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Field Oriented Control of DFIG Based Wind Energy System Using Battery Energy Storage System

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Abstract

Wind power 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. Wind energy conversion using Doubly Fed Induction Generator (DFIG) is one of the most important types of renewable energy generations. The wind farm power output has large fluctuations due to sudden wind speed changes. Fluctuate power can often cause the violation of voltage and frequency limits in the weak system. It can be severe problem for the system stability also. The control system in the proposed arrangement of DFIG is able to reduce power fluctuation with the help of Battery Energy Storage System (BESS). In order to decouple the active and reactive powers generated by the machine, field oriented control is applied. As a result, high performance control of power can be achieved. The developed method has been tested through modelling a DFIG based wind energy system with BESS using SimPower System tools of MATLAB and simulated for operation as a grid connected system. The performance of DFIG based wind energy system demonstrates satisfactory performance under different wind speed conditions.

Keywords: Doubly Fed Induction generator (DFIG); Stator Flux Oriented Reference Frame; Battery Energy Storage System (BESS)

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1. 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 energy 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, 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.

2. Doubly Fed Induction Generator (DFIG)

In DFIG machine 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.

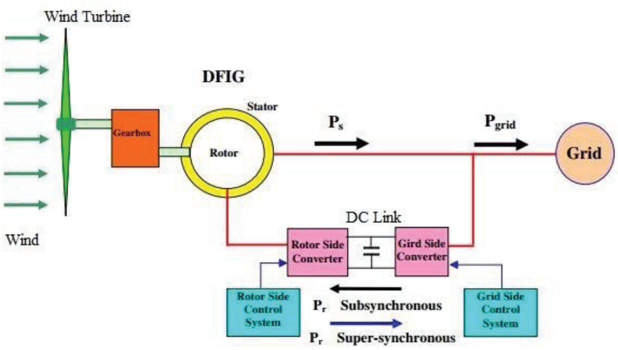

Fig.1. Basic configuration of a DFIG wind turbine [2]

At synchronous speed, the magnetic field of the rotor rotates at the same speed as the stator magnetic field. The DFIG then operates as asynchronous machine with DC current in rotor windings such that the rotor power is zero and therefore all active power from the DFIG will flow from the stator of the machine to the grid. When the wind speed enhances gradually, the speed of the rotor increases beyond synchronous speed, which causes a negative slip and super synchronous operation. In this case, power flows to the grid from both the stator windings and the rotor windings. As the wind speed decreases, the rotor speed also decreases and the machine operates in sub- synchronous mode with positive slip. Rotor absorbs active power from the grid such that it consumes power for rotor winding excitation. Hence as a generator, DFIG delivers power at constant voltage and constant frequency through stator, while rotor is supplied through a static power converter at variable voltage and variable frequency. The rotor part of the machine may absorb or deliver electric power.

3. Control of Doubly Fed Induction Generators

In DFIG, the Rotor Side Converter (RSC) controls production of torque through direct control of rotor currents. In this case, the converter in the rotor side apply voltage to windings in rotor part that corresponds to the desired current. By controlling the rotor currents the slip can be controlled and so the speed of the machine. Rotor Side Converter will operate at different frequencies corresponding to the availability of variable rotor speed based on wind speed.

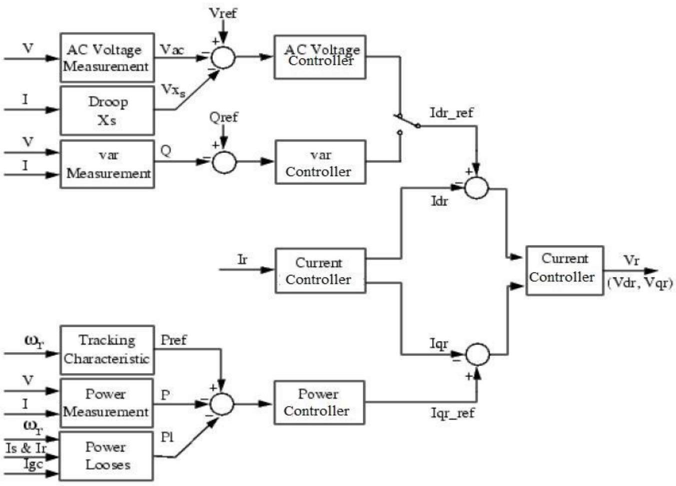

Fig.2. Rotor Side Converter Control [5]

