Small Signal Stability Analysis of a Wind Penetrated Electricity Distribution System

P. Venkata Narayana, K. H. Phani Sree

Abstract—The new types of generating systems such as wind generators, PV based static generators, diesel generators, and power from cogeneration plants have been introduced in to the system resulting in new challenges to stability, operation and control of the power system and its components. The reason being intermittent nature of the such types of generation. Due to their unregulated operation, the generators may impose a serious threat to the small signal stability. This paper analyses the small signal stability of the test distribution system at various penetration levels of wind generation in to the test system. For this purpose, eigen values and participation factor approaches have been chosen for analysis.

Keywords— Distributed generation, small signal stability, eigen value analysis, participation factor, Power System Analysis Toolbox (PSAT)

I. INTRODUCTION

Power systems are steadily growing with ever larger capacity. Formerly separated systems are interconnected to each other. Modern power systems are evolved into systems of very large size, stretching out hundreds and thousands of kilometers. With growing generation capacity, different areas in a power system are added with even larger inertia. With electric utility restructuring, public environmental policy, and expanding power demand, small distributed generators are in great need in order to satisfy on-site customer energy needs. Major improvements in the economic, operational, and environmental performance of small, modular units have been achieved through decades of intensive research. The use of renewable energy technologies exhibits a significant growth in nowadays power systems mainly due to critical factors such as limited available primary energy resources used in conventional power plants, the fast increase in fuel prices, and environmental concerns. Wind power constitutes the renewable generation technology which has experienced the fastest growing among all types of renewable generation technologies currently investigated. Extrapolating the current trend into the future, it is easy to foresee installed wind capacities exceeding 50 % of the overall capacity in some countries in the not too distant future.

Manuscript published on 30 December 2014.
***Correspondence Author(s)**
P. Venkata Narayana, Department of EEE, Jawaharlal Nehru Technological University, College of Engineering, Hyderabad, India.
K. H. Phani Sree, Department of EEE, Jawaharlal Nehru Technological University, College of Engineering, Hyderabad, India.

Large integration of wind power into power networks will affect considerably the dynamic behavior of the power system since wind based generation systems and conventional synchronous generators exhibit fundamentally different transient responses. This stems first and foremost from their inherently different dynamic characteristics. Additionally, wind generation systems result in the reduction of the overall system inertia pegged to the network in relation to the installed capacity. Furthermore, modern power networks are operated close to their security limits due to economical and technical considerations. It is increasingly recognized that the investigation of the small-signal stability of power systems yields important results that are complementary to those yielded by the usual transient stability investigations. The advantage of studying the small-signal stability by using eigenvalue analysis when compared to transient stability investigations is that it gives a complete overview of the small-signal stability of the current system operating state, whereas in transient stability investigations only one event at a time can be simulated. The drawback of eigenvalue analysis is, that a linearized set of equations is used and that the higher order terms are neglected, which may lead to erroneous results, particularly when a system is described by strong non-linear equations. Keeping in mind these limitations, eigenvalue analysis is nevertheless considered a powerful tool. The small signal stability (SSS) problem of a power system occurs usually due to insufficient damping of electromechanical oscillations. However, further research is required for better understanding of the main factors influencing the impact of large scale wind power integration on small signal stability. This paper provides an attempt to assess how large scale wind power integration influences the small signal stability, since these stability constraints are essential for power system security, as evidenced in recent blackouts throughout the world. The small signal stability of a 15 bus test distribution comprising conventional thermal power plants and a SCIG based wind power plant were evaluated through modal analysis and time domain simulations respectively.

