JJEE

Volume 3, Number 1, 2017
Pages 75-85

Jordan Journal of Electrical Engineering

ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

High Renewable Energy Penetration Impact on Voltage and Transient Stability

Aouda A. Arfoa

Department of Electrical Power Engineering and Mechatronics, Tafila Technical University, Tafila, Jordan
e-mail: oda@ttu.edu.jo

Received: December 26, 2016 *Accepted: February 11, 2017*

Abstract— Due to environmental and economic concerns, there are numerous attempts to find more efficient and clean ways of generating electric power. High renewable energy penetration (wind energy) has increased. Renewable energy resources penetration into the conventional power grid is a challenging task. In this paper, the high renewable energy penetration impact on voltage and transient stability is studied by evaluating the nature of the relaying system needed, critical clearing time of circuit breakers, voltage level, and transfer capability between systems.

Keywords— Renewable energy, Rotor angle, Synchronous machine, Transient stability, Voltage stability, Wind energy.

I. INTRODUCTION

Due to continuous growth and deregulation in electric power grid, voltage stability is the main problem concerning utilities. The limited fossil fuel based resources and the rising public awareness of environmental protection have created a growing interest in renewable energy resources .The large scale of Renewable Energy Penetration impacts the power system increasingly. One of the effects is shown in voltage stability especially with wind energy penetration. As usual, power system stability needs to be maintained as it is subject to the occurrence of small or large disturbances. The tendency of a power system to restore forces equals to or greater than the disturbing forces. The state of equilibrium is known as stability. If the forces tending to hold machines in synchronism with one another are sufficient to overcome the disturbing forces, the system is said to remain stable (to stay in synchronism) [1]. Large disturbances such as the loss of a generator, a symmetrical fault or short circuit fault, are closely associated with the transient stability related to the dynamic behavior of the system during a fault before the fault is cleared from the system. Small disturbances such as load changes or fluctuations in mechanical power inputs of a generator are constantly perturbing the power system, especially when the influence of variable wind speed is considered in a wind energy conversion system [2].

Transient stability studies deal with the effects of large, sudden disturbances such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads. Transient stability studies are needed to ensure that the system can withstand the transient condition following a major disturbance. A number of methods/algorithms have been proposed in literature for voltage stability analysis. Some of these methods are based on PV-QV curves [3]-[4], continuous power flow [5], basis of probabilistic load flow (PLF), model analysis [6], energy function [7], and bifurcation theory [8]. In [9] the method used is based on unscented transformation (UT), static and dynamic approaches [10]. A method known as the equal-area criterion can be used for a quick prediction of stability. This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance. The method is only

---

Corresponding author's e-mail: oda@ttu.edu.jo

applicable to a one-machine system connected to an infinite bus or a two-machine system. Because it provides a physical insight to the dynamic behavior of the machine, the application of the method to analyze a single machine connected to a large system is considered here.

II. RENEWABLE ENERGY MODEL (WIND ENERGY) FOR STABILITY STUDIES

The construction of wind farms is not universally welcomed because of their visual impact. Environmental effects of wind power are generally less problematic than those of any other power source. Proportion rise increased costs, a need to upgrade the grid, and a lowered ability to supplant conventional production may occur. The intermittency of wind seldom creates problems when using the wind power to supply a low proportion of the total demand. The management techniques such as exporting and importing power to neighboring areas or reducing demand when wind production is low can mitigate these problems.

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power production capacity. Obviously, sites with steady high wind produce more energy over the year [11]

III. SYNCHRONOUS GENERATOR MODELS FOR STABILITY STUDIES

A synchronous machine connected to an infinite bus through a double circuit transmission line (Fig. 1) is considered here as the study system. The model of the third order structure of the synchronous machine, derived in [12] and used here, is described by (1):

$$\begin{aligned}
\dot{\delta} &= \omega \\
\dot{\omega} &= \frac{1}{J}(T_m - T_e - D\omega) \\
\dot{e}'_q &= \frac{1}{T'_{do}}(E_{fd} - e'_q - (x_d - x'_d)i_d)
\end{aligned} \tag{1}$$

The main variables and constants of (1) are:

$$T_e = \frac{v_d.i_d + v_q.i_q}{\omega} \cong \frac{v_d.i_d + v_q.i_q}{\omega_0}; \phi = \tan^{-1}\frac{Q}{P};$$

$$i_d = \frac{e'_q - v_q}{x'_d}; i_q = \frac{v_d}{x_q}; i = \frac{\sqrt{P^2 + Q^2}}{v_t};$$

$$v_d = v_t \sin\delta; v_q = v_t \cos\delta; i_d = i\sin(\delta + \phi); i_q = i\cos(\delta + \phi)$$

