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Voltage stability analysis of wind power plant integration into transmission network of Nepal

Sagar Dharel[1], Rabindra Maharjan[2,*]

[1]*Advanced College of Engineering and Management, Institute of Engineering*

[2]*Pulchowk Campus, Institute of Engineering, Tribhuvan University,*

Corresponding email: rabinmaha@gmail.com

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Abstract

Government of Nepal has realized that wind energy could become a major source of alternative energy to solve energy crisis in the country as well as serve the purpose of energy mix. Various studies have identified several locations with potential for wind power generation in Nepal. The integration of wind power plant to the national grid, however, raises concerns regarding the power system stability. The voltage stability of the grid is a key issue, the effect on which increases with the increase in wind power penetration in the grid. This study performs voltage stability analysis due to high penetration of wind power in Integrated Nepalese Power System (INPS). Both steady state and dynamic stability study is performed using the power system simulation software DigSILENT/PowerFactory for different types of wind turbine generators.

Keywords: *Dynamic study, INPS, voltage stability, wind turbine*

1. Introduction

Wind energy technology has developed and improved a great deal in last two decades with increase in wind turbine sizes but reduction in manufacturing cost (Ackerman, 2012). The reduction in cost has resulted in high penetration of wind energy in the transmission network. For example, wind energy has provided 15 per cent of the EU's electricity demand in 2019 and constitutes the third largest energy source in China (Lee & Zhao, 2019). According to Global Wind Energy Council (GWEC) report 2019, a total of 651 GW of wind energy capacity has already been installed globally with 60.4 GW of wind energy capacity installed in 2019 (Lee & Zhao, 2019). The global wind statistics 2019 by World Wind Energy Association (WWEA) suggested that there are now 112 countries with grid connected wind turbines, out of which 36 countries have more than 1000 MW installed and, 10 countries with more than 10,000 MW. It is the most installed renewable technology all over the world. (IRENA, 2020)

Nepal has high potential of various kind of renewable energy. The Government of Nepal (GoN) has been supporting promotion and development of renewable energy technologies since last two decades. Alternative Energy Promotion Center (AEPC), established by the Government, performed the wind resources assessment under the Solar and Wind Energy Resource Assessment (SWERA) project. The SWERA report, estimated Nepal's gross wind power potential to be 3000 MW. In Nepal, wind potential for power generation is favorable in surrounding hills of Kathmandu Valley, Annapurna range, Tansen of Palpa, Lomangthang of Mustang and Khumbu regions of Nepal (SWERA, 2006; 2008).

Wind turbine technology is constantly evolving and it can be fixed speed or variable speed type, employed with induction generator, synchronous generator or permanent magnet generator, and with or without power electronics converter. Most of the wind turbine technology employ induction generators, which contribute asynchronous power to the system, and as such, a large penetration of wind generation will impact the stability of the system, particularly the voltage stability of the system (Chi et al., 2006; Chen et al., 2009).

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. Voltage instability problems arise in power systems with heavy loads, disturbance or with shortage of reactive power. (Kundur, 1994) The interconnection of induction generator to the grid either demands reactive power from the grid or is provided with less reactive power supply capability in the form of power electronics converters, contributing to voltage instability problems (Pena et al., 1996; Maharjan & Kamalsadan, 2013).

This paper studies the impact of wind turbine integration into Integrated Nepalese Power System (INPS). Both steady state voltage stability analysis and transient voltage stability analysis is conducted using simulation tool DigSILENT/ PowerFactory. Power Voltage (P-V) curves and Voltage-Reactive Power (V-Q) curves are obtained for various points of interconnection in the network for steady state analysis. The voltage recovery characteristic of the wind generator after a three-phase fault is studied in transient voltage stability analysis.

2. Wind Energy Technology

A variety of wind energy conversion systems (WECS) are being used all over the world with different conversion system topology. The most commonly used wind turbine configuration is classified by their ability to control speed. Fixed speed induction generator (FSIG) or Type A and doubly fed induction generator (DFIG) or type C are the two most common wind turbine installed around the world (Ackerman, 2012; Chen et al., 2009).

2.1 Fixed Speed Induction Generator (FSIG)

Fixed speed induction generator (FSIG) are the wind turbines with the induction generator whose rotor speed is fixed regardless of the wind speed. These generators were predominantly employed during early installations of wind generators. These units require reactive power support from the grid and are usually equipped with capacitor banks to provide the necessary reactive power. (Ackerman, 2012)

2.2 Doubly Fed Induction Generator (DFIG)

Doubly fed induction generator (DFIG) is a variable speed wind turbine with partial scale frequency converter. These generator uses wound rotor induction generator and a partial scale frequency converter on the rotor circuit. The partial scale frequency converter performs the reactive power compensation and smoother grid operation Ackerman, 2012; Chen et al., 2009).

