Analysis of Small Signal Stability on Wind Power Integration to Integrated Nepal Power System (INPS)

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Abstract- With large wind energy integration into power systems, wind farms begin to influence power systems in a much more significant manner. As wind energy systems utilize different generator technologies from the one utilized in the conventional power plants, the steady-state, transient and small-signal dynamics, as well as, power system stability will thus be significantly affected. The impact of wind energy systems on the power system dynamics and stability is thus of practical importance.

As there is a significant increase in installation of wind turbines equipped with doubly-fed induction generator (DFIG) in recent years, a dynamic model of the DFIG wind turbine is firstly developed in this study. The model is validated against field measurement data, and the validation gives confidence about the accuracy and applicability of the developed model. DFIG wind farms consist of tens to hundreds of identical DFIG wind turbines increasing the complexity of the wind farm model and simulation time.

In this study, the steady-state behavior of the DFIG is examined. Comparison is made with the conventional synchronous generators (SG) and squirrel-cage induction generators to highlight the differences between the machines. The initialization of the DFIG dynamic variables and other operating quantities is then discussed. Various methods are briefly reviewed and a step-by-step procedure is taken to avoid the iterative computations in initial condition.

The dynamical behavior of the DFIG is studied with eigen value analysis. Modal analysis is performed for both open-loop and closed-loop situations. The effect of parameters and operating point variations on small signal stability is observed. Financial analysis has been done using CREST model tool, which shows that the project is feasible in case of Nepalese subsidiaries..

Keywords – Wind Turbine Generation, Small Signal Stability, Integrated Nepal Power System.

I. INTRODUCTION

The small signal stability is the ability of power system remains in operating equilibrium when small disturbances are created such that the oscillations created in the system are suppressed and the deviations of system state variables remain small for a long time. If the magnitude of oscillations continues to increase or sustain indefinitely, this is the case for system unstable. The small signal stability of power system is affected by many factors such as initial operating conditions, characteristics of various control devices and strength of electrical connections among different components of system. It is inevitable that the power system cannot be operated if the system is unstable in terms of small signal stability. The stability of power system consisting synchronous machine has a major attention in past and also will obtain an immense attention in future too. The small signal stability programs and its simulation programs can be used for controller design, stability status and system dynamics. The present trend in power system restructuring and deregulation has increased operation efficiency. The high penetration of distributed generation (DG) like renewable such as wind turbine generators (WTGs) has an impact on system stability. The use of controllers on WTGs or use of FACT devices at an appropriate position enables the system stability and security.

Small signal stability is the ability of power system to maintain synchronism when the system is subjected to small disturbances. The small disturbances may be either change in consumer's load or generation power of generating stations. The system may be unstable due to steady increase in generator rotor angle due to lack of synchronizing torque or rotor oscillations of increasing amplitude due to lack of sufficient damping torque. In integrated power system with newer technologies, specially wind turbines, power systems may adversely be affected due to the requirement of scheduling of spinning reserves and energy storage because wind power is variable and difficult to predict. Wind power may have problems of frequent occurrence of voltage dips, grid frequency variations and low power factor due to the location and intermittent nature of wind turbine generators. Therefore, the disturbances due to integration of wind turbine in integrated power system must be studied to imply the problems and also probable solutions to overcome the problem.

The wind turbines are very much using in the world as well as in Nepal. The wind turbine standalone is useful but when it is connected to the grid then it impacts on the stability of the grid. The research gap in the thesis is how the stability changes while wind turbines are added to grid and how much power can be integrated at the prescribed location and is not studied in Nepalese power system. The more the connection point of wind turbine into the grid, then how it affects the participation factor and small signal stability of the grid should be studied.

This study focuses on study of the impact on voltage profile and stability of the grid and analyzes small signal stability with participation factor and Eigen value analysis and determine wind power sensitivity in INPS due to wind power integration.

Further, the latter sections of this paper discusses on the WTG impact on the system stability but limited to technical discussion on voltage profile Eigen value analysis and Eigen sensitivity analysis. It does not consider thermal limit, current handling capacity, network sensitivity effect of impedance matching and harmonic resonance. It only provides information about whether system is stable or not while integration or adding a wind power to the grid. It does not specify the protection system that can be used for WTG unit in association with grid system. The reconfiguration of grid distribution system affects the power flow in networks and this reconfiguration is also not studied in this study. The variable renewable energy (VRE) cannot supply constant power at all the times and that effect is not considered.