$$v_{bd} = v_d - r_e i_d + x_e i_q; v_{bq} = v_q - r_e i_q - x_e i_d$$

$$v_B = \sqrt{v_{bd}^2 + v_{bq}^2}; x_d = x_{ad} + x_l; x_q = x_{aq} + x_l$$

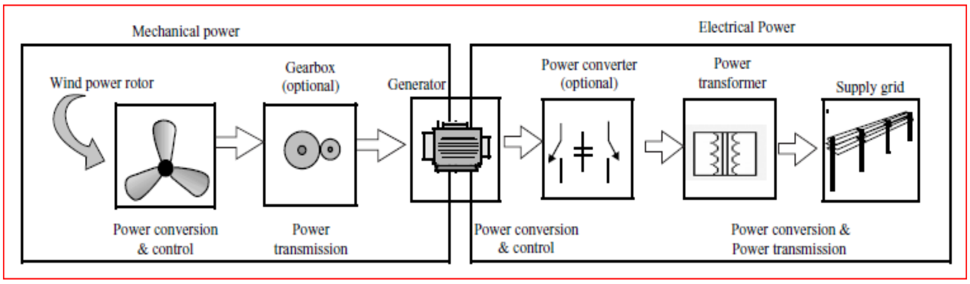


Fig. 1. Wind generation modeling

IV. ANALYSIS TECHNIQUES USING P-V AND Q-V CURVES ANALYSIS METHOD

Both P-V and Q-V curves are widely used methods for predicting voltage collapse incidents by industries [13]. P-V curve analysis is used to determine the voltage stability of a radial system. A large meshed network and P-V curves are useful in deriving how much load shedding should be done to establish pre-fault network conditions even with the maximum increase of reactive power supply generated from the automatic switching of various capacitors or condensers. Q-V curve is the relationship between reactive powers support (Q) and the reception of end voltage for different values of active power P. One of the results that can be reached from the curves Q-V is the sensitivity of the loads to reactive power sources [14].

V. SIMULATION RESULTS: ANALYSIS AND DISCUSSION

A. Voltage Stability Simulation

A.1. Case 1: Without Renewable Energy Penetration

This system, as shown in Fig. 2, has 9 buses 132kV [12] with three synchronous generators connected at bus 2, 3 and 1 when buses 8, 6 and 5 have load. I used IEEE–9 bus benchmark details for simulation purposes. In this case, I examine the 9-bus system without renewable energy penetration. The Q-V curve for bus 5 with 175MW, 275 MW and 375 MW is shown in Fig 3a-c, respectively.

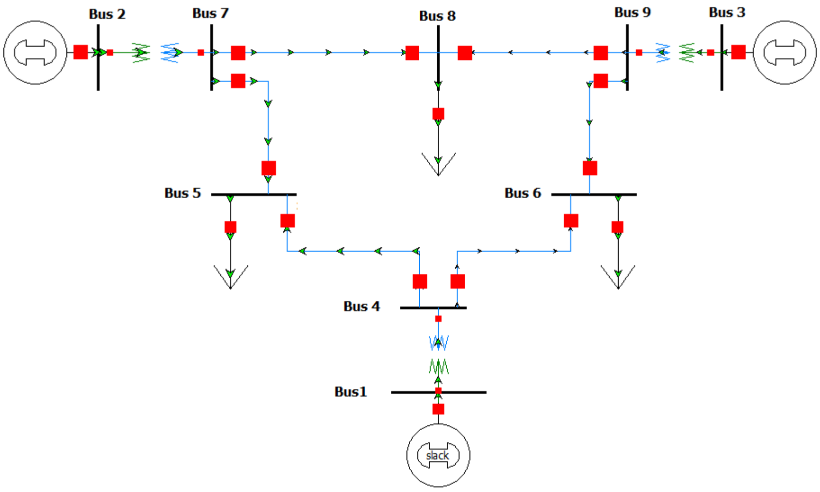
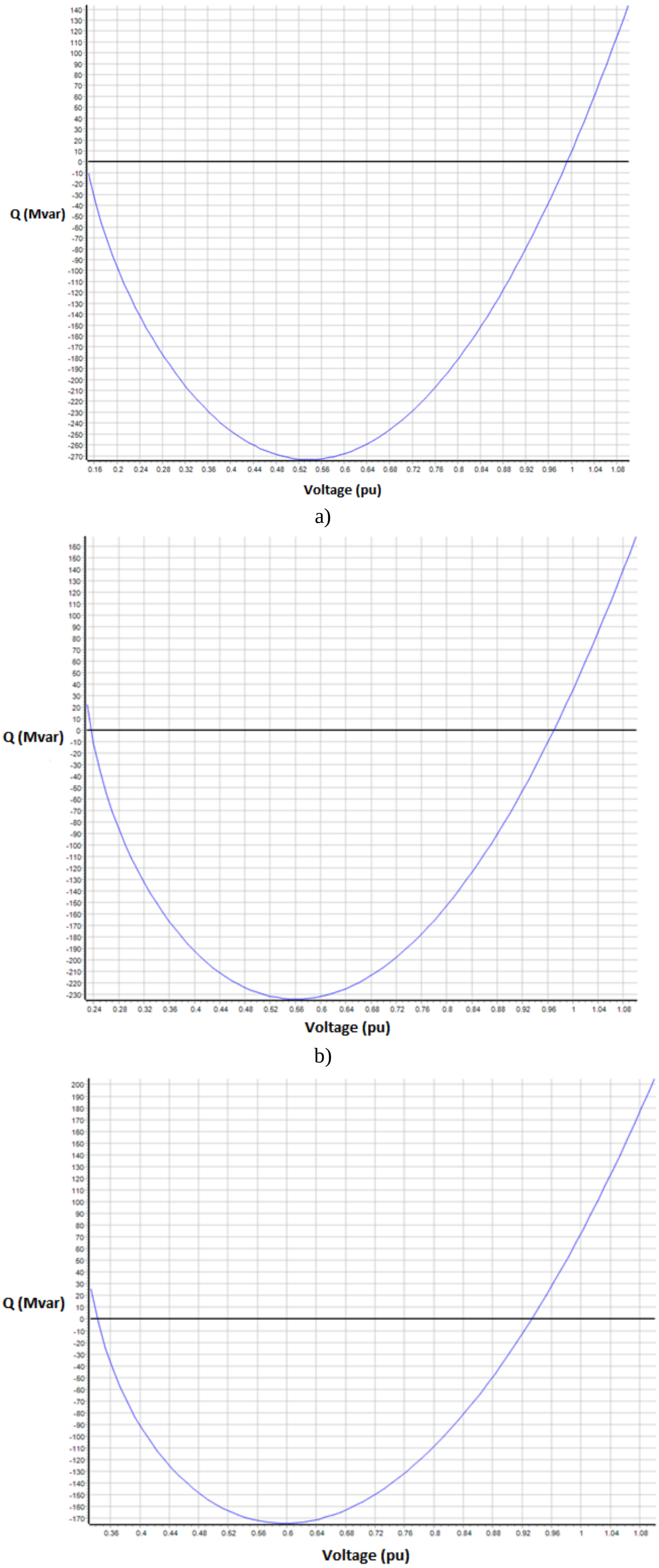