Variable speed wind turbines equipped with doubly fed induction generator are becoming more widely used for its advanced reactive power and voltage control capability (Chen et al., 2009). Contrary to fixed-speed wind machines, these are capable of providing reactive power to the grid. The converter and control schemes associated with these machines permit controlling the active and reactive power output to the desired level. The DFIG can be operated in one of two control modes; firstly, fixed power factor (PF) control, where the turbine controls reactive power production in order to achieve a specified power factor; secondly, terminal voltage control, where the reactive power is controlled to meet a target voltage However, the reactive power capability of the PWM converter is not on par with the synchronous generator and when the voltage control requirement is beyond the capability of the DFIG, the voltage stability of the grid is affected (Chi et al., 2006; Srawan KVS, 2014; Maharjan & Kamalsadan, 2017).

3. Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. (Kundur, 1994) The main factor causing instability is the inability of the power system to meet the demand for reactive power. Voltage stability of a power system is affected by various system elements and parameters. Strength of transmission network and power transfer level, generator reactive power/voltage control limits, load characteristics, characteristics of reactive compensation devices, action of voltage control devices such as on-load tap changers, etc. affect the voltage stability. For the purpose of analysis voltage stability is classified into two classes: small disturbance voltage stability and large disturbance voltage stability.

3.1 Small Disturbance Voltage Stability

Small-disturbance voltage stability is concerned with a system's ability to control voltages following small perturbations such as incremental changes in system load. This concept is useful in determining the change in system voltage, at any instant, in response to the small changes in the system. The basic processes contributing to small-disturbance voltage instability are essentially of a steady-state nature. There are various methods for analysis of voltage stability such as Power Voltage (P-V) curves and Voltage-Reactive Power (V-Q) and static analysis (Kundur, 1994). The PV curves and VQ curves can be effectively used to determine stability margins and stability limits of a power system. (Sulaiman, 2015)

3.1.1 PV curves

PV curve is a relationship between bus voltage and the injected power. The PV curve in an interconnected network is drawn with the help of series of load-flow solutions (Kundur, 1994). After a bus is identified as point of interconnection (POI) of wind turbine-, the wind active power injection at that bus is gradually increased and the system load is adjusted according to the new generation to obtain the PV curve. The process is performed for three different types of wind turbine.

i	Wind turbine 1-	FSIG no load compensation
ii.	Wind turbine 2-	FSIG with load compensation
iii.	Wind turbine 3-	DFIG

3.1.2 VQ curves

VQ curve is a powerful tool for steady state voltage stability analysis. It gives the relationship between bus voltages and the reactive power injections or absorptions. It helps in determining the steady state voltage stability limits, reactive power margins of the system and the sensitivity of the bus voltages with respect to the reactive power injections (Taylor, 1994). VQ curves at the POI for the three wind turbines presented in section 3.1.1 are obtained by a series of load flow solutions for different active power outputs.

3.2 Large Disturbance Voltage Stability (Transient Voltage Stability)

Large disturbance voltage stability is concerned with a system's ability to control voltages following a large disturbance such as system faults, loss of generation or circuit contingencies. This ability is determined by the system load characteristic and the interactions of controls and protections. The study period of interest may extend from a few seconds to tens of minutes. The typical approach to study the large disturbance voltage stability is to run time domain simulation under different scenarios. (Cutsem, 1998) During the simulation of transient analysis, generic dynamic data of generators are used. Built-in model of exciter and governor are used as controllers of the generators. IEEE type 1 and HYGOV are the built-in models of automatic voltage regulators and governors used respectively. The dynamic model of wind generators is also implemented in the DigSILENT/ PowerFactory.

4. Description of Studied System

Analysis is performed in three different buses in INPS as the point of interconnection which are Suichatar (132 kV), Pokhara (132 kV) and M. Marshyangdi (132 kV). Fig. 1 shows portion of INPS with wind integration in the above-mentioned buses shown inside red circle.

