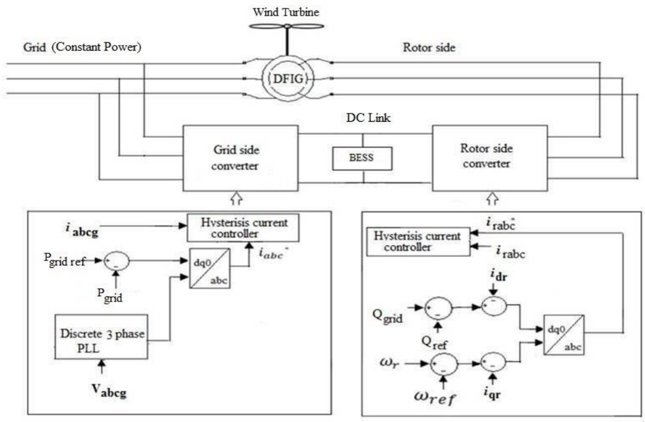

Fig. 6. Simulation Diagram

The waveforms for wind velocity, torque, rotor currents, active power by DFIG, active power by battery, grid power and grid frequency are obtained with respect to time for different wind speeds as in fig 7-fig12. The reference grid power here is set to 1000 W. Though the wind speed varies from a low to high during a given period of time, the power fed to the grid and hence the overall energy supplied to the grid remains constant irrespective of these variations in wind speed. Independent control of active and reactive power is achieved by using a stator voltage-oriented or stator flux-oriented approach for the control of the converters.

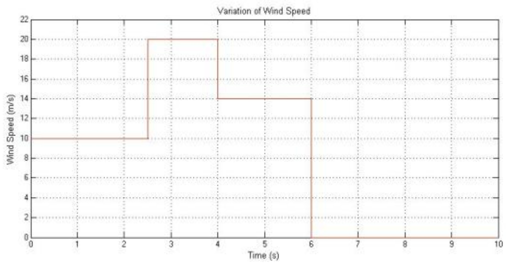

Fig. 7. Wind Velocity

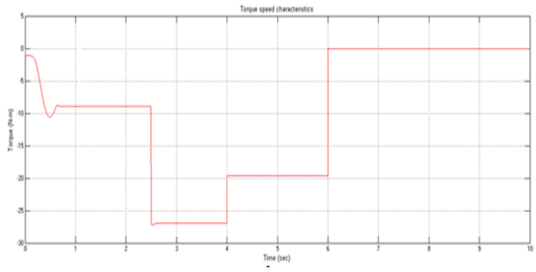

Fig. 8. Torque exerted by DFIG

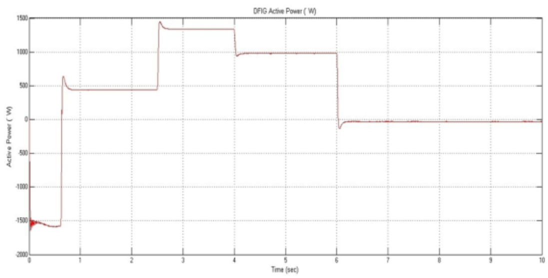

Fig. 9. Active Power by DFIG

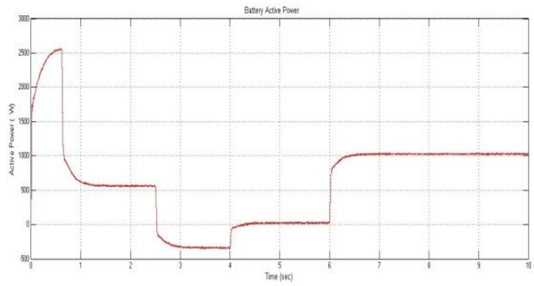

Fig.10. Variation of Active Power by Battery

Though the wind speed varies from a low to high during a given period of time, the power fed to the grid and hence the overall energy supplied to the grid remains constant irrespective of these variations in wind speed as shown in table II.

Table II. Active power of Stator and BESS

Time (Sec)	Wind Power (m/s)	Stator Power (W)	Battery Power (W)
0-2.5	10	450	550
2.5-4	20	1400	-400
4-6	14	1000	0
6-10	0	0	1000

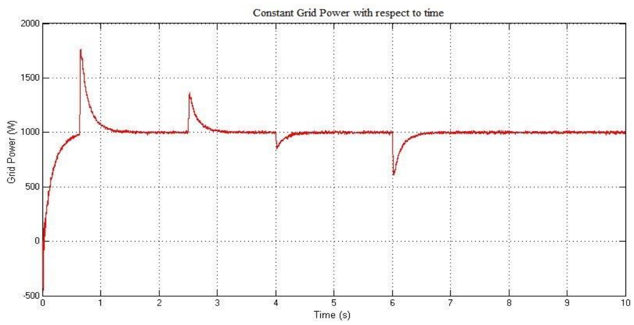

Fig. 11 Variation of Grid Power with respect to time

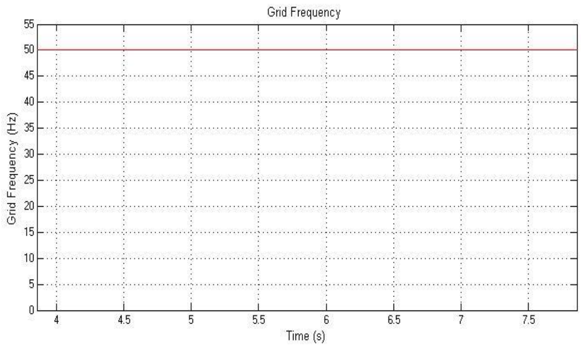

Fig. 12 Grid Frequency at 50 Hz

VII. CONCLUSION

A configuration of DFIG based WECS with a BESS in the dc link has been proposed with a stator-flux oriented vector control strategy to maintain the grid power constant. The vector control allows easy decomposition of active and reactive powers on the stator side. This can be achieved by developing the control algorithm in two axis synchronously rotating reference frame in which each axis takes care of either the active or reactive power control. The performance of the proposed control strategy on a DFIG based WECS with BESS has been demonstrated under different wind speeds. The modified control strategy is able to supply a constant power to the grid throughout and thus maintaining a constant flow of energy to the grid irrespective of the variations in the wind speed.

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