Fig. 2. IEEE 9-bus system without renewable energy penetration



a)

b)

c)

Fig. 3. Q-V curve at bus 5 with: a) 175MW, b) 275MW and c) 375MW

A. 2. Case 2: With Renewable Energy Penetration instead of Synchronous Generator

In this case, I replaced the system with renewable energy resources (wind energy) at bus 3 as shown in Fig. 4. Wind plant is integrated at bus 3 with a step up transformer 0.69/13.8 kV. The integrated wind farm has been taken as an aggregation of 1.5 MW wind turbine type 3. The renewable energy capacity is 117 MW connected with a step-up transformer. The Q-V curve for bus 5 with 175MW, 275 MW and 375 MW is shown in Fig 6a-c, respectively.

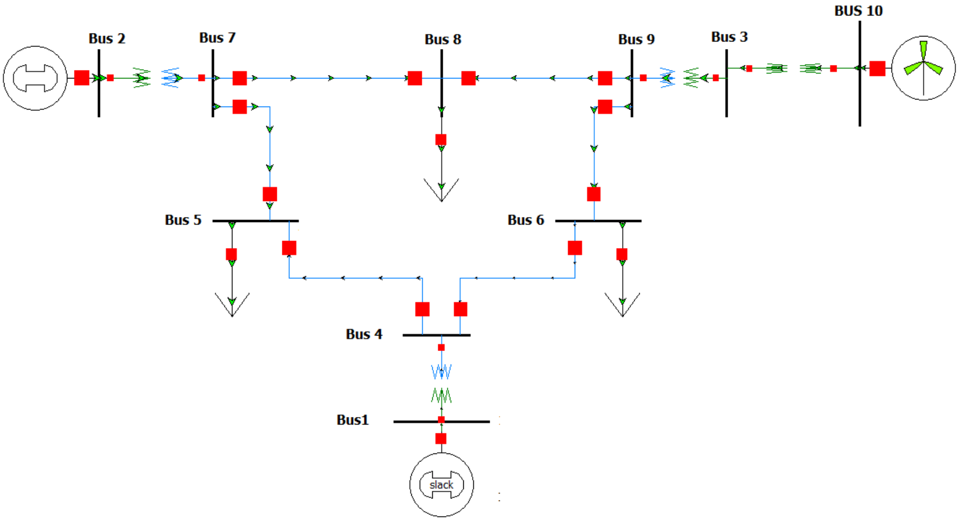


Fig. 4. IEEE 9-bus system with renewable energy penetration at bus 5

A.3. Case 3: Renewable Energy Penetration with the Original System

In this case, I replaced the system with renewable energy resources (wind energy) at bus 8 as shown in Fig. 5. Renewable energy capacity is 117MW connected with a step-up transformer. The Q-V curve for bus 5 with 175MW, 275MW and 375MW is shown in Fig 7a-c, respectively.