II. Problem Formulation and Methodology

The outline of this work begins from the literature review, in which the wind power generation and the impact on the grid, when integrated to the existing grid is studied. At the review stage, issues of wind farm integration are investigated, the methodologies for system impact study relevant to small signal stability integration is explored.

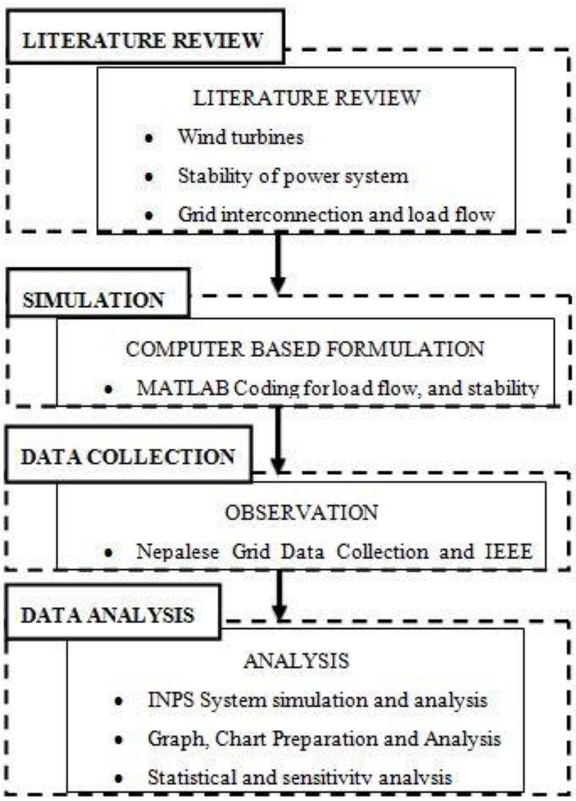


Fig 1: Methodological Block Diagram for Study

In Literature, wind turbine characteristics, wind turbine power generation capability, power system stability and methods for power flow are studied. The prescribed process of methods to study the stability is formulated and simulated in MATLAB. The data of wind turbine power generation and its feasibility is collected from Alternative Energy Promotion Centre (AEPC) and the integrated Nepalese power system data is collected from Nepal Electricity Authority (NEA). A formulated simulation is done into the INPS and WTG data and analysis is performed for the integrated system.

Small Signal Stability Analysis

The stability analysis for the power system is performed under the condition that the DFIG is added to the grid. In stability analysis, the Eigen values and its vector, participation factor are important for the study. The system data is arranged and then the load flow is performed without and integration of DFIG and stability of the system is studied. After that, the DFIG is integrated to the grid and then the load flow is performed to check the power flow in the network and stability is checked from Eigen value analysis. If the system is found stable, then the results are saved so can be used further. If system is not found to be stable, then the DFIG parameters are varied with respect to the power and the DFIG reactance. The *figure 2* shows the flow chart for the stability analysis and other subsections in this section are used to describe the involved equations and mathematical formulations.

Formation of System State Matrix:

The non-linear model of whole system can be represented by non-linear equations. The equations are in state space form are as follows:

$$\dot{x}=f(x,y,u) \quad (1)$$
$$0=g(x,y) \quad (2)$$

Where x is state variables, y is output variables and u is input variables.
The equations (1) and (2) are linearized and system state matrix Asys is formed.

$$\dot{\Delta x} = A_{sys}\Delta x \quad (3)$$

The Eigen value of A_{sys} is calculated for the computation for the small signal stability. The Eigen values are may be real or complex or zero. The complex Eigen values appear always in complex conjugate pair. For stable operation, all Eigen values λ_i must be in the left half plane.

$\lambda_i = (\sigma_i \pm j\omega_i)$ and $\sigma_i < 0$

The time constant T [s], damping ratio ζ and oscillating frequency f [Hz] of Eigen value is given by:

$$T=\frac{1}{|\sigma|} \quad (4)$$
$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \quad (5)$$
$$f = \frac{\omega}{2\pi} \quad (6)$$

The DFIG is connected to load (PQ) bus through a transformer and a bus. If n_{dfg} is the number of DFIGs then the total number of buses is increased by n_{dfg}. The set of

Differential Algebraic Equations (DAE) of DFIG has been performed in MATLAB coding.