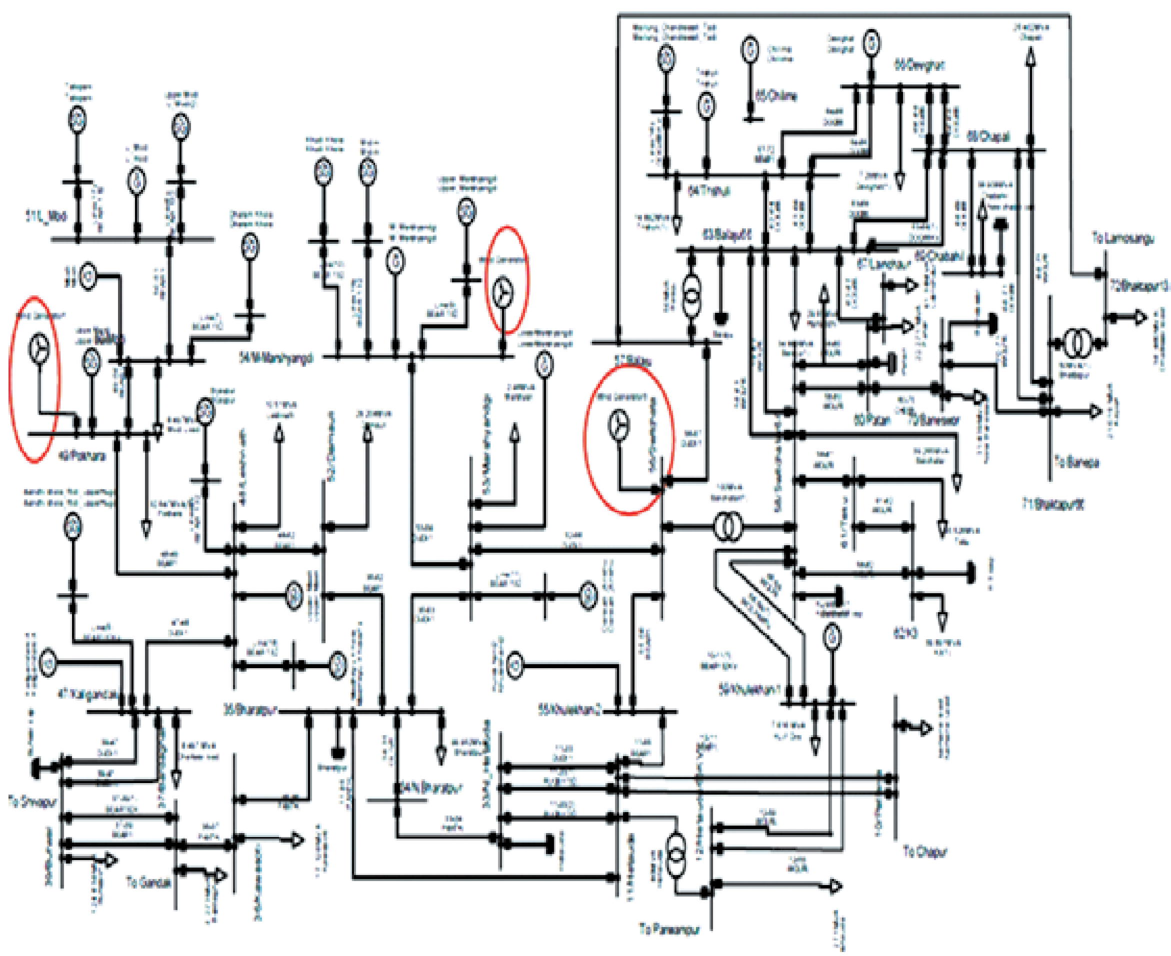

Figure 1: INPS network

Analysis of wind penetration with different type of wind turbines are performed. For each type of wind turbines presented in section 3.1.1, PV curves and VQ curves are obtained through a series of load flow solutions. For transient voltage stability analysis, voltage recovery characteristics of FSIG and DFIG wind turbine is studied in each of the three locations.

5. Steady State Voltage Stability Analysis

5.1 PV Curve Analysis

Wind turbine based on different generators are connected into the transmission grid. When the wind turbine output is low the POI voltage is not significantly affected. As the wind turbine output goes on increasing the POI voltage reduces significantly and decreases fast near the voltage collapse point. The PV curves of the buses as the wind turbine active power increased are shown in Fig. 2 to Fig. 4.

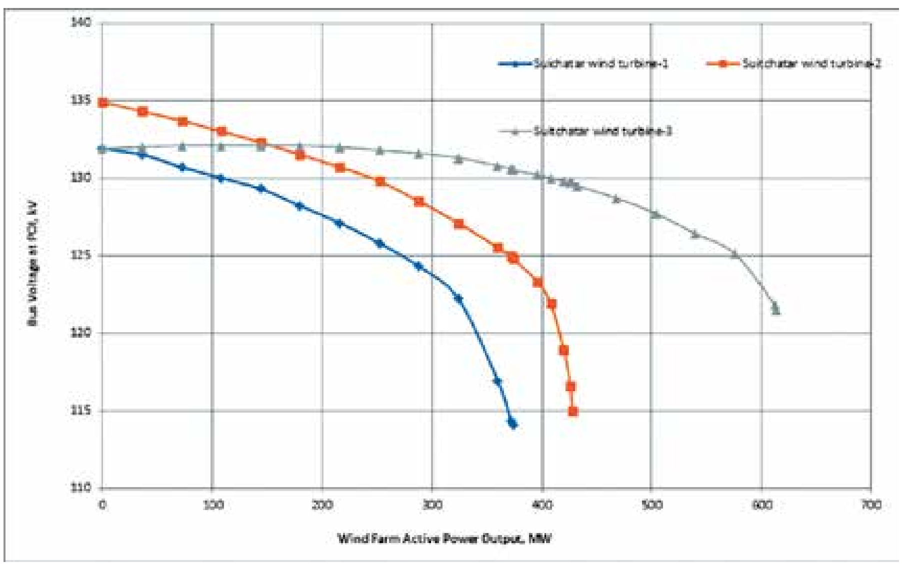

Figure 2: PV curves at Suichatar

The base voltage of Suichatar bus is 131.9 kV (1 pu). In the case of wind turbine-1, the bus voltage is maintained around 1 pu for low wind penetration i.e. around 36 MW. As the penetration is higher the rate of decrease in the voltage is increased. The voltage drop is sharp around the nose point which is 374 MW, 114.1 kV (0.86 pu). In case of wind turbine--2, 75 MVAR compensation is used and the voltage has risen to 134.9 kV (1.02 pu) and the voltage stability limit has slightly improved. The nature of the curve remains similar to the wind turbine-1. In case of wind turbine-3, the voltage stability limit is a very high value, 614 MW; nearly double than in case of wind turbine--1. The voltage of the bus remains 1 pu for a large part of the curve, moreover, voltage profile of the bus has slightly increased for penetration up to 200 MW. The nose point (active power limit) for the three different turbines vary as they have different reactive power capability. Wind turbine-1, do not have reactive power generation capability hence, requires reactive power support from the grid and the active power limit is the lowest. The active power injection limit can be increased by increasing the reactive power capability of the reactive power compensating devices or by increasing reactive power capability of PWM converters for wind turbine-3.

