International Academic Institute for Science and Technology

International Academic Journal of Science and Engineering
Vol. 1, No. 2, 2014, pp.82-95
ISSN 2454-3896

International Academic Journal of Science and Engineering

www.iaiest.com

Evaluation of DFIG placement on small signal stability in multi-machine power systems

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Abstract

Doubly fed induction generator (DFIG) behavior is different from synchronous generators. So, integration this generators with conventional synchronous generators, can make so many challenges for power systems. The most important challenge, can be doubly fed induction generator effect on dynamic and transient stability of power system. In this paper, small signal and transient stability analysis of a two-area power system is investigated that contains conventional synchronous generators and DFIG. Then the effect of DFIG placement in different buses is discussed. At first, small signal stability analysis without power system stabilizer (PSS) is carried, then synchronous generator equipped with PSS. Also, the best place in order to installation of DFIG in power system is determined and transient stability analysis has been done on it. To implementation of simulations, MATLAB software is used.

Keywords: synchronous generator, doubly fed induction generator, automatic voltage regulator, power system stabilizer, small signal stability

Introduction:

In recent years, the approach of using renewable energy instead of fossil fuels have been considered by energy suppliers. Among the various renewable resources, wind power is assumed to have the most favorable technical and economical prospects (S. Heier, 2006). The wind turbine generators (WTGs) are divided into two basic categories: (i) fixed speed and (ii) variable speed. A fixed-speed WTG generally uses a squirrel-cage induction generator to convert the mechanical energy from the wind into electrical energy. DFIG is popular type of variable speed WTGs. Variable speed WTGs can offer increased efficiency in capturing the energy from wind along with better power quality and with the ability to regulate the power factor, than fixed-speed WTGs, by consuming or producing reactive power.

In the DFIG, the rotor is connected to power system through the back-to-back converter, while the stator is connected directly to power system. The control scheme of DFIG decouples the rotational speed of rotor from the grid frequency (Mullerr S. et al, 2006; Bhinal M. et al, 2014). Because of differences between DFIG and synchronous generators behavior, integration of these generators can make many challenges for power system. The most important challenge is dynamic stability of power system.

Dynamic modelling of DFIG for small signal stability presented in [4-8]. Using the proposed model, eigenvalues analysis is down and their participation factor in order to determine the effect of state variable on oscillation modes are calculated. The effect of Proportional-Integral (PI) controllers to adjust the rotor speed reactive power and pitch angle in (Mei Francoise, Pal Bikash, 2005) is investigated. Wind farms effect in a multi-machine power system on oscillation modes are analyzed (J.J Sanchez Gasca et al, 2004). The influences of increasing the load and length of transmission lines and different penetration levels of a constant speed wind turbine generator is studied (Thakur D, Mithulanathan, 2009).

In (Gautam Durga et al, 2011), supplementary control strategy is designed for DFIG power convertors to mitigate the impact of reduced inertia due to significant DFIG penetration in a large power system. Small signal behavior of DFIG in power factor control mode and voltage control mode were extensively analyzed (Tsourakis G. et al, 2009). In order to investigating effect of DFIG control strategies, a complete model is used (Feng We et al, 2006) and the results of eigenvalue and transient stability analysis is shown that by using proper control strategies, the dynamic and transient stability of power system increased. The advanced control capabilities of DFIG are used in (Hughes FM et al, 2005) to enhance network damping via an auxiliary power system stabilizer loop. In (Katrhikeyan Krishnan, Lakshmi ponnusamy, 2014) a method has been proposed base on GSO algorithm for the coordinated synthesis of power system stabilizer (PSS) parameters in multi-machine power system. The results shown that the presence of PSS can effectively enhance the dynamic stability of power system.

The effect of automatic voltage regulator (AVR) and power system stabilizer has been evaluated (Graham J.W Dadegon, 2007) and shows that the presence of AVR and PSS improve transient and dynamic stability of power system, respectively. Optimization algorithms can be used to model and optimize the design of power systems. For example, Jafarian et al., (2016) applied evolutionary algorithm, called MOPSO, to optimize the parameters of a gas turbine. Other evolutionary algorithms, and their applications are summarized and utilized in Tavana et al., (2016), Mobin et al., (2017), and Li et al., (2016).

In this paper, the impact of a wind farm connected to power system in terms of small signal and transient stability been evaluated. At the same environmental conditions, in order to find the best place to install DFIG, small signal stability analysis has been investigated in different places. The results indicate that the presence of DFIG causes dynamic instability of power system. In this paper, to improve the dynamic and transient stability, the use of power system stabilizer is proposed. Eigenvalue and transient analysis indicate the effectiveness of the proposed method for increasing the stability of power system.

