Modeling and Neuro-Fuzzy Control of DFIG in Wind Power Systems for Grid Power Leveling

MoganapriyaKrishnakumar andPanneerselvamManickam

Abstract—**This paper presents a control strategy for Doubly Fed Induction Generator in which stator is directly connected to grid, but the rotor terminals are connected to grid via power converter. The proposed topology includes a BESS which would help in storing/releasing additional power in case of higher/lower wind speed to maintain constant grid power. A neuro-fuzzy vector control scheme was presented where the rotor side voltage source converter was controlled to independently control the generated active and reactive power as well as the rotor speed to track the maximum wind power point. The wind generator mathematical model and control strategy is developed and simulation studies are carried out in MATLAB/Simulink. The simulation results indicate that the active and reactive powers in the system are controlled effectively to maintain the grid power constant.**

Keywords- Doubly fed induction generator (DFIG), power converter, vector control, wind energy conversion system (WECS).

I. INTRODUCTION

THE need for renewable energy sources for electric power generation has been increased due to limitations in the conventional power generations such as decreasing reserves and adverse effect on the environment. Among all the renewable energy sources the contribution of the wind energy conversion system (WECS) is effective and it is reliable energy resource. The wind is fluctuating in nature and needs variable speed generator and it is most acceptable for WECS. In the wind driven DFIG, the stator terminals is directly connected to the grid, but the rotor terminals are connected to the grid through a variable frequency AC/DC/AC converter. The rotor can freely differ from the grid frequency(50 to 60Hz), by using the converter to control the rotor currents, it is possible to adjust the active and reactive power to the grid independent of the generator turning speed. The DFIG has several advantages such as variable speed constant frequency operation , wide speed operation, reduced size of converters in rotor size as the power converter needs to handle a fraction(typically 20-30%) of the total power to achieve full control the generator. The power flow in in DFIG is bi-directional i.e both the stator and the rotor are able to supply active power. The power flow from/to the rotor and the stator can be controlled both in magnitude and in direction so that it is possible to generate electrical power at constant voltage and constant frequency at the stator terminal and inject it into the grid over a wide operating range [6], [7].

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A battery energy storage system is connected to the DC link capacitor through a bi-directional power converter. Below the synchronous speed the rotor side converter (RSC) acts as the voltage source inverter and the active power flows from the grid to the rotor side. At super-synchronous speed the grid side converter (GSC) acts as inverter while the RSC acts as rectifier and delivers power to the grid. In this system a battery in the dc link is incorporated to fed constant power to the grid. The average power for the system is calculated from the available wind speeds and this calculated average power is fed to the grid to reduce the power fluctuations on the grid. At the higher wind speeds (and the machine operating at super-synchronous speed), power output of the WECS is higher as compared to the average power and, therefore, the extra power is stored in the battery. In contrast, at the lower wind speeds (and the machine operating at sub-synchronous speed) the power is drawn from the battery to maintain the average power fed to the grid. The control system utilize PI controller which has fixed proportional and integral gains and so the system has pre-determined response and cannot be changed easily. To get the best system response fuzzy logic controller has been used.

The neuro-fuzzy logic controller was used to control the generator speed to maximize the electric power generation by tracking the maximum power and also to control the active and reactive power through the rotor side control. A single variable was used as an input to the neuro-fuzzy controller which is the error signal of the controlled variable. The design of the fuzzy system is based on methods for tuning the membership functions (MFs) so as to minimize the output error. Any one of the parameters, generator speed, active, and reactive power, can been chosen as input to the controller. The input for each neuro-fuzzy gain tuner is chosen to be the error signal of the controlled parameter. The choice of only one input to the system simplifies the design of the system.

In this paper, a control strategy is developed for a grid connected doubly fed induction generator based wind energy conversion system. Converter used is a double sided PWM converter joining the machine rotor to the grid and to decouple active and reactive powers generated by the machine, stator flux oriented vector control is applied. With this configuration, the power converters could be rated at lower power levels, a battery is directly tied to the DC link of the rectifier-inverter pair connected to the generator terminal. The energy storage device is controlled so as to smooth out the total output power from the wind turbine as the wind speed varies. Neuro-fuzzy logic controller has been used to maximize the total power generation and to control the active and reactive power to maintain the grid power constant. The wind generator mathematical model and control strategy is developed. The performance comparison of the neuro-fuzzy controller with PI controller is made with simulated responses under synchronous, sub-synchronous and super-synchronous modes of operation.