The base voltage of Pokhara bus is 131.4 kV (0.995 pu) similar to Butwal bus. However, the voltage stability limit of Pokhara bus is much lesser than Suichatar bus. The impact of wind integration is higher in this bus voltage than the Suichatar bus indicating Pokhara bus is a weak bus. The voltage stability limit is 184 MW, 219 MW and 372 MW for wind turbine--1, wind turbine--2 and wind turbine--3 respectively.

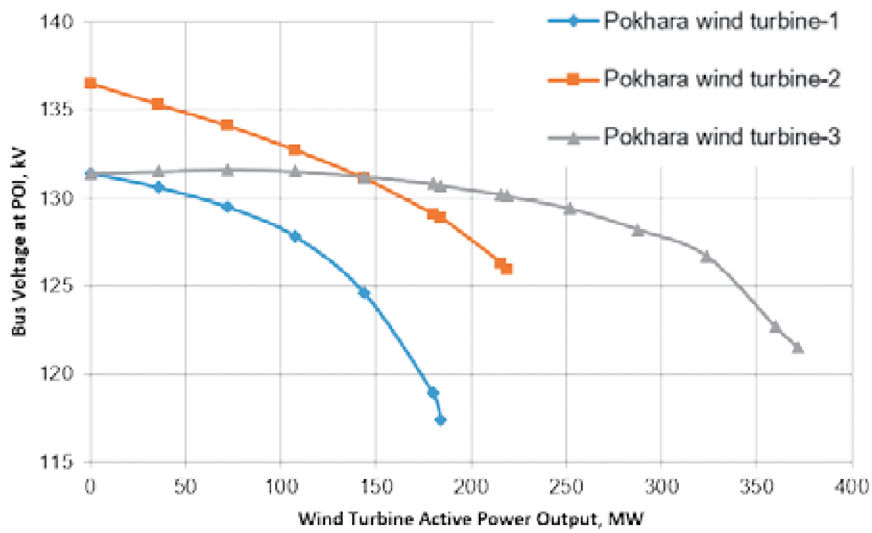

Figure 3: PV curves at Pokhara

The peculiar nature of PV curves in M. Marshyangdi bus is attributed to the assignment of the bus as a voltage-controlled bus. M. Marshyangdi generator is directly connected to this bus and Upper Marshyangdi, Midim and Khudi Khola generators are connected by radial lines. M. Marshyangdi and Upper Marshyangdi are operated on voltage control mode set at 1 pu. Thus, Wind integration via this bus does not affect the bus voltage until the reactive power capabilities of the generators are not exceeded. Once the reactive power of the generators has been exceeded, further wind integration makes the system unstable. The voltage stability limit is 257 MW, 314 MW and 440 MW for wind turbine--1, wind turbine--2 and wind turbine--3 respectively.

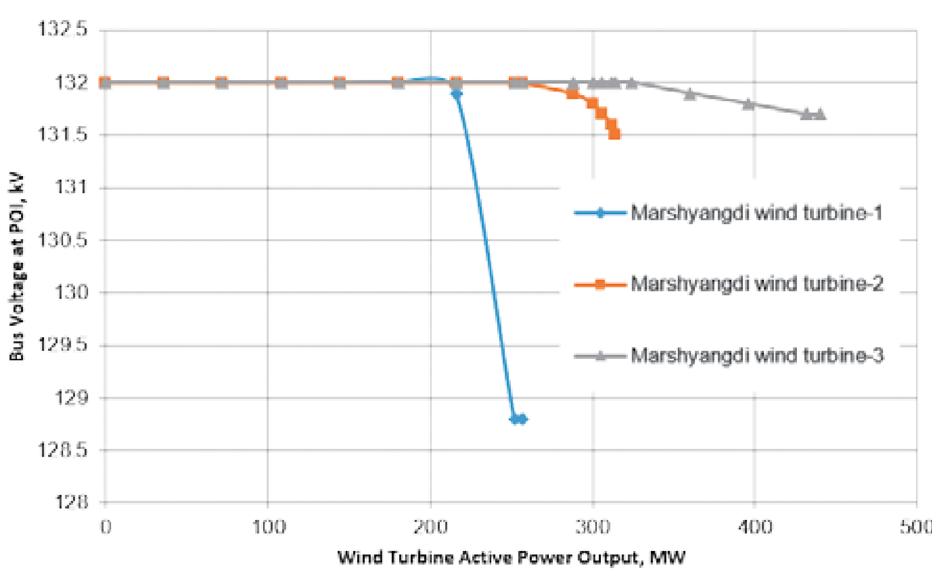

Figure 4: PV curves at M. Marsyangdi

5.2 VQ Curve Analysis

The VQ curves of the buses for different types of wind turbines are shown in Fig. 5-10. The reactive power margin in all three types of wind turbines decreases as the wind turbine active power output increases. However, the reactive power margin decreases significantly in case of wind turbine-1 and wind turbine-2 whereas wind turbine-3 has lesser impact. The reactive power margin without wind penetration is 790.83 MVAR in Suichatar bus which decreases to 362.95 MVAR in case of wind turbine-1, 398.9 MVAR in case of wind turbine-2 and 675.5 MVAR in case of wind turbine-3, when the active power output of each wind turbine is 252 MW. The reactive power margin in wind turbine-3 is about twice that of wind turbine-1.

