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Small Signal Stability of Power System with SCIG, DFIG Wind Turbines

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***Abstract*— Voltage stability issue is a key problem which attracting worldwide attention because voltage stability may leads to voltage collapse. This paper investigates the impact of Squirrel Cage induction generator (SCIG) and Doubly Fed Induction Generator (DFIG) on the power system small signal stability. Here considered wind generators are SCIG which is fixed speed and DFIG is variable speed. Small signal stability study has been conducted on a modified IEEE 14 bus system with SCIG, DFIG wind turbine systems and their simulation results have been analyzed in this paper. Fixed speed wind generators are more simple to operate and reliable but they are limited as energy output of a wind turbine and stability issues are consider. Variable speed wind generators of similar rating improve stability of the system. All these modeling's, simulations have been done in Power system Analysis Toolbox (PSAT), which is a MATLAB based toolbox to evaluate power system.**

Keywords*— *Small Signal Stability; Wind turbine; SCIG; DFIG; DDSG; PSAT

I. INTRODUCTION

Wind energy is abundant in nature and pollution frees [1]. In recent days, wind power generation has been increasing continuously. Currently fixed speed and variable speed induction generators are using for wind power generation. Integration of a wind power into grid arise issues like voltage stability, transient stability problem, also due to dependence on weather conditions [2]. Power system stability is depending on parameters belongs to turbines, generators, governors. They affect both small signal stability and transient stability. In [3] the authors investigate multilayered neural networks to determine the transient stability of power system using PSAT software. In [4] doubly fed induction generator modeling and its converter design for stability studies have been discussed. Dynamic modeling of DFIG wind turbine and its controller's description to improve transient stability of system has been discussed in [5]. Analyzing the different types of wind turbines and their technology, design issues, advantages, disadvantages have been discussed. Comparisons among different wind turbines based on their performance, cost are presented and their market share in present day world also included [6, 7]. Voltage stability can be enhanced by using static compensator. Voltage profile variation under different load condition can be controlled by static compensator (STATCOM) [8, 9]. In [10] impacts of wind power on power systems voltage and transient stability have been discussed. Effect of fixed and variable speed grid connected induction generators on power system voltage stability is discussed and it is also observed that integration of large scale wind power into the transmission network has the potential to improve voltage stability of grid by injecting the reactive power in to it [11, 12]. In [13] the authors investigate the modeling and transient stability analysis of wind power integrated modified IEEE 14 bus system. In [14] a comparison is made among 3 main type of wind turbines such as constant speed wind turbine (CSWT), Doubly Fed Induction Generator (DFIG), Direct Drive Synchronous Generator (DDSG) and their transient characteristics were analyzed and simulated in a fault applied network. Small signal stability of the system with Squirrel Cage Induction Generator (SCIG) has been discussed in [15] using PSAT and the location of Eigen values represent small signal stability. DFIG behavior for grid disturbances is simulated and experimental verification also done in [16]. In [17] different rotor current control methods of DFIG wind turbines and role of converter to design DFIG are presented. Nordic grid model implemented using PSAT and it is also validated through time domain simulation by applying small and large disturbances in [18]. DFIG, SCIG, PMSG wind turbine configurations, simulations, power quality issues and their technical comparisons are included in [19]. In [20] a new control method is proposed to improve SCIG wind turbine performance at all operating regions and its mathematical model is described.

This paper investigates small signal stability of three different wind generator configurations when connected to modified IEEE 14 bus system. This paper also introduced mathematical modeling of these wind generators in section II. SCIG, DFIG based IEEE modified 14 bus systems are simulated using PSAT [21] are shown in III. All these simulation work has done in PSAT software version 2.1.8. After simulations all results are compared and analyzed in section IV, concluded in V.

II. SMALL SIGNAL STABILITY

In this section small signal stability of the system has been analyzed. It is defined as the capability of a power system to retain to its original stable state after subjected to a small disturbance which leads to a small incremental change in

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power system state variables. In other words the system's response to a small disturbance in power system state variables.

PSAT based Eigen value analysis has been done to determine small signal stability of the system. Here correlation between Eigen values and power system dynamics is discussed. For this, a liberalized model is developed to find out the correlation between Eigen values, steady state matrix and time domain simulation. State space equation and output equation is given by

$$\dot{X}(t) = f(x,u,t) \tag{1}$$

$$y(t) = g(x,u,t) \tag{2}$$

Where equation 1 has all state variables such as 'u' is the input variables, 't' is the time and 'y'is the output function. The linearization of above 2 equations will help to study the response to small variations. In order to obtain this, polynomial equations are developed using Taylor's series formula where higher order terms are neglected. Linear combination of system is presented as

$$\begin{aligned} \dot{X} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{3}$$

Here A, B, C and D are obtained from the Jacobean matrix which contains partial derivates of the functions in terms of 'f' and 'g' respectively to the input variable 'u' and the state variable X .

