EFFECT OF WIND TURBINE GENERATORS ON THE SMALL SIGNAL STABILITY OF POWER SYSTEMS

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ABSTRACT: *Wind energy provides a viable and environmentally friendly option. It can add security to national energy system with decreasing global reserves of fossil fuels. So for increasing wind power penetration, the wind farms (WFs) will be directly influencing the power system. Recent technologies related to wind energy are mostly equipped with doubly fed induction generators (DFIG) because of its many advantages. This paper establishes simulation model with the IEEE 9 and IEEE 14 bus systems considering replacement of the synchronous generator in these systems one by one by wind turbines based DFIG at the same MVA ratings and changing the location of wind resources. The PSAT simulation environment based on Matlab software is used to analyze the small signal stability of the grid interconnection of the different types of wind turbines. The results show that wind power integration can have a positive or negative impact on small signal stability of the power system depending on the location of the wind farm.*

KEYWORDS: *Wind Energy, Doubly Fed Induction Generators, Power System Small Signal Stability, PSAT, Wind Farm.*

INTRODUCTION

The major share of electrical power is generated from fossil fuels which are limited sources, expensive, and create environmental pollution. So there is another view to reduce the dependency on fossil fuels in the generation of the electricity by using available renewable energy resources. One of these renewable energies is wind energy which is gaining increasing importance throughout the world especially in the early 1970s, with the first oil price shock, interest in the power of the wind re-emerged [1]. Wind turbines (WTs) can either operate at fixed speed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine, the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those is the operation in both sub-synchronous and super synchronous speed regime extracting maximum power from wind [2, 3] and control active and reactive power [4]. One of the variable speed type is the doubly fed induction generators (DFIG) are being preferred nowadays. The modern DFIG as described in [5] uses back to back converter which controls the rotor voltage and the speed of wound rotor induction machine. The grid side converter of the rotor circuit exchanges real power with the grid and maintains the DC voltage across the capacitor. The rotor side converter is controlled so that in sub-rated region maximum wind power is extracted and in rated region constant torque is extracted. The grid side converter of the rotor circuit exchanges real power with the grid and

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maintains the DC voltage across the capacitor. The rotor side converter is controlled so that in sub-rated region maximum wind power is extracted and in rated region constant torque is extracted. Various studies have been carried out regarding the effect of WT on small signal stability analysis. In [6], analyze the small signal stability of wind power systems, using Squirrel Cage Induction Generators and Doubly Fed Induction Generators which are today the most used rotating machines for manufacturers on wind farms. In [7], the small signal stability of power systems with large scale wind power penetrations is investigated. The inter-area oscillation damping ratio of the 12 bus test power system increases when there are larger wind power penetrations in the power system, which implies that the power system is more stable. In [8], identify the influence of wind power on the power system small signal stability considering factors like direction of power flow in the tie-line, Transmission line length of the location of wind resources to the main grid, integration level and generator technology. PSAT is a static and dynamic analysis and control toolbox for power system based on MATLAB. It purposes some options: Power Flow Analysis, Optimal Power Flow, Small signal Stability Analysis and Time Domain Simulation, etc. Network Topology design uses model library of SIMULINK or directly edits data files. To improve the accuracy of analysis, PSAT provides a lot of static and dynamic models: Bus, Transformer, Transmission line, PV, PQ, and Balance Node, Circuit Breaker, Line Failure, Constant Power Load, Synchronous motor, induction motor and so on. Source code of the software package is completely open. Users can write and modify the source code for research purposes according to research interests [16].

This paper is organized as follows: Section Two is an introduction to small signal stability, in Section Three, the study methodologies used in this paper are briefly discussed, the model of wind turbine based on DFIG is described in Section Four, the test systems models built in PSAT used in this paper is briefly discussed in Section Five while the simulation results and conclusion is presented in Sections Sex and Sven.