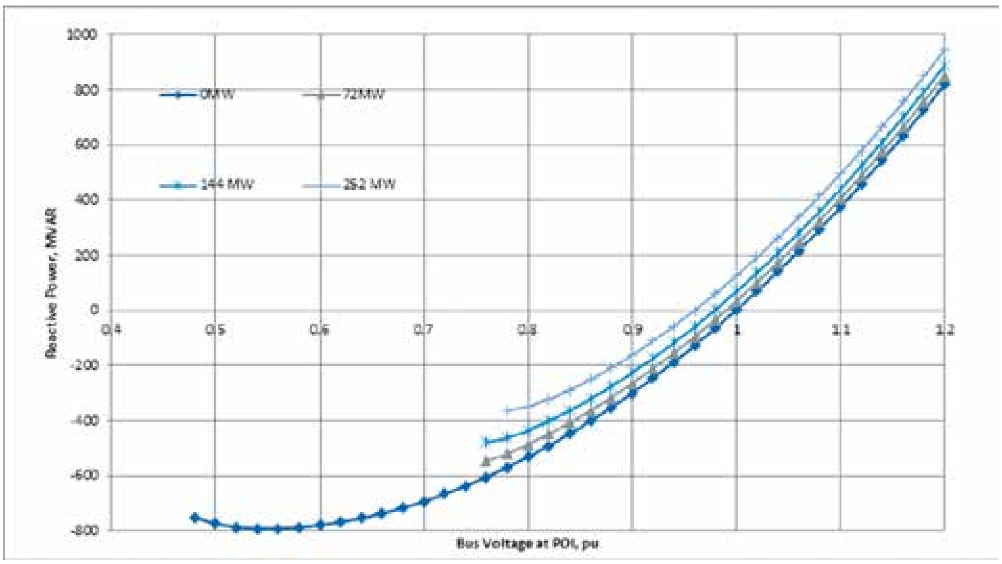

Figure 5: VQ curves at Suichatar for Wind Turbine 1

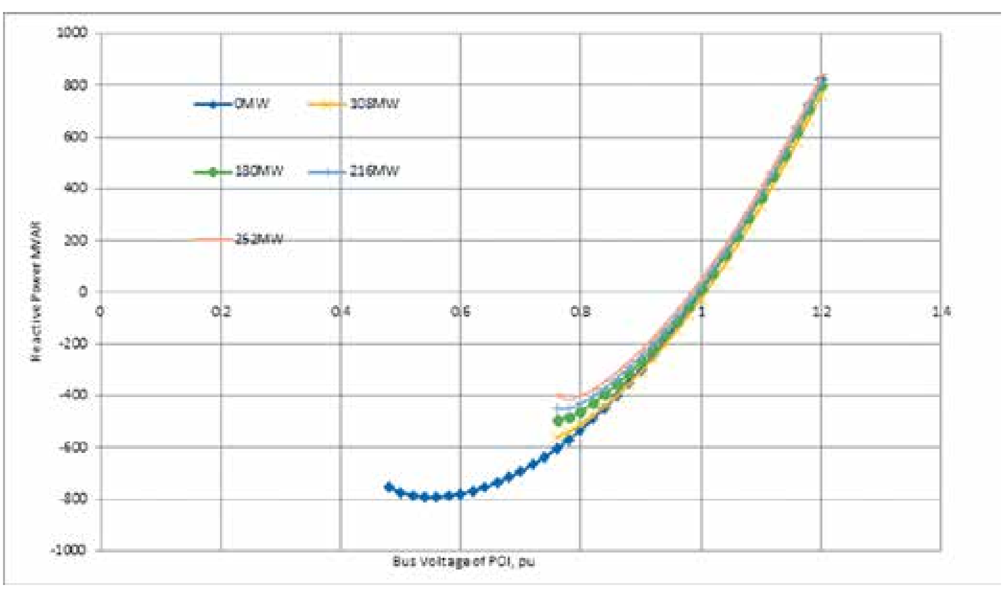

Figure 6: VQ curves at Suichatar for Wind Turbine 2

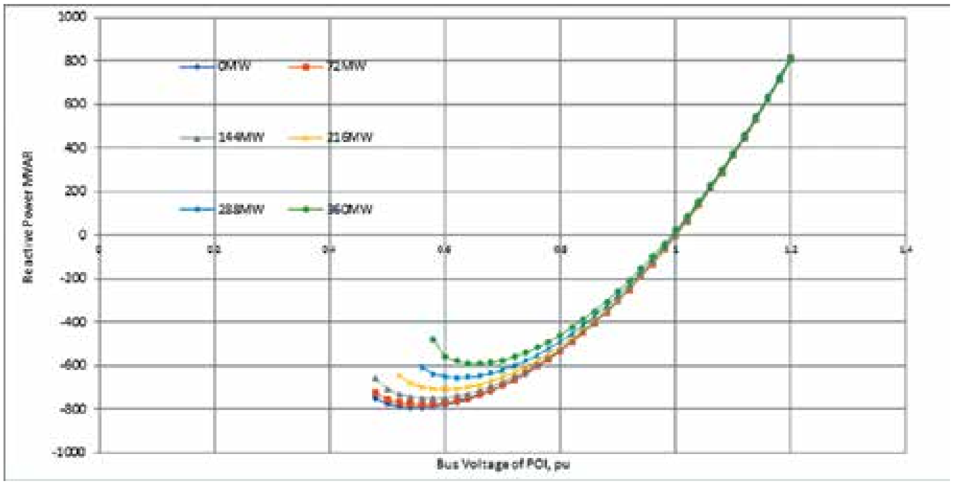

Figure 7: VQ curves at Suichatar for Wind Turbine 3

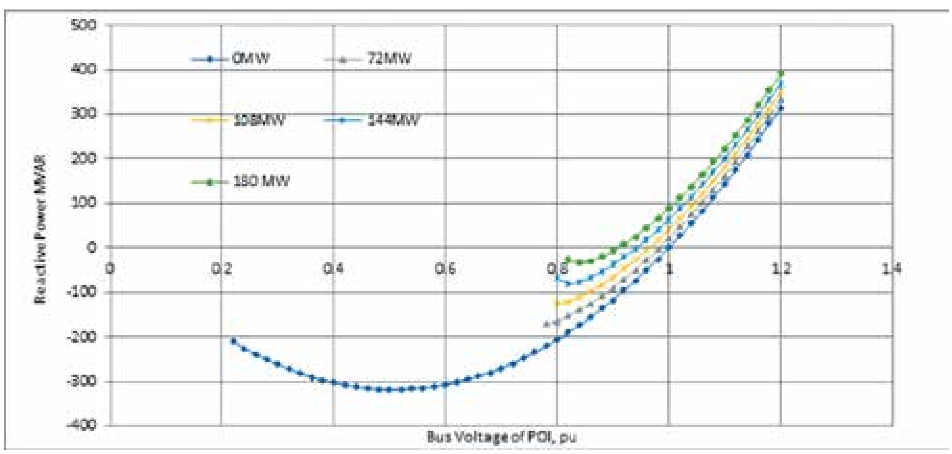

Figure 8: VQ curves at M Marsyangdi for Wind Turbine 1

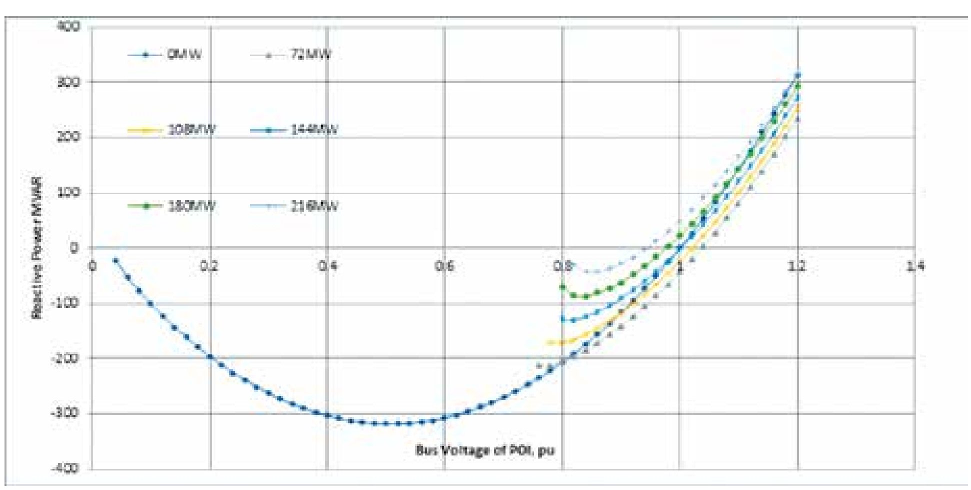

Figure 9: VQ curves at M Marsyangdi for Wind Turbine 2

While constructing the VQ curves of M. Marshyangdi bus, the generator is operated in power factor mode. Construction of VQ curve requires a voltage-controlled element to be connected to the bus whose voltage setting is varied to get various results of voltage and reactive power. If the bus is already a voltage-controlled bus the load flow cannot be performed as there are more than one voltage-controlled elements with different settings.

