# Transient Stability Analysis of Power System with Grid Integration of Wind Generation

D. Rakesh Chandra, F. Grimaccia, M. Sailaja Kumari, M. Sydulu, M. Mussetta

## Nomenclature

| | |
|---|---|
| $H_m$ | Rotor Inertia |
| $H_{wr}$ | Turbine inertia |
| $i_r$ | Current w.r.to real axis |
| $i_m$ | Current w.r.to imaginary axis |
| $i_{ds}$ | d- axis stator current |
| $i_{dc}$ | d- axis converter current |
| $i_{qc}$ | q- axis converter current |
| $i_{qs}$ | q- axis stator current |
| $K_s$ | Shaft Stiffness |
| $P$ | Active Power |
| $P_r$ | Rotor side active power |
| $P_w$ | Mechanical Power |
| $Q$ | Reactive power |
| $Q_r$ | Rotor side reactive power |
| $r_s$ | Stator Resistance |
| $T_e$ | Electrical torque |
| $T_{wr}$ | Mechanical torque |
| $V_r$ | Voltage w.r.to real axis |
| $V_m$ | Voltage w.r.to imaginary axis |
| $V_{ds}$ | d- axis stator voltage |
| $V_{qs}$ | q- axis stator voltage |
| $V_{dr}$ | d- axis rotor voltage |
| $V_{qr}$ | q- axis rotor voltage |
| $V_{qc}$ | q- axis converter voltage |
| $V_{dc}$ | d- axis converter voltage |
| $x_0$ | Total reactance |
| $x_s$ | Stator reactance |
| $x_m$ | Magnetizing reactance |
| $\psi_{ds}$ | d- axis stator flux linkage |
| $\psi_{qs}$ | q- axis stator flux linkage |

## I. Introduction

Wind energy is abundant in nature and pollution free. In recent days, wind power generation has been increasing continuously worldwide. Currently fixed speed and variable speed induction generators are used for wind power generation.

Thus integration of wind power into grid raises issues like voltage stability, transient stability. Power system stability depends on parameters which belong to turbines, generators and control systems.

They affect both small signal stability and transient stability [1].

Investigated using a multilayered neural network to determine the transient stability of power system using PSAT software. In [2] modeling and design of a doubly fed induction generator and its converter have been discussed for stability issues. Dynamic modeling of DFIG wind turbine and its controller's description to improve transient stability of system has been discussed in [3]. Analysis of different types of wind turbines and their technology, design issues, advantages and disadvantages have also been described. Comparison of different wind turbines based on their cost-performance is presented and their actual market share is also included in [4], [5]. The impact of large scale wind penetration of DFIG wind turbine on small signal stability, transient stability and their sensitivity analysis has been discussed in [6]. Relation between wind power penetration and rotor angle stability has been explored in [7].

In [8] the impacts of wind power on power systems voltage and transient stability have been discussed evaluating the effect of fixed and variable speed grid connected induction generators on power system voltage stability. 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 appropriate amount of reactive power [9].

In [10] the authors investigated modeling and transient stability analysis of integrated wind power with a modified IEEE 14 bus system. In [11] a comparison is made among 3 main types of wind turbines such as constant speed wind turbine (CSWT), Doubly Fed Induction Generator (DFIG) and Direct Drive Synchronous Generator (DDSG).

Transient characteristics were analyzed for all types of wind turbines and simulated in a network with fault.

Small signal stability of the system with Squirrel Cage Induction Generator (SCIG) has been discussed in [12] using PSAT with localization of Eigen values which represented small signal stability. DFIG behavior for grid disturbances is simulated and experimental validation done in [13]. In [14] different rotor current control methods of DFIG wind turbines and role of converter to design DFIG are presented. Nordic grid model is implemented using PSAT and it is also validated through time domain simulation by applying small and large disturbances in [15].

Simple DFIG wind turbine model has been developed and implemented for grid integration studies in [16], [17]. Proposed a new control method to improve SCIG wind turbine performance at all operating regions and its mathematical model is described. Large scale wind power integration into the grid and its impacts on small signal stability of power system with permanent magnet synchronous generator has been discussed in [18], [19].