II. SYSTEM MODELLING

The modelling approach adopted in this paper is as explained below

A. Synchronous Generator

The sixth order model of synchronous generator is considered for stability analysis in this paper. The Park-Concordia model is used for synchronous machine equations, whose scheme is depicted in Fig 1.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

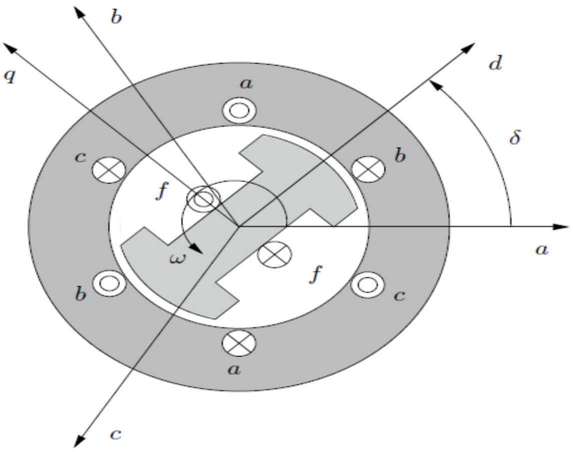

Fig. 1. Synchronous machine model

The link between the network phasors and the machine voltage is as follows:

$$v_d = V\sin(\delta - \theta)$$
$$v_q = V\cos(\delta - \theta)$$

Power injections are expressed in the form:

$$P = v_d i_d + v_q i_q$$
$$Q = v_q i_d - v_d i_q$$

This model is obtained assuming the presence of a field circuit and an additional circuit along the d-axis and two additional circuits along the q-axis. The system has six state variables (δ, ω, $e_q^{'}$, $e_d^{'}$, $e_q^{''}$, e'_d) and the following equations:

$$\dot{\delta} = \Omega_b(\omega - 1)$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1))/M$$

$$\dot{e}_q^{'} = (e_q^{'} - \left(x_d - x_d^{'} - \frac{T_{d0}^{''}}{T_{d0}^{'}}\frac{x_d^{''}}{x_d^{'}}(x_d - x_d^{'})\right) i_d + (1 - \frac{T_{AA}}{T_{d0}^{'}}) v_f^{*})/T_{d0}^{'}$$

$$\dot{e}_d^{'} = (-f_s(e_d^{'}) + \left(x_q - x_q^{'} - \frac{T_{q0}^{''}}{T_{q0}^{'}}\frac{x_q^{''}}{x_q^{'}}(x_q - x_q^{'})\right) i_q)/T_{q0}^{'}$$

$$\dot{e}_q^{''} = (-e_q^{''} + e_q^{'} - \left(x_d^{'} - x_d^{''} - \frac{T_{d0}^{''}}{T_{d0}^{'}}\frac{x_d^{''}}{x_d^{'}}(x_d - x_d^{'})\right) i_d + (\frac{T_{AA}}{T_{d0}^{'}}) v_f^{*})/T_{d0}^{''}$$

$$\dot{e}_d^{''} = ((-e_d^{''} + e_d^{'}) + \left(x_q^{'} - x_q^{''} + \frac{T_{q0}^{''}}{T_{q0}^{'}}\frac{x_q^{''}}{x_q^{'}}(x_q - x_q^{'})\right) i_q)/T_{q0}^{''}$$

The electrical power is given as:

$$P_e = (v_q + r_a i_q) i_q + (v_d + r_a i_d) i_d$$

B. Induction Generator

The induction generators are popularly employed in wind power generation applications, small and micro hydro and some thermal plant. The mechanical torque is assumed to be constant. The squirrel cage induction generator (SCIG) model has been considered. The steady state equivalent circuit of an SCIG is shown in Fig. 2.

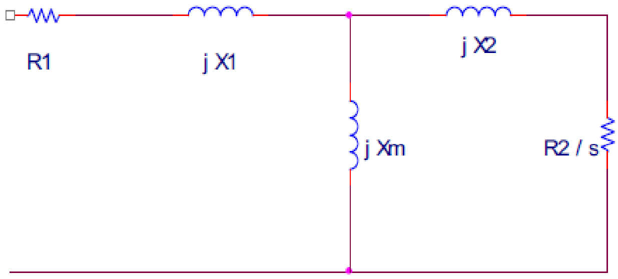

Fig. 2. Steady state equivalent circuit of induction generator

The differential equations taken from the transient equivalent circuit in terms of the voltage behind the stator resistance r_s are as follows:

$$e_r' - v_r = r_s i_r - x' i_m$$
$$e_m' - v_m = r_s i_m + x' i_r$$
$$v_r = -r_s i_r + x' i_m + e_r'$$

where

e_r is the transient voltage on real axis,

e_m is the transient voltage on imaginary axis.

