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Study for Performance Comparison of SFIG and DFIG Based Wind Turbines

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Abstract - This paper gives a comparative performance analysis of Singly Fed Induction Generator (SFIG) and Doubly Fed Induction Generator (DFIG) systems driven by variable pitch wind turbines of same generation capacity of 9 MW. For reactive power compensation of SFIG system driven wind turbine STATCOM is used while DFIG system driven wind turbine is capable of reactive power compensation. The performance analysis is done in study state and dynamic state using simulated results of MATLAB/simulink. This paper shows that DFIG systems offer several advantages in comparison to SFIG systems. DFIG systems are cost effective and provide simple pitch control, less flicker also improve system efficiency as turbine speed is adjusted as a function of wind speed to maximize output power.

Keywords – Asynchronous Generator (ASG), Doubly Fed Induction Generator (DFIG), Generated Power (P_{Gen}), Mechanical Power (P_{mech}), Singly Fed Induction Generator (SFIG), Wind Turbine(WT).

I. INTRODUCTION

A wind energy conversion system mainly consists of the wind turbine, the generator and the power electronic converters. Figure 1 shows the basic mechanical electrical functional chain in wind power generation. The control characteristics of the electric generator and remaining control-related properties of wind-turbines, particularly blade pitch control or stall behavior, must be considered collectively.

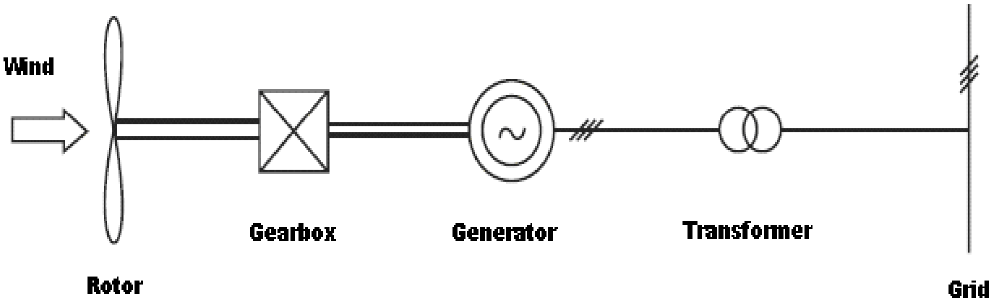


Figure 1 Mechanical-electrical functional chain in wind power generation

1.1 Wind Energy Situation

Power generation from the non-conventional sources is the need of the day. Wind is one of the cost-effective with respect to other renewable energy sources available. Wind electrical power systems are cost competitive, environmentally clean and safe renewable power sources compared to fossil fuel and nuclear power generation. Technical advancements in trapping wind energy has been noticed over 2 to 3 decades, holding it a strong competitive position with the conventional power generation technologies. Table 1.1 shows the global wind power statistics for the various countries China being at the top in the grid-connected wind energy capacity [1].

In spite of the advantages, wind power has its own shortcomings low energy density requires a large capture unit and its availability varies from time to time. With the advancement in the present day technologies, research has led to stronger, lighter and more efficient designs of the blades. Recently, power electronic converters have been widely accepted for the variable speed wind turbine. For the different machines: cage-type induction machines, wound-rotor induction machines and permanent magnet synchronous machines, various voltage-fed or current-fed converter topologies have been proposed.

Rank	***Nation***	***2009***	***2010***	***2011***	***2012***
1	China	25,777.00	44,733	62,364	75,564
2	United States	35,159.00	40,180	46,919	60,007
3	Germany	25,777	27,215	29,075	31,332
4	Spain	19,149.00	20,676	21,673	22,796
5	India	10,925.00	13,065	15,880	18,421
6	United Kingdom	4,092	5,204	6,018	8,445
7	Italy	4,850	5,797	6,737	8,144
8	France	4,521	5,660	6,640	7,196
9	Canada	3,319	4,008	5,265	6,200
10	Portugal	3,535	3,702	4,083	4,525

Usage of doubly-fed induction generator (DFIG) technology allows extracting maximum energy from the winds for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.

1.2 Singly Fed Induction generator (SFIG for WT)

Induction generators coupled directly to the grid have been successfully used in wind turbines for decades. Particularly in combination with the stall-controlled three-bladed wind rotors, they initially represented by far the most commonly used electrical concept.

The squirrel-cage rotors used in smaller systems are unsurpassed with respect to cost and low maintenance and do not require a complicated blade pitch control arrangement. Small induction generators have comparatively high nominal slip values which provide sufficient compliance to the grid. They can, therefore, be synchronized to the grid without field excitation and without elaborate synchronization measures in the range of its synchronous speed.