Discussed Wind power integration impact on generation and dispatch of power system and optimal operation has been performed. This paper investigates transient stability of two different wind generator configurations when connected to modified IEEE 14 bus system.

The paper also describes the mathematical modeling of these wind generators. All the simulations have been performed using PSAT software version 2.1.8 [20].

After simulations the results of all the wind turbine generators for various cases are compared and analyzed. Discussion on system behavior for 3 phase fault at a bus is presented and conclusion drawn.

## II. Mathematical Modeling and Control

In this section two wind turbine designing, controlling models are analyzed and their mathematical models are illustrated, namely SCIG and DFIG wind turbines. Here SCIG is a fixed speed turbine where as DFIG is variable speed wind turbines.

The main design criterion for wind turbine is based on average wind speed. Generally wind speed ranges from 7 to 10m/s for a good windy site. Maximum power extraction for wind turbines can be possible between 10 to 15m/s. Higher wind speeds have a low frequency of occurrence, due to which oversized wind turbines are not economical.

The wind turbine operates at constant power if the speed is above rated speed and it operates until cutout speed is reached. Higher wind speed will lead to more stress on wind turbine. Therefore, wind turbine needs a control mechanism in order to regulate the generated power [21].

### *II.1. SCIG Wind Turbine*

The simplest electrical configuration of a wind turbine is fixed speed type wind turbine with squirrel cage induction generator. SCIG consists of mechanical drive train, blade control system, reactive power compensation device, induction generator. SCIG operates at fixed speed i.e. maximum variation in the rotor speed is 2% only.

In this configuration reactive power compensation can be done dynamically to meet power demand.

SCIG equations are developed with respect to real (*r*) and imaginary (*m*) axis in terms of network reference angle.

The power absorbed is given by:

$$P = v_r i_r + v_m i_{qm} \tag{1}$$

$$Q = v_m i_r - v_r i_m + b_c \left( v_r^2 + v_m^2 \right) \tag{2}$$

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

$$e_r^{'} - v_r = r_S i_r - x^{'} i_m \text{ and } e_m^{'} - v_m = r_S i_m + x^{'} i_r \tag{3}$$

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

$$e_r^{'} = \Omega_b \left(1-\omega_m\right) e_m^{'} - \left(e_r^1 - \left(x_0 - x^{'}\right) i_m\right) / T_0^{'} \qquad (4)$$

$$e_m^{'} = -\Omega_b \left(1-\omega_m\right) e_r^{'} - \left(e_m^1 - \left(x_0 - x^{'}\right) i_r\right) / T_0^{'} \qquad (5)$$

In (5), (6) $x_0$, $x^{'}$ and $T_0$ are calculated from the generator parameters:

$$x_0 = x_s + x_m \qquad (6)$$

$$x^{'} = x_S + \frac{x_R x_m}{x_R + x_m} \qquad (7)$$

$$T_0^{'} = \frac{x_R + x_m}{\Omega_b r_R} \qquad (8)$$

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

$$\begin{aligned} &\dot{\omega}_{mr} = \left(T_{wr} - K_s \gamma\right) / \left(2H_{wr}\right) \text{and} \\ &\dot{\omega}_m = \left(K_s \gamma - T_e\right) / \left(2H_m\right) \end{aligned} \qquad (9)$$

$$\dot{\gamma} = \Omega_b \left(\omega_{wr} - \omega_m\right) \qquad (10)$$

where $T_e$ (electrical torque) is given by :

$$T_e = e_r^{'} i_r + e_m^{'} i_m \qquad (11)$$

The mechanical torque is:

$$T_{wr} = \frac{P_w}{\omega_{wr}} \qquad (12)$$

In (12) $P_w$ is the mechanical power extracted from wind. The wind and rotor speeds are related by (13):