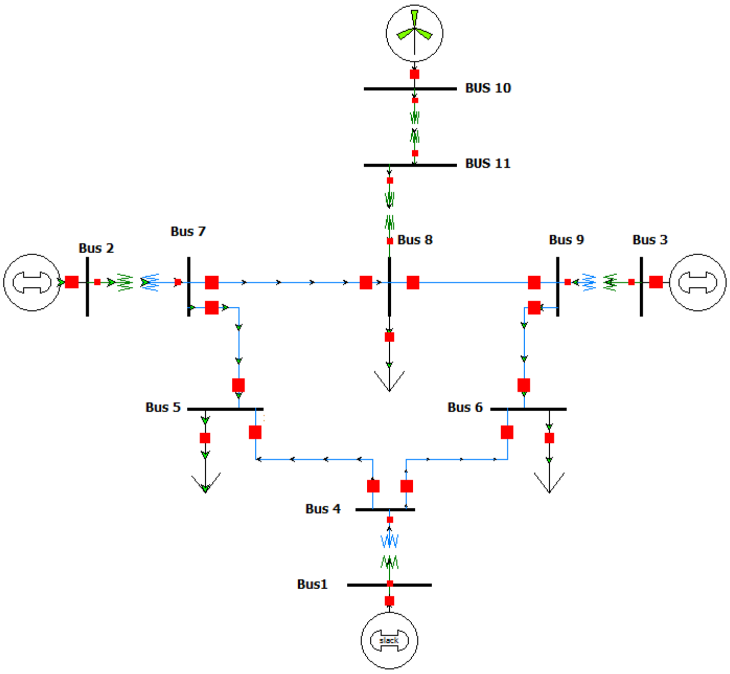
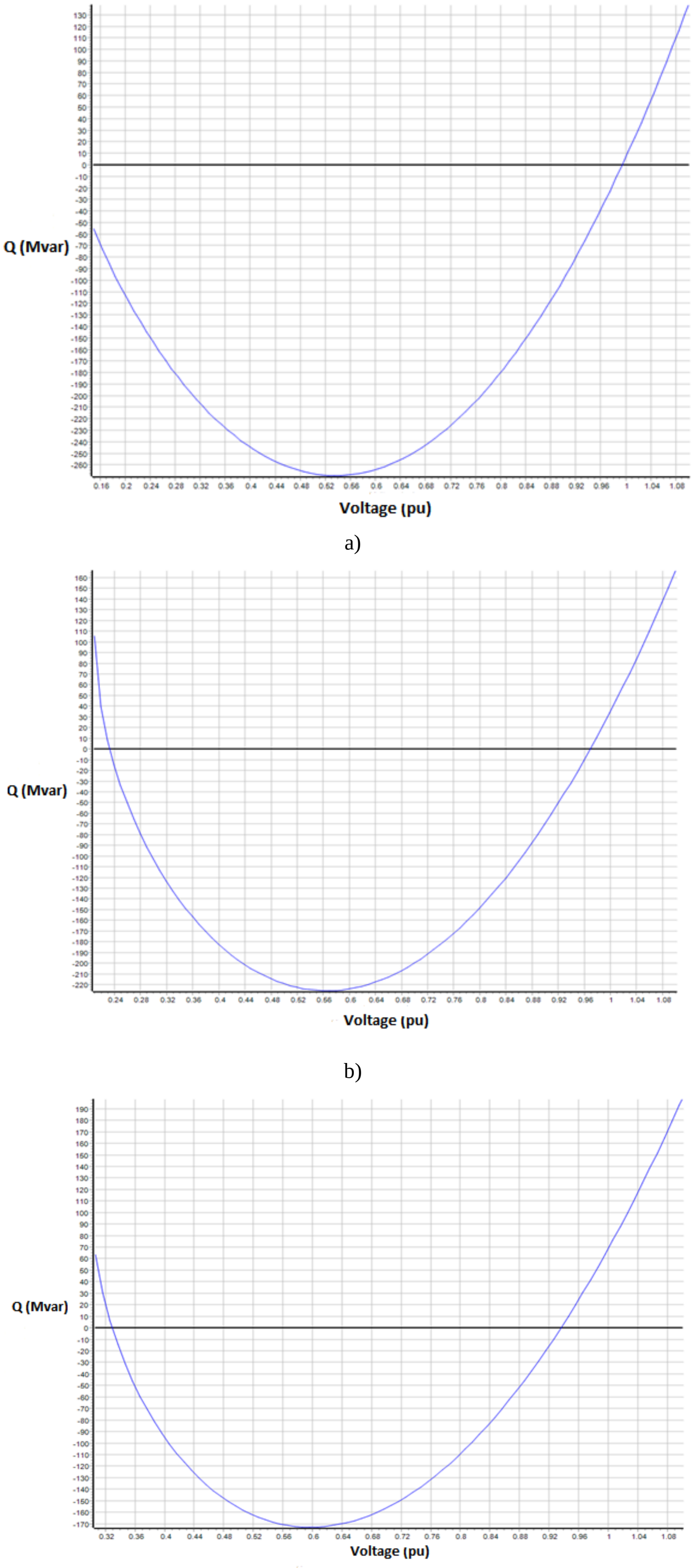