II. SYSTEM DESCRIPITION

The basic configuration of DFIG used in thispaperisshown inFig.1The wind turbine is mechanically connected to the doubly fed induction generator through a gear box and a coupling shaft system. The wound rotor induction generator is fed from both the stator and rotor sides. The stator is directly connected to the grid while rotor is fed through two back-to-back four quadrant PWM power converters (RSC and GSC) connected by a battery in the DC-link capacitor.

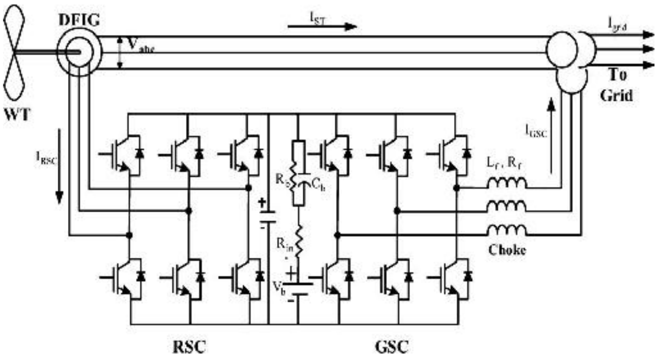


Fig. 1.DFIG configuration.

The power flow from/to the rotor and the stator can be controlled both in magnitude and in direction so that it is possible to generate electrical power at constant voltage and constant frequency at the stator terminal and inject it into the grid over a wide operating range. This system is regulated by a control system, which consists of two parts, electrical control of the DFIG and mechanical control of the wind turbine blade pitch angle. This work focuses on the control of the reactive power flow, which is achieved by control of power converter.

III. DESIGN ISSUSES IN PROPOSED WECS

A. Design of Wind Turbine

The output power of the turbine and the wind velocity has the nonlinear relation. The output power of the turbine is given by the following equation [16]:

$$\text{Pmech} = \tfrac{1}{2}C_p \pi \rho R^2 v^3 \quad (1)$$

Where ρ and R correspond to the air density and the radius of the turbine propeller, respectively.

The power coefficient can be described as the portion of mechanical power extracted from the total power available from the wind, and it is unique for each turbine. This power coefficient is generally defined as a function of the tip-speed-ratio λ which, in turn, is given by

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

Where ω represents the rotational speed of the wind turbine. Hence, the TSR can be controlled by controlling the rotational speed of the generator.

B. Design of BESS

The design of a suitable rating of the BESS is very necessary for satisfactory operation of the pro-posed configuration of WECS. The rating of the BESS is decided by the total energy stored into it and this energy is stored for only those periods in which power generated by the machine is more than the average value that is to be fed to the grid. The average value of the power to be fed to the grid is calculated on the basis of the available wind speeds at that site.

IV. CONTROL STRATEGY

The control strategy of the RSC and GSC consists of an "active and reactive power" controlling outer loop and the "current control" inner loop. A detailed explanation of the control strategy and the mathematical equations governing the same are presented below.

The exclusive control feature of the DFIG is that simultaneous and decoupled regulation can be made for active variables (speed, active power, or torque) and reactive variables (voltage, reactive power, or power factor). This can be achieved by developing the control algorithm in a two axis synchronously rotating reference frame, in which each axis takes care of either the active or reactive powers control. When the rotor power is allowed to flow in both directions, the control can be realized over a wide range of the rotor speeds, above and below and synchronous speed.

A. Control of GSC

The distinct feature of this work lies in modifying the active power outer loop of the GSC. The grid power is regulated to be a fixed value (determined by the average power as calculated earlier) and this is given as the reference active power. This is then compared with the actual grid power at any instant and the error is processed using a neuro-fuzzy controller to generate the q-axis component of the reference grid current.

For the reactive power outer-loop control of the GSC, the controlled variable can be the stator reactive power. When it is controlled, the reactive power set point can be obtained in dif-ferent ways depending on the power sharing strategy with the GSC. The d and q components of the reference grid currents to be given to the PWM controller of the GSC are obtained from the reference active and reactive powers components.

The system considered in this work has both an active and a reactive powers loop. The active power loop of the system includes the grid power regulation to obtain "grid power leveling." The reference reactive power can be set to zero for the unity power factor operation.