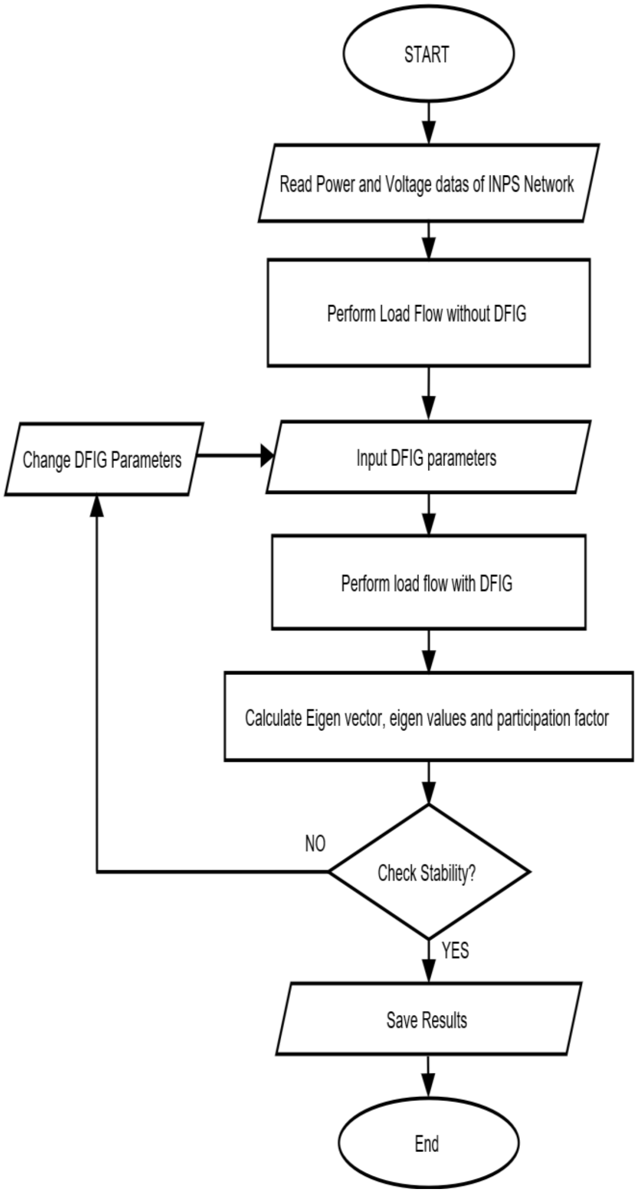


Figure 2: Flow Chart for Stability Analysis

Then, the modal matrices were introduced to express the Eigen properties of A_{sys}. Eigen Value Sensitivity has been performed by taking partial derivative of all eigen values λ_i to a_{kj} *where*, a_{kj} be the element of matrix $\tilde{A}_{sys}$ (k-th row and j-th column element of $\tilde{A}_{sys}$).

Similarly, the participation factor (pf) determines the contribution of dominant states (row-wise) to particular modes (Eigen value in column-wise). The participation matrix (P) was generated which is the combination of right eigenvector and left eigenvector.

Network Equations for Generation and Load Bus:

The network equations for generation buses are as follows:

$$P_{Li}(V_i) = \sum_{k=1}^{n} V_i V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) - I_{di} V_i \sin(\delta_i - \theta_i) - I_{qi} V_i \cos(\delta_i - \theta_i) \quad (7)$$

$$Q_{Li}(V_i) = \sum_{k=1}^{n} V_i V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) + I_{qi} V_i \sin(\delta_i - \theta_i) - I_{di} V_i \cos(\delta_i - \theta_i) \quad (8)$$

The network equations for load buses are as follows:

$$P_{Li}(V_i) = \sum_{k=1}^{n} V_i V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) \quad (9)$$

$$Q_{Li}(V_i) = \sum_{k=1}^{n} V_i V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) \quad (10)$$