SMALL-SIGNAL STABILITY

Small-signal stability is the ability of the interconnected synchronous machines of a power system to remain in synchronism when the power system is subjected to small disturbances. Of particular importance in the analysis of small-signal stability is the determination of the electromechanical modes of oscillation (EMO). The electromechanical modes involve the rotors of individual generators or of groups of generators oscillating or swinging against each other and can be subdivided into inter-area, local-area and intra-station modes [9]. Small-signal stability requires that the electromechanical modes are adequately damped; their damping depends on a number of factors, e.g. system operating conditions, the characteristics of machine excitation systems, the use of power system stabilizers (PSSs), line outages,… etc.

STUDY METHODOLOGY

The dynamic behavior of a power system can be described by a set of *n* first order nonlinear ordinary differential equations [9]:

$$\dot{x}=f(x,u),\ y=g(x,u) \qquad (1)$$

Where:

$x = [x_1, x_2 \ldots .x_n]^T$ Is the vector of system state variables;

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$y = [y_1, y_2, \ldots y_m]^T$ Is vector of system outputs variables;

$u = [u_1, u_2, \ldots u_r]^T$ Is the vector of system input variables;

$f = [f_1, f_2, \ldots f_n]^T$ and $g=[g_1, g_2, \ldots g_m]^T$ are the vectors of nonlinear functions defining the states and the outputs respectively of the system. For small signal stability analysis a small change occurred to the system can be expressed in Eq. (1) as:

$$\Delta \dot{\boldsymbol{x}} = \boldsymbol{A}\Delta\boldsymbol{x} + \boldsymbol{B}\Delta\boldsymbol{u} \textbf{ and } \Delta\boldsymbol{y} = \boldsymbol{C}\Delta\boldsymbol{x} + \boldsymbol{D}\Delta\boldsymbol{u} \qquad (2)$$

Where the prefix Δ denotes a small deviation, Δx is the state vector, Δy is the output vector, A is the state matrix, B is the input matrix, C is the output coefficient matrix, and D is a matrix describing the connection between the input and output variables.

The eigenvalues λ of the state matrix A can be determined by solving the characteristic equation of A.

$$A=\begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}, B=\begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}, C=\begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} D=\begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m}{\partial u_r} & \cdots & \frac{\partial g_m}{\partial u_r} \end{bmatrix}$$

$$\det(\mathbf{A} - \lambda \mathbf{I}) = 0 \qquad (3)$$

This leads to the complex eigenvalues λ of A in the form

$$\lambda = \sigma \pm j\omega \qquad (4)$$

According to Lyapunov's first method [9]. The small signal stability of a nonlinear system is given by the roots of the characteristic equation (3) the eigenvalues λ of A from equation (4) can be used:

- When the eigenvalues have negative real parts, the original system is asymptotically stable.
- When at least one of the eigenvalues has a positive real part, the original system is unstable.
- When at least one of the eigenvalues has zero value, the original system is critically stable [10].

The participation factor of mode i, can be computed using equation 5 [11]:

$$P_1=\begin{bmatrix} \mathrm{P1i} \\ p2i \\ \vdots \\ pni \end{bmatrix} \qquad (5)$$

$$p_{ki}=\frac{|\varphi||\Psi|}{\sum_{k=1}^{n}|\varphi \mathrm{ki}||\Psi\ \mathrm{ik}|} \qquad (6)$$

n is the number of state variables, p_{ki} is the participation factor of the k^{th} state variable into mode i, φ_{ki} is the i^{th} element of the k^{th} right eigen vector of A, Ψ_{ik} is the n^{th} element of the i^{th} left eigen vector of A.