Case study:

Two- area and four machine power system as shown in Fig.1 has been considered to evaluate the small signal performance in the presence of DFIG. The system consists of two similar areas connected by a weak tie. Each area consists of two coupled units, each having a rating of 900MVA and 20KV. Any one synchronous generator is replaced by DFIG at a time.

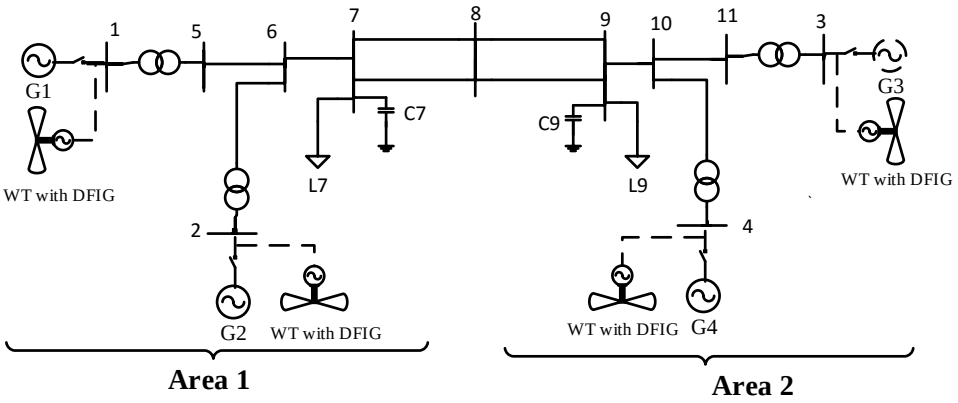


Figure 1: Two area test system

Modelling of DFIG

The schematic of DFIG interfaced with electrical grid is shown in Fig.2. The following assumptions for modelling of DFIG has been considered:

- Stator current is negative when flowing toward the machine; ie. Generator convection is used.
- Equations are derived in the synchronous reference frame.
- q-axis is 90° ahead of the d-axis.

The stator of the induction machine carries three-phase windings. The windings produce a rotating magnetic field which rotates at synchronous speed. The dynamic equations for stator and rotor in d-q references frame rotating at synchronous speed are described in Eqs. (1)-(3) (Krause PC et al,2002; Anaya-Lara O. et al, 2009).

Stator voltage equations:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = R_s \begin{bmatrix} -i_{ds} \\ -i_{qs} \end{bmatrix} + \omega_s \begin{bmatrix} -\varphi_{qs} \\ \varphi_{ds} \end{bmatrix} + \frac{1}{\omega_b} \frac{d}{dt} \begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \end{bmatrix} \tag{1}$$

Rotor voltage equations:

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = R_r \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + S\omega_s \begin{bmatrix} -\varphi_{qr} \\ \varphi_{dr} \end{bmatrix} + \frac{1}{\omega_b} \frac{d}{dt} \begin{bmatrix} \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} \tag{2}$$

Flux equations in terms of stator and rotor currents:

$$\begin{cases} \varphi_{ds} = -X_{ss} i_{ds} + X_m i_{dr} \\ \varphi_{qs} = -X_{ss} i_{qs} + X_m i_{qr} \\ \varphi_{dr} = X_{rr} i_{dr} - X_m i_{ds} \\ \varphi_{qr} = X_{rr} i_{qr} - X_m i_{qs} \end{cases} \tag{3}$$

Where V_{ds} and V_{qs} are d and q-axis stator voltage, respectively. V_{dr} and V_{qr} are d and q-axis rotor voltage. i_{ds} and i_{qs} are d and q-axis stator current. i_{dr} and i_{qr} are d and q-axis rotor currents, respectively.is rotor reactance, X_r is stator reactance, X_s is rotor resistance, R_r stator resistance, is R_s is rotor speed and S is slip. ω_s is magnetization reactance, X_m

The expression for the stator and rotor currents as the state variables are obtained by substituting the flux Eqs.(3) into the stator and rotor voltage Eqs.(1) and (2), respectively.