Power Flow Analysis

Newton Raphson method is used for the power flow analysis of the integrated network system. The flow chart of the power flow analysis is presented in figure 3. The node voltage and the impedance of each line are subjected to initialize and the mismatch matrices of active power (P) and reactive power (Q) are calculated. The mismatch matrices are used to determine the solution of the equations presented in equation (7) and (8) for generator bus and equation (9) and (10) for load buses. If the solution is not converged, then the Jacobian matrix is formed to solve the equations and then the voltage and voltage angle are determined. The Jacobian matrix for 3-bus system is presented in equation 11.

$$\begin{bmatrix} \Delta Q_3 \\ \Delta P_2 \\ \Delta P_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial Q_3}{\partial V_3} & \frac{\partial Q_3}{\partial \delta_2} & \frac{\partial Q_3}{\partial \delta_2} \\ \frac{\partial P_2}{\partial V_3} & \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial \delta_3} \\ \frac{\partial P_3}{\partial V_3} & \frac{\partial P_3}{\partial \delta_2} & \frac{\partial P_3}{\partial \delta_3} \end{bmatrix} \begin{bmatrix} \Delta V_3 \\ \Delta \delta_2 \\ \Delta \delta_3 \end{bmatrix} \quad (11)$$

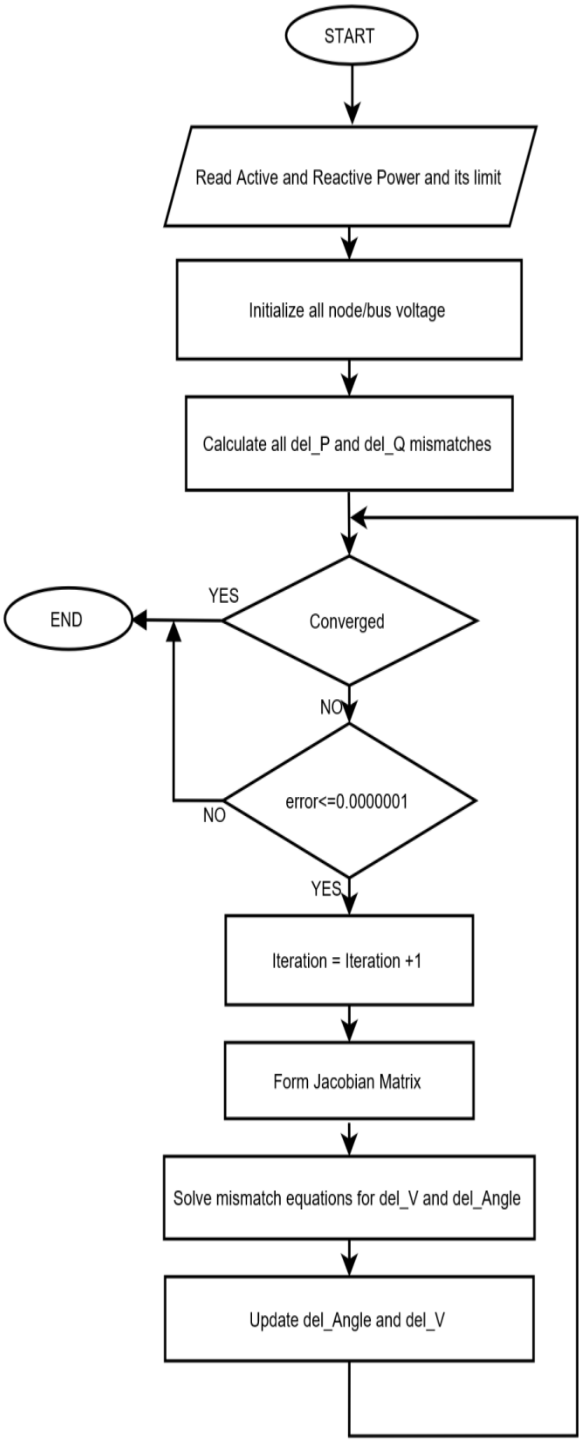


Figure 3: Flow Chart for Newton Raphson Method of Power Flow

III. Model Development and Results

The proposed methodology, which has been described in section II of this paper, uses to evaluate the Eigen values and participation factor. The proposed methodology for stability analysis, Eigen vector determination and sensitivity analysis is coded in MATLAB scripting language and is tested for standard IEEE – 9 bus system consisting 3 machines. The IEEE bus test system is considered for the benchmark of the study in this research for validation and verification of the model and method. The proposed methodology code is firstly verified for IEEE standard bus systems and then it is applied for Integrated Nepalese Power System networks. Cost of Renewable Energy Spreadsheet Tool (CREST Tool) has been used in order to check financial viability of the technology. The obtained results are described in subsections below.