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MODELING OF WIND TURBINE BASED ON DFIG

The equations of the double feed induction generator in terms of the d and q axes and neglecting the stator and rotor flux transients can be written as [12]:

- For the stator circuit:

$$v_{ds} = -Rs\, i_{ds} + (x_s + x_m)i_{qs} + xmi_{qr} \quad (7)$$

$$v_{qs}= -Rsi_{qs} - (x_s + x_m)i_{ds} + xmi_{dr} \quad (8)$$

- For the rotor circuit:

$$v_{dr}= -Rri_{dr} + (1 - \omega)(x_r + x_m)i_{qr} + x_m i_{qs} \quad (9)$$

$$v_{qr}= -Rri_{qr} + (1 - \omega)(x_r + x_m)i_{dr} + x_m\, i_{ds} \quad (10)$$

Where:

v_{ds}, v_{qs}: d and q axes stator voltages; i_{ds}, i_{qs}: d and q axes stator currents; i_{dr}, i_{qr}, d and q axes rotor currents;

R_s, R_r, Stator and rotor resistances; x_s Stator self-reactance; x_r, Rotor self-reactance; x_m Mutual reactance; ω Rotor speed.

The wind turbine generator shaft and the gearbox are modeled in [13] as a lumped inertia H; therefore, the motion equation can be represented by:

$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e) \quad (11)$$

Where:

T_m: Mechanical torque;

T_e: Electromagnetic torque

This simplification in the inertia is valid only if it is assumed that the controllers associated to the DFIGs are able to quickly minimize the shaft oscillations [13]. The electromagnetic torque is represented by:

$$T_e= x_m(i_{qr}\, i_{ds} - i_{dr} i_{qs}) \quad (12)$$

Vector control schemes decouple the control of active and reactive power in the rotor. Thus, the active power derived from the wind turbine power-speed characteristic Pw(ω) is associated with the rotor current in the q axis as follows:

$$iqr = \left(-\frac{Xs+xm}{xmV} pw(\omega m) / \omega m - iqr\right)\frac{1}{Te} \quad (13)$$

$$idr = K_V(V - V_0)\, {}^{V}\!/_{xm} - idr \quad (14)$$

Where

V: Actual terminal voltage; V0: Desired terminal voltage.

This controller uses the current rotor speed to optimize the energy extracted from the wind. Furthermore, for rotor speeds greater than 1 pu., the power is set to 1 pu. and for rotor speeds lower than 0.5 pu. the power is set to zero. The limits for the rotor currents are then computed in PSAT as follows:

$$\text{iqr max} = -\frac{Xs+xm}{xm} P_{min} \quad (15)$$

$$\text{iqr}_{min} = -\frac{Xs+xm}{xm} P_{max} \quad (16)$$

$$\text{idr max} = -\frac{Xs+xm}{xm} Q_{min} + \frac{Xs+xm}{xm2} \quad (17)$$

$$\text{idr min} = -\frac{Xs+xm}{xm} Q_{max} + \frac{Xs+xm}{xm2} \quad (18)$$

These limits are carefully selected to ensure a proper dynamic and steady state operation of the model.

The wind is modeled by using the Weibull distribution available in [12], with a shape factor equal to two, which results in a Rayleigh Distribution.

TESTED SYSTEMS

Two systems are used in this study, namely, the IEEE 14 and the IEEE 9 bus systems models. The single line diagram of the IEEE 14 and the IEEE 9 bus systems models are built in PSAT as shown in Figs. 1. and 2., respectively. The IEEE 14 bus system is comprised of five synchronous generators providing active and reactive power to the system connected at buses 1, 2, 3, 6 and 8, three synchronous condensers connected at buses 3, 6, and 8. Automatic voltage regulators (AVR) type II are incorporated in each machine and Turbine governor Type 1 connecting to generators connected at buses 1 and 2. The model for the synchronous generator connected at bus 1 is a 5^{th} order model, and the models for the generators connected at buses 2, 3, 6, and 8 are 6^{th} order models. The IEEE 9 bus system is containing three synchronous generators providing active and reactive power to the system connected at Buses 1, 2, and 3 all generator are 4^{th} order model and incorporate with Automatic voltage regulators (AVR) type II [13]:

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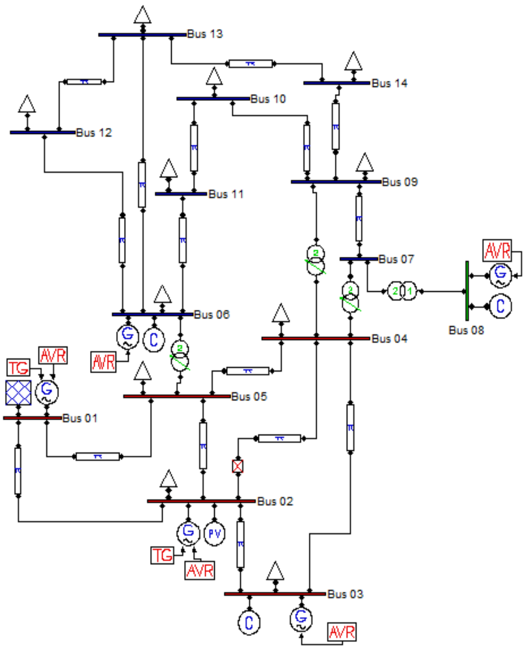

Fig. 1. The IEEE 14 bus system model

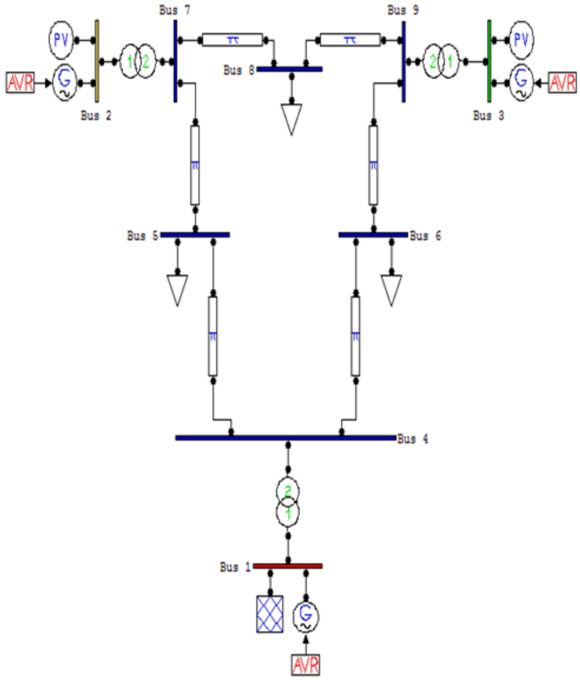

Fig. 2. The IEEE 9 bus system model.

SIMULATION RESULTS

For this study two main cases have been studied, in each case we check the small signal stability of the tested system depending on the value of eigen values of the system which get from the linearization of the differential algebraic equations that describe the dynamic operation of the tested system around the equilibrium points of the power flow calculation as discussed in section three. This cases as follows:

- CASE (A): Represents the base case where all generators in the system are synchronous generator and there is no wind farm based on doubly fed induction generator (WF based on DFIG) in the system.
- CASE (B): Replacing the synchronous generator at buses 2, 3, 6, and 8 one by one for IEEE 14 bus system and buses 2 and 3 for IEEE 9 bus system by WF based on DFIG which have the same MW output of synchronous generators.

NORMAL CASE (A)

In this case, the small signal stability of the tested systems without connecting any WF based on DFIG are computed with positive and zero eigen values of the system with its dominant states as shown in Tables 1 and 2.