Fig. 5. IEEE 9-bus system with renewable energy penetration at bus 8

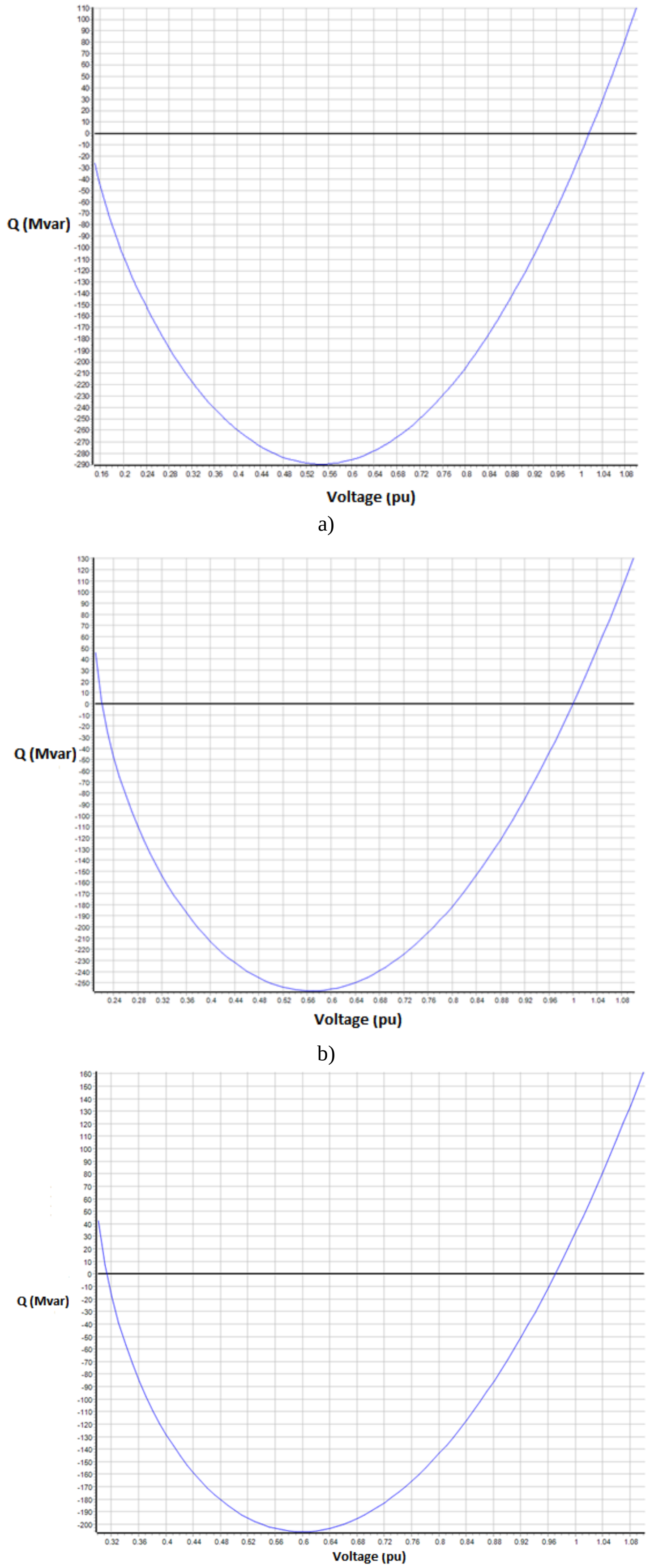


a)

b)

c)

Fig. 6. Q-V curve at bus 5 with: a) 175MW, b) 275MW and c) 375MW



a)

b)

c)

Fig. 7. Q-V curve at bus 5 with: a) 175MW, b) 275MW and c) 375MW

Fig. 6 shows RE penetration instead of one original generator, whereas Fig. 7 represents RE penetration without removing any original generator from the system. By examining Q-V curves at bus 5 based on the location of penetration and presentation of RE penetration, I can see the penetration by replacing one of the existing generators. The percentage of RE penetration is higher than penetration without removing any original generator. Reactive power will decrease, while the RE penetration increases and the system voltage will be more near to instability. The difference in voltage magnitude at all buses in the test system has been shown in Fig. 8. Active power at bus 5 has been increased in steps. The bus voltages 5, 6 and 8 are shown in Table 1. When load is increased to more than 475MW, load flow analysis of test system fails to touch. As shown in Fig. 9, reactive power at bus 5 decreases, but the RE penetration increases. The RE penetration results in the stability of the system voltage.