A. Model Building

IEEE 9 Bus System is used as a Test System for this study. Modeling of IEEE 9 bus system and INPS of Nepal is carried out on using MATLAB.

The IEEE 9 bus test system is presented in figure 5 which includes three synchronous machines. In this system, bus 5, 6, and 8 are the load buses.

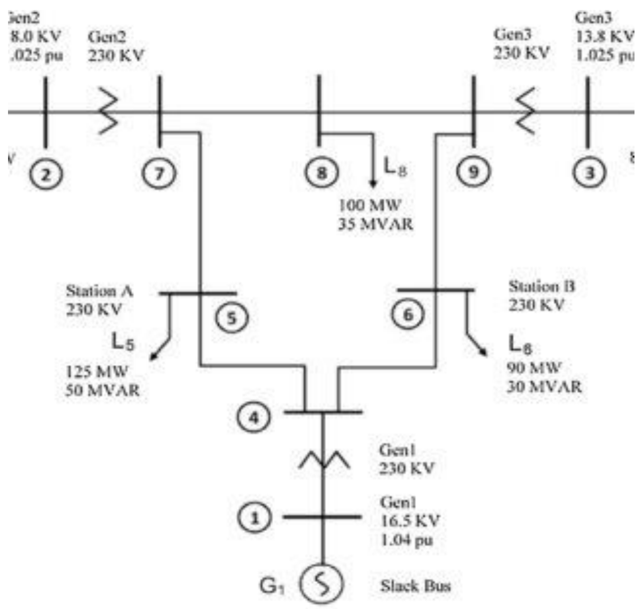


Fig 4: IEEE 3 machine 9 bus system

The following assumptions are made during the modeling INPS and study:

1. The 66 kV bus and higher voltage bus system is considered for the Integrated Nepalese Power System (INPS).
2. The total sixty – six bus is included in the system. In eastern region and western region of Nepal, the INPS system is almost radial structure which is lumped to a point to get minimum errors in load flow solution. The eastern region power generation and load are lumped to Dhalkebar substation and western region power generation and load are lumped to Butwal substation. After this, the total bus in the system is forty-three and analysis is performed for the forty-three bus system

Table 1: Base Case load flow solution

Bus No.	V (pu)	Theta (rad)	P (pu)	Q (pu)
1	1.040	0.000	0.716	0.270
2	1.025	0.162	1.630	0.067
3	1.025	0.081	0.850	-0.109
4	1.026	-0.039	0.000	0.000
5	0.996	-0.070	-1.250	-0.500
6	1.013	-0.064	-0.900	-0.300
7	1.026	0.065	0.000	0.000
8	1.016	0.013	-1.000	-0.350
9	1.032	0.034	0.000	0.000

The variation of minimum Eigen values is presented in table 2. Individually, the best location of DFIG is found to be bus 5 since minimum Eigen value improvement is highest in this bus. In this system, the optimum loading at bus 5, 6, and 8 are 0.79 pu, 0.96 pu and 1.04 pu respectively. When the DFIG connected to bus 5, 6, and 8 simultaneously then the power flow and the Eigen sensitivity is found to be -0.41693 ±*j* 0.4582 with P = 0.94 pu and -0.40671 ±*j* 8.3160 with P = 0.94 pu. The Eigen value plot before and after DIFG connection is presented in figure 5 and figure 6 respectively.

Table 2: Eigen Values for IEEE 9 bus system

Bus	P	Q (-ve)	Eigen Values
5	0.5	0.2	-0.42416 ±j 9.1278
6	0.5	0.2	-0.38835 ±j 8.8458
8	0.5	0.2	-0.41847 ±j 0.4784

The DFIG unit of power 0.5 pu is connected to the system then the load flow solution shows the improvement of voltage limit and power flow. The flow solution after DFIG connection is presented in table 3.