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

$\rho$ = air density

$c_p$ = Rotor power coefficient

$\lambda$ = Tip speed ratio

$A_r$ = Area of cross section of rotor

$V_w$ = Wind speed

### *II.2. DFIG Wind Turbine*

A large number of modern wind turbines are equipped with a DFIG that has the stator connected directly to the electrical network, that means it operates synchronously at the network frequency, and the three phase wound rotor connected via a back-to-back voltage source converter. In doubly fed induction generator steady state electrical equations are assumed, considering that 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 the following equations:

$$v_{ds} = -r_S i_{ds} + \left(\left(x_S + x_m\right) i_{qs} + x_m i_{qr}\right) \qquad (14)$$

$$v_{qs} = -r_S i_{qs} - \left(\left(x_S + x_m\right) i_{ds} + x_m i_{dr}\right) \qquad (15)$$

$$v_{dr} = -r_R i_{dr} + \left(1 - \omega_m\right)\left(\left(x_R + x_m\right) i_{qr} + x_m i_{qs}\right) \qquad (16)$$

$$v_{qr} = -r_R i_{qr} - \left(1 - \omega_m\right)\left(\left(x_R + x_m\right) i_{dr} + x_m i_{ds}\right) \qquad (17)$$

The injected active and reactive power into the grid depends on both stator current and grid side current of the converter. Final equations are given by (18), (19).

Where *d*, *s*, *q*, *c* denote d-axis, stator, q-axis and converter respectively:

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dc} i_{dc} + v_{qc} i_{qc} \qquad (18)$$

$$Q = v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qc} i_{dc} - v_{dc} i_{qc} \qquad (19)$$

Rotor side powers are as shown in Eqs. (20):

$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \text{ and } Q_r = V_{qr} i_{dr} - V_{dr} i_{qr} \qquad (20)$$

Now, if we assume a lossless converter, having unity power factor on the grid side of the converter, then:

$$P_c = P_r \;\; \& \;\; Q_c = 0 \qquad (21)$$

Finally injected power into the grid becomes:

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dc} i_{dc} + v_{qc} i_{qc} \qquad (22)$$

$$Q = v_{qs} i_{ds} - v_{ds} i_{qs} \qquad (23)$$

In generator, a single shaft motion equation model is used and it is assumed that converter control can filter shaft dynamics. For this reason, tower shadow effect is not considered. Therefore:

$$\dot{\omega}_m = \left(T_m - T_e\right) / 2H_m \qquad (24)$$

$$T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \qquad (25)$$

The relation between generator currents and stator flux is given as in (26):

$$\psi_{ds} = -\left(\left(x_S + x_m\right)i_{ds} + x_m i_{dr}\right) \text{ and} \\ \psi_{qs} = -\left(\left(x_S + x_m\right)i_{qs} + x_m i_{qr}\right) \tag{26}$$

Hence the electrical torque $T_e$ is given by:

$$T_e = x_m\left(i_{qr}i_{ds} - i_{dr}i_{qs}\right) \tag{27}$$

Then both the mechanical torque and the extracted mechanical power equations are the same as reported for SCIG turbine. Converter dynamics are simplified and faster than considered electromechanical transients. Here converter is modeled as an ideal current source. $i_{qr}$, $i_{dr}$ are state variables and they are used to control both rotor speed and voltage respectively. Converter currents differential equations are as shown below in Eqs. (28) and (29):

$$\dot{i}_{qr} = \left(-\frac{x_s + x_m}{x_m V}P_w^*\left(\omega_m\right)/\omega_m - i_{qr}\right)\frac{1}{T_{\in}} \tag{28}$$

$$\dot{i}_{dr} = K_V\left(V - V_{ref}\right) - V/x_m - i_{dr} \tag{29}$$

where $P_w^*\left(\omega_m\right)$ is known as power – speed characteristic which approximately optimizes the wind energy captured and it is calculated based on current rotor speed value.

In DFIG wind turbine, electromechanical torque control and rotor excitation can be done by using back-to-back converter. The converter size is a fraction of generator rating and generally lies between 15 to 30%. DFIG can be operated in both sub synchronous and super synchronous speed because converter can operate bidirectionally [21].

### *II.3. Wind Model*

In this paper a Weibull distribution wind speed model with nominal wind speed of 15m/s is used, [20].