TABLE 1
VOLTAGE AT BUS 5, 6 AND 8 WITH LOAD VARIATION AT BUS 5

Load at Bus 5, MW	Voltage at Bus 5, p.u.	Voltage at Bus 6, p.u.	Voltage at Bus 8, p.u.
125	1.02266	1.02394	1.08511
175	1.01739	1.02425	1.08430
225	1.00988	1.02318	1.08292
275	0.99991	1.02063	1.08092
325	0.98710	1.01642	1.07820
375	0.97088	1.01028	1.07464
425	0.95031	1.00171	1.07001
475	0.92364	0.98986	1.06389

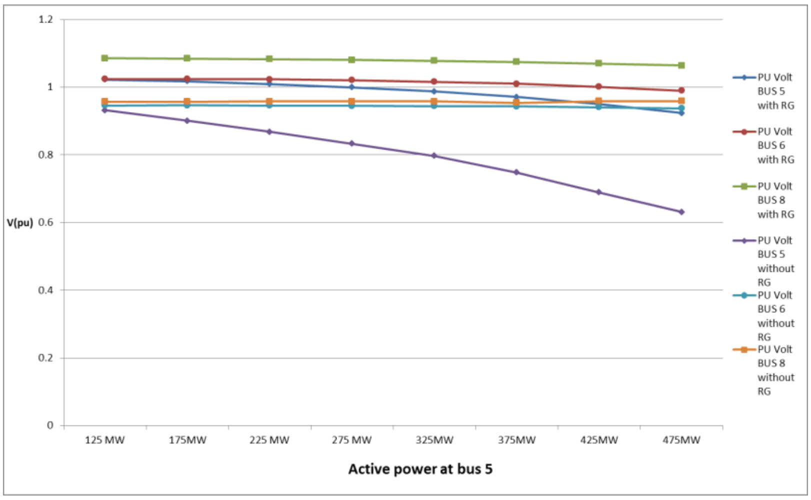


Fig. 8. Variation of voltage versus active power at bus 5, bus 6 and 8 with RE penetration

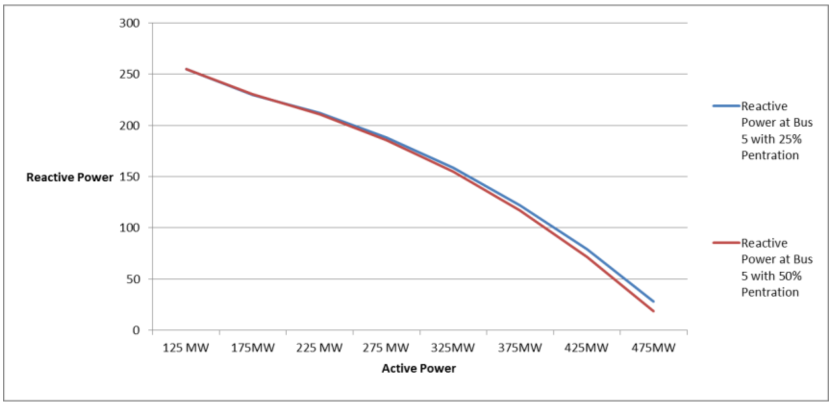
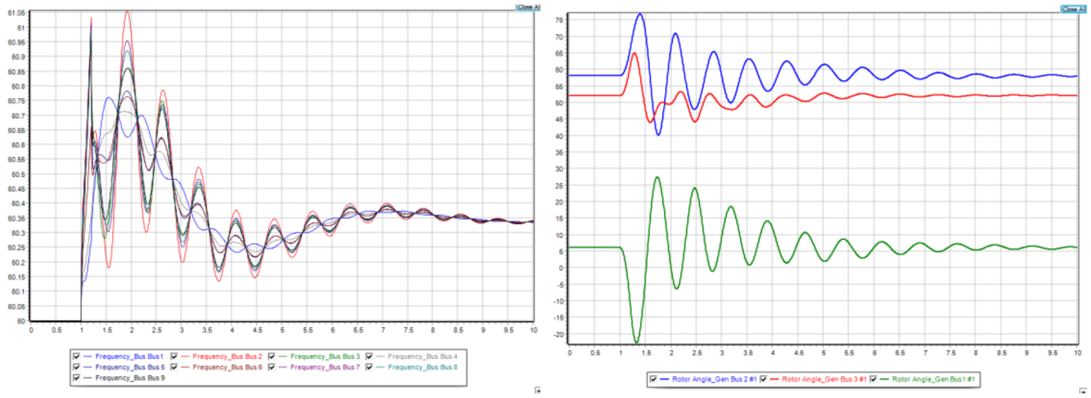