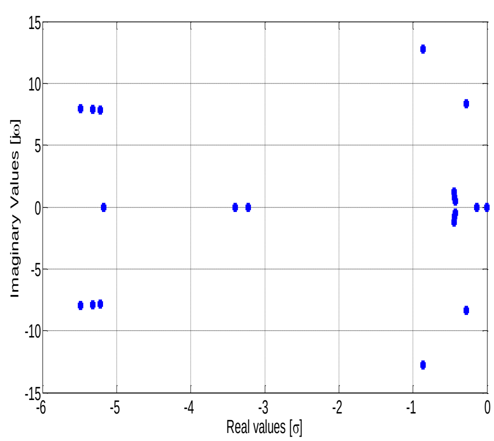


Figure 5: Eigen values Without DFIG

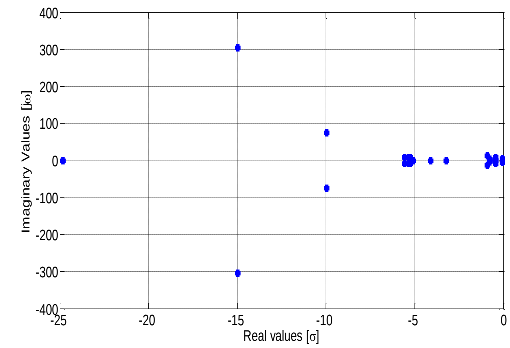


Figure 6: Eigen values With DFIG

Table 3: Load flow solution when DFIG connected

Bus No.	V (pu)	Theta (rad)	P (pu)	Q (pu)
1	1.040	0.000	0.722	0.528
2	1.025	0.163	1.630	0.222
3	1.025	0.080	0.850	-0.033
4	1.012	-0.040	0.000	0.000
5	0.958	-0.070	-1.750	-0.700
6	1.001	-0.066	-0.900	-0.300
7	1.016	0.065	0.000	0.000
8	1.008	0.012	-1.000	-0.350
9	1.028	0.033	0.000	0.000
10	0.951	-0.051	0.500	-0.190

DFIG integrated to INPS System

With the assumptions, the total bus in the system is forty-three and analysis has been performed for the forty-three bus system. The INPS map parameters were used for simulation. The base load flow solution for 43 bus INPS system and the voltage profile was observed.

In the base case without DFIG, most of the Eigen values are falling on imaginary axis with complex value as presented in figure 9. The Eigen value on imaginary axis shows the system is critically stable.

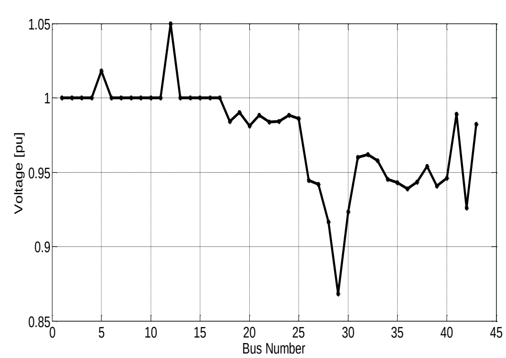


Figure 1: Voltage profile for base load flow solution of INPS system

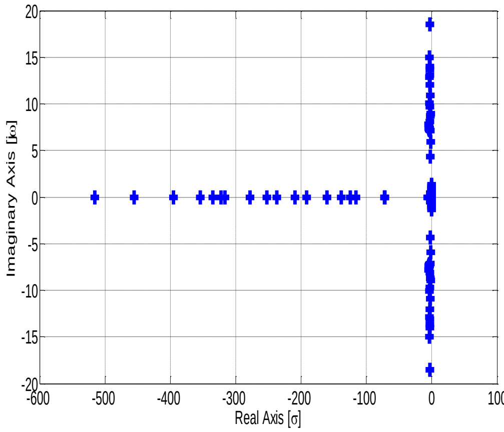


Figure 2: Eigen value plot of INPS system without DFIG

The DFIG connection in the INPS system is considered with five cases for the small signal stability. The DFIG is connected to the bus which is nearest to feasible wind power generation or available wind power generation. In INPS, the six bus selected for DIFG connection are: Balaju 132, Bhaktapur, Nawalparasi, Makwanpur, and Acham. The DFIG active power is variant form 0.1 pu to 0.5 pu for the connection bus and reactive power is variant in respective of active power. The active and reactive power has power factor approximately varies from 0.85 to 0.9 lagging and thus the system has maximum value of Q is 0.4 times of value of P.