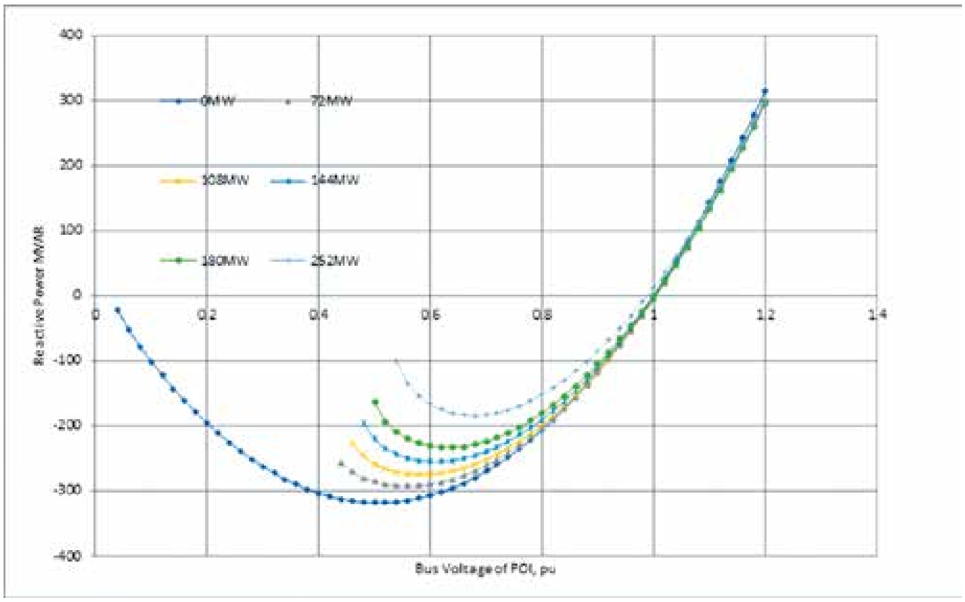

Figure 10: VQ curves at M Marsyangdi for Wind Turbine 3

The initial reactive power margin of 318.14 MVAR is decreased to 26.7 MVAR, 69.2 MVAR and 233.2 MVAR in case of wind turbine-1, wind turbine-2 and wind turbine-3 respectively when the active power output of each wind turbine is 180 MW.

Similarly, the VQ curves of Pokhara bus are also obtained for various active power output of wind turbine based on different generators. The initial reactive power margin in Pokhara bus is around 514.39 MVAR. When the wind turbine active power output is 144 MW, the reactive power margin decreases to 176.97 MVAR in case of wind turbine-1, 253.14 MVAR in case of wind turbine-2 and 446.36 MVAR in case of wind turbine-3. Even if the active power output of wind turbine-3 is increased to 288 MW (twice of 144MW), the reactive power margin is greater than in the case of wind turbine-1 with 144 MW output.

6. Transient Voltage Stability Analysis

In transient voltage stability analysis, the voltage response of wind generator is studied after the application of an external three-phase fault on a line. The voltage recovery characteristics i.e., whether the wind generator can acquire a stable voltage after application of three phase fault is studied. The switching time i.e., tripping of the faulted line is taken as 150 ms.

6.1 Transient Voltage Stability of FSIG

Fig. 11-12 show the generator voltage response and reactive power consumed by a single generator of 6 MW capacity in a wind farm connected. Generally, a wind farm contains numerous wind turbine and power is fed to common point to the POI. Since all the wind generators in the wind farm are identical with same voltage response and reactive power characteristics., study of only one generator is enough.

