Effect of High Wind Penetration, Grid Strengthening and Compensation on Steady State Operating Point of DFIG Interfaced Power System

D. Padma Subramanian, Anly Abraham

***Abstract*— This paper presents the effect of high wind penetration, grid strengthening and compensation on steady state operating point of a power system interfaced with Doubly Fed Induction Generator (DFIG). A model of DFIG to interface with the load flow program is presented. A MATLAB program is developed and effectiveness of developed program is tested in a standard IEEE-9 bus system, interfaced with DFIG at ninth bus. The impact of varying wind velocity in cases of high wind penetration, grid strengthening and compensation on the steady state behavior of the grid connected DFIG system is studied and the results are presented.**

***Index Terms*— Doubly fed induction generator, High wind penetration, Power flow analysis,**

List of Nomenclature

ρ	Air density
P_e	Electrical power
X_m	Magnetizing reactance
θ	Pitch angle
C_p	Power coefficient of the turbine
P_{mech}	Power extracted from the wind turbine
R	Radius of swept area
$\bar{I}_r = I_r\angle\theta_r$	Rotor current
$\bar{V}_r = V_r\angle\emptyset_r$	Rotor excitation voltage
X_{lr}	Rotor leakage reactance
$X_r = X_{lr} + X_m$	Rotor reactance
R_r	Rotor resistance
ω	Rotational speed of rotor
S	Slip
$\bar{I}_s = I_s\angle\theta_s$	Stator current
X_{ls}	Stator leakage reactance
$X_s = X_{ls} + X_m$	Stator reactance
R_s	Stator resistance
$\bar{V}_s = V_s\angle 0^{\circ}$	Stator voltage
A	Swept area of the blades
U_w	Wind speed

I. INTRODUCTION

Environmental concerns and increased power demand have encouraged the electrical power generation from the use of renewable energy sources, and wind energy is prominent among them [1,2].Wind power is used in large-scale wind farms for national electrical grid as well as in small individual turbines for providing electricity to rural residences or grid-isolated locations[3].

The design and successful operation of large-scale wind powered generators face a number of formidable problems. Both induction generator and synchronous generators can be used for wind turbine system. Induction generators can be used in a fixed speed system or a variable- speed system, while synchronous generators are normally used in power electronic interfaced variable speed systems [4].

DFIG based wind turbines are more popular because of their favorable cost/performance attribute resulting primarily from the need for a much smaller converter rating compared to the machine rating [5].

A DFIG is wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter. The power flow of DFIG has two paths: one from the stator to the grid directly, and the other from the rotor through its frequency converter to the grid [6]. In DIFG, the slip rings are making the electrical connection to the rotor. If the generator is running super-synchronously, electrical power delivered to the grid through both the rotor and the stator. If the generator is running sub synchronously, electrical power is delivered into the rotor from the grid [7],[8]. The DFIG can have independent active and reactive power under normal grid conditions [9].

A thorough understanding of the modeling, control, and dynamic as well as the steady state analysis of this machine is necessary to optimally extract the power from the wind and accurately predict its performance. Modeling of DFIG wind turbine in order to extract maximum possible mechanical power from the wind according to the wind velocity and tip-speed ratio has been described in [10].In [11], steady state analysis of DFIG is developed by assuming that the machine is excited on the rotor side by a slip frequency current injected from an exciter mounted on the same shaft of the machine. In [12], a method is discussed for incorporating the non-linear fifth-order model of DFIG wind turbines based on the N-R algorithm for obtaining the steady-state electrical variables of the machine under certain given conditions. In [13], voltage fed current regulated rotor-side and grid-side control of DFIG under steady and transient conditions has been studied. Analysis of DFIG's steady state operating conditions and several ways for including DFIGs in load flow analysis is discussed well in [14]. A modified N-R method considering wind power is proposed in [15]. In [16], steady state analysis of grid connected system with squirrel cage induction

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generator (SCIG) and effect of increased number of SCIGs is discussed.