Case 1: [Balaju] DFIG Connected to Bus 5 with P=0.5 and Q=0.2

In this case, the DFIG is connected to bus 5with the P and Q value of 0.5 pu and 0.2 pu respectively. The minimum Eigen value in this case is found to be -0.05155 which is real and lies in real axis. The figure 10 shows the plot of Eigen values on imaginary plane which shows that most of the Eigen values are lies on real axis and also at origin and figure 11 shows the Eigen sensitivity. Some of the Eigen values are complex conjugate. The system is more stable than the base case because most of the Eigen values are lies on real axis and also at origin. The farthest pole at real axis is -517.13 and the complex conjugate poles ± j300 are farthest from the origin. The voltage profile is presented in table 5 and the bus voltage at bus 44 is 1.011 pu which is in stable range of (1±0.5) pu. The active and reactive power injected by DFIG system are 0.5 pu and 0.19 pu respectively.

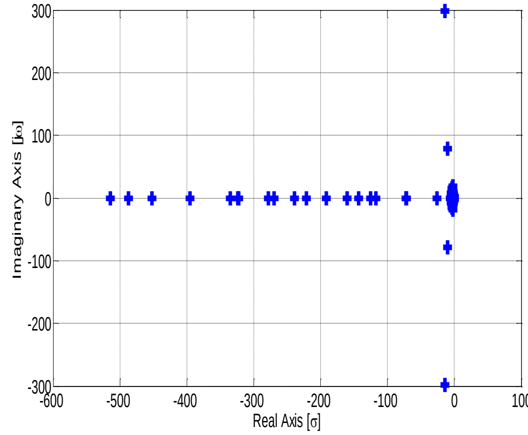


Figure 3: Eigen value plot of INPS system with DFIG for case 1: Balaju

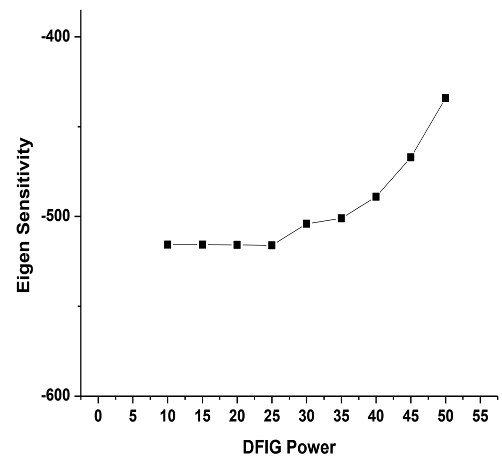


Figure 4: Eigen sensitivity plot for case 1

Case 2: [Bhaktapur] DFIG Connected to Bus 10 with P=0.5 and Q=0.2

In this case, the DFIG is connected to bus 10 which is Bhaktapur in INPS system. The DFIG power to be integrated with the P and Q value of 0.5 pu and 0.2 pu respectively. The minimum Eigen value in this case is found to be -0.0137. The figure 12 shows the plot of Eigen values on imaginary plane which shows that most of the Eigen values are lies on real axis and also at origin. Some of the Eigen values are complex conjugate. Some Eigen values are lies on right side of the imaginary axis. The system is not stable than the base case because most of the Eigen values are lies on right side of the imaginary axis. The farthest from the origin are beyond -500 on left half plane and within 100 on right half plane. The voltage profile is presented in table 6 and the bus voltage at bus 44 is 0.947 pu which is not in stable range of (1±0.5) pu. The active and reactive power injected by DFIG system are 0.5 pu and 0.101 pu respectively.

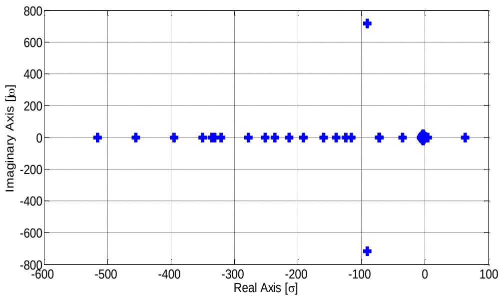
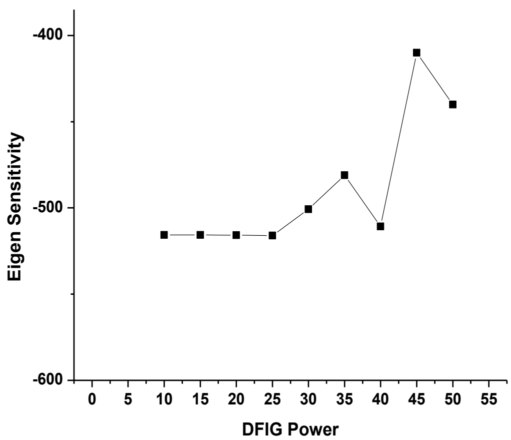