Representation of Weibull distribution is as follows:

$$f\left(v_w, c, k\right) = \frac{k}{c^k}v_w^k e^{-\left(\frac{v_w}{c}\right)^k} \tag{30}$$

where $v_w$ the wind is speed and $c$, $k$ are constants whose values are 20 and 2 respectively. Wind speed $v_w\left(t\right)$ variation in terms of Weibull distribution is:

$$v_w\left(t\right) = \left(-\frac{\ln e\left(t\right)}{c}\right)^{\frac{1}{k}} \tag{31}$$

Here wind speed profile representation is in PU. Weibull distribution is presented in this case as shown in Fig. 1.

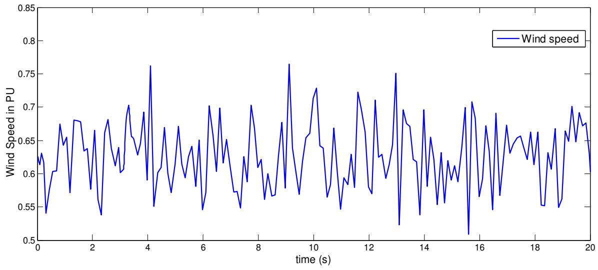

Fig. 1. Weibull distribution wind speed

## III. Transient Stability Analysis of IEEE 14 Bus System

The ability of a synchronous machine to maintain a synchronism with the power system when subjected to a severe disturbance, like faults, breaker interruptions etc. is known as transient stability. In this section a modified IEEE 14 bus system transient stability analysis has been performed when the considered system is connected to SCIG, DFIG wind turbines.

At bus number 3, both SCIG and DFIG wind turbines are connected as shown in Fig. 2 and Fig. 3 respectively. Taking the results by connecting wind turbines 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 wind turbines are connected at other busses. Here a 3 phase fault which is relatively a more severe fault, is applied at bus number 4, at time $t$=3 seconds as shown in Fig. 2, and critical clearing time for this fault is set to 150ms.

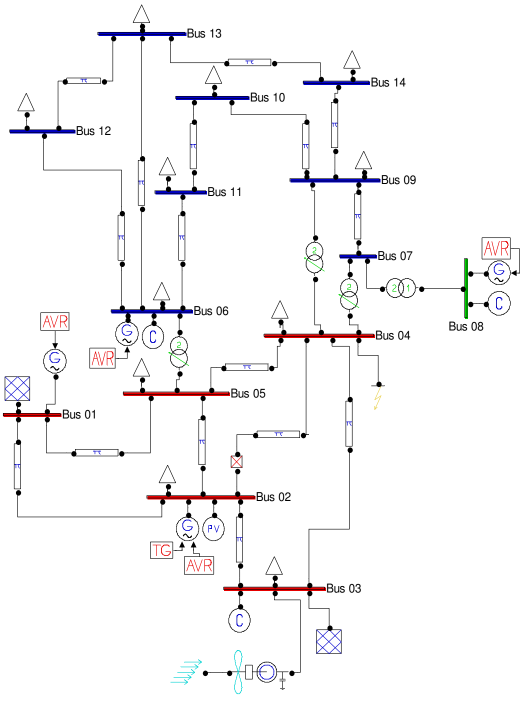

Fig. 2. Wind turbines connected at bus 3 to modified IEEE14 bus system When fault is applied at bus 4

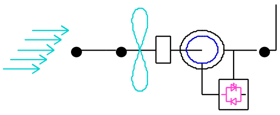

Fig. 3. DFIG connection in the place of SCIG to modified IEEE14 bus system

# IV. Results and Discussion

Analysis of generator rotor angles, bus angles, voltages at all buses and rotational speeds of generators (when fault applied at bus 4) are shown in Fig. 4 to Fig. 11 for SCIG and DFIG based wind turbines. From Fig. 4 to Fig. 7 it is clear that the rotor angles and bus angles deviation are higher in the case of SCIG than that with DFIG.