The actual electrical power output, measured at grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) of the machine and is compared with the reference power obtained from the tracking characteristic as shown in fig. 2. A Proportional-Integral controller is used to minimise the error in power to zero. The output of this regulator is the reference rotor current I_{qr_ref} which is given to the rotor terminal by converter C_{rotor}. This is the component of current which results the electromagnetic torque T_{em}. The actual I_{qr} component is compared with I_{qr_ref} and the error is minimised to zero by controller. The output of this current controller is the voltage V_{qr} generated by C_{rotor}. The voltage at grid terminals is regulated by the reactive power generated or taken by the converter C_{rotor}. The reactive power is exchanged between C_{rotor} and the grid, via the machine. In the exchange process the generator takes reactive power to supply its leakage and mutual inductances. The reactive power which is in excess is delivered to the grid or to C_{rotor}.

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

- A measurement system measuring vector components of AC currents to be controlled as well as the DC link voltage V_{dc}.
- An outer regulation loop consisting of a DC voltage regulator.
- An inner current regulation loop consisting of a current regulator which regulates the magnitude and phase angle 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.

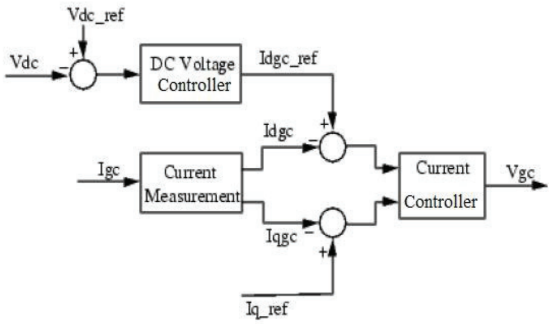

Fig.3. Grid Side Converter Control [5]

4. Field Oriented Control

Field Oriented Control originates from the decoupled control of flux-current and torque-current in AC drives. It resembles the principle of de-coupled control of excitation and armature current in direct current machines. When wound rotor machine is grid connected, active power and reactive power are close-loop controlled, and they produce required reference flux and torque currents in field oriented control.[13]
Consider the DFIG space phasor model in dq coordinates:

$$I_s R_s + V_s = -\frac{d\psi_s}{dt} - jw_1\psi_s; \quad \psi_s = L_s I_s + L_m I_r \tag{2}$$

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

Considering stator flux oriented control scheme as shown in fig. 4, such that for power grid operation, ψ_s is almost constant, since voltage in stator side are constant in amplitude, phase and frequency.

$$\psi_s = \psi_d \tag{4}$$

$$\psi_q = 0 \tag{5}$$

$$\frac{d}{dt}\psi_q = 0 \tag{6}$$

$$P = \frac{3}{2}\omega_1\psi_d\frac{L_m I_{qr}}{L_s} \tag{7}$$

$$Q = \frac{3}{2}\omega_1\frac{\psi_d}{L_s}(\psi_d - L_m I_{dr}) \tag{8}$$

Equation (7) and (8) indicates that under field oriented control scheme, the active power given or absorbed through the stator winding can be regulated through the rotor current I_{qr}, and the reactive power can be controlled through the rotor current I_{dr}. Both active power and reactive power depend upon stator flux and stator frequency .This concept constitutes the base for indirect vector control of active and reactive power , by maintaining the rotor currents I_{dr} and I_{qr} in dq co-ordinates [13].

The source side converter is grid connected via a step-up transformer. Generally the converter in source side utilise a power filter to reduce current harmonics flow into the power source.