The expression for the reference q-axis grid current is as

$$i_{gqref} = \left(k_{pp} + \frac{k_{ip}}{s}\right)\left(p_{ref} - p_{grid}\right) \quad (3)$$

Where k_{pp} and k_{ip} are proportional and integral constants

of the grid power regulator respectively.
The reference d-axis grid current is chosen according to the reactive power sharing between the stator and the GSC, and it can be chosen to be zero, for a unity power factor operation.
These reference currents are then compared with the sensed grid side currents and the obtained error signal is processed with a PI controller to generate the control voltages for the PWM generator on the grid side. The expressions for thecontrol voltages in the d-q frame are given as

$$v_{dgsc} = \left(k_{pgsc} + \frac{k_{igsc}}{s}\right)\left(i_{gdref} - i_{gd}\right)$$
$$v_{qgsc} = \left(k_{pgsc} + \frac{k_{igsc}}{s}\right)\left(i_{gqref} - i_{gq}\right) \quad (4)$$

Where i_{gd} and i_{gq} are the sensed d-q components of the grid currents respectively.

B. Control of RSC

The RSC is a dedicated controller for the "machine" and hence the active and reactive power outer loops are chosen to extract the maximum power from the wind and to maintain a unity power operation of the stator. The active power set point can be obtained from the instantaneous value of the rotor speed and the rotor current is controlled in the stator flux-oriented reference frame to obtain the desired active power according to the optimum torque speed characteristics. The set point for the reactive power can be calculated from the active power set point and a desired power factor (considered to be unity in the present work). In the stator flux-oriented reference frame, the d-axis rotor current is used to control the required reference reactive power.
The reference rotor currents are generated from reference active and reactive power set points as

$$i_{rqrf} = -\frac{l_s}{v_s l_m} p_{sref},$$
$$i_{rdref} = \frac{\varphi_s}{l_m} - \frac{l_s}{v_s l_m} Q_{sref} \quad (5)$$

These values of rotor currents are compared with the sensed values of rotor currents and the obtained error signal is processed with a controller to generate control voltages for the PWM generator on the rotor side. The expressions for the control voltages on the d-q reference frame are given as

$$v_{drsc} = \left(k_{prsc} + \frac{k_{irsc}}{s}\right)\left(i_{rdref} - i_{rd}\right)$$
$$v_{qrsc} = \left(k_{prsc} + \frac{k_{irsc}}{s}\right)\left(i_{rqref} - i_{rq}\right) \quad (6)$$

Where i_{rd} and i_{rq} are the sensed d-q components of the rotor currents and k_{prsc} and k_{irsc} are the proportional and integral constants of the rotor side current regulator, respectively.

C. Design of neuro-fuzzy controller

In the neuro-fuzzy system, a learning method similar to that of neural network is used to train and adjust the parameters of the membership functions. Neuro adaptive learning techniques provide a method for the fuzzy modeling procedure to learn information about a data set. Then the parameters of membership functions that best allow the associated fuzzy inference system to track the given input/output data. The absolute value of the error signal is used to calculate the scheduled proportional and integral gains using the neuro-fuzzy controller for each of the speed, active and reactive power controllers.

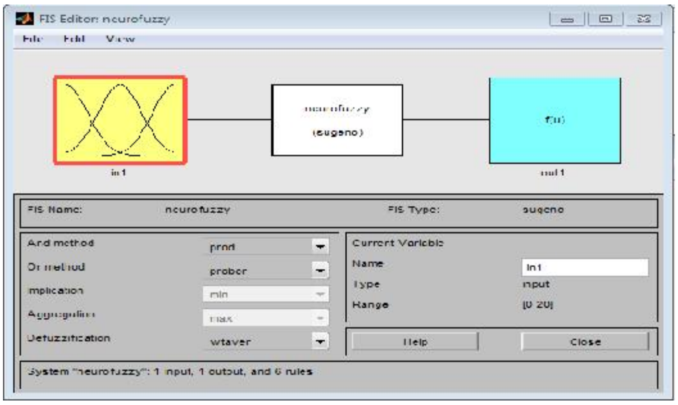


Fig. 2. Fuzzy Inference System

The developed neuro-fuzzy system is a first-order Sugeno type which has a single input with six Gaussian distribution membership functions. It has six *if–then* rules. A simple structure of the developed neuro-fuzzy system is used where the input is the error signal of the controlled variable of speed, active, or reactive power. The training is performed using the hybrid back-propagation algorithm. The training data used are collected from extensive simulations of the vector controller system.