In this paper, a modeling of DFIG for steady state analysis of DFIG interfaced grid system is presented. The effect of high wind penetration, grid strengthening and compensation is studied in detail with varying wind velocity.

This paper comprises of the following sections: Section 2 deals with the modeling of wind turbine and DFIG for steady state analysis. In section 3 presents power flow analysis of grid connected WECS. Section 4 describes about test system used for steady state analysis. In section 5, effect of high wind penetration, grid strengthening and compensation is discussed. Conclusion is presented in section 6.

II. MODELING FOR STEADY STATE ANALYSIS

In this section, modeling of wind turbine and DFIG for steady state analysis is presented. The general structure of WECS for steady state analysis is shown in fig 1.

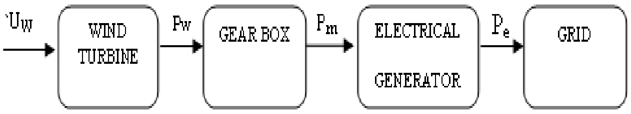

Fig.1. Block diagram of WECS

A. Wind Turbine Model

The power obtained by the turbine is a function of wind speed. The simple model used commonly to represent the turbine is based on the power coefficient C_p versus the tip speed ratio λ [17]. The mechanical power extracted from the wind turbine is given by,

$$P_{mech} = \frac{1}{2}\rho A U_w^3 C_p \qquad (1)$$

C_p is a function of the blade pitch angle θ and the tip speed ratio λ defined as,

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

The variation of C_p with the variation of u_w and λ is non-linear in nature [18].The C_p is generally represented as,

$$C_p(\lambda,\theta) = C_1\left(\frac{C_2}{\Lambda} - C_3\theta - C_4\theta^x - C_5\right)e^{\frac{-C_6}{\Lambda}} \qquad (3)$$

where, C_1 to C_6 and x are constants.

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \qquad (4)$$

B. Doubly Fed Induction Generator Model

The steady state equivalent circuit shown in fig 2 is used in this paper for analysis. The equations for stator and rotor real and reactive power are employed as given in [19]. The expression for the electrical power can be obtained as

$$P_e = -I_r^2 R_r \frac{1-s}{s} - \frac{1-s}{s} R_e(\bar{V}_r \bar{I}_r^*)$$

$$= \frac{(s-1)}{A^2 + B^2}(C + D + E) \qquad (5)$$

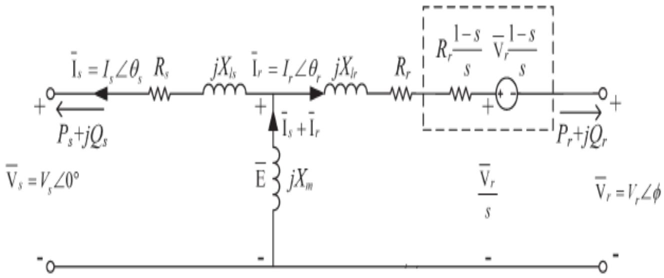

Fig. 2. Steady state equivalent circuit of DFIG

where,

$$A = sR_sX_r + R_rX_s\,,$$

$$B = R_rR_s + s(X_m^2 - X_rX_s),$$

$$C = sR_rX_m^2V_s^2 - R_sX_m^2V_r^2$$

$$D = (A - 2R_rX_s)X_mV_sV_r\cos\emptyset_r$$

$$E = (B - 2R_sR_r)X_mV_sV_r\sin\emptyset_r$$

III. POWER FLOW ANALYSIS OF GRID CONNECTED WECS

The power flow study is to determine complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined [20].