Wind turbine model for DFIG

In power system studies, wind turbine model is important. The mathematical equation of a one-mass model is given by Eq.(4):

$$\frac{d\omega_r}{dt} = \frac{1}{2H}\left(T_m - T_e\right) \tag{4}$$

Where H is inertia constant in KWs/KVA, T_e and T_m respectively are electromagnetic torque and, mechanical torque as follow:

$$T_e = X_m\left(i_{dr} i_{qs} - i_{qr} i_{ds}\right) \tag{5}$$

$$T_m = \frac{P_w}{\omega_r} \tag{6}$$

Where P_w is the mechanical power extracted from the wind and is as follows:

$$P_w = \frac{\rho}{2} C_p(\lambda, \beta) A_r V_m^3 \tag{7}$$

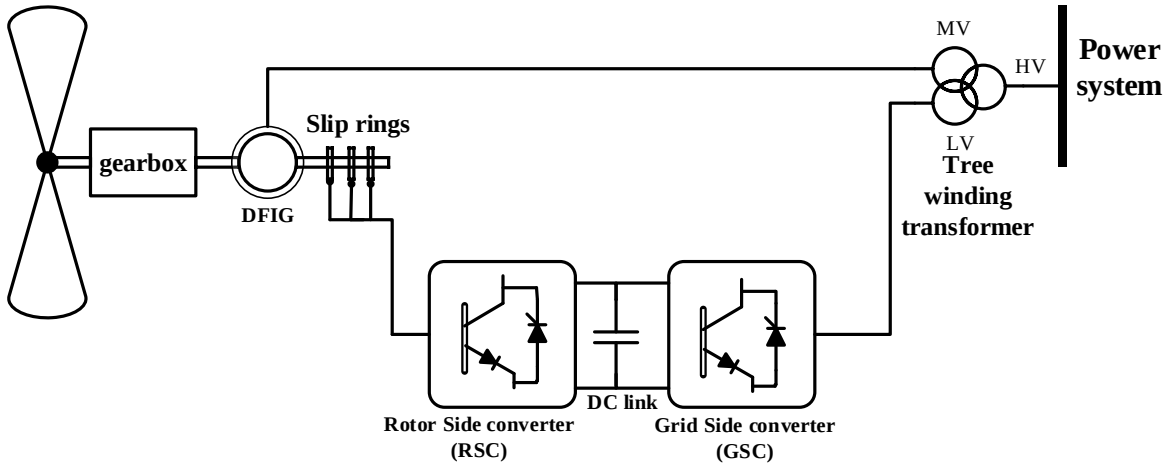


Figure 2: Schematic of DFIG integrated with electrical grid

Where ρ is the air density, V_m is wind speed, β is the pitch angle, A_r is the area swept by the rotor and λ is the blade tip speed ratio. The performance Co-efficient or the power Co-efficient, C_p is as follows:

$$C_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}}$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (8)$$

$C_p(\lambda, \beta)$ has a maximum $C_p^{\max}$ for a particular tip speed ratio, λ_{opt}, and pitch angle $\beta = 0$.

A typical wind turbine characteristics and maximum power point extraction curve is shown in Fig. 3(a). The speed control of the DFIG is achieved by driving the generator speed along the optimum power-speed characteristic curve, as shown in Fig. 3(a) which corresponds to maximum energy capture from the wind. The complete generator torque speed characteristics is shown in Fig. 3(b). When generator speed is less than the low limit or higher than the rated value, the reference speed is set to the minimal value or rated value, respectively. When generator speed is between the lower limit and the rated value, the rotor speed reference can be obtained by substituting λ into Eq.(7) as follows:

$$\lambda = \frac{V_t}{V_w} = \eta_{GB}\frac{2R\omega_r}{PV_w} \quad (9)$$

Where V_t is the blade tip speed, V_w is the wind speed, η_{GB} is the gearbox ratio, P is the number of poles of the induction generator and R is the wind turbine blade radius.