x´: transient reactance

Reactance x_o, transient reactance x´ and transient time constant $T´_o$, are obtained from the generator parameters as given below:

$$x_0 = x_s + x_m$$
$$x' = x_s + \frac{x_R x_m}{x_R + x_m}$$
$$T_0' = \frac{x_R + x_m}{\Omega_b r_R}$$

On the other hand, to simulate the mechanical parts as gear box and shafts, the mechanical equations which are taken into account are the turbine inertia H_{wr} and rotor inertia H_m, and shaft stiffness K_s as shown below:

$$\dot{w}_{wr} = \frac{(T_{wr} - K_s\gamma)}{2H_{wr}}$$
$$\dot{w}_m = \frac{(K_s\gamma - T_e)}{2H_m}$$
$$\dot{\gamma} = \Omega_b(w_{wr} - w_m)$$

where γ is the slip factor and

ω represents rotor speed indices.

C. Description of the Distribution System

A 15 bus distribution system is adopted for performing the small signal stability analysis with increased wind penetration. The test system is shown in Fig. 2 which is based on the distribution feeder in the Kumamoto area of Japan. To perform small signal stability analysis, a wind generation unit is connected on bus 15.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-4 Issue-7, December 2014

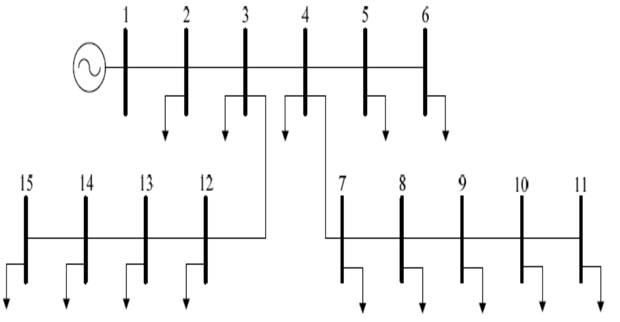

Fig. 2. Single line diagram of the test distribution system

III. SMALL SIGNAL STABILITY ANALYSIS

A. There are fifteen state variables, which are numbered and listed as follows:

1. Delta (rotor angle) of synchronous generator
2. Omega (rotor speed) of synchronous generator
3. E1q(q-axis transient voltage) of synchronous generator
4. E1d (d-axis transient voltage) of synchronous generator
5. E2q (q-axis sub transient voltage) of synchronous generator
6. E2d (d-axis sub transient voltage) of synchronous generator
7. Vm of the exciter
8. Vr of the exciter
9. Vf of the exciter
10. Vw of the wind
11. Omega_t of the constant speed wind turbine
12. Omega_m of the constant speed wind turbine
13. Gamma of the constant speed wind turbine
14. Er of the constant speed wind turbine
15. Em of the constant speed wind turbine

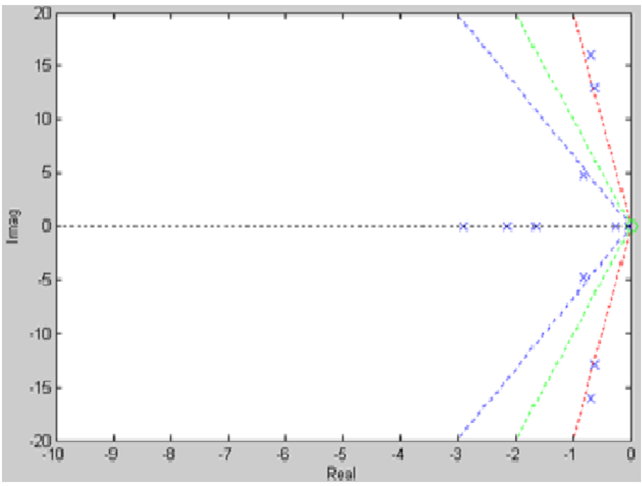

Fig. 3 Eigen values of the distribution system

The Eigen values of the system gives the information about the small signal stability. The system under study has fifteen eigen values with the wind generator connected to the system, which is shown in Fig.3. Since all the Eigen values lie on the left side of the imaginary axis, the system is said to be asymptotically stable. Eigen value analysis may be used to determine the acceptable renewable energy penetration before the system loses its small signal stability.