In this paper, the power flow analysis is carried out to study the effect of increasing number of wind generator connected to existing grid. The N-R method is modified to include DFIG into the gird. The re-constructed N-R equations for grid connected WECS can be given as [16],

$$\begin{bmatrix}[\Delta P]\\ [\Delta Q]\\ [\Delta P_m]\end{bmatrix} = \begin{bmatrix}\left[\frac{\partial P}{\partial\theta}\right] & \left[\frac{\partial P}{\partial V}\right] & \left[\frac{\partial P}{\partial s}\right]\\ \left[\frac{\partial Q}{\partial\theta}\right] & \left[\frac{\partial Q}{\partial V}\right] & \left[\frac{\partial Q}{\partial s}\right]\\ \left[\frac{-\partial\Delta P_m}{\partial\theta}\right] & \left[\frac{-\partial\Delta P_m}{\partial V}\right] & \left[\frac{-\partial\Delta P_m}{\partial s}\right]\end{bmatrix}\begin{bmatrix}[\Delta\theta]\\ [\Delta V]\\ [\Delta s]\end{bmatrix} \qquad (6)$$

where $[\Delta P_m]$ is power mismatch matrix of DFIG, which is given by $\Delta P_m = P_{mech} - P_e$ from (1) and (5). The diagonal element $\frac{\partial\Delta P_m}{\partial s}$ is given by eqn (7)

$$\frac{\partial(P_{mech} - P_e)}{\partial s} = \left[\frac{1}{2}\rho A U_w^3 C_1[C_2 - FC_6]e^{\frac{-C_6}{\Lambda}}\frac{\frac{\omega_s R}{U_W}}{(\lambda + 0.08\theta)^2}\right] - \frac{1}{(A^2+B^2)^2}\left\{\left[(C + D + E) + (s-1)\left(\frac{\partial C}{\partial s} + \frac{\partial D}{\partial s} + \frac{\partial E}{\partial s}\right)\right] \times (A^2 + B^2) - (s-1)(C + D + E) \times \left(2A\frac{\partial A}{\partial s} + 2B\frac{\partial B}{\partial s}\right)\right\}$$

For N_l load buses, N_g generator buses and N_w wind farms with DFIG the dimension of (6) will be

$$(2N_g + 2N_l + N_w - 1) \times (2Ng + 2N_l + N_w - 1)$$

IV. DESCRIPTION OF TEST SYSTEM USED FOR STEADY STATE ANALYSIS

The single line diagram of modified 9-bus system for power flow analysis with WECs is shown in figure 3.
The data for test system is given in appendix.

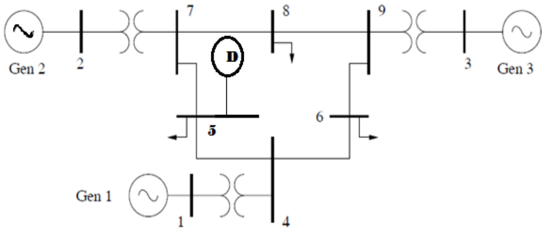

Fig.3. Single line diagram of DFIG interfaced IEEE 9- bus system

V. LOAD FLOW ANALYSIS WITH DFIG BASED WECS

The N-R power flow analysis is carried with test system by interfacing WECS in bus 9. Effect of high wind penetration, grid strengthening and compensation is discussed in following sections.

A. *Effect of high wind penetration*

The number of DFIGs in bus determines the loading effect of the system. To analyze effect of increasing the number of DFIG at WECS terminal, initially power flow analysis is carried out for one DFIG connected at bus 9. Repeated runs were performed by increasing the number of DFIGs. The corresponding plots of voltage, real power and reactive power consumed, for wind speeds ranging from 5m/s to 25 m/s, obtained from power flow analysis are shown in figs 4, 5 and6