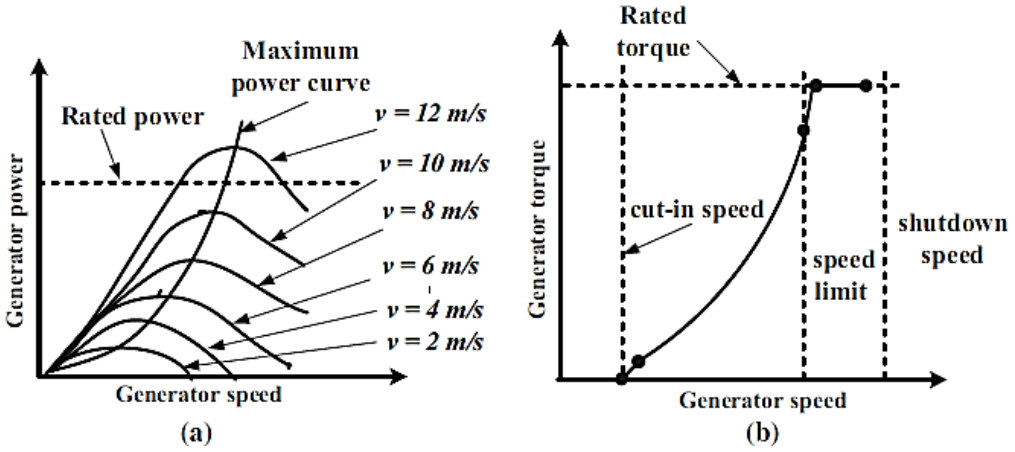


Figure 3: Control strategies for DFIG; (a) characteristic for maximum power point tracking, (b) Control strategies for DFIG

Torque and Voltage Control Scheme

The purpose of the torque controller is to modify the electromagnetic torque of the generator according to wind speed variations and drive the system to the optimal operating point reference. The complete block diagram of torque control scheme is shown in Fig.4.

The voltage control or power factor control at the terminal of DFIG is achieved through the rotor side converter. The terminal voltage will increase or decrease with the change in reactive power delivered to the grid. The voltage controller should fulfil the following requirements in such a situation:

- The reactive power consumed by the DFIG should be compensated.
- If the terminal voltage is too low or too high compared with the reference value, then i_{dr-ref} for d-axis rotor current should be adjusted appropriately.

The complete block diagram of the DFIG terminal voltage controller is shown in Fig.5. All the variables shown in the block diagram are in per unit (Bhinal Mehta et al, 2015).

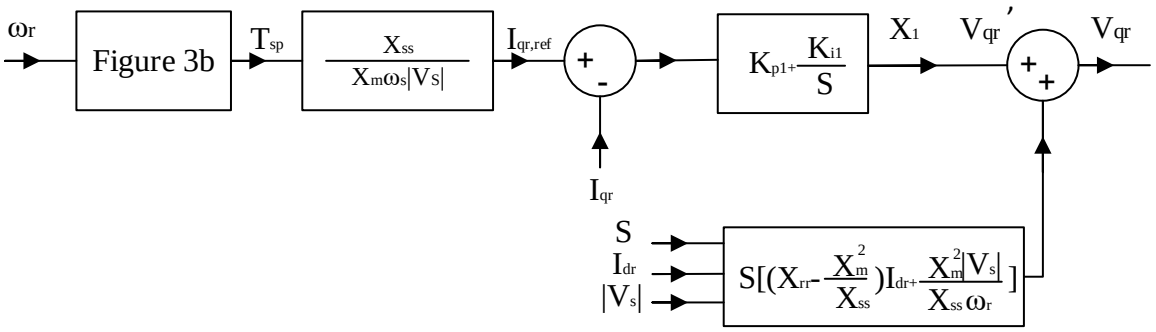


Figure 4: Torque control scheme

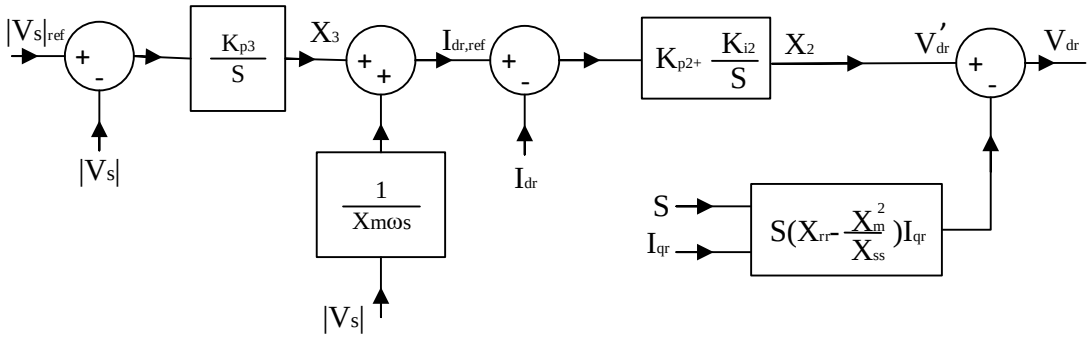


Figure 5: Voltage control scheme

Modelling of power system stabilizer

In order to damping oscillations of power system, PSS applying additional signals to the excitation system or AVR. The deviation rotor speed (Δω), frequency, terminal voltage and oscillating power are the most common input signal for PSS. The block diagram of power system stabilizer and automatic voltage regulator is shown in Fig.6. where K_{stab} is the controller gain, T_w is a washout time constant (s) and T_1 to T_4 are lead-lag time constants (s). AVR and PSS parameters for each generator should be selected to ensure that system performance under a wide range of operating conditions is appropriate.