Description of the system	Positive Eigen number	Dominant states of Positive Eigen number	Zero Eigen number	Dominant states of Zero Eigen number
No Wind farm	--	--	44	delta of synchronous 1

TABLE1: Eigen values and dominant state of the IEEE 14 bus without WF

Description of the system	Positive Eigen number	Dominant states of Positive Eigen number	Zero Eigen number	Dominant states of Zero Eigen number
No Wind farm	--	--	Eigen number 22 Eigen number 23	Speed of synchronous 1 Delta of synchronous 1

TABLE 2: Eigen values and dominant state of the IEEE 9 bus without WF

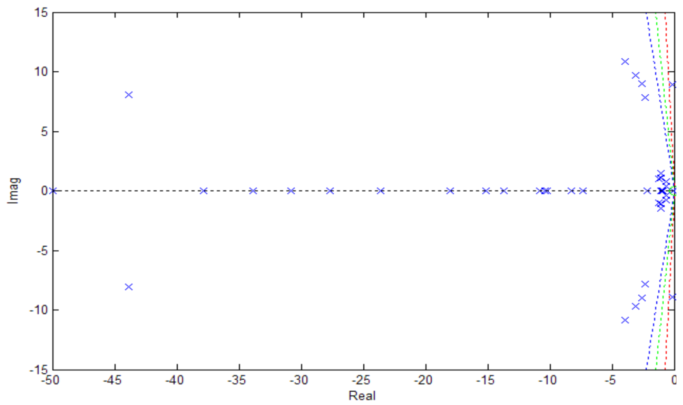

Fig. 3. Distribution of the computed eigen values of the IEEE 14 bus without wind farm

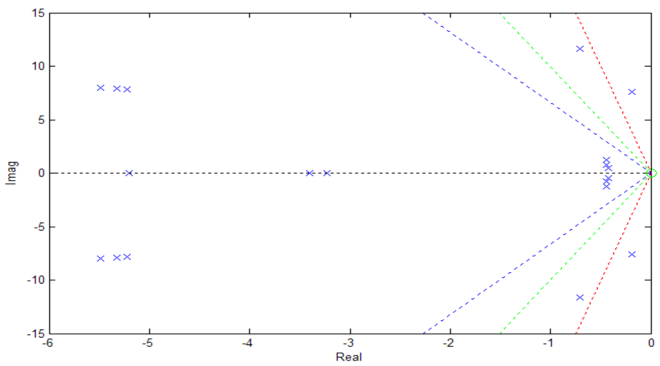

Fig. 4. Distribution of the computed eigen values of the IEEE 9 bus without wind farm.

ANALYSIS OF RESULTS CASE (A)

The simulation results are shown in Fig. 3. and Table 1. The IEEE 14 bus system has 55 eigen numbers all of them are negative except the eigen number λ_{44} is zero value so the system is critically stable. The participation factors associated with the delta of synchronous generator connected at bus1 with this critically stable of the system. Similarly Fig. 4. and Table 2 show the simulation results of the IEEE 9 bus system. It can be shown that the IEEE 9 bus system has 24 eigen numbers. All the eigen numbers are negative except for the eigen number λ_{22} and λ_{23} have zero values so the system is critically stable. The participation factors associated with the delta of synchronous generator connected at bus1 and speed of synchronous generator connected at bus 1 with this critically stable state.

CASE (B)

In this case, the synchronous generator that is connecting at the original tested system is replaced by WF based on DFIG one by one. So the synchronous generator at buses 2, 3, 6, and 8 is replaced by

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WF based on DFIG which have output 60, 60 ,25 and 25 MVA respectively for the IEEE 14 buses system, and replace the synchronous generator at buses 2, and 3 by WF based on DFIG which have output 100 MVA each for the IEEE 9 bus system, then compute the small signal stability of the system in each case with positive and zero eigen values with its dominant state as show in Table 3.