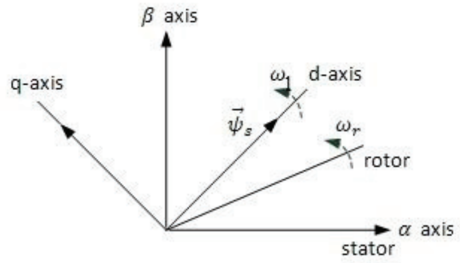

Fig. 4. Stator Flux Oriented Reference Frame [7]

Neglecting the harmonics due to switching in the converter, the machine losses and converter losses, the active power balance equation is as follows:

$$V_{dc}I_{dc} = \frac{3}{2}V_d I_d = P_r \; ; \; V_q = 0 \tag{9}$$

But, with the PWM depth, m_1, as known

$$V_d = \frac{m_1}{2\sqrt{2}}V_{dc} \tag{10}$$

Hence DC link voltage V_{dc} can be controlled through I_d control. The reactive power delivered from the source Q_r is

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

$$= \frac{3}{2}V_d I_q \quad since\ V_q = 0 \tag{11}$$

Consequently, the reactive power from the power source to or from the source side converter can 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 [13].

5. Design of Battery Energy Storage System

The battery energy storage system is connected to the DC link of the back-to-back power converters of the wound rotor induction generator through a bi-directional power converter. The converter in the rotor side 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 with power 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 battery system is very important for satisfactory operation of the proposed system of Wind Energy Conversion System. At higher wind speeds, the output power of the wind energy system is higher as compared to the average power and therefore, the additional power is stored in the battery. When the wind speed is low, the power is drawn from the battery to maintain the average power fed to the grid. Hence it can be ensured that the power given to the grid side is always maintained constant resulting in an efficient and stable source of electrical power to the grid. The SIMULINK modeling of the proposed system is done using the Thevenin's equivalent model as shown in fig.5. Since the battery is an energy storage unit, its energy is represented in kWh. If a capacitor is used to model a battery unit, then the capacitance can be determined from

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

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

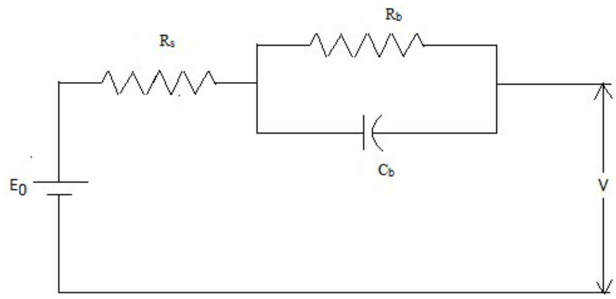

Fig. 5. Thevenin's Equivalent of BESS

In the Thevenin's equivalent model of battery, R_s is the equivalent external and internal resistances 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 [2].

Table 1 Battery Parameters

Parameters	Value
Rating	1
Battery voltage	3
Battery series resistance	5
Internal capacitance	640 F
Internal Resistance	10000 Ω

6. 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 behaviour at different wind speeds.

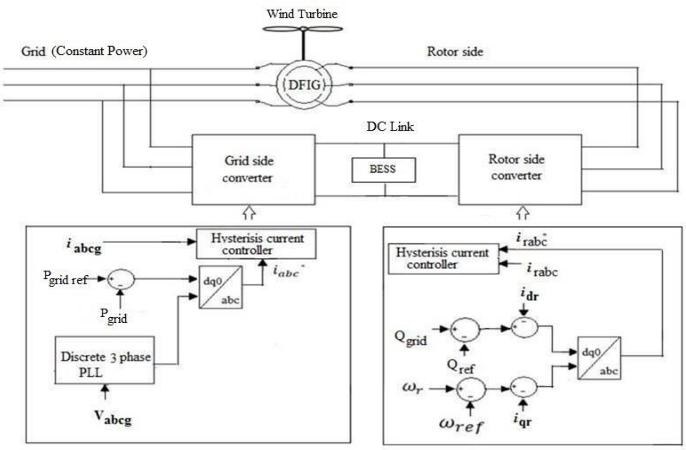

Fig. 6. Simulation Diagram

BESS is placed in between these two converters. Synchronous Reference Frame method is used for reference signal generation. Independent control of active and reactive power is achieved by using stator flux-oriented approach for the control of the converters.