An improvement can only be achieved via a higher nominal slip value. This, however, is in conflict with efficiency, generator weight and cost. Nevertheless, the nominal slip of an induction generator can be manipulated to a certain extent. There are various methods to increase slip. The most obvious possibility is designing the rotor for a higher slip values. The example of an induction generator with a rated power of 1200 kW shows to what extent this affects efficiency (Figure 1). Overall generator mass also increases with increasing nominal slip. Up to a nominal slip of a few percent, the increase in cost is not so serious, if it is kept in mind that the generator itself constitutes only a small part of the cost of the total electrical system.

One disadvantage of induction generators with increased slip which must not be ignored is the problem of heat dissipation. Generator cooling and with it the entire cooling air ducting system in the nacelle must be designed for a higher throughput. Seen overall, a generator design with a nominal slip of 2 to 3% should represent a feasible compromise for providing a minimum amount of speed compliance with justifiable additional expenditure and loss of efficiency.

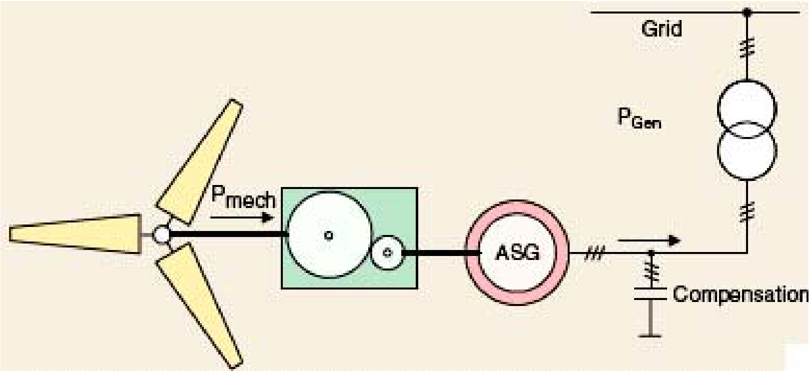


Figure 3 Fixed speed concept of SFIG

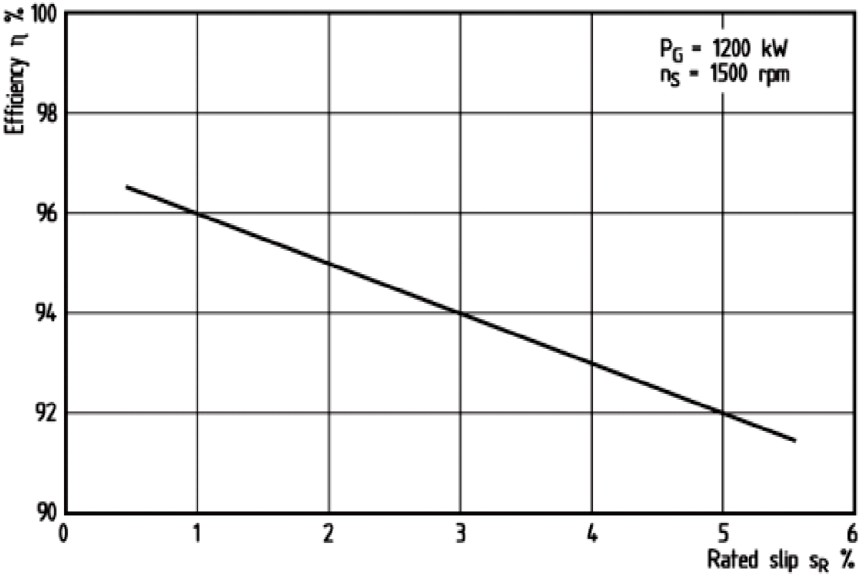


Figure 4.Efficiency of an induction generator as a function of rated slip.

1.3 Doubly-Fed Induction Generator (DFIG) System

The doubly-fed induction generator (DFIG) is a 'special' variable speed induction machine and is widely used as modern large wind turbine generators. It is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through an AC/DC/AC pulse width modulated (PWM) converter. The AC/DC/AC converter normally consists of a rotor-side converter and a grid-side converter. By means of the bi-directional converter in the rotor circuit, the DFIG is able to work as a generator in both sub-synchronous (positive slip $s > 0$) and over-synchronous (negative slip $s < 0$) operating area. Depending on the operating condition of the drive, the power is fed in or out of the rotor. If ($\boldsymbol{P}_{\text{rotor}} < 0$): it is flowing from the grid via the converter to the rotor in sub-synchronous mode or vice versa ($\boldsymbol{P}_{\text{rotor}} > 0$) in over-synchronous mode. In both cases (sub-synchronous and over-synchronous) the stator is feeding energy to the grid ($\boldsymbol{P}_{\text{stator}} > 0$) [6].