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} \quad D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r} \end{bmatrix}$$

Where A , B , C and D are state matrix, input matrix, output matrix and coefficient matrix respectively. In order to find linearized state equation in frequency domain these matrices have to be transformed using Laplace transform. Finally Eigen values will obtain after below equation has satisfied [15].

$$\det(sI - A) = 0 \tag{4}$$

A. Modeling of SCIG Wind turbine

SCIG equations are developed with respect to real (r) and imaginary (m) axis in terms of network reference angle. In synchronous rotating frame of reference, the relation between the stator machine voltage and the network is

$$\begin{aligned} v_r &= V\sin(-\theta) \\ v_m &= V\cos(\theta) \end{aligned} \tag{5}$$

And the absorbed power is given by

$$\begin{aligned} P &= v_r i_r + v_m i_{qm} \\ Q &= v_m i_r - v_r i_m + b_c\left(v_r^2 + v_m^2\right) \end{aligned} \tag{6}$$

Where b_c is the fixed capacitor conductance. The voltage differential equations which were behind the stator resistance r_s is given by:

$$\begin{aligned} e_r^{'} - v_r &= r_S i_r - x^{'} i_m \\ e_m^{'} - v_m &= r_S i_m + x^{'} i_r \end{aligned} \tag{7}$$

The relation between currents, voltage and state variables is as follows:

$$\begin{aligned} \dot{e}_r^{'} &= \Omega_b(1-\omega_m)e_m^{'} - \left(e_r^1 - \left(x_0 - x^{'}\right)i_m\right)/T_0^{'} \\ \dot{e}_m^{'} &= -\Omega_b(1-\omega_m)e_r^{'} - \left(e_m^1 - \left(x_0 - x^{'}\right)i_r\right)/T_0^{'} \end{aligned} \tag{8}$$

Here x_0, $x^{'}$ and T_0 are calculated from the generator parameters.

$$\begin{aligned} x_0 &= x_s + x_m \\ x^{'} &= x_S + \frac{x_R x_m}{x_R + x_m} \\ T_0^{'} &= \frac{x_R + x_m}{\Omega_b r_R} \end{aligned} \tag{9}$$

The differential equations in terms of mechanical parameters such as rotor inertia H_m, turbine inertia H_{wr} and shaft stiffness K_s is given by

$$\begin{aligned} \dot{\omega}_{wr} &= (T_{wr} - K_s\gamma)/(2H_{wr}) \\ \dot{\omega}_m &= (K_s\gamma - T_e)/(2H_m) \\ \dot{\gamma} &= \Omega_b(\omega_{wr} - \omega_m) \end{aligned} \tag{10}$$

Where Te (electrical torque) is given by

$$T_e = e_r^{'} i_r + e_m^{'} i_m \tag{11}$$

The mechanical torque is:

$$T_{wr} = \frac{P_w}{\omega_{wr}} \tag{12}$$

Here Pw is the mechanical power extracted from wind. Wind and the rotor speeds are related as

$$P_w = \frac{\rho}{2} c_p(\lambda) A_r v_w^3 \tag{13}$$

ρ = air density

Cp= Rotor power coefficient

λ = Tip speed ratio

A_r = Area of cross section of rotor

v_w = Wind speed

B. *Modeling of DFIG Wind turbine*

This particular section focused on mathematical modeling of DFIG. Doubly fed induction generator steady state electrical equations are assumed, the flux dynamics of stator and rotor are fast in comparison with grid dynamics and the generator decoupling from the grid can be done by the converter control mechanism. These assumptions lead to

$$\begin{aligned} v_{ds} &= -r_S i_{ds} + \left((x_S + x_m) i_{qs} + x_m i_{qr}\right) \\ v_{qs} &= -r_S i_{qs} - \left((x_S + x_m) i_{ds} + x_m i_{dr}\right) \\ v_{dr} &= -r_R i_{dr} + (1-\omega_m)\left((x_R + x_m) i_{qr} + x_m i_{qs}\right) \\ v_{qr} &= -r_R i_{qr} - (1-\omega_m)\left((x_R + x_m) i_{dr} + x_m i_{ds}\right) \end{aligned} \tag{14}$$