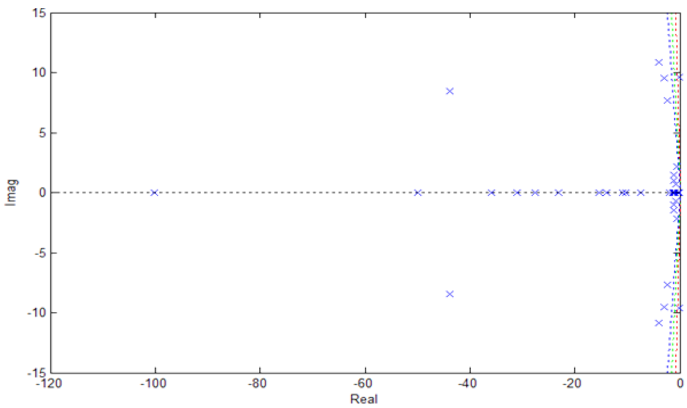

Fig. 5. Distribution of the computed eigen values for case B of the IEEE 14 bus system when WF based on DFIG at bus 2

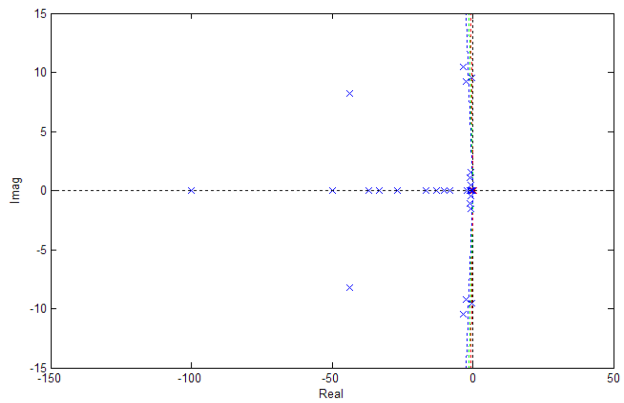

Fig. 6. Distribution of the computed eigen values for case B of the IEEE 14 bus system when WF based on DFIG at bus 3.

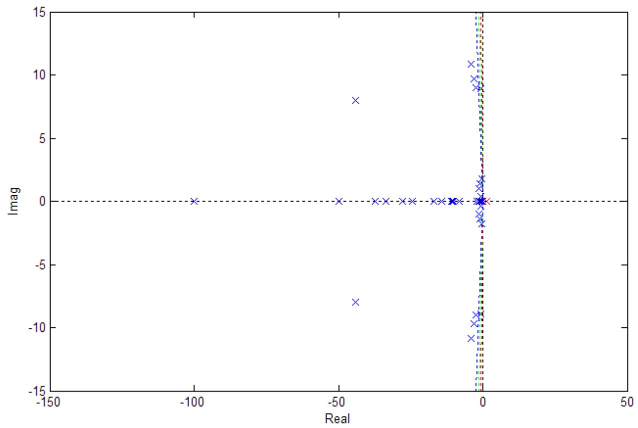

Fig. 7. Distribution of the computed eigen values for case B of the IEEE 14 bus system when WF based on DFIG at bus 6

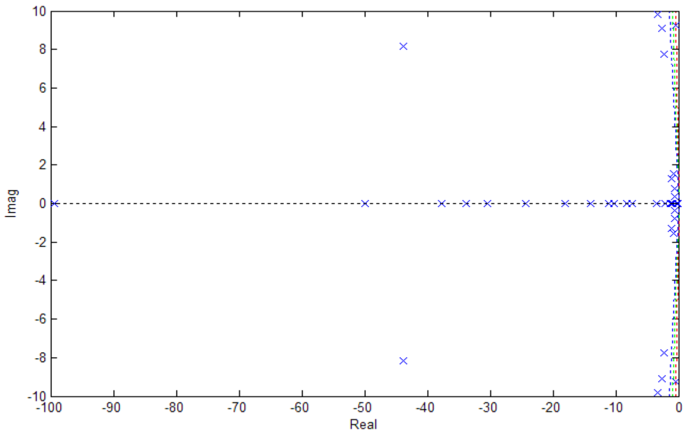

Fig. 8. Distribution of the computed eigen values for case B of the IEEE 14 bus system when WF based on DFIG at bus 8.