For variable speed systems with limited variable-speed range, e.g. ±30% of synchronous speed, the DFIG is reported to be an interesting solution. A detailed representation of DFIG with its back to back converters is depicted in Figure 3 The back-to-back converter consists of two converters, i.e., rotor-side converter (RSC) and grid-side converter (GSC), connected "back-to-back." Between the two converters a DC-link capacitor is placed. With the rotor-side converter it is possible to control the torque or the speed of the DFIG. Doubly fed induction machines can be operated as a generator as well as a motor in both sub-synchronous and super synchronous speeds using the rotor side converter control. Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation.

The speed–torque characteristics of the DFIG system can be seen in Figure 4 As also seen in the figure, the DFIG can operate both in motor and generator operation with a rotor-speed range of $\pm \Delta\omega_r^{\max}$ around the synchronous speed, ω_s.

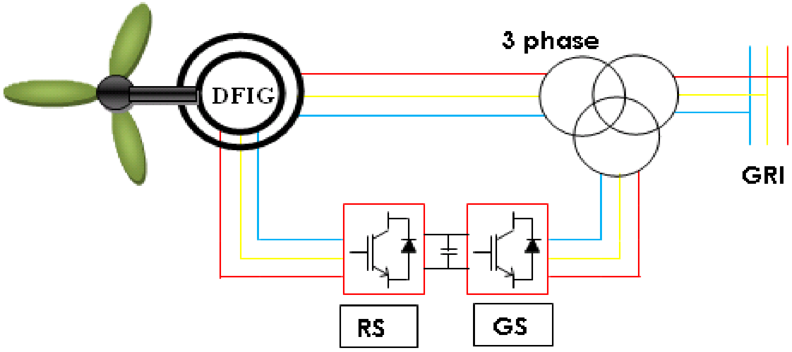


Figure 5. Schematic of conventional DFIG wind system.

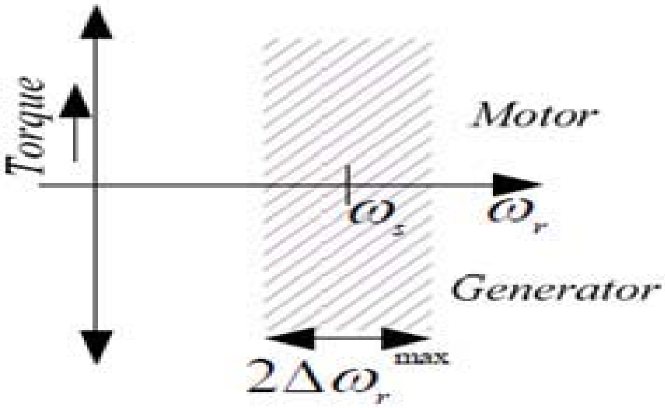


Figure 6 Speed-torque characteristics of DFIG system

II. SIMULATION OF SFIG SYSTEM FOR VARIABLE-PITCH WIND TURBINES

In this section, the simulation results obtained using MATLAB / Simulink are presented to study the steady state and dynamic performance of a wind power plant equipped with SFIG system connected to a distribution system.

2.1 Operation of SFIG Driven by Variable-Pitch Wind Turbines

A wind farm consists of six 1.5 MW wind turbines is connected to a 25 KV distribution system exports power to a 120 KV grid through a 25 km 25 KV line feeder. The 9 MW wind farm is simulated by three pairs of 1.5 MW wind turbines. The induction generator (IG) is squirrel cage induction generator. The stator winding is connected directly to the 50 Hz grid and the rotor is driven by a variable pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for wind exceeding the nominal speed 9 m/s (fig.7). In order to generate the power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. The single line diagram of this system is illustrated in Figure.

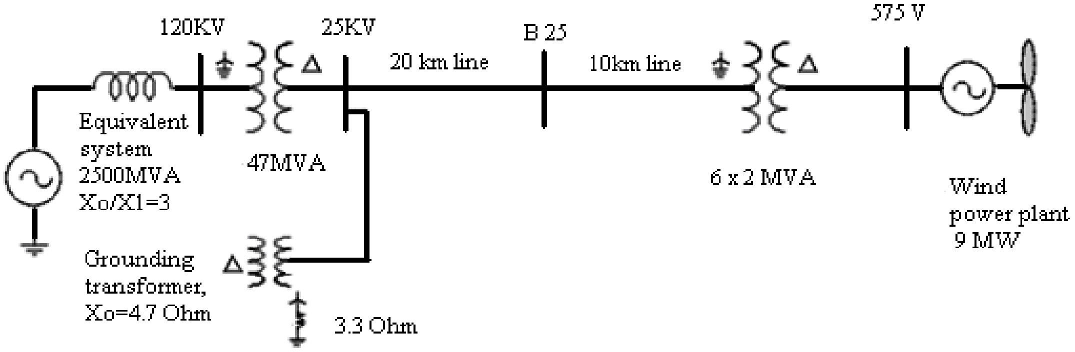


Figure 7. Single line diagram of a wind power plant connected to a distribution system (for SFIG)

Reactive power absorbed by the induction generator is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 KVAR for each pair of 1.5 MW wind turbine). The rest of the reactive power required to maintain the 25 KV voltage at the bus B25 close to 1 pu is provided by a 3 MVAR STATCOM.