Further, the rotor angle deviations are low in magnitude and show better damping with DFIG. For the voltage at individual busses and generator rotational speeds (from Fig. 8 to Fig. 11), maximum peak and oscillations reduce in case of DFIG when compared to SCIG. Fig. 12 and Fig. 13 shows current waveforms of direct and quadrature axis of DFIG wind turbine respectively. Fig. 14 and Fig. 15 shows rotor speeds of SCIG and DFIG wind turbines respectively.

The power electronic control provides more effective damping in case of DFIG. The main disadvantage with SCIG wind turbine is the requirement of more reactive power to produce rotating magnetic field. Generally external capacitor banks are used to compensate reactive power in case of SCIG wind turbine. DFIG wind turbines are advantageous as they can be able to supply active power at constant voltage and frequency even though rotor speed may vary.

DFIG wind turbine magnetization can be done from rotor circuit itself to make reactive power control and active power control independent to each other. In DFIG system, rotor circuit can fed reactive power to the stator through the grid side converter.

In this way, DFIG can support the grid more in terms of power system transient stability. The comparison of all these results demonstrate that DFIG based wind turbines have shown better performance when system is subjected to a severe fault while being tested for the transient stability of the system.

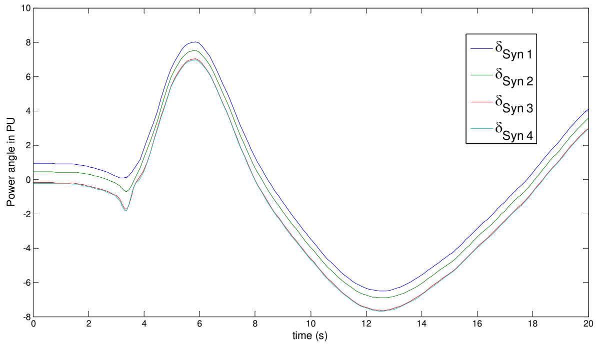

Fig. 4. Rotor angles of modified IEEE14 bus system with SCIG

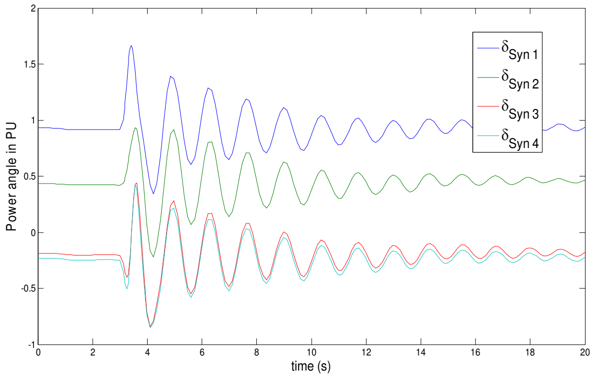