Where the stator voltage depends on both grid voltage magnitude and phase:

$$\begin{aligned} v_{ds} &= V \sin(-\theta) \\ v_{qs} &= V \cos(\theta) \end{aligned} \tag{15}$$

The injected active and reactive power in to the grid depends on both stator current and grid side current of the converter. Finally equations are as follows:

$$\begin{aligned} P &= v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dc} i_{dc} + v_{qc} i_{qc} \\ Q &= v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qc} i_{dc} - v_{dc} i_{qc} \end{aligned} \tag{16}$$

This can be rewrite by considering converter power equations which are shown below. Grid side converter powers are:

$$\begin{aligned} P_c &= v_{dc} i_{dc} + v_{qc} i_{qc} \\ Q_c &= v_{qc} i_{dc} - v_{dc} i_{qc} \end{aligned} \tag{17}$$

Rotor side powers are

$$\begin{aligned} P_r &= v_{dr} i_{dr} + v_{qr} i_{qr} \\ P_r &= v_{qr} i_{dr} - v_{dr} i_{qr} \end{aligned} \tag{18}$$

Now, if we assume converter is loss less and a unity power factor on the grid side of the converter then:

$$\begin{aligned} P_c &= P_r \\ Q_c &= 0 \end{aligned} \tag{19}$$

Finally injected power into the grid

$$\begin{aligned} P &= v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dr} i_{dr} + v_{qr} i_{qr} \\ Q &= v_{qs} i_{ds} - v_{ds} i_{qs} \end{aligned} \tag{20}$$

In generator, motion equation single shaft model is used and it is assumed that converter controls can be able to filter shaft dynamics. For this reason, tower shadow effect is not considered. So

$$\dot{\omega}_m = (T_m - T_e)/2H_m$$

$$T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \tag{21}$$

The relation between generator currents, stator flux is given as:

$$\begin{aligned} \psi_{ds} &= -\left((x_S + x_m) i_{ds} + x_m i_{dr}\right) \\ \psi_{qs} &= -\left((x_S + x_m) i_{qs} + x_m i_{qr}\right) \end{aligned} \tag{22}$$

Thus the electrical torque Te is given by

$$T_e = x_m \left(i_{qr} i_{ds} - i_{dr} i_{qs}\right) \tag{23}$$

And the mechanical torque, extracted mechanical power equations are same as mentioned in SCIG.

C. *Wind Model*

In this paper Weibull distribution wind speed model with nominal wind speed as 15m/s is used. Representation of Weibull distribution is as follows:

$$f(v_w, c, k) = \frac{k}{c^k} v_w^k e^{-\left(\frac{v_w}{c}\right)^k} \tag{24}$$

Here v_w is the wind speed and C, K are constants whose values are 20, 2 respectively. Wind speed $v_w(t)$ variation in terms of Weibull distribution is

$$v_w(t) = \left(-\frac{\ln e(t)}{c}\right)^{\frac{1}{k}} \tag{25}$$

Generally c value varies from 1 to 10 and k value is greater than 3 [21].

III. SIMULATED SYSTEMS

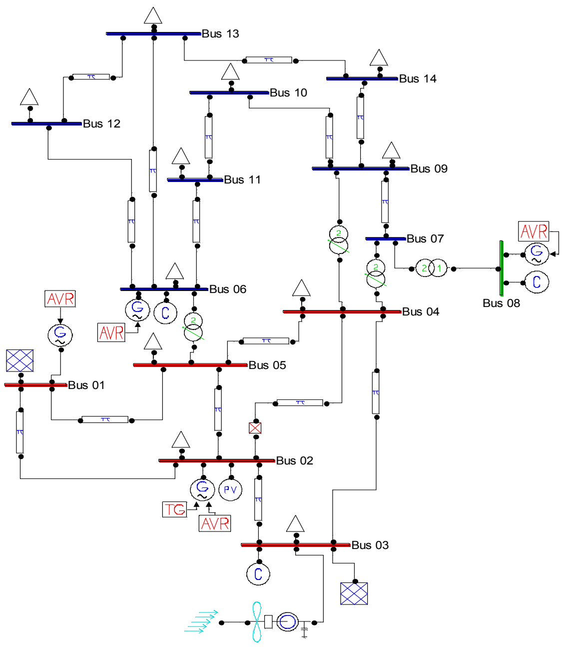

Fig. 1. SCIG connected to modified IEEE14 bus system

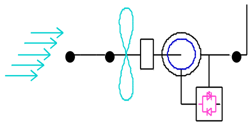

Fig. 2. DFIG connected to modified IEEE14 bus system

Based on above mentioned mathematical modeling analysis, simulation of modified IEEE 14 bus system which is based on PSAT has been built as follows. At bus number 3, both SCIG and DFIG wind turbines are connected as shown in figures Fig. 1 and Fig. 2 respectively. Taking the results by connecting DFIG at bus number 3 has no particular importance, it has been chosen randomly since at any bus the results may be same. Similar results may appear if DFIG is connected at other busses.