V.MATLAB-BASED MODELING

The MATLAB-based modeling of the proposed configuration of DFIG-based WECS with a BESS consists of a mechanical system (wind turbine) and the electrical system (DFIG with back-to-back voltage source converters)

A. Wind Turbine Modeling

The mechanical power output of the wind turbine is given by (1) and in that equation the power coefficient is very important parameter. The power output of wind turbine is dependent on the power coefficient given as [15].

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda + c_8\beta} - \frac{c_2 c_9}{\beta^3+1} - c_3\beta - c_4\beta^{c_5} - c_6\right) *$$

$$e^{\left(\frac{-c_7}{\lambda+c_{8\beta}}+\frac{c_7 c_9}{\beta^3+1}\right)} + c_{10}\lambda \qquad (7)$$

λ is the tip speed ratio and given by the (2). The maximum Value of $Cp = 0.48$ is for $\beta = 0$ degree and $\lambda = 8.1$. This particular value of λ is defined as nominal value. The coefficients used are given in Appendix A.

B. Battery Bank Design and Modeling

The MATLAB-based modelling of the battery is done using the Thevenin's equivalent of it as shown in Fig.1. Since the battery is an energy storage unit, its energy is represented in kWh, when a capacitor is used to model the battery unit, the capacitance C_b can be determined from

$$C_b = \frac{kwh*3600*10^3}{0.5(V_{ocmax}^2 - V_{ocmin}^2)} \quad (8)$$

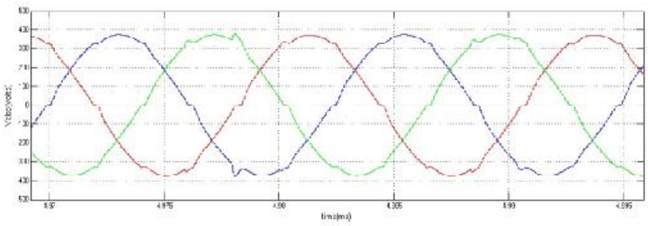
Where V_{ocmin} and V_{ocmax} are the minimum and maximum open circuit voltage of the battery under fully discharged and charged conditions. In the Thevenin's equivalent model of the battery, R_s is the equivalent resistance (external + internal) of parallel/series combination of a battery, which is 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 a battery is small, the resistance R_b is large.

C. Electrical System Modeling

The electrical system modeling is carried by using the sim power system toolbox of MATLAB-SIMULINK. The parameters of DFIG used in the model are given in Appendix. The discussed control strategy is implemented on the RSC and the GSC. The developed model is tested for the proposed control strategy to achieve grid power leveling under different speeds of operation of the generator and the results are presented in detail in the next section.

VI. RESULTS AND DISCUSSION

The model of WECS shown in Fig. 2 is developed in the MATLAB-SIMULINK as described and results are presented to demonstrate the control of active and reactive power at different wind speeds.



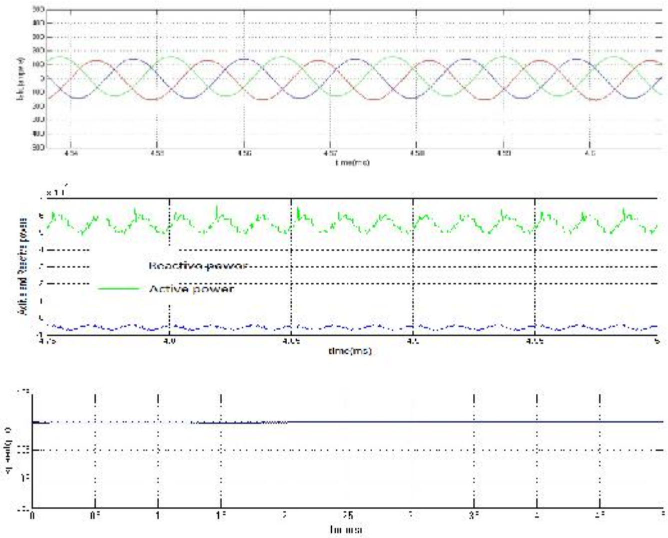


Fig. 3. Performance of the system with PI controller at synchronous speed (wind speed=10 m/s, rotor speed=1 pu).