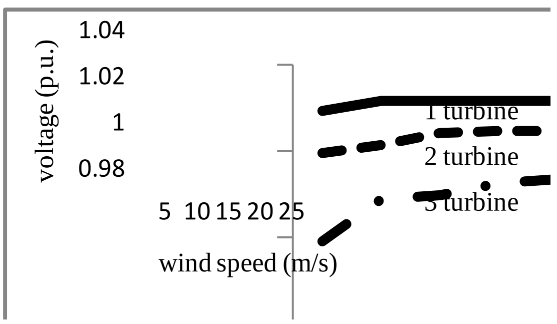

Fig 4: Voltage variation with wind speed

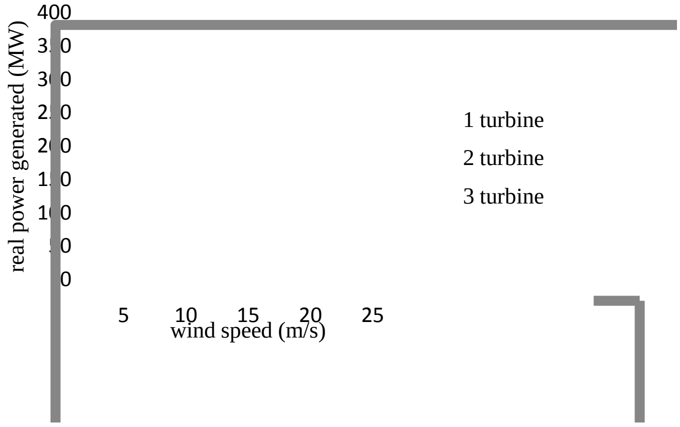

Fig 5: Real power variation with wind speed

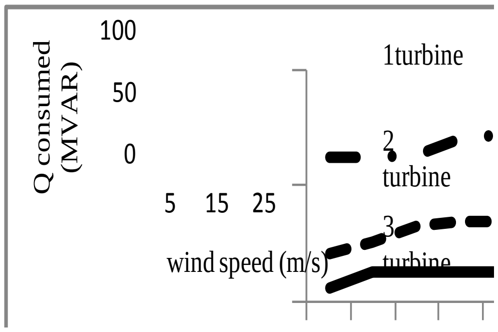

Fig 6: Reactive power consumption with wind speed

From figures 4 and 6, it is clear that as the number of DFIGs increases reactive power consumed increases, and as a result, the voltage drops. From figure 5, it is clear that as more wind turbines are interconnected, the real power generated increases. However, when the number of DFIGs connected is more than three the load flow program, diverges indicating the possibility of a runaway condition.

B. *Effect of grid strengthening*

More number of wind turbines is required in wind farms to meet the increased power demand. Hence, grid needs to be strengthened to accommodate more number of DFIGs. The effective impedance between the PCC (bus 9) and the grid (bus 6) is reduced by half, and hence the grid becomes stiffer. The corresponding plots of voltage, real power and reactive power consumed after grid strengthening is shown i figs 7, 8 and 9.