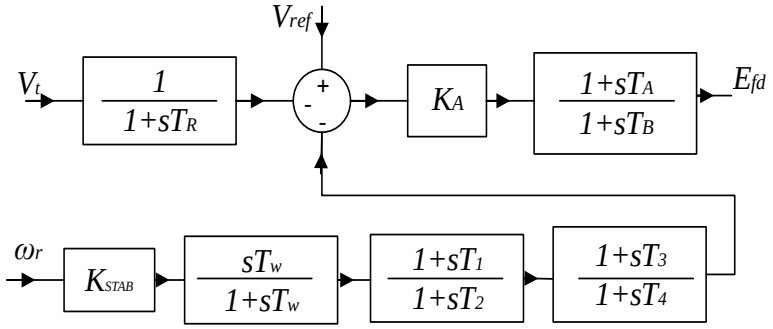


Figure 6: Block diagram of AVR and PSS

Small signal stability

The small signal stability and the dynamic performance of power system are related to the damping of the electromechanical modes of oscillation. This oscillatory behavior is associated fundamentally with (i) the variation in electrical torque developed by synchronous machines as their rotor angles change, (ii) the inertia of their rotors. The frequencies associated with these modes of oscillation are typically in the range from 0.5 to 4 Hz.

Modes of oscillations

Electromechanical modes of oscillation consist of local area mode and inter-area mode, which having frequency range of 0.8-2Hz and 0.2-0.8 Hz, respectively. Small signal stability requires that these modes should be adequately damped. The presence of PSS greatly influence the damping of these modes and can be assessed by means of eigenvalue analysis. The eigenvalue analysis can be carried out by linearizing the system about an operating point and representing it in state space form. For stability, all of the eigenvalues must lie in the left half complex plane. Any eigenvalue in right half plan denotes an unstable dynamic mode and system instability. The damping contribution provided by any means shifts the location of the eigenvalues associated with the dominate oscillatory modes to the left half of the plane.

Eigenvalues computation

The behavior of a power system, can be described by the complete set of n-first order non-linear ordinary differential and algebraic equations. The differential and algebraic of synchronous generators are given in (P. Kundur et al, 1994).

$$\dot{x} = f(x, z, u) \tag{10}$$

$$o = g(x, z, u) \tag{11}$$

Where x, z and u are state, algebraic and input variables. f and g are differential and algebraic vectors. In eigenvalue analysis Eqs.(10) and (11) linearized about an operating point. Finally, the poles of system are the roots of the characteristic equations given by:

$$\det(SI - A) = 0 \tag{12}$$

Above equation can be written as characteristic equation:

$$\det(A - \lambda I) = 0 \tag{13}$$

The value of λ which satisfy the characteristic equations, are known as the eigenvalues of matrix A. the number of eigenvalues are equal to the number of first-order differential equation. Eigenvalues may be real or complex as shown:

$$\lambda_i = \alpha_i \pm j\beta_i \tag{14}$$

For a given eigenvalue, frequency and damping ratio of oscillation can be calculated by using the following expressions:

$$f_i = \frac{\beta_i}{2\pi} \tag{15}$$

$$\zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}} \tag{16}$$

Results and discussions

As already mentioned, the power system shown in Fig.1 is used for evaluation of small signal stability. In order to determine the best location for the replacement of DFIG with signal stability. In order to

determine the best location for the replacement of DFIG with synchronous generators, eigenvalue analysis for two following cases was evaluated.

- Case 1: The remaining synchronous generators are without power system stabilizer.
- Case 2: The remaining synchronous generators are equipped with power system stabilizer.

The result of eigenvalue analysis for case1 is shown in Fig.7 and dominant eigenvalues, frequency and damping ratio of oscillations are shown in table1.