Now open the "Wind Farm" blocks and look at "Wind Turbine 1". Also open the turbine menu and look at the two sets of parameters specified for the turbine and the generator. Each wind turbine block represents two 1.5 MW turbines. Now in the turbine menu, select "Turbine data" and check "Display wind-turbine power characteristics". The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 4 m/s to 10 m/s. The nominal wind speed yielding the nominal mechanical power (1pu = 3 MW) is 9 m/s. The wind turbine model (from the DR library) and the STATCOM model (from the FACTS library) are phasor models that allow transient stability type studies with long simulation times.

The wind speed applied to each turbine is controlled by the “wind 1” to “wind 3” blocks of the MATLAB / Simulink model. Initially, wind speed is set at 8 m/s., than starting at t = 2s for “wind turbine 1”, wind speed is increased to 11 m/s in 3 seconds. The same gust of wind is applied to turbine 2 and turbine 3, respectively with 2 seconds and 4 seconds delay.

2.2 Simulation of SFIG System Driven by Variable-Pitch Wind Turbines

2.2.1 SFIG System Parameters for Simulation

Generator Parameters: -

(i) Nominal power (VA): $6\times 1.5\times 10^6$ W / 0.9 MVA (6×1.5 MW at 0.9 pf, for six generators).
(ii) L-L voltage (V_{rms}): 575 V. (iii) Frequency (Hz): 50. (iv) Stator resistance (R_s) and Leakag reactance (L_s) (pu): 0.004843 and 0.1248. (v) Rotor R_r and L_r (pu): 0.004377 and 0.1791 (vi) Magnetizing inductance, L_m (pu): 6.77 (vii) Inertia constant (H): 5.04 MW/MVA (viii) Friction factor: 0.01 pu (ix) Pair of poles: 3

Turbine Parameters

(i) Nominal wind turbine mechanical output power (Watts) = $2\times 1.5\times 10^6$ (ii) Base wind speed (m/s) = 9 (iii) Maximum power at base wind speed (pu of nominal mechanical power) = 1 (iv) Base rotational speed (pu of base generator speed) = 1 (v) Pitch angle controller gain (K_p, K_i) = 5, 25 (vi) Maximum pitch angle (deg.) = 45 (vii) Maximum rate of change of pitch angle (deg. /s) = 2.

2.2.2 Turbine Response to a Change in Wind Speed

Start simulation and observe the graphs on the “Wind Turbines” scope monitoring active and reactive power, generator speed, wind speed and pitch angle for each wind turbine.

For each pair of wind turbines generated active power starts increasing smoothly (together with the wind speed) and reaches its rated value of 3 MW in approximately 8 seconds. Over that time frame turbine speed will have increased from 1.0028 pu to 1.0047 pu. Initially, the pitch angle of the turbine blades is zero degree. When the output power exceed 3 MW, the pitch angle is increased from 0 degree to 8 degree in order to bring the output power back to its nominal value. We will observe that the absorbed reactive power increases as the generated active power increases. At nominal power, each pair of wind turbine absorbs 1.47 MVAR. For 11 m/s wind speed, the total exported power measured at bus B25 is 9 MW.