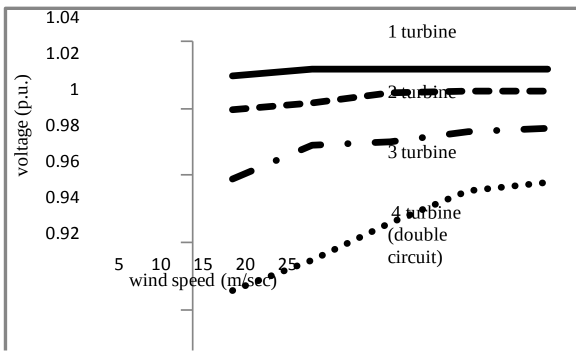

Fig7: Voltage after grid strengthening

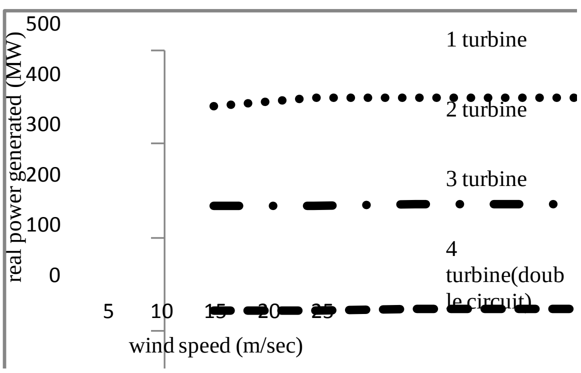

Fig 8: Real power after grid strengthening

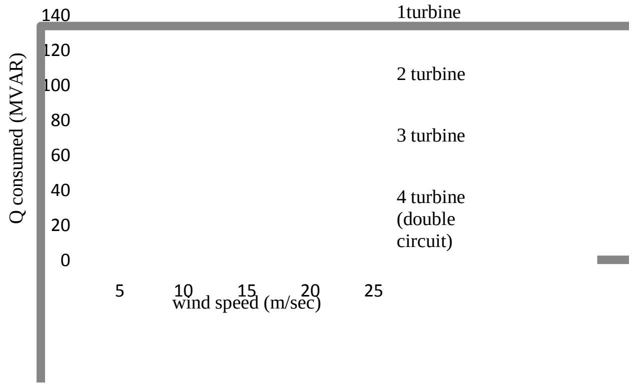

Fig 9: Q consumed after grid strengthening

From figs 7, 8 and 9 it can be observed that the system voltage, reactive power and real power follows the same behavior as in section 5.1 when the grid is strengthened using a double-circuited line. In this case, the system is able to accommodate four WTGs as compared to three WTGs in the analysis without grid strengthening .However, grid strengthening by increasing the number of lines is not advisable beyond a certain level, which leads to the necessity of compensation for WTGs.

C. Effect of compensation

In general, fixed capacitors are connected with DFIGs for reactive power compensation. Hence, effect of different types of compensation on the steady state behavior of power systems interfaced with DFIG is studied in following sections.

1 .Shunt Compensation

Analysis is carried out on high wind penetrated (four turbines) grid strengthened system to show the effect of shunt compensation by using 150 KVAR and 200 KVAR. Figs 10 and 11 shows the effect of fixed shunt compensation of WTGs

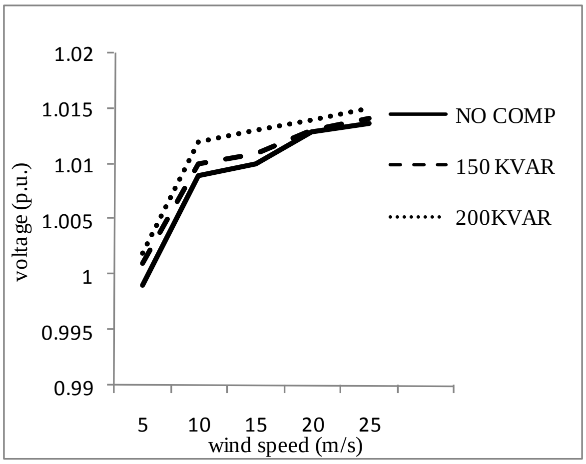

Fig10: Effect on voltage with shunt compensation

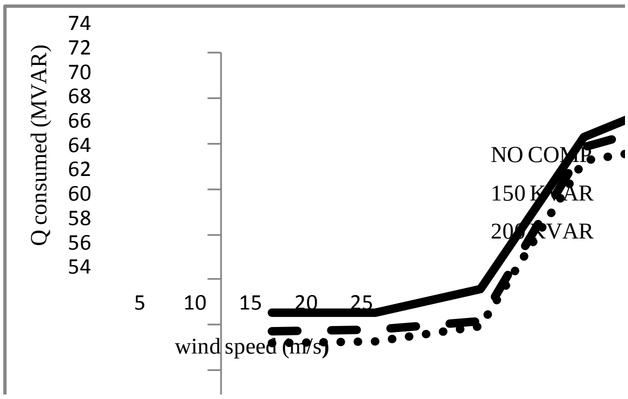

Fig 11: Effect on consumed reactive power with shunt compensation

From fig 10, it is clear that the voltage profile improves as the shunt compensation is increased. From figure 11, it can be observed that reactive power consumption reduces when the compensation level increases.

2. Series compensation

To show the effect of series compensation in increasing the real power transmitted, analysis is extended on the high wind penetrated grid strengthened system. Series capacitor reactance equal to 50% and 70% of transmission line reactance are selected for analysis.