The waveforms for wind velocity, torque, rotor currents, active power by DFIG, active power by battery and grid power 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 remains constant irrespective of the variations in wind speed.

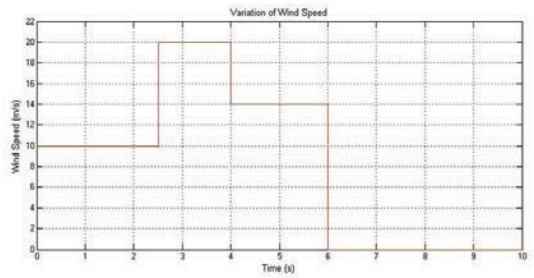

Fig. 7. Wind Velocity

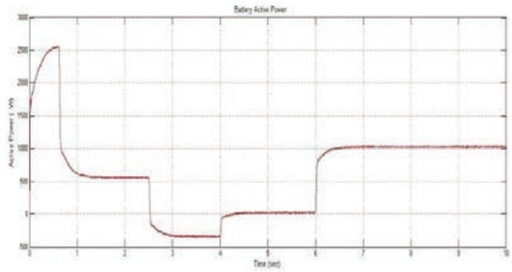

Fig.10. Variation of Active Power by Battery

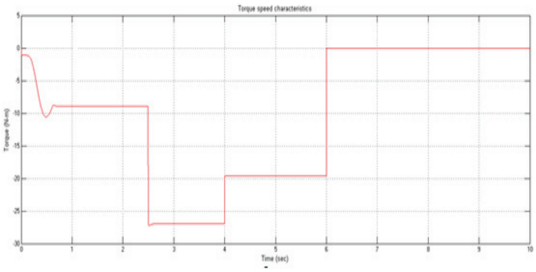

Fig. 8. Torque exerted by DFIG

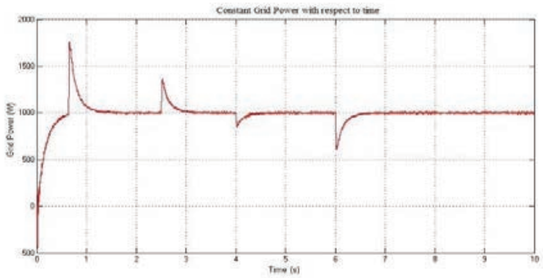

Fig. 11 Variation of Grid Power with respect to time

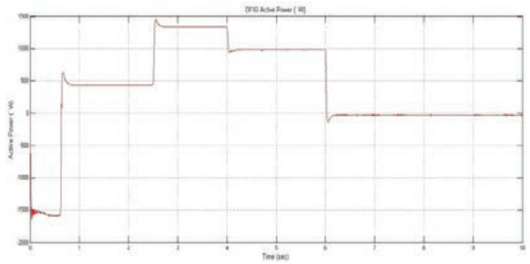

Fig. 9. Active Power by DFIG

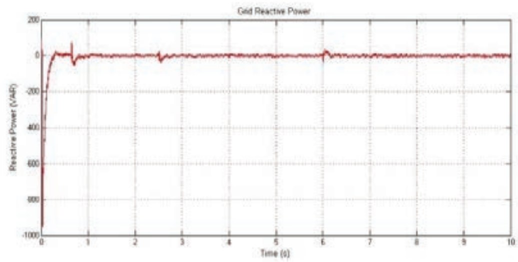

Fig. 12 Variation of reactive power with respect to time

The waveforms for wind velocity, torque, rotor currents, active power by DFIG, active power by battery and grid power 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 remains constant irrespective of the variations in wind speed.

Table 2. 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

7. **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 constant grid power. 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 axes synchronously rotating reference frame such that each axis takes care of either the active or reactive power control. The performance of the proposed system on Doubly Fed Induction Generator 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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