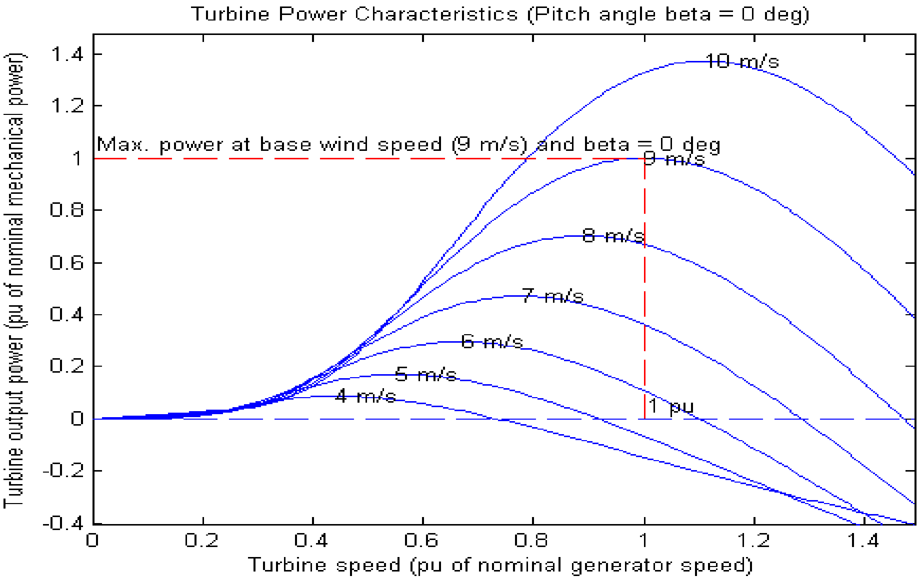


Figure 8 Turbine mechanical power as a function of turbine speed for wind speed ranging

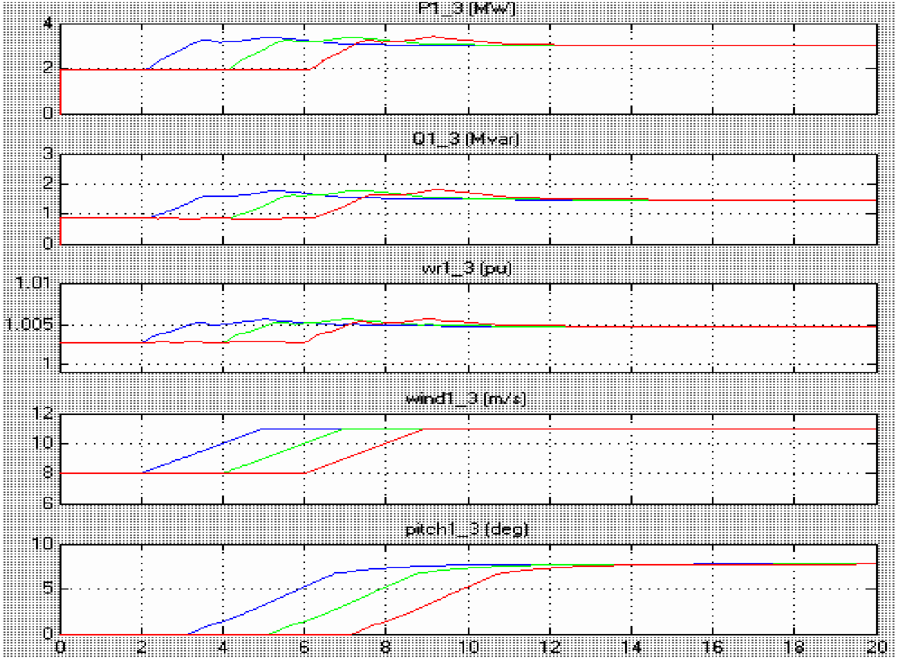


Figure 9 Variation of active power, reactive power, generator speed, wind speed and pitch angle for each turbine

III. SIMULATION OF DFIG SYSTEM FOR VARIABLE-PITCH WIND TURBINES

In this session, the simulation results obtained using MATLAB / Simulink are presented to study the steady state and dynamic performance of a wind power plant equipped with DFIG system connected to a distribution system.

3.1 Operation of DFIG Driven by Variable-Pitch Wind Turbines

In this case a wind farm consists of six 1.5 MW wind turbines connected to a 25 KV distribution system exporting power to 120 KV grid through a 30 km 25 KV feeder. A 2300 V, 2 MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 pf) and of a 200 kW resistive load is connected to the same feeder at bus B25. A 500 kW load is also connected on the 575 volt bus of the wind farm. The single line diagram of this system is illustrated in the figure.

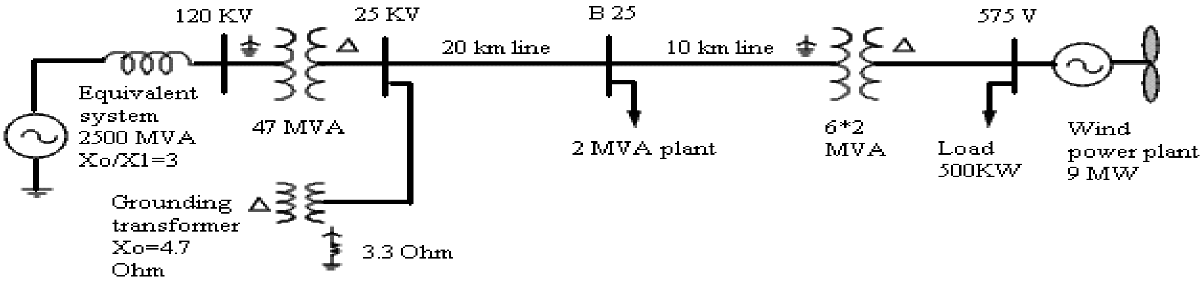


Figure 10. Single line diagram of a wind power plant connected to a distribution system (DFIG)

Wind turbines use a doubly-fed induction generator consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based pulse width modulated (PWM) inverter to feed the induction generator with variable voltage and frequency source. The stator winding is connected directly to 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing the mechanical stresses on the turbine during the gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability of the power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel cage induction generator.