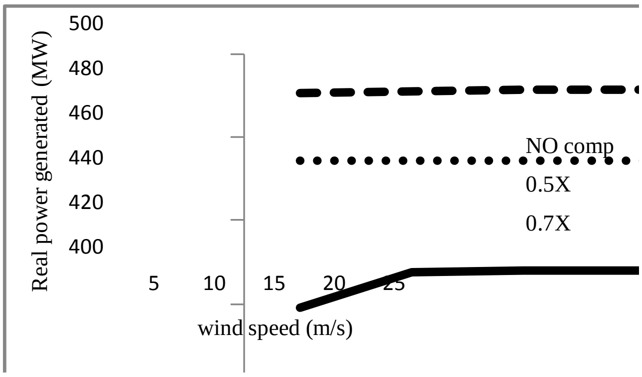

Fig 12: Effect on real power with series compensation

It can be observed from figure 12 that series compensation enhances the real power transmission capability of high wind penetrated gird strengthened system from 474.268 MW to 491.09 MW at wind speed of 10 m/sec when percentage compensation increases from 50% to 70 %.

3. Series-Shunt compensation

In this section series –shunt compensation is performed to know the effect of the combined series and shunt compensation

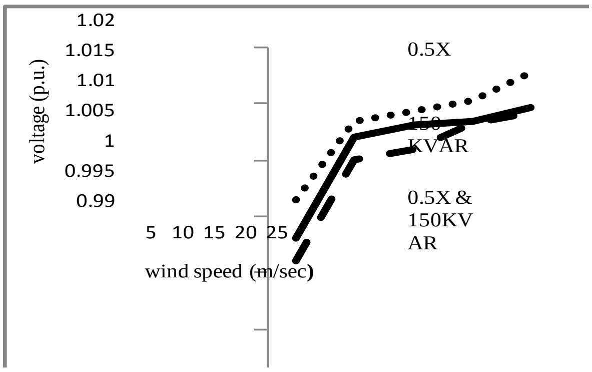

Fig 13: Effect of series shunt compensation on voltage profile

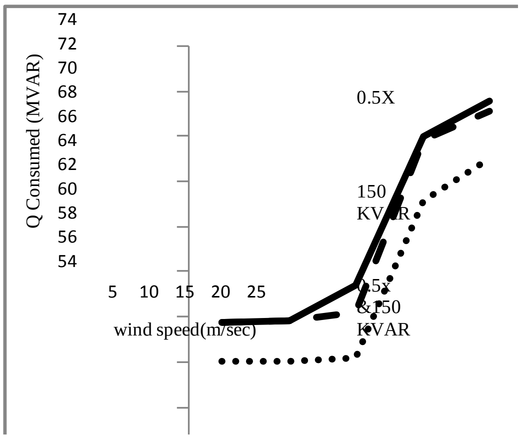

Fig14: Effect of series shunt compensation on Q consumed

From fig 13, it is clear that the voltage improves in series –shunt compensation than individual series and shunt compensation. The reactive power consumption considerably reduced in series-shunt compensation and it is clear from fig 14. Thus, Series-shunt compensation enhances the individual advantages of both series and shunt compensation.

The system can accommodate more number of wind turbines after compensation when compared to high wind penetrated grid strengthened system without compensation. A comparison on maximum number of turbines that can be connected to the system in cases considered above is tabulated in table 1

TABLE 1: COMPARISON OF MAXIMUM NO OF WIND TURBINES IN EACH CASE

ANALYSIS PERFORMED	MAXIMUM NUMBER OF WIND TURBINES
Before grid strengthening	3
After grid strengthening	4
Shunt compensation	6
Series compensation	6
Series-shunt compensation	8

VI. CONCLUSION

In this paper, Power flow analysis is performed for WECS interfaced with the standard IEEE 9-bus system, which yields steady state operating point. Effect of high wind penetration, effect of grid strengthening and effect of compensation is studied in this paper for wind velocity ranging from 5 m/sec to 25 m/sec. Observations in each analysis is summarized as,

Effect of high wind penetration

From the analysis of high wind penetrated system, it is found that the reactive power consumption increases when number of DFIGs increase and as result there is voltage drop in the system. The system goes into a runaway condition when the system interfaces fourth DFIG to the grid. Hence, grid strengthening is advised to accompany more number of DFIGs.