In this system, two pairs of complex low frequency oscillations were observed which are summarized in the following table.

THE OSCILLATORY MODES EXISTING IN THE DISTRIBUTION SYSTEM

Modes	Real Part	Imaginary Part	Damping Ratio	Frequency
1,2	-0.48374	14.8556	0.0325	2.3656
3,4	-0.72993	12.8273	0.0568	2.0448

B. Participation Factor

The contributions of states on oscillations were observed by evaluating the participation factors of each state on a particular mode. The participation factor of the kth state in the ith eigen mode may be given by

$$P_{ki} = \phi_{ki}\psi_{ik}$$

ϕ_{ki} = the element on the kth row and ith column of the modal matrix ϕ

= kth entry of the right eigenvector ϕ_i

ψ_{ik} = the element on the ith row and kth column of the modal matrix ψ

ϕ_{ki} = kth entry of the left eigenvector ψ_i

C. Eigen Value Analysis

Eigen value or Modal analysis describes the small signal behaviuor of the system i.e. the behavior linearised around one operating unit. The Eigenvalue analysis investigates the dynamic behavior of a power system under different characteristic frequencies (‘modes’). In a power system, it is required that all modes are stable.

The following tables show the participation factor of various states on different oscillation modes.

Impact of Penetration of Wind energy on Participation factors of State Variables for Modes 1,2

State	5% Wind	10% Wind	15% Wind	20% Wind	25% Wind	30% Wind
1	0.01592	0.01541	0.0148	0.01416	0.01348	0.01272
2	0.01592	0.01541	0.0148	0.01416	0.01348	0.01272
3	0.01813	0.02947	0.03907	0.04728	0.05442	0.0607
4	0.00371	0.00303	0.00236	0.00176	0.00135	0.00129
5	0.00223	0.00706	0.01424	0.02042	0.02579	0.03049
6	0.00297	0.00244	0.0019	0.00142	0.00108	0.00103
7	0.00029	0.00048	0.00063	0.00076	0.00088	0.00097
8	0.00802	0.01327	0.01761	0.02132	0.02458	0.02751
9	0.01784	0.02962	0.03935	0.04761	0.05477	0.06106
10	0	0	0	0	0	0
11	0.03108	0.0297	0.02863	0.02793	0.02754	0.02742
12	0.42613	0.41187	0.39828	0.38662	0.37627	0.36672
13	0.25375	0.24372	0.23527	0.229	0.22449	0.22146
14	0.20352	0.1957	0.18833	0.18195	0.1763	0.17116
15	0.00049	0.00283	0.00472	0.0056	0.00559	0.00475

Observations

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

For Modes 1, 2, the PFs of state-5 increased from 0.00223 to 0.03049. Furthermore, the PFs of state-8 increased significantly from 0.00802 to 0.02751 and the PFs of state-9 were increased significantly from 0.01784 to 0.06106. Also, the PFs of state-15 increased significantly from 0.00049 to 0.00475.