3.2 Simulation of DFIG System Driven by Variable-Pitch Wind Turbines

In the case presented here, the rotor is running at sub-synchronous speed for wind speeds lower than 10 m/s and it is running at super-synchronous speed for higher wind speeds. The turbine mechanical power as function of turbine speed is displayed in the figure for wind speed ranging from 5 m/s to 16.2 m/s. These characteristics are obtained with the specified parameters of the turbine data.

The DFIG is controlled to follow the ABCD curve. Turbine speed optimization is obtained between point B and point C on this curve. The six wind turbine farm is simulated by a single wind turbine block by multiplying the following three parameters by six, as follows

1. The nominal wind turbine mechanical output power: $6 \times 1.5 \times 10^6$ watts, specified in the turbine data menu.
2. The generator rated power: $6 \times 1.5 \times 10^6 / 0.9$ MVA (6×1.5 MW at 0.9 pf), specified in the generator data menu.
3. The nominal dc bus capacitor: $6 \times 1000\ \mu F$, specified in the converters data menu.

The mode of operation is set to voltage regulation in the control parameters dialog box. The terminal voltage will be controlled to a value imposed by the reference voltage (V_{ref} = 1 pu) and voltage droop (X_s = 0.02 pu).

3.2.1 DFIG System Parameters for Simulation Generator Parameters

(i) Nominal power (VA): $6 \times 1.5 \times 10^6 / 0.9$ MVA (6×1.5 MW at 0.9 pf, for 6 generators) (ii) L-L voltage (V_{rms}): 575 V (iii) Frequency (Hz): 50 (iv) Stator resistance, R_s and rotor leakage inductance, L_s (pu): 0.00706 and 0.171 (v) Rotor R_r and L_r (pu): 0.005 and 0.156 (vi) Magnetizing inductance Lm (pu): 2.9 (vii) Inertia constant, H: 5.04 MW/MVA (viii) Friction factor (pu): 0.01 (ix) Pair of poles: 3

Turbine Parameters

(i) Nominal wind turbine mechanical output power (Watts) = $6 \times 1.5 \times 10^6$ (ii) Tracking characteristic speed [Speed_A, Speed_B, Speed_C, Speed_D (pu)] = 0.7, 0.71, 1.2, 1.21. (iii) Power at point C (pu/mechanical power): 0.73 (iv) Wind speed at point C (m/s): 12 (v) Pitch angle controller gain (K_p) = 500 (vi) Maximum pitch angle (deg.) = 45 (vii) Maximum rate of change of pitch angle (deg./s) = 2

3.2.2 Turbine Response to a Change in Wind Speed

Let's observe the turbine response to a change in wind speed. Initially, wind speed is set at 8 m/s, then at t = 5 seconds, wind speed increases suddenly at 14 m/s.

At t = 5 seconds, the generated active power starts increasing smoothly (together with the wind speed) to reach its rated value of 9 MW in approx. 15 seconds. Over that time frame the turbine speed increases from 0.8 pu to 1.21 pu. Initially, the pitch angle of the turbine blades is zero degree and the turbine operating point follows the dashed curve of the turbine power characteristics up to point D. Then the pitch angle is increased from 0 deg. to 0.76 deg. to limit the mechanical power. Observe also the voltage and generated reactive power. The reactive power is controlled to maintain a 1 pu voltage. At nominal power, wind turbine absorbs 0.68 MVar (generated Q = - 0.68MVar) to control voltage at 1 pu. If we change the mode of operation to Var regulation with generated reactive power Q ref set to 0, we will observe that the voltage increases to 1.021 pu when the turbine generates its nominal power at unity power factor.