Effect of grid strengthening

It is clear that without line strengthening the grid cannot accommodate more than three DFIGs. The load flow analysis is performed after reducing the effective impedance to half, and it is found that after grid strengthening four uncompensated turbines can be connected to the grid.

Effect of compensation

The effect of series, shunt and series-shunt compensation is studied.

Shunt compensation

It is found that there is an improvement in voltage profile and decrease in the reactive power consumption. The system can accommodate six DFIGs when the high wind penetrated grid strengthened system is compensated with 150 and 200 KVAR fixed shunt capacitors.

Series compensation

The series compensated high wind penetrated grid strengthened system can accommodate six DFIGs. The series compensation enhances an improvement in real power generation

Series –Shunt compensation

The combined effect of series and shunt compensation is performed for the combination of 50% series compensation and 150 KVAR shunt compensation. There is an improvement in voltage profile in series shunt compensation than individual series and shunt compensation. A series-shunt compensated high wind penetrated grid strengthened system can accommodate maximum of eight DFIGs.

APPENDIX

Test system data
1. Bus data

Bus no	Bus type	Generation (p.u.)		Load (p.u.)		DFIG (p.u.)		Voltage Magnitude (p.u.)
		P_G	Q_G	P_L	QL	P_{DFIG}	Q_{DFIG}	
1	Swing	-	-	-	-	-	-	1.0400
2	PV	1.63	-	0.00	0.0	0.0	0.0	1.0253
3	PV	0.85	-	0.00	0.0	0.0	0.0	1.0253
4	PQ	0.00	0.0	0.00	0.0	0.0	0.0	-

5	PQ	0.00	0.0	1.25	0.0	0.2	0.1	-
6	PQ	0.00	0.0	0.90	0.3	0.0	0.0	-
7	PQ	0.00	0.0	0.00	0.0	0.0	0.0	-
8	PQ	0.00	0.0	1.00	0.35	0.0	0.0	-
9	PQ	0.00	0.0	0.00	0.0	0.0	0.0	-

2. Line data

FROM BUS	TO BUS	SERIES RESISTANCE (P.U.)	SERIES REACTANCE (P.U.)	SHUNT SUSCEPTANCE (P.U.)
1	4	0.0000	0.0576	0.0000
4	6	0.0170	0.0920	0.1580
6	9	0.0390	0.1700	0.0580
9	3	0.0000	0.0586	0.0000
9	8	0.0119	0.1008	0.2090
8	7	0.0085	0.0720	0.1490
7	2	0.0000	0.0625	0.0000
7	5	0.0320	0.1610	0.3060

WECS Data

DATA FOR WIND TURBINE

Air density $\rho = 1.223\ Kg/m^3$, Power coefficients C_1=0.5, C_2=116, C_3=0.4, C_5=5, C_6=21, R=3m, Blade pitch angle = 6°.

DFIG Data:

Stator resistance Rs=0.00706; Stator leakage reactance Xls=0.171; Rotor resistance Rr =0.005; Rotor leakage reactance Xlr=0.156; Magnetizing reactance Xm=0.92.