Table1: Dominant eigenvalues for case 1

	Eigenvalue	**Frequency of oscillation (in Hz)**	**Damping ratio (%)**
Location of DFIG: Bus 1	-1.704±j25.15 -0.3534±j10.05 3.12±j4.742 -0.0423+0j 5.716+0j	4.003 1.6 0.75 0 0	6.67 3.51 -54.97 100 -100
Location of DFIG: Bus 2	-2.663±j28.75 -0.2154±j8.491 -1.52±j7.673 -9.597±j0.6726 10.66+0j 0.3762+0j 3.254+0j	4.575 1.35 1.22 0.1 0 0 0	9.22 2.53 19.43 99.76 -100 -100 -100
Location of DFIG: Bus 3	-3.128±j23.31 -0.3495±j9.899 2.644±j4.731 -5.171±j0.7703 6.576+0j -0.09488+0j	3.7 1.575 0.75 0.122 0 0	13.3 3.53 -45.78 98.87 -100 100
Location of DFIG: Bus 4	-0.3579±j9.801 -0.3591±j7.203 -5.092±j16.67 -0.1339±j0.421 4.43+0j 1.442+0j	1.56 1.146 2.65 0.064 0 0	3.65 4.98 29.21 30.43 -100 -100

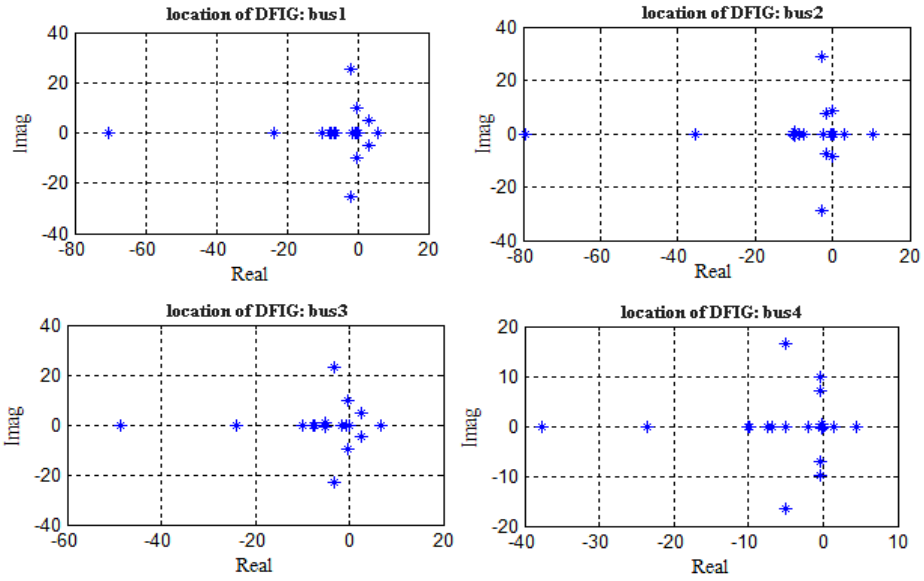


Figure 7: Plot of eigenvalue for case 1

The results reveal that the replacement of the synchronous generator by DFIG at any bus make the system dynamically unstable. To making the system stable, the synchronous generators equipped with PSS. The plot of obtained eigenvalues for case 2 is shown in Fig.8 and dominant eigenvalues are listed in table2.