Fig. 5. Rotor angles of modified IEEE14 bus system with DFIG

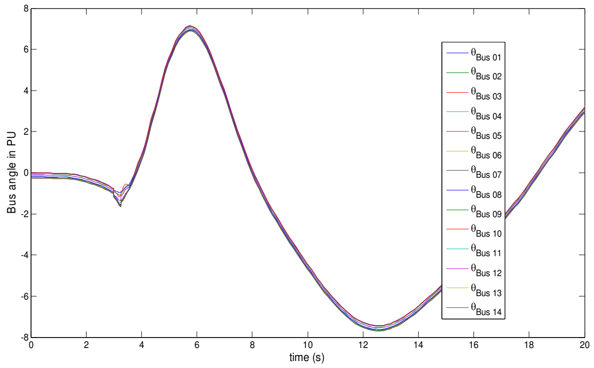

Fig. 6. Bus angles of modified IEEE14 bus system with SCIG

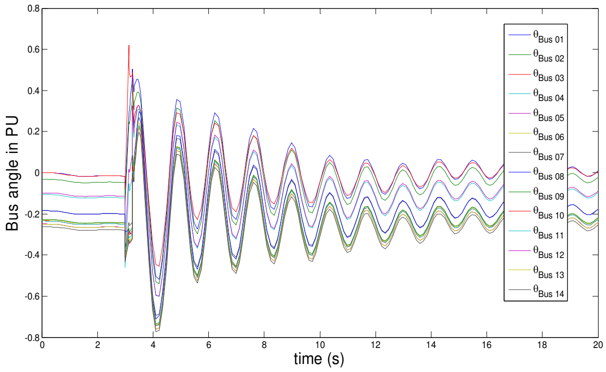

Fig. 7. Bus angles of modified IEEE14 bus system with DFIG

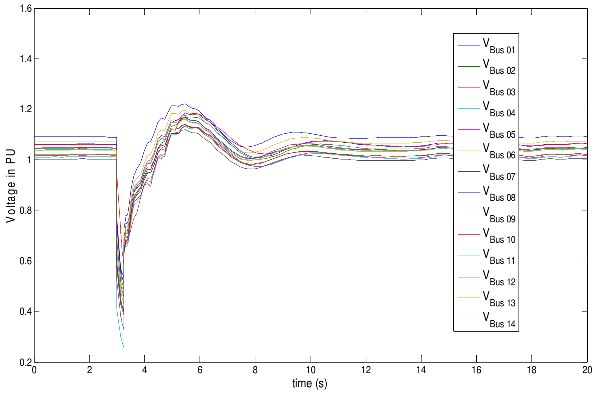

Fig. 8. Voltages of modified IEEE14 bus system with SCIG

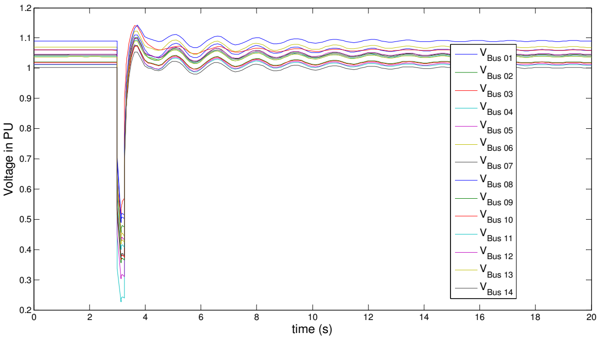

Fig. 9. Voltages of modified IEEE14 bus system with DFIG

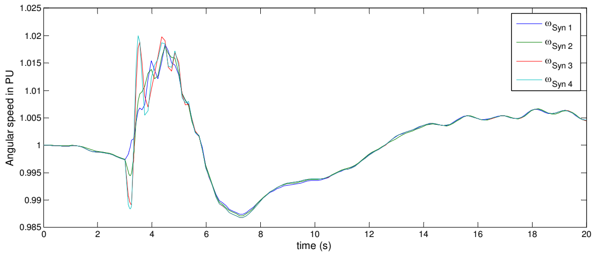

Fig. 10. Rotational Speeds of modified IEEE14 bus system Generators with SCIG

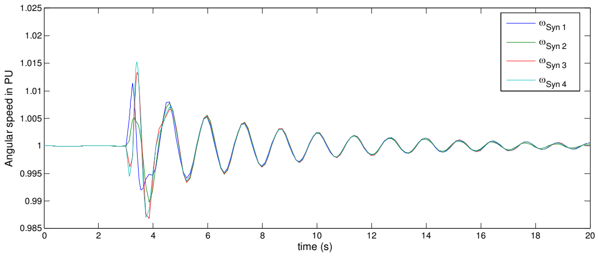

Fig. 11. Rotational Speeds of modified IEEE14 bus system Generators with DFIG

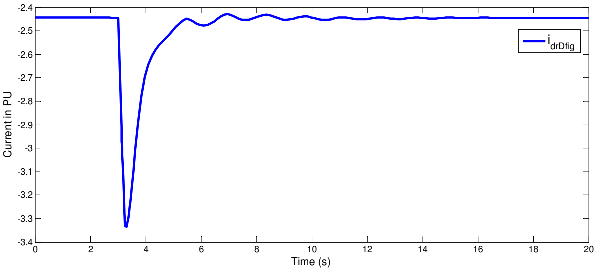

Fig. 12. Rotor Current $I_{dr}$

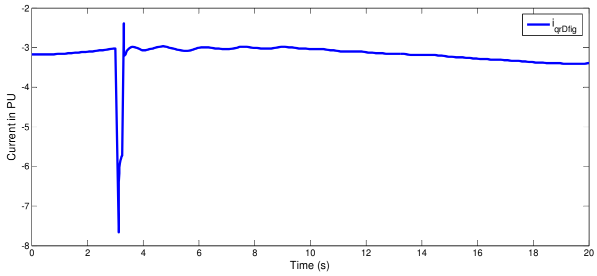

Fig. 13. Rotor Current Iqr

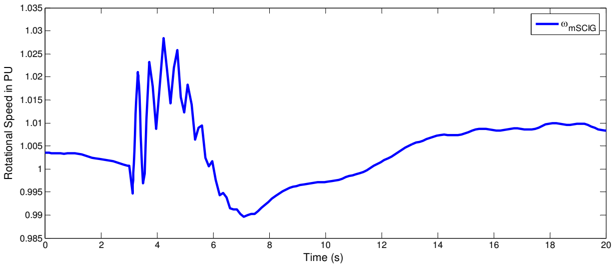

Fig. 14. Rotational Speed of SCIG

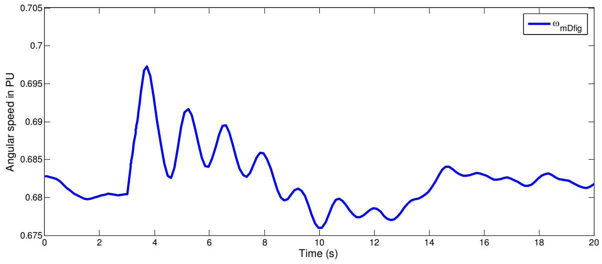

Fig. 15. Rotational Speed of DFIG

# V. Conclusion

In this paper an attempt has been made to study the effect of wind integration on the transient stability of power system using PSAT. Case studies are performed on modified IEEE 14 bus system.

In the transient stability analysis, rotor angle stability, voltage stability, bus angles at all busses and rotational speeds of individual generators have been analyzed.

Among all transient stability related issues, DFIG shows better performance and SCIG shows poor performance. All results are visualized with graphical representation. In SCIG only a single fixed capacitor is present to supply reactive power and thereby to maintain voltage profile. In DFIG, control is provided by the power electronic converter by which it can either import or export reactive power from the grid.