Figure 5: Eigen value plot of INPS system with DFIG for case 2: Bhaktapur



The cases 1 and 2 are selected arbitrarily to show the stability concept using Eigen value analysis. The both cases are compared the base case and shows stability and instability differences. The reactive power is not installed at those locations but considered for the DFIG system. For DFIG system, base value of power is chosen 100 kVA and therefore the power varies as P = 0.1 pu, and P = 0.2 pu for 10 kW and 20 kW respectively. The load flow for 44 bus (one added due to DFIG penetration) was conducted and results showed that voltage profile was within the limit and voltage stability has been observed.

Financial Analysis of Wind Energy

The financial analysis is performed to show the economic reasonability for wind turbine integration and also the variation on energy cost is presented. The financial calculations and certain assumptions are based on reference of National Renewable Energy Laboratory (NREL) and spreadsheet of NREL is used for wind energy calculations. The levelized cost of energy varies with the energy production and is depicted in figure 19. The project capacity factor shows the variation on energy production and corresponding levelized cost is presented. The levelized cost of energy decreases with the increase in capacity factor increment and thus the higher capacity of generation provide the lower cost of energy.

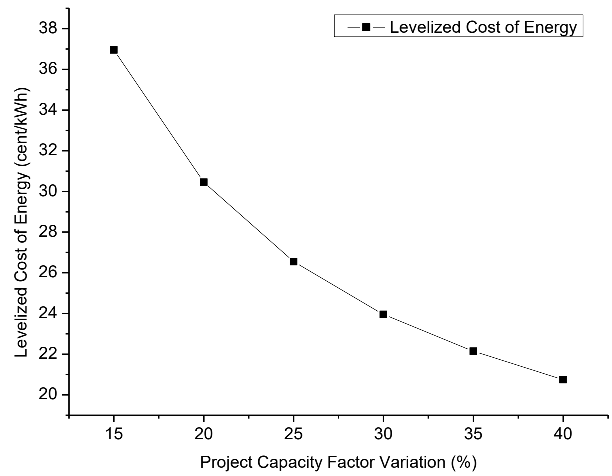


Figure 19: Levelized cost of energy versus project capacity variation

Figure 20 presents the approximate cumulative cash flow for 35% project capacity factor variation which also assumes the subsidy that is provided for wind turbine installation by AEPC. It shows the investment is returned within 5 years from the investment date. The subsidy is not taken as a return value in this calculation. The detail financial analysis has been performed and annual cash flows were plotted to obtain the graph in figure 20.

In financial analysis, project life is considered 25 year and wind energy production variation is considered from 15 % to 40 %. The equity of subsidy is 90% for the installation cost and other cost are financed. In this analysis, it was found that the cost of energy goes on decreasing while increasing of the energy production variation. The analysis shows that the project is feasible in case of Nepalese subsidiaries. The project has NPV zero in 3.14 years or the payback period of the system is 3.14 years and project seems financially feasible.

Figure 6: Approximate Cumulative Cash Flow versus project year

CONCLUSION

The minimum Eigen values for the nine bus and INPS bus systems are compared with that of the corresponding systems with DFIG at different locations, one at a time and also in combination. After connection of DFIGs at load buses of such large multi-machine systems, the improvement in Eigen values occurs. This means the rate of reaching the overall system to steady state becomes faster when DFIG is connected one at a time or in combination. These improvements in Eigen values are location dependent as indicated in the result. The Eigen value sensitivity analysis is done to find the optimum loading at load bus where the DFIG is connected. The more the powers Ptot and Qtot feed by DFIG to grid, the more the improvement in Eigen values. By observing the negative sign in Eigen value sensitivity, the maximum limit of power or the optimum loading to the grid can be determined.

In financial analysis, project life is considered 25 years and found acceptable payback period.

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