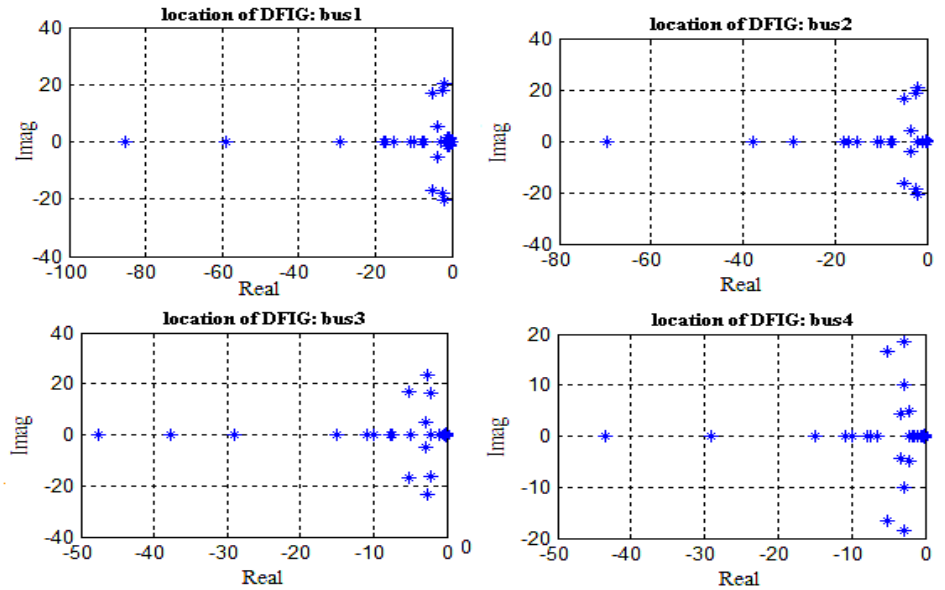


Figure 8: Plot of eigenvalue for case 2

Table2 : Dominant eigenvalues for case 2

	Eigenvalue	Frequency of oscillation (in Hz)	Damping ratio (%)
Location of DFIG: Bus 1	-2.393±j17.79	2.8314	13.33
	-2.154±j20.15	3.207	10.63
	-5.065±j16.92	2.694	28.68
	-3.537±j5.162	0.821	56.53
	-0.583±j1.258	0.2	42.06
	-0.973±j1.4	0.2228	57.23
	-0.2074±j0.074	0.012	94.27
Location of DFIG: Bus 2	-2.165±j20.86	3.32	10.32
	-2.289±j18.77	3.987	23.15
	-5.092±j16.67	2.653	29.21
	-3.339±j4.302	0.645	61.32
	-0.1992±j0.1749	0.027	75.16
	-0.2581±j0.3227	0.05	62.45
Location of DFIG: Bus 3	-2.557±j23.57	3.75	10.79
	-2.204±j16.18	2.57	13.5
	-5.092±j16.67	2.65	29.21
	-2.791±j4.626	0.73	51.68
	-0.1339±j0.302	0.048	40.57
	-0.2753±j0.3234	0.05	65.54
Location of DFIG: Bus 4	-2.756±j10.06	3.06	26.42
	-2.89±j18.44	2.93	15.48
	-2.253±j4.93	0.78	41.56
	-7.461±j0.01997	0.003	99.99
	-0.1671±j0.2208	0.035	60.35
	-5.092±j16.67	2.65	29.21
	-3.339±j4.302	0.68	61.31

The results clearly indicate that by equipping the synchronous generators with PSS, dynamic stability of power system improved. By comparing the results of DFIG installed on different buses, it can be concluded that by DFIG placement at bus 4, the best dynamic stability of power system is obtained. By considering DFIG at bus 4, transient analysis is done. For this purpose a disturbance of three-phase fault for the duration of 0.25sec was created at time, t=5s, at bus 8. For case 1, the transient response of rotor speed of all generators are depicted in Fig9. It is clearly seen that in this case, the system dynamically is

unstable. For case 2, the transient responses of rotor speed and angle of generators are shown in Figs 10 and 11, respectively.

The results of transient analysis are consistent with the results of eigenvalue analysis and reveal that the PSS play a vital role to improve the dynamic and transient stability of power systems.