IV. Simulation Results & Discussions

The impact of wind turbines on power system lead to a small signal stability problem. In SCIG based systems, all poles (Eigen values) lie within the unit circle except one pole, that lie on the circumference of the circle which is shown in Fig. 3. This shows that system is marginally stable. In DFIG based system all poles lie within the unit circle as shown in Fig. 4, so system is completely stable as small signal stability is considered. For further clarification, complete statistics of SCIG, DFIG based systems regarding small signal stability are given below with Z domain analysis (graphical representation) of individual systems. System stability depends upon the Eigen values location.

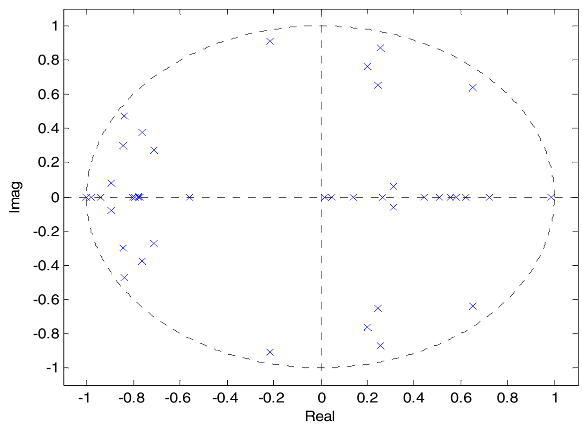

Fig. 3. Z Domain analysis graphical representation of modified IEEE14 bus system with SCIG

STATISTICS

DYNAMIC ORDER	49
EIGS WITH Re(mu) < 0	22
EIGS WITH Re(mu) > 0	27
REAL EIGS	25
COMPLEX PAIRS	12
ZERO EIGS	0

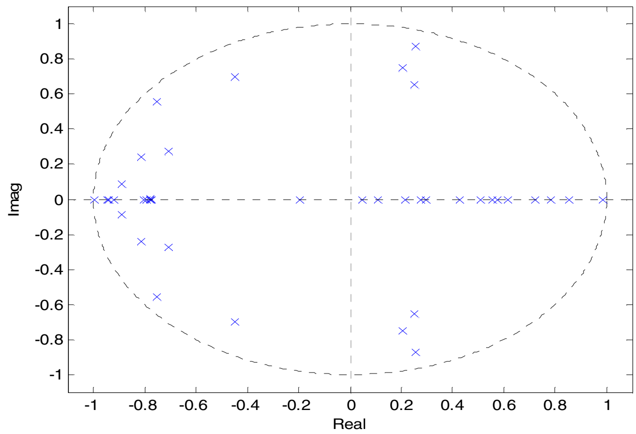

Fig. 4. Z Domain analysis graphical representation of modified IEEE14 bus system with DFIG

STATISTICS

DYNAMIC ORDER	48
EIGS WITH Re(mu) < 0	22
EIGS WITH Re(mu) > 0	26
REAL EIGS	30
COMPLEX PAIRS	9
ZERO EIGS	0

Here small signal stability problems that have been discussed are rotor angle stability, bus angles variation and their simulations results have shown above. In case of SCIG rotor angles are deviated as shown in Fig. 5, by which the system is said to be near to instability. Where as in case of DFIG rotor angles (Power angle) are almost constant with time (in Fig. 6.) by which we can conclude that system is completely stable. Coming to bus angles at individual buses, SCIG based systems having deviations but DFIG based systems deviations are very less when compared to SCIG as shown in figures Fig. 7 and Fig. 8 respectively. From the above simulation results it is clear that DFIG based system is more suitable to integrate into power system for wind power generation than SCIG system as power system small signal stability is consider.