DFIG wind turbine is having not only power electronics based control but also rotor side control.

These two inherent controlling techniques make DFIG wind turbines quite efficient when power system transient stability is considered.

# References

[1] A. Karami, S.Z. Esmaili, "Transient stability assessment of power systems described with detailed models using neural networks," Elsevier, *Electrical Power and Energy Systems*, vol.45, no.1, pp.279-292, 2013.

[2] Istvan Erlich, Jorg Krestschmann, Jens Fortmann, S. Mueller-engelhardt, H.Wrede, "Modeling of Wind Turbines Based on Doubly- Fed Induction Generators for Power System Stability Studies", *IEEE Transactions on Power Systems*, vol.22, no.3, pp.909-919, 2007.

[3] H.N.D. Le, S. Islam, "Substantial control strategies of DFIG wind power system during grid transient faults," *IEEE TRANSMISSION AND DISTRIBUTION CONFERENCE AND EXPOSITION*, pp.1-13, 2008.

[4] N. Goudarzi, W.D. Zhu, "A review on the development of wind

turbine generators across the world" Springer, *International Journal on Dynamic Control*, no.1, pp. 192-202, 2013.

[5] H. Li, Z.Chen, "Overview of different wind generator systems and their comparisons," *IET Renewable Power Generation*, vol.2, no.2, pp.123-138, 2008.

[6] Durga Gautam, Vijay Vittal, Terry Harbour, "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems," *IEEE Transactions On Power Systems*, VOL. 24, NO. 3, pp.1426-1434, 2009.