Impact of Penetration of Wind energy on Participation factors of State Variables for Modes 3,4

Stat e`	5% Wind	10%Wi nd	15%Wi nd	20%Wi nd	25%Wi nd	30%Wi nd
1	*5e-005*	*0.0001*	*0.00015*	*0.00019*	0.00024	0.00029
2	*5e-005*	*0.0001*	*0.00015*	*0.00019*	0.00024	0.00029
3	*0.3139*	*0.3055*	*0.29815*	*0.29187*	0.28657	0.28217
4	*0.00461*	*0.00501*	*0.00528*	*0.00541*	0.00543	0.00532
5	*0.15454*	*0.14986*	*0.14584*	*0.14246*	0.13967	0.13741
6	0.00257	0.0028	0.00296	0.00306	0.0031	0.00308
7	0.00408	0.00397	0.00389	0.00383	0.00378	0.00374
8	0.16417	0.15965	0.15547	0.15166	0.14819	0.14504
9	0.31512	0.3066	0.29914	0.29275	0.28736	0.28286
10	0	0	0	0	0	0
11	0.00223	0.00392	0.00527	0.00635	0.00722	0.0079
12	0.01112	0.01973	0.02699	0.03328	0.03889	0.04399
13	0.01186	0.02091	0.02832	0.03446	0.03961	0.04396
14	0.00158	0.00747	0.01253	0.01674	0.0202	0.02292
15	0.0141	0.01438	0.01588	0.01774	0.01952	0.02101

Observations

For Modes 3, 4, the PFs of state-12 increased from 0.01112 to 0.04399. Furthermore, the PFs of state-13 increased significantly from 0.01186 to 0.04396 and the PFs of state-14 were increased significantly from 0.00158 to 0.02292. Thus, it has been observed that the Participation of some states have significantly increased with increased wind penetration. The participation of the remaining states changes slightly in either direction.

IV. Conclusions

The small signal stability of a test distribution system is investigated with increased penetration of wind energy. The impact of wind energy penetration on the distribution system is estimated by calculating the participation factors of different states at different oscillation modes. The penetration is varied to study the impact on small signal stability. The sensitivity parameter and time domain simulation are used for stability analysis. Low frequency oscillation modes with approximate frequency of 3 Hz were observed. The results show that rotor flux variables of wind generators participate significantly in the system oscillations. The oscillatory modes dominated by wind generator states are less sensitive with power fluctuations and relatively well damped as compared to the modes dominated by synchronous generator states. The increased penetration of wind power has a positive impact on the oscillation damping of the synchronous generator.

V. Appendices

A. Test Distribution System Data

The distribution system data is given in the following tables. The per unit values are based on 30 MVA and 11.432 kV.

Line Data of Test Distribution System

Sending Node	Ending Node	R(p.u.)	X(p.u.)	B(p.u.)
1	2	0.00315	0.075207	0.00000
2	3	0.00033	0.001849	0.00150
3	4	0.00667	0.030808	0.03525
4	5	0.00579	0.014949	0.00250
5	6	0.01414	0.036547	0.00000
4	7	0.00800	0.036961	0.03120
7	8	0.00900	0.041575	0.00000
8	9	0.00700	0.032346	0.00150
9	10	0.00367	0.016940	0.00350
10	11	0.00900	0.041575	0.00200
3	12	0.02750	0.127043	0.00000
12	13	0.03150	0.081405	0.00000
13	14	0.03965	0.102984	0.00000
14	15	0.01061	0.004153	0.00000

Load Data Test Distribution System

Bus	P_{load}(p.u.)	Q_{load}(p.u.)
2	0.02080	0.0021
3	0.04950	0.0051
4	0.09580	0.0098
5	0.04420	0.0045
6	0.01130	0.0012
7	0.06380	0.0066
8	0.03230	0.0033
9	0.02130	0.0022
10	0.02800	0.0029
11	0.21700	0.0022
12	0.01320	0.0014
13	0.00290	0.0003
14	0.01610	0.0016
15	0.01390	0.0014