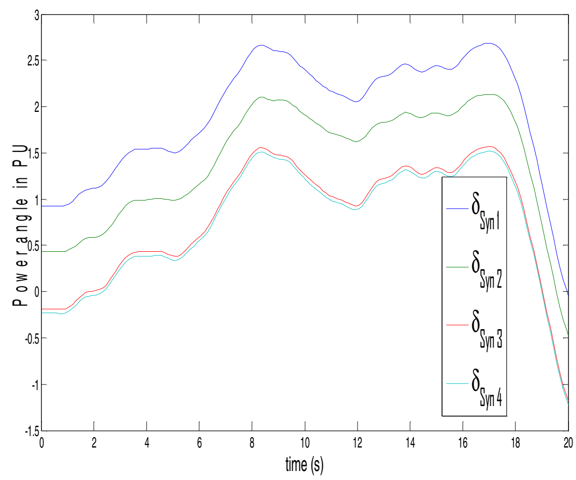

Fig. 5. Rotor angle deviations of modified IEEE14 bus system with SCIG

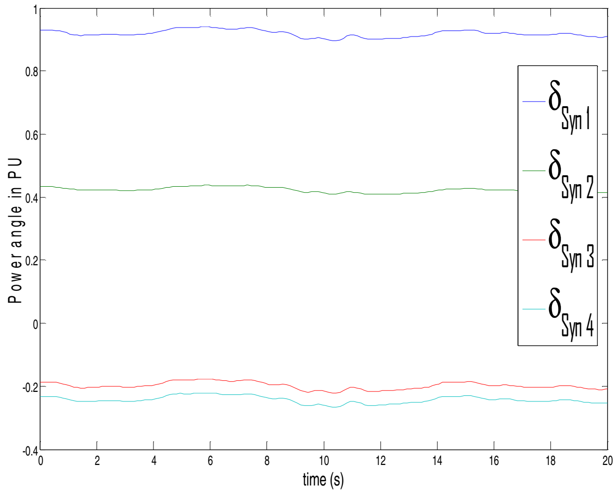

Fig. 6. Rotor angle deviations of modified IEEE14 bus system with DFIG

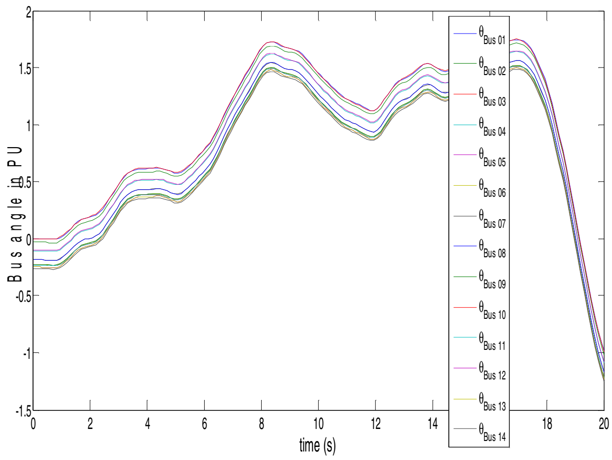

Fig. 7. Bus angle variations of modified IEEE14 bus system with SCIG

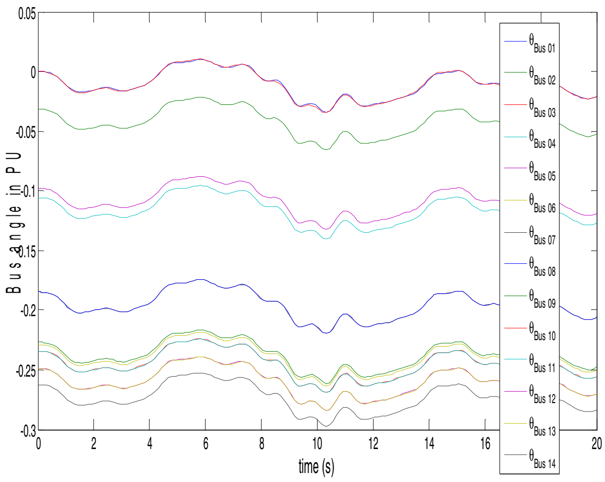

Fig. 8. Bus angle variations of modified IEEE14 bus system with DFIG

V. CONCLUSION

In this paper modified IEEE14 bus system is used and its small signal stability is investigated after injecting wind power with SCIG and DFIG wind turbines. Simulation results show that SCIG based system is marginally stable where as DFIG based system is completely stable and rotor angle stability, angular stability of DFIG is more predominant than SCIG. SCIG consisting of a fixed capacitor which may not sufficient to meet reactive power demand by the system. Where, DFIG consists of power electronics based controlling system and rotor side control mechanism. These two inherent controlling techniques help to maintain reactive power in the system and thereby it can improve small signal stability of the system.

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