[7] Eknath Vittal, Mark O'Malley, Andrew Keane, "Rotor Angle Stability With High Penetrations of Wind Generation," *IEEE Transactions On Power Systems*, vol. 27, no. 1, pp.353-362, 2012.

[8] E. Muljadi, T.B. Nguyen, M.A. Pai, "Impact of Wind Power Plants on Voltage and Transient Stability of Power Systems," *IEEE CONFERENCE ON ENERGY 2030*, pp.1-7, 2008.

[9] D. Devaraj, R. Jeevajyothi, "Impact of Wind Turbine Systems on Power System Voltage Stability," *IEEE INTERNATIONAL CONFERENCE ON COMPUTER, COMMUNICATION AND ELECTRICAL TECHNOLOGY*, pp.411-416, 2011.

[10] A.G. Pillai, P.C. Thomas, K. Sreerenjini, S. Baby, T. Joseph, S. Sreedharan, "Transient stability analysis of wind integrated power systems with storage using central area controller," *IEEE INTERNATIONAL CONFERENCE ON MICROELECTRONICS, COMMUNICATIONS AND RENEWABLE ENERGY*, pp.1-5, 2013.

[11] Hui Ouyang, Peiqiang Li, Lin Zhu, Yuanzhao Hao, Changhong Xu, Chunguang He, "Impact of large-scale wind power integration on power system transient stability," *IEEE INTERNATIONAL CONFERENCE ON INNOVATIVE SMART GRID TECHNOLOGIES*, pp.1-6, 2012.

[12] Y.U. Lopez, J.A.D. Navarro, "Small signal stability analysis of wind turbines with squirrel cage induction generators," *IEEE INTERNATIONAL CONFERENCE ON TRANSMISSION AND DISTRIBUTION CONFERENCE AND EXPOSITION* pp.1-10, 2008.

[13] A. Petersson, T. Thiringer, L. Harnefors, T. Petru, "Modeling and experimental verification of Grid Interaction of a DFIG Wind Turbine," *IEEE Transactions on Energy Conversion*, vol.20, no.4, pp.878-886, 2005.

[14] A. Petersson, L. Harnefors, T. Thiringer, "Evaluation of Current Control Methods for Wind Turbines Using Doubly- Fed Induction Machines," *IEEE Transactions on Power Electronics*, vol.20, no.1, pp.227-235, 2005.

[15] Y. Chompoobutrgool, Wei Li, L. Vanfretti, "Development and implementation of a Nordic grid model for Power System small-signal and transient stability studies in a free and open source software," *IEEE POWER AND ENERGY SOCIETY GENERAL MEETING*, pp.1-8, 2012.

[16] Yazhou Lei, Alan Mullane, Gordon Lightbody, Robert Yacamini, "Modeling of the Wind Turbine With a Doubly Fed Induction Generator for Grid Integration Studies," *IEEE Transactions on Energy Conversion*, vol.21, no.1, pp.257-264, 2006

[17] M.Q. Duong, F. Grimaccia, S. Leva, M. Mussetta, E. Ogliari, "Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system," *Elsevier, Renewable Energy*, 2014.

[18] Li-Bao Shi, Li Kang, Liang-Zhong Yao, Shi-Yao Qin, Rui-Ming Wang and Jin-Ping Zhang, "Effects of Wind Generation Uncertainty and Volatility on Power System Small Signal Stability," *Journal of Electrical Engineering and Technology*, Vol. 9, No. 1: 60-70, 2014.

[19] Jae-Kun Lyu, Jae-Haeng Heo, Mun-Kyeom Kim and Jong-Keun Park "Impacts of Wind Power Integration on Generation Dispatch in Power Systems," *Journal of Electrical Engineering and Technology*, Vol. 8, No. 3: 453-463, 2013.

[20] F. Milano, *Power System Analysis Toolbox*, Version 1.3.4, Software and Documentation, July 14, 2005.

[21] Mircea Eremia, Mohammad Shahidehpour, *Handbook of Electrical Power System Dynamics: Modeling, Stability, and Control,* The Institute of Electrical and Electronics Engineers, 2013.