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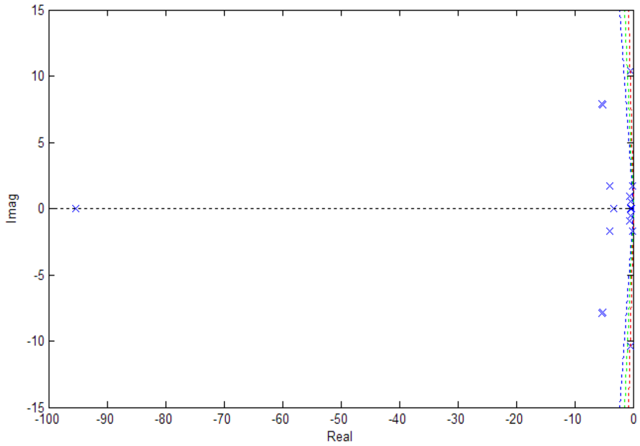

Fig. 9. Distribution of the computed eigen values for case B of the IEEE 9 bus system when WF based on DFIG at bus 2

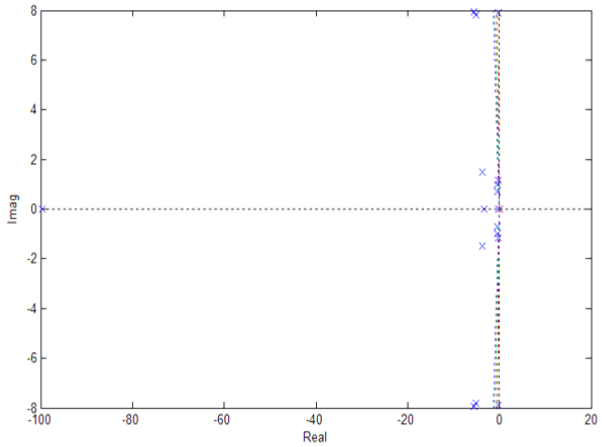

Fig. 10. Distribution of the computed eigen values for case B of the IEEE 9 bus system when WF based on DFIG at bus 3

Description of the system	Positive Eigen number	Dominant states of Positive Eigen number	ZERO Eigen number	Dominant states of ZERO Eigen number
Wind farm at bus 2	--	--	--	--
Wind farm at bus 3	Eigen number 28	Speed of DFIG (Ω)	--	--
Wind farm at bus 6	--	--	--	--
Wind farm at bus 8	Eigen number 25	Speed of DFIG (Ω)	--	--

TABLE 3: Eigen values and dominant state of the IEEE 14 bus system when containing WF based on DFIG

Description of the system	Positive Eigen number	Dominant states of Positive Eigen number	ZERO Eigen number	Dominant states of ZERO Eigen number
Wind farm at bus 2	--	--	--	--
Wind farm at bus 3	Eigen number 14	Speed of DFIG (Ω)	--	--

TABLE 4: Eigen values and dominant state of the IEEE 9 bus system when containing WF based on DFIG

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ANALYSIS OF RESULTS CASE (B)

The simulation results are shown in Figs. 5, 6, 7, 8, and Table 3. It is shown that the IEEE 14 bus system when containing WF has 50 eigen numbers all of them have negative values so the system is stable when WF based on DFIG connected at buses 2 and 6 one by one. Unlike another cases when WF based on DFIG connected at buses 3 and 8 the system is unstable with the participation factors associated with the speed of DFIG connected at buses 3 and 8. The results of the IEEE 9 bus system shown in Figs. 9, 10 and Table 4 show that this system has 21 eigen numbers after connecting WF at one location at bus 2 or bus 3. The system is stable when WF connected at bus 2 but that system is unstable when the synchronous generator at bus 3 is replaced by the same rating of MVA of WF, The participation factors associate the speed of DFIG with this instability of the system.