Figure 3, 4, and 5 show the performance of the system with PI controller at synchronous speed, sub-synchronous speed and super-synchronous speed respectively. The waveforms for stator voltage (Vabc), stator current (Iabc), active and reactive powers and rotor speed 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 55kW by grid power control strategy. 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.

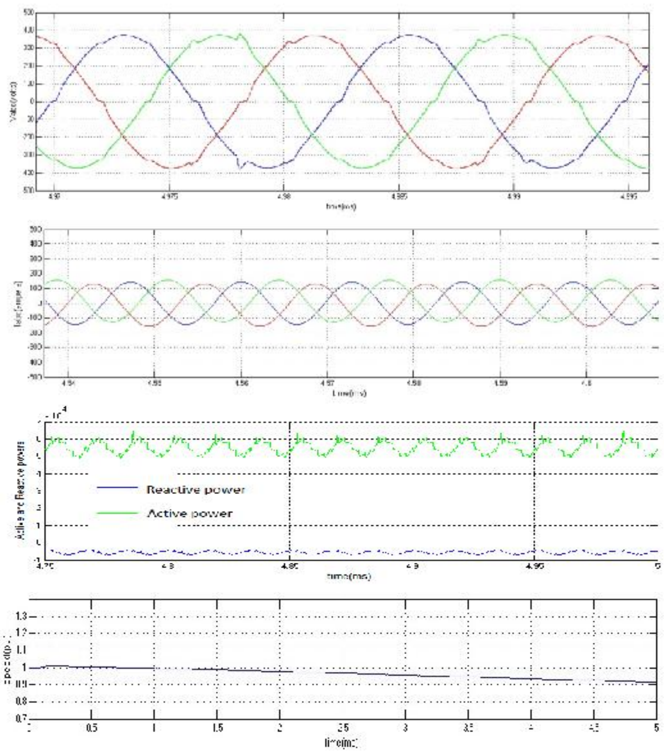


Fig. 4. Performance of the system with PI controller at sub-synchronous speed (wind speed=8 m/s, rotor speed=0.9 pu).

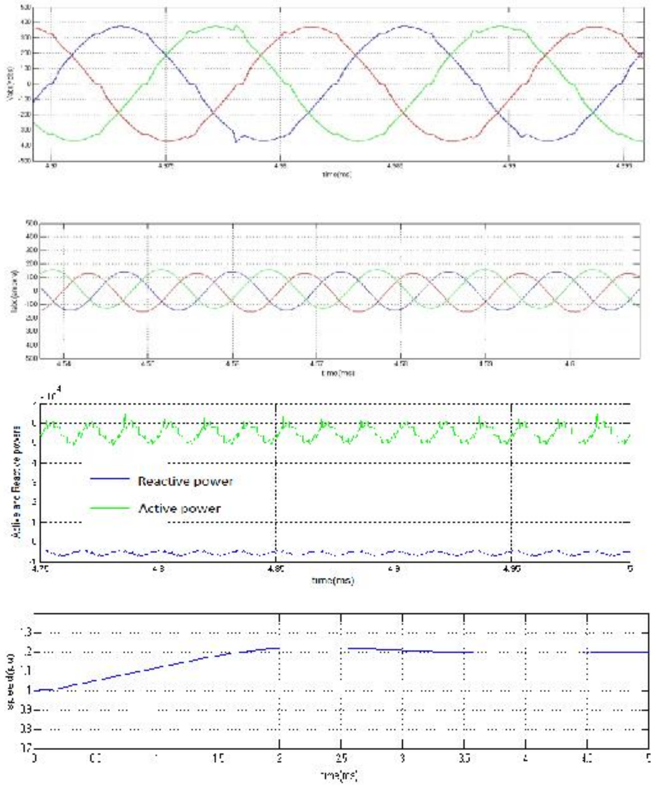


Fig. 5. Performance of the system with PI controller at super-synchronous speed (wind speed=12 m/s, rotor speed=1.2 pu).