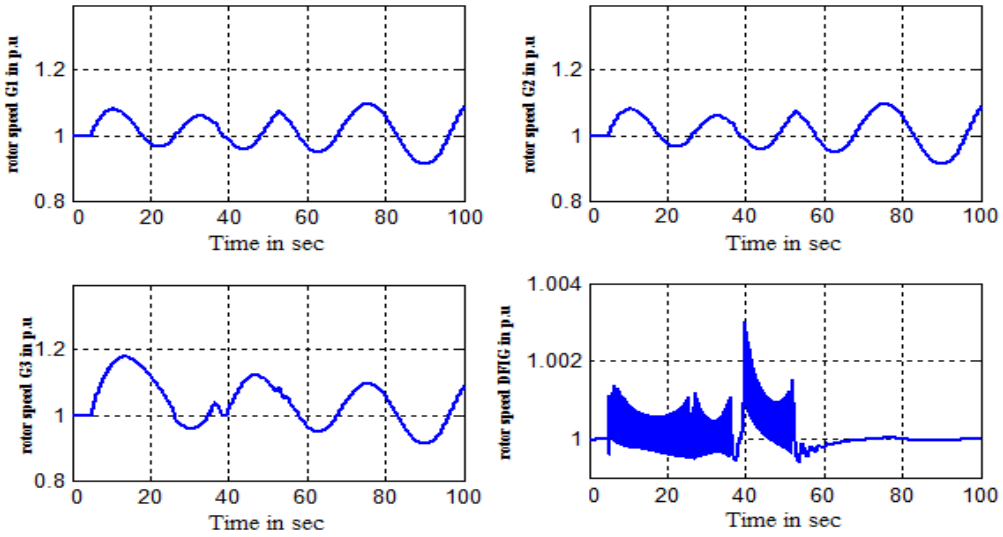


Figure 9: Transient responses for rotor speed of all generator for case1

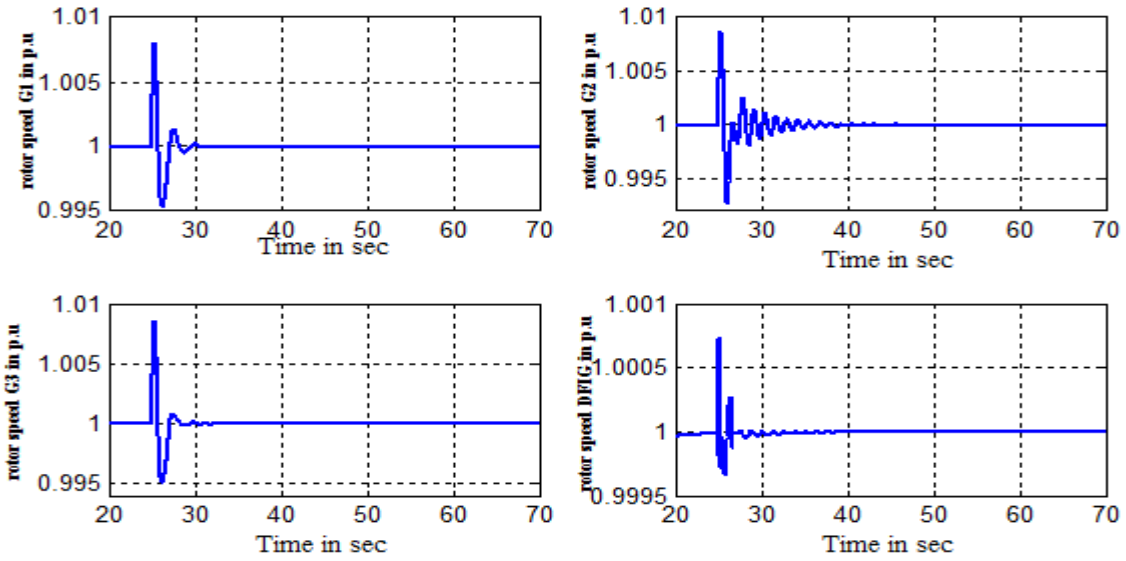


Figure 10: transient response for rotor speed of all generator for case2

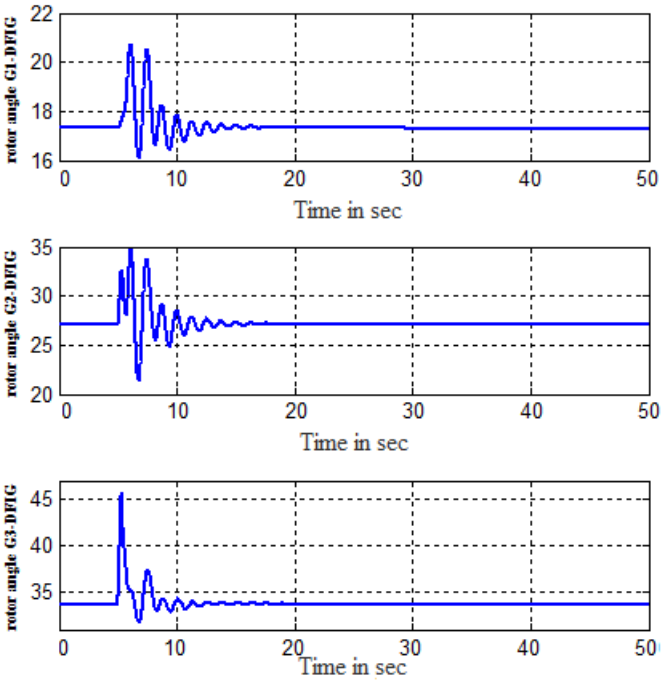


Figure 11: Transient response for rotor angle of generators for case 2

Conclusion:

Since the behavior of DFIG is different from conventional synchronous generator, So integration wind turbines based-DFIG, affect the dynamic and transient stability of power system. In this paper, a comprehensive assessment of DFIG in power system is provided. Furthermore, impact of DFIG placement is investigated. The result reveal that the replacement of the synchronous generator by DFIG at any bus, makes the system dynamically unstable. To make the system stable, the synchronous generators equipped with PSS. The eigenvalue results show that the PSS increase the damping ratio of oscillation modes and as a result increase the dynamic and transient stability of power system. At future work it is suggest that to increase the damping ratio of oscillating modes, the power system stabilizer used in DFIG control schemes. To adjust the parameters of proposed PSS, optimization algorithms can be used so that the stability of power system will be increased.

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