REFERENCES

1. Jadhav H.T and Roy.R, "A Critical Review on the Grid Integration Issues of DFIG Based Wind Farms", 10th International Conference on Environment and Electrical Engineering, 2011,pp 1-4.
2. N.P.Padhy and Kiran Jasthi, "Load Flow Algorithm for Practical Distribution Systems Comprising Wind Generators", in proceeding of International Conference on energy, automation and signal, 2011,pp 310-315.
3. S.ChandraHas, Dr.P.Ajay-D-Vimalraj, and G.R.K.D.Satya Prasad, "Power Enhancement of Wind Energy Conversion System Using Hybrid Method', International Journal Of Advanced Engineering Sciences And Technologies ,vol no. 7, no. 2, pp 248 – 253,2011.
4. Sunil Kumar., Nitin Goel and P.R.Sharma, "Investigation On Doubly Fed Induction Generator Steady State Parameters", International Journal of Power System Operation and Energy Management, vol.-1,pp 2231-4407,2012.
5. S.Engelhardt.,I.Erlich.,CFeltes.,J.Kretschmann.,andF.Shewarega,
6. "Reactive Power Capability of Wind Turbines Based on Doubly Fed Induction Generators', IEEE Transactions on Energy Conversion ,vol 26.,no 1,2011.
7. P M Balaji., B Rami Reddy and R Granadam,"A Study on the Integration of Wind Turbine Coupled Doubly Fed Induction Generator to the Electrical Grid", The IUP Journal of Electrical & Electronics Engineering, vol. 4, no. 4, pp. 22-35,2011.
8. Balasubramaniam Babypriya and Rajapalan Anita, "Modelling, Simulation and Analysis of Doubly Fed Induction Generator For Wind Turbines", Journal Of Electrical Engineering, vol. 60, no. 2, pp79–85,2009.
9. Sharma Pawan.,Bhatti Tricholen Singh and R.K.Seha Srinivasa,"Doubly Fed Induction Generator: an Overview", Journal of Electrical and Electronics Engineering,vol.3, pp189-194,2010.
10. C. Rabelo, W. Hofmann, J. L. da Silva, R. G. de Oliveira, and S. R. Silva,"Reactive Power Control Design in Doubly Fed Induction Generators for Wind Turbines", IEEE Trans. Ind. Electron., vol. 56, no. 10, pp. 4154– 4162,2009.
11. B.Chitti Babu and K.B.Mohanty,"Doubly-Fed Induction Generator for Variable Speed Wind Energy Conversion Systems- Modeling & Simulation", International Journal of Computer and Electrical Engineering, vol. 2, no. 1, pp-1793-8163,2010.
12. Ahmad M.Alkandari.,Soliman Abd-Elhady Soliman and Mansour H.Abdel-Rahman,"Steady State Analysis of a Doubly Fed Induction Generator", Energy and Power Engineering, vol.3, pp 393-400,2011.
13. Vieira J.P.A and Nunes M.V.A,"Analysis of Steady-State_Operation_of_DFIG-Based Wind Turbines in Power Systems", IET conference on Renewable Power Generation, pp 1-5,2011.
14. Satish Choudhury, K.B.Mohanty, and B.Chitti Babu, "Performance Analysis of Doubly-Fed Induction Generator for Wind Energy Conversion System", Proc. PSU-UNS International Conference on Engineering and Technology (ICET-2011), Phuket, Thailand, pp.532-536, 2011.
15. J.Fernando., M.Padron and Andres Elias Feijoo Lorenzo, "Calculating Steady-State Operating Conditions For Doubly-Fed Induction Generator Wind Turbines", IEEE transactions on power systems, vol.25, no. 2, pp 922-928,2010.
16. Yan Li., Yulei Luo., Buhan Zang and Chengxong, ,"A Modified Newton Raphson Power Flow Method Considering Wind Power", in proceedings of Power and Energy Engineering Conference (APPEEC) Asia Pacific, pp. 1-5,2011.
17. R.Jayashri, "Analysis and performance enhancement of grid connected wind energy conversion system", PhD thesis, Anna University, Chennai,2007.
18. S. N. Bhadra, D. Kastha, S. Banerjee,"Wind Electrical Systems",Oxford University Press, New Delhi,2009.
19. S.Heier, " Grid Integration of wind Energy Conversion Systems", John Wiley and Sons,1998
20. Chien-Hung Liu and Yuan-Yih Hsu,"Effect Of Rotor Excitation Voltage On Steady State Stability And Maximum Output Power Of A Doubly Fed Induction Generator", IEEE Transactions on Industrial Electronics, vol. 58, no 4,pp 1096-1109,2011.
21. Saadat H, "Power System Analysis", Tata Mc Graw Hill, New Delhi 1999, 2002 edition.

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