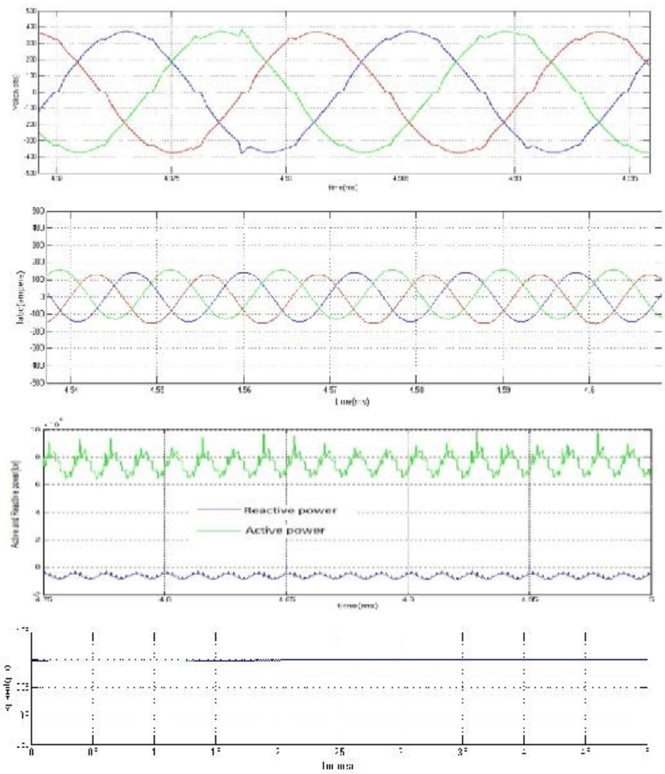


Fig. 6. Performance of the system with Neuro-fuzzy controller at synchronous speed (wind speed=10 m/s, rotor speed=1pu).

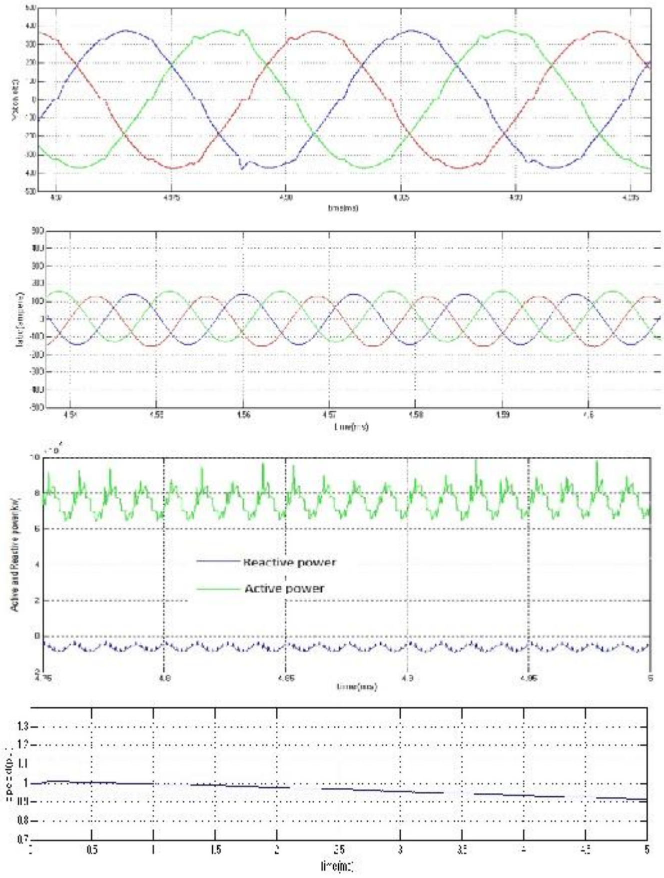
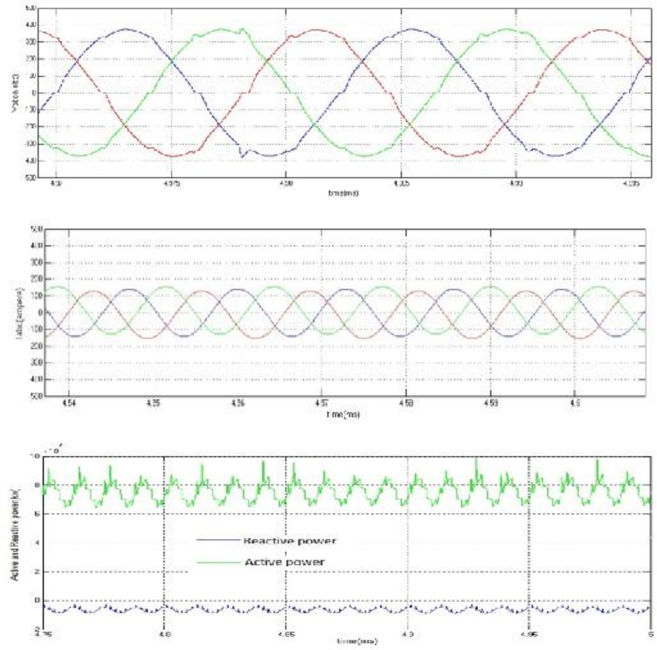