CONCLUSION

Small signal analysis has been carried out for the IEEE 14 bus system and the IEEE 9 bus system on aspect of inserting the power generated by wind turbines based on DFIG instead of synchronous generator at generation buses one by one at the same power output rating and changing the location of wind farm. The eigen value sensitivity has been used to observe the influence of wind power on the Small signal stability of the system. The results show that wind power integration can have a positive or negative impact on small signal stability of power systems. These impacts depend on the location of the wind farm. In this study, the system is small-signal critically stable when it does not have wind turbines based on DFIG but it is small signal stable when replacing the synchronous generator at some locations, unlike another replacement at other locations, the system is small signal unstable. PSAT is a powerful and practical tool for modeling and analysis of power systems, and a good platform for engineering design and theoretical research.

REFERENCES

[1] T. Ackermann, "Wind Power in Power Systems, England," John Wiley & Sons, 2005.

[2] F. Mei, “Small signal modeling and analysis of doubly fed induction generators in wind power applications,” Ph.D. Thesis 2007, Imperial College London, University of London.

[3] Al. Nunes, “Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated inElectrical Grids,” IEEE Transaction on Energy Cnversion, vol., 19, No, 4, December 2004

[4] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, Wind Energy Handbook. John Wiley & Sons, Ltd, 2001.

[5] B. C. Pal and F. Mei, “Modeling adequacy of the doubly fed induction generator for small-signal stability studies in power systems,” IET Renewable Power Generation, March 2008.

[6] Y. U. López1, J. A. Dominguez, "Small Signal Stability Analysis of Wind Turbines," http://www.researchgate.net, 2015.

[7] H. Weihao, C. Su, Z. Chen, "Impact of Wind Shear and Tower Shadow Effects on Power System with Large Scale Wind Power Penetration," IECON 2011 – 37th Annual conference on IEEE Industrial Electronics Society, PP 878-883.

[8] T. R. Ayodele, A. A. Jimoh , J. L. Munda, J. T. Agee," The Influence of Wind Power on the Small Signal Stability of a Power System", 2008

ISSN 2053-5783(Print), ISSN 2053-5791(online)

[9]. P. Kndur, "Power System Stability and Control," Tata McGraw- Hill Publishing Company Limited-2001, New Delhi.

[10] S. P. Teeuwsen, "Assessment of the Small Signal Stability of Interconnected Electric Power Systems under Stressed Load Flow Conditions by the Use of Artificial Neural Networks," July 2001.

[11] F. Mei and B. C. Pal, "Modelling and small-signal analysis of a grid connected doubly-fed induction generator," in Power Engineering Society General Meeting, 2005. IEEE, 2005, vol. 3, pp. 2101-2108.

[12] F. Milano, "PSAT, Matlab-based Power System Analysis Toolbox," 2014, [Online]. Available: http:// www.power.uwaterloo.ca/~fmilano.

[13] G. Tousraki and B. M. Nomikos "Effect of wind parks with doubly fed asynchronous generators on small-signal stability," Electrical power system research 79 , 2009, pp. 190-200.

[14] G. Ledwich. "Small signal stability analysis of power systems with high penetration of wind power," Power system clean energy (2013) , pp. 241-248.

[15] Bin Sun, Zhengyon He, Yong Jia, Kai Lio "Small-Signal Stability Analysis of Wind Power System Based on DFIG,"energy and power engineering, 2013, 5, pp. 418-422.

[16] B. Liu, H. Guo, G. Go, "Research on Small-Signal Stability of Power System Connected with Different Wind Turbines Based on PSAT," 2014 17th International Conference on Electrical Machines and Systems (ICEMS), Oct. 22-25, 2014, Hangzhou, China.

[17] D. J. Vowles, C. Samarasinghe, M. J. Gibbard, "Effect of Wind Generation on Small-Signal Stability - A New Zealand Example," IEEE, 2008, pp(3-8)

ISSN 2053-5783(Print), ISSN 2053-5791(online)