REFERENCES

1. S. Dahal, N. Mithulananthan, T. Saha , "Investigation of Small Signal Stability of a Renewable Energy based Electricity Distribution System", in Power and Energy Society General Meeting, 2010 IEEE.
2. F. P. de Mello, J. W. Feltes, L. N. Hannett, and J. C. White, "Application of Induction Generators in Power Systems," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-101, pp. 3385-3393, 1982.
3. Slootweg, J. G. and Kling, W. L. "Modelling and Analysing Impacts of Wind Power on Transient Stability of Power Systems", Wind Engineering. Vol. 26, no. 1, 2002, pp. 3-20.
4. P. Kundur, "*Power System Stability and Control*," New York: Mc.Graw-Hill, 1994.
5. J. G. Slootweg, "Wind Power: Modelling and Impact on Power System Dynamics", PhD thesis, Technische Universiteit Delft, December 2003.
6. R. D. Fernández, R. J. Mantz, and P. E. Battaiotto, "Impact of wind farms on a power system. An eigenvalue analysis approach," *Renewable Energy,* vol. 32, pp. 1676-1688, 2007.
7. A. Mendonca, and J.A.P. Lopes, "Impact of large scale wind power integration on small signal stability", International Conference on Future Power Systems, Nov. 2005.
8. P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Cañizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Tylor, T. Van Custem, and V. Vittal, "Definition and Classification of Power System Stability", IEEE Transactions on Power Systems, Vol. 19, No. 2, pp. 1387 – 1401, May 2004.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

9. G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A. Stankovic, C. Taylor, and V. Vittal, “Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance”, IEEE Transactions on Power Systems, Vol. 20, No. 4, Nov. 2005, pp. 1922 – 1928.
10. I. Erlich, J. Kretschmann, J. Fortmann, S. Mueller-Engelhardt, and 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, Aug. 2007, pp. 909 - 919.
11. Milano F. Power System Analysis Toolbox (PSAT). Documentation for PSAT version 2.0.0, March 24, 2006.
12. Milano F. Power System Analysis Toolbox (PSAT). Documentation for PSAT version 1.3.4, July 14, 2005.
13. Slootweg, Han. De Vries, Eize. “Inside wind turbine. Fixed vs. Variable speed. Renewable energy world”, January 2003.
14. Slootweg, J.G.. “Wind Power Modelling And Impact On Power System Dynamics”, PROEFSCHRIFT. PhD Thesis. Delft University of Technology. 2003.
15. Lynch, Stephen. “Dynamical Systems with Applications using Matlab”, Birkhauser. 2004.
16. J. G. Slootweg. S. W. H. De Haan, H. Polinder, And W. L. Kling, “General Model For Representing Variable Speed Wind Turbines In Power System Dynamics Simulations”, IEEE Transactions On Power Systems, Vol. 18, No. 1, February 2003.
17. IEEE PES Working Group on System Oscillations, “Power System Oscillations”, IEEE Special Publication 95-TP-101, 1995.
18. Ong, Chee Mun. “Dynamic simulations of Electric Machinery Using Matlab – Simulink”, Purdue University. Prentice Hall.
19. R. Thresher, M. Robinson, and P. Veers, “To Capture the Wind”, IEEE Power and Energy Magazine, Vol. 5, No. 6, Nov.-Dec. 2007, pp. 34 –46.
20. Shearer, J.L. Kulakowski, B. Gardner John. “Dynamic Modelling and control of engineering systems”, 2e. Prentice Hall. 1997.
21. Lynch, Stephen. “Dynamical Systems with Applications using Matlab”, Birkhauser. 2004.
22. Kothari. Nagrath. Modern Power systems Analysis. 3e. Mc-Graw Hill. 2004.
23. Kazachkov, Yuri., Stapleton, Steve. “Modeling wind farms for power systems stability studies”, Power technology magazine. 95. April 2004.

AUTHOR PROFILE

P. Venkata Narayana, has been working as Assistant Professor in EEE of the JNTUH College of Engg., Hyderabad for 8 years.He Obtained his B.Tech (EEE) from S.V.U.College of Engg., Tirupati in 1995 and obtained Masters in Energy Systems from J.N.T.U.Hyderabad in 2001. His Research areas include renewable energy, power systems, energy audits.

Smt. K. H. Phani Sree, has been working as Assistant Professor in EEE of the JNTUH College of Engg., Hyderabad for 11 years.She Obtained B.Tech (EEE) from NagarjunaUniversity in 2000 and obtained Masters in Power Systems from N.I.T.Trichy in 2002. Her Research areas include renewable energy, power systems, Power Electronics.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)