Fig. 9. Reactive power versus active power at bus 5 with 25% and 50% RE penetration

B. Transient Stability Simulation (Fault Analysis)

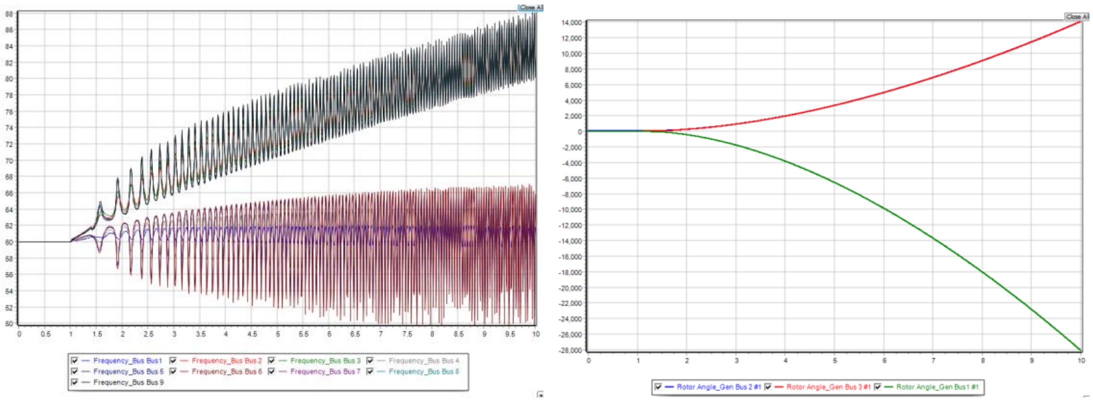
B.1. Case 1: Fault Analysis without Renewable Energy Penetration

A temporary three-phase bolted fault occurs at mid-point of one of the line between buses 5-4. The fault was applied for 0.2s. The frequency and rotor angle curves are shown in Fig. 10. The rotor angle will oscillate back and forth at its natural frequency. The damping present in the machine will cause these oscillations to subside; and a new steady state operation will be established. Thus, the system is unstable when fault is cleared in 0.4s; and phase angle increases without limits as shown in Fig. 11. The simulation is repeated for a clearing time of 0.45s, which is found to be critically stable.



a) b)

Fig. 10. Frequency (a) and rotor angle (b) curves with a three phase fault applied for 0.2s

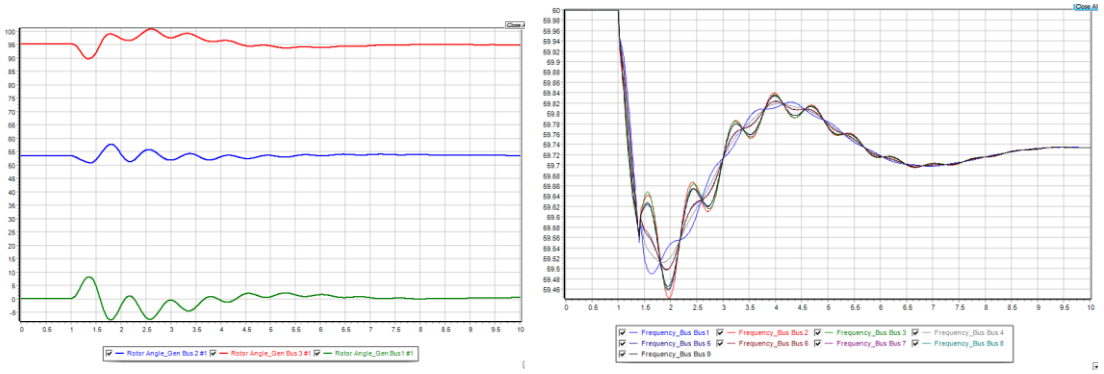


a) b)

Fig. 11. Frequency (a) and rotor angle (b) curves with three phase fault applied for 0.4s