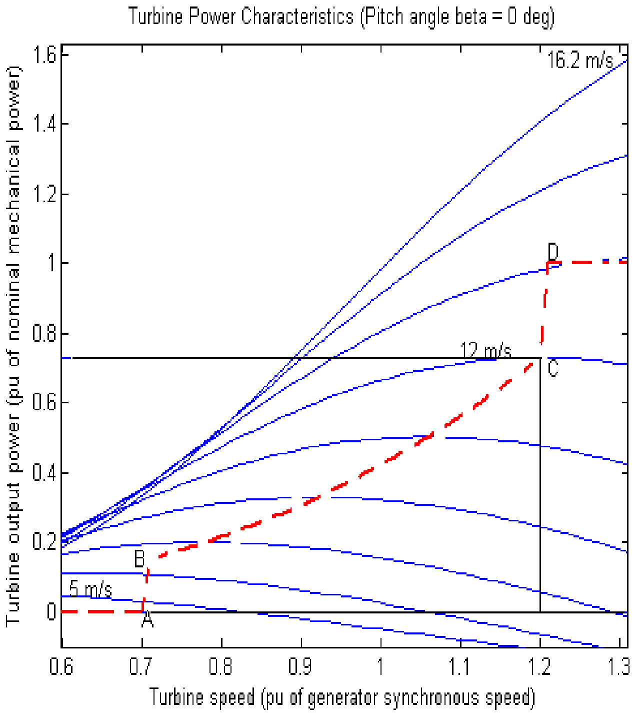


Figure 11. The turbine mechanical power as function of turbine speed for wind speeds ranging from 5 m/s to 16.2 m/s.

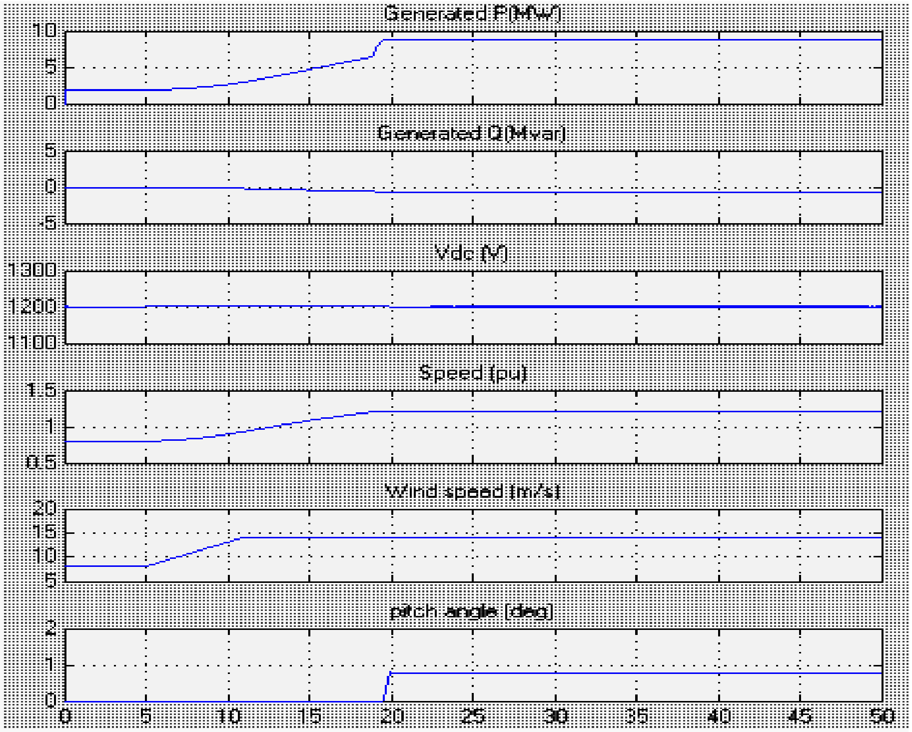
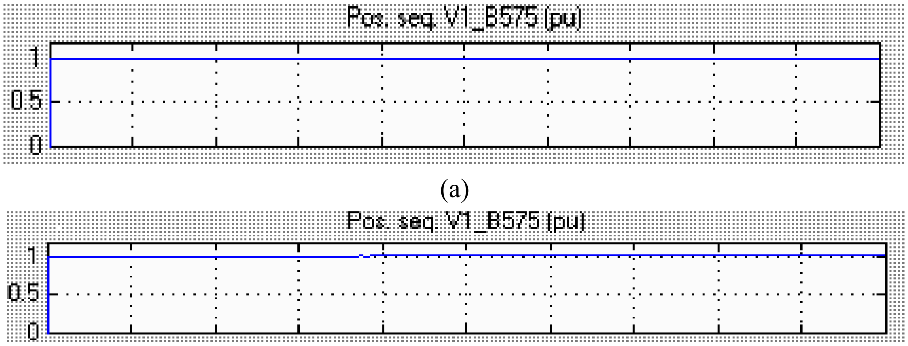


Figure 12 Wind turbine voltage, current, active power, reactive power, dc bus voltage and turbine speed.



(a)

(b)

Figure 13 Voltage at turbine terminals i.e., at bus B575. a) In voltage regulation mode, and b) In Var regulation mode.

IV. CONCLUSION

Thus modern high-power wind turbines are capable of adjustable speed operation and if equipped with DFIG systems offer several advantages in comparison to SFIG systems.