Fig. 7. Performance of the system with Neuro-fuzzy controller at sub-synchronous speed (wind speed=8 m/s, rotor speed=0.9 pu).



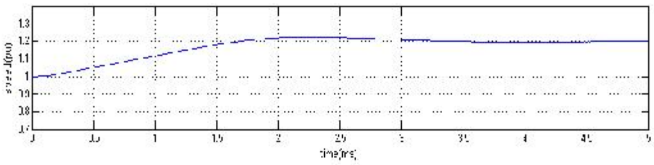


Fig. 8. Performance of the system with Neuro-fuzzy controller at super-synchronous speed (wind speed=12 m/s, rotor speed=1.2 pu).

Figs 6, 7 and 8 show the performance of the system with Neuro-fuzzy controller at synchronous speed, sub-synchronous speed and super-synchronous speed respectively. The waveforms for stator voltage (Vabc), stator current (Iabc), active and reactive powers and rotor speed are presented for different wind speeds. With the Neuro-fuzzy controller the value of the grid power is maintained to be constant at 65kW in different wind speeds which is higher than the grid power in case of system with PI controller. 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 neuro fuzzy inference system uses well defined parameter set for the delivery of maximum power output to the grid lines.

The neuro-fuzzy inference system uses well defined parameter set for the delivery of maximum power output to the grid lines. Using neuro fuzzy control, we can produce controller outputs more reliable because the effect of other parameters such as noise and events due to wide range of control region and online changing of the controller parameters can be considered. The wind generation system is highly non-linear process since it is involved power electronic equipment. So non-linear controller is necessary for controlling non-linear process. So we are using an estimator based intelligent controller i.e. neuro-fuzzy controller.

From the results it is seen that, 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. Thus the modified control strategy with neuro-fuzzy controller is able to negotiate the grid power gusts due to the variable wind speeds in an efficient way.

VII CONCLUSION

A configuration of a DFIG-based WECS with a BESS in the dc link has been developed with a control strategy to maintain the grid power constant. The performance of the proposed control strategy on a DFIG-based WECS with BESS has been demonstrated with PI controller and Neuro-fuzzy controller under different wind speeds. From the simulation results it has been observed that the system responses are satisfactory with both controllers under different wind speed conditions. The neuro-fuzzy inference system uses well defined parameter set for the delivery of maximum power output to the grid lines and so it delivers more active power than in the case of the system with PI controller. Hence the important control strategies like the maximum power point tracking (MPPT) and unity power factor operation at the stator terminal are satisfactorily observed. Placing a BESS in the dc link of a DFIG-based WECS proves to be a satisfactory implementation in terms of maintaining a constant power at the grid.

APPENDIX

Coefficients in the Empirical Expression for the Power Coefficient C_p

$C_1 = 0.5176$, $C_1 = 116$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 0$, $C_6 = 5$, $C_7 = 21$, $C_8 = 0.08$, $C_9 = 0.035$, $C_{10} = 0.0068$.

Parameters of the DFIG

Rated power	100 kW
Stator voltage/Frequency	330V/50Hz
Stator/Rotor turns ratio	0.38
Pole numbers	4
Stator Resistance	0.005 pu
Rotor Resistance	0.003 pu
Stator Leakage inductance	0.171 pu
Rotor leakage inductance	0.156 pu

Parameters of the Battery

Battery Nominal Voltage (V_b)	600 Volts
Internal Resistance (R_b)	5000 Ω
Internal Capacitance (C_b)	0.06 F
Battery Series resistance (R_s)	0.00094 Ω

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