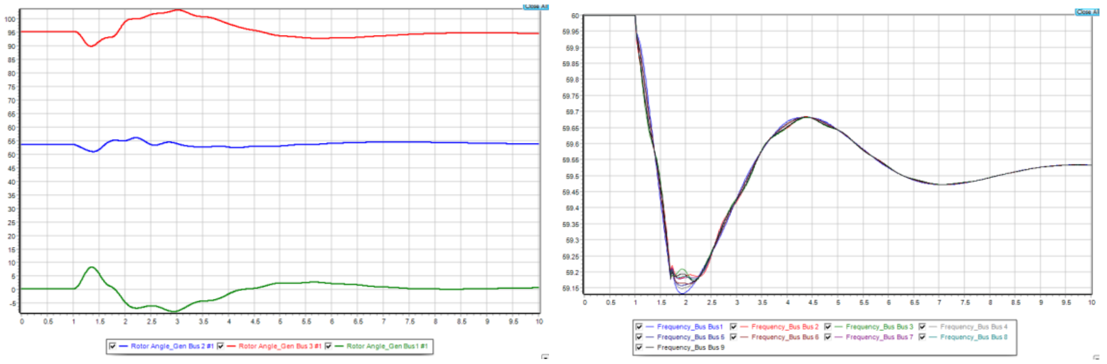
B.2. Case 2: Fault Analysis with Renewable Energy Penetration

A temporary three-phase bolted fault occurs at mid-point of one of the line between buses 5-4 with renewable energy penetration at bus 8. The fault was applied for 0.4s. The frequency and rotor angle curves are shown in Fig. 12. The rotor angle will oscillate back and forth at its natural frequency. The damping present in the machine will cause these oscillations to subside; and a new steady state operation will be established. The simulation is repeated for a clearing time of 0.7s, which is found to be stable as shown in Fig. 13. It can be concluded that with wind energy penetration, the line fault voltage at bus 5 could be collapsed due to decreases in the reactive power margin.



a) b)

Fig. 12. Frequency (a) and rotor angle (b) curves with three phase fault applied for 0.2s



a) b)

Fig. 13. Frequency (a) and rotor angle (b) curves with three phase fault applied for 0.2s

VI. CONCLUSION

In this paper, I examine the impact of RE (wind energy) on 9-bus system on voltage and transient stability. Voltage instability and transient stability detection has been studied and assessed.

Results found for two cases without and with renewable energy penetration with RE penetration instead of one original generator and RE penetration form a system with different penetration percentages. Renewable energy penetration helps reduce the reactive power and dispose the system to voltage instability. Suitable reactive power must be inoculate in the system to mark its voltage stability. The results are expected for the impact of adding wind renewable energy was negative, simply because of the dynamics of the wind system. It can be concluded that, with wind energy penetration, the fault voltage could be collapsed due to decreases in reactive power borders.

REFERENCES

[1] H. Saadat, *Power System Analysis*, McGraw-Hill, 2009.

[2] M. Edrah, K. Lo, and O. Lara, "Impact of high penetration of DFIG wind turbine on rotor angle stability of power system," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 759-766, 2015.

[3] R. Londero, C. Affonso, and J. Vieira, "Long term voltage stability analysis of variable speed wind generators," *IEEE Transactions on Power Systems*, vol. 30, no. 1 , pp. 439-447, 2015.

[4] V. Ajjarapu, *Computational Techniques for Voltage Stability Assessment and Control*, Springer, 2009.

[5] V. Ajjarapu and C. Christy, "The continuation power flow: a tool forsteady state voltage stability analysis," *IEEE Transactions on Power Systems*, vol. 7, no. 1, pp. 416-423, 1992.

[6] R. Schlueter, I. Hu, M. Chang, J. Lo, and A. Costi, "Methods for determining proximity to voltage collapse," *IEEE Transactions on Power Systems*, vol. 6, no. 1, pp. 285-292, 1991.

[7] C. Canizares, F. Alvarado, C. DeMarco, I. Dobson, and W. Long, "Point of collapse methods applied to AC/DC power systems," *IEEE Transactions on Power Systems*, vol. 7, no. 2, pp. 673-683, 1992.

[8] B. Gao, G. Morrison, and P. Kundur, "Voltage stability evaluation using modal analysis," *IEEE Transactions on Power Systems*, vol. 7, no. 4, pp. 1529-1542, 1992.

[9] F. Gubina and B. Strmcnik, "A simple approach to voltage stability assessment in radial networks," *IEEE Transactions on Power Systems*, vol. 12, no. 3, pp. 1121-1128, 1997.

[10] M. Moghavvemi and M. Faruque, "Technique for assessment of voltage stability in ill-conditioned radial distribution network," *IEEE Power Engineering Review*, vol. 21, no.1, pp. 58-60, 2001.

[11] M. Pantos, G. Verbic, and F. Gubina, "An improved method for assessing voltage stability based on network decomposition," *Electrical Power and Energy Systems*, vol. 25, no.5, pp. 324-330, 2006.

[12] M. Rawat and S. Vadhera, "Analysis of wind power penetration on power system voltage stability," *Proceedings of IEEE International Conference on Power Systems*, pp. 1-6, 2006.

[13] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.

[14] M. Kashem, V. Ganapathy, and G. Jasmon, "Network reconfiguration for enhancement of voltage stability in distribution networks," *IEE Proceedings- Generation, Transmission and Distribution*, vol. 147, no.3, pp. 171-175, 2000.