- DFIG systems are cost effective and provide simple pitch control as the controlling speed of the generator (frequency) allows the pitch control time constants to become longer reducing pitch control complexity and peak power requirements. At lower wind speed, the pitch angle is usually fixed. Pitch angle control is performed only to limit maximum output power at high wind speed.
- This adjustable speed operation reduces mechanical stresses as energy of gusts of wind is stored in mechanical inertia of turbine, creating an “elasticity” that reduces torque pulsation and hence improving power quality. This eliminates electrical power variations i.e., less flicker.
- This also improves system efficiency as turbine speed is adjusted as a function of wind speed to maximize output power. Operation at maximum power point can be realized over a wide power range.

There is a possibility of adjustable speed operation using SFIG systems but it has to be equipped with full power converter at stator, which is to be rated 1 pu total system power and thus expensive. This scheme will result in more conducting and switching losses. The DFIG system results in reduced inverter cost and losses because inverter rating is typically 25% of total system power, while the speed range of DFIG is ±33% around the synchronous speed. Further the DFIG technology enables the power electronic converters to generate or absorb reactive power, thus eliminating the need of installing capacitor banks as in the case of squirrel cage induction generators in SFIG systems.

REFERENCES

[1] World Wind Energy Association, WWEA 2010, 9th World Wind Energy Conference and Exhibition, WWEC 2010, Istanbul, Turkey, 15-17 June 2010, Available:www.wwec2010.com, Publication: March 2010.
[2] Erich Hau, “Wind Turbines - Fundamentals, Technologies, Applications, Economics”, Springer Publishing, pp. 319-347, Second Edition, Year 2005.
[3] Gary L Johnson, “Wind Energy Systems”, Prentice Hall Inc., Electronic Edition, pp. 1-1 to 1-21 and 4-1 to 4-43, Manhattan, KS, October, 2006.
[4] M. G. Say, “Alternating Current Machines”, LBS Publishing, Fifth edition, 1986.
[5] Deicke, M. Doncker, Muller. S, Rik W, “Doubly Fed Induction Generator Systems for Wind Turbines’, IEEE Industry Applications Magazine, May/June 2002.
[6] R. Pena, J. Clare and G. Asher, “Doubly Fed Induction Generator using Back-to- Back PWM Converters and its Application to Variable-Speed Wind Energy Generation,” Proc. Inst. Elect. Eng., Electric Power Applications, Vol. 143, No.3, pp. 231–241, May 1996.
[7] Jakana Ekanayake, Lee Holdsworth and Nick Jenkins, “Control of DFIG Wind Turbines”, IEEE Power Engineer, February 2003.
[8] Stefan Lundberg, Andreas Petersson, “Energy Efficiency of Electrical Systems in Wind Turbines” Electric Power Engineering, Sweden, 2003
[9] Donald Marier (Editor, Alternative sources of energy magazine), “Wind Power for the Home Owner – A Guide to Selecting, Siting and Installing an Electricity Generating Wind Power System”, pp.83-95, Home and Garden Publication.
[10] B R Pai and M S Ramaprasad, “Power Generation Through Renewable Sources of Energy”, TMH Publishing, Conference paper by K. S. Rao, Gujarat Energy Development Agency (GEDA); “Techno-Economic Considerations for Wind Power Generation in Gujarat”, TMH Publication, 1991.
[11] P. Kundur, “Power System Stability and Control”, Tata McGraw-Hill Publishing, Second reprint, 2006.
[12] Rui Melicio, V. M. F Mendes, “Doubly Fed Induction Generator Systems for Variable Speed turbine”, ISEL, DEEA, 1950-062 Lisboa (Portugal), 2006.

[13] Chengyong Zhao, Gengyin Li, Guoping Liu, Ming Yin, Ming Zhou, "Study on the Control of DFIG and its Responses to Grid Disturbances", IEEE Transaction on Power Systems", Vol.4, 2006.

[14] E. Muljadi, C. P. Butterfield and J. Chachon, H. Romanowitz, "Power Quality Aspects in Wind Power System", IEEE Power Engineering Society, General Meeting, Montreal, Quebec, Canada, June 18-22, 2006.

[15] Henrik Stiesdal, "The Wind Turbine Components and Operation", Special Issue Bonus Energy A/S, pp.5-10, Autumn 1999.

[16] National Renewable Energy Laboratory (nrel.gov) (U S Department of Energy website), Student Resources on Renewable Energy, Wind Issues, 'Grid Integration', Conference Paper, NREL/CP-500-39813, January 2006.

[17] World Institute of Sustainable Energy (WISE) Publication "Green Energy" Vol. 4, Sept-Oct & Nov-Dec 2008, Special issue for "Wind India 2008".