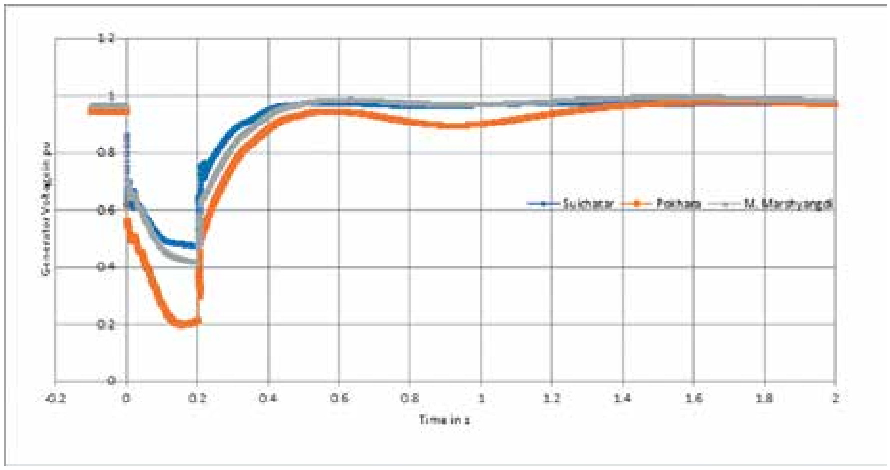

Figure 11: Voltage recovery characteristic of FSIG

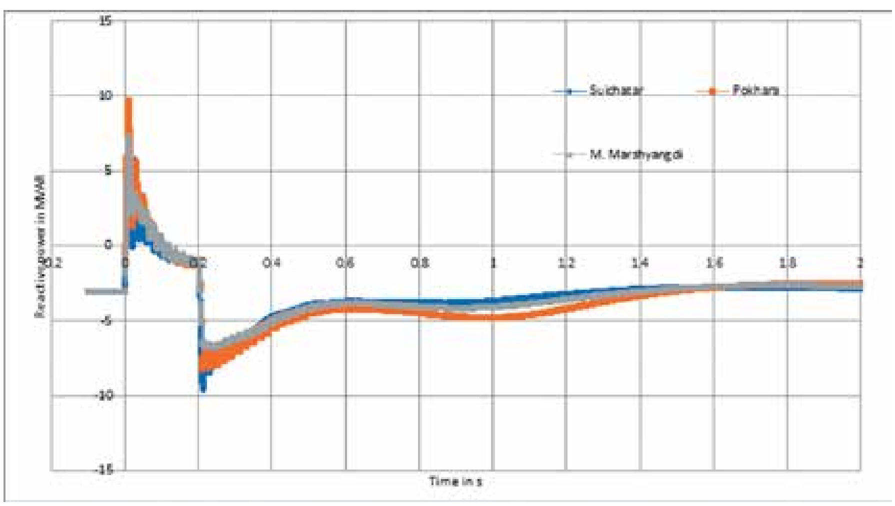

Figure 12: Reactive power consumption of FSIG

At Suichatar bus, the short circuit fault is defined in Suichatar-Marshyangdi line at time T= 0s and the line is tripped after 150 ms. The voltage recovery characteristics of the wind generator for varying amount of wind penetration is studied. The voltage reaches as low as 0.4 pu but ultimately recovers and attains a steady value of 0.98 pu. It can be seen that before fault the reactive power consumption of the wind generator is 3 MVAR and during transient period the consumption is as high as 9 MVAR. It is observed if the installed capacity of FSIG is larger than 96 MW in Suichatar bus, then the system does not regain steady state even if the fault is cleared in infinitely small time. When all the generators in the wind turbine are considered, there will be large reactive power consumption which affects the stability of the system.

At Pokhara bus and M. Marshyagndi bus, the fault is defined in Lekhnath-Damauli line and Marshyangdi line respectively. Fig. 11 and 12 show the voltage and reactive power response of FSIG of 72 MW and 36 MW installed capacity in Pokhara bus and M. Marsyangdi bus respectively. The system fails to converge if the installed capacity of the wind farm is increased further.

6.2 Transient Voltage Stability of DFIG

Fig. 13 to Fig. 16 shows the voltage characteristics and the reactive power consumption of DFIG for different buses. The fault occurs at time T=0s and the time frame of study is taken as 2 s. The DFIG is on PQ control mode with Q=0 MVAR prior to the fault. However, during fault the DFIG also consumes reactive power in transient period and affects the generator voltage and hence, the stability of the system.

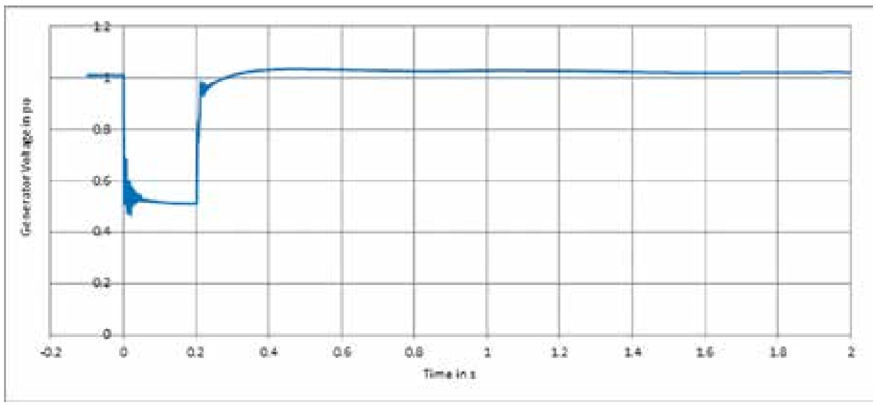

Figure 13: Voltage recovery characteristic of DFIG at Suichatar

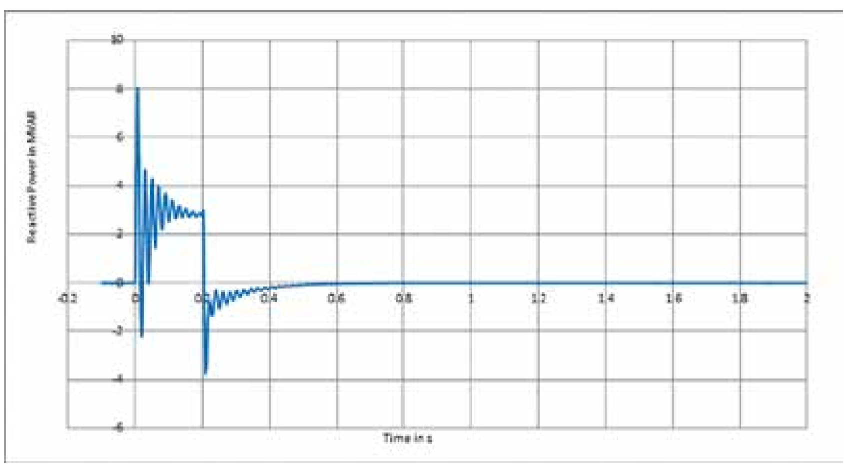

Figure 14: Reactive power consumption of DFIG at Suichatar

Figure 13 and Figure 14 shows the voltage and reactive power response of DFIG with capacity of 120 MW connected to Suichatar bus. The system fails to converge for more than 120 MW installed capacity of the wind turbine. The step size for the time axis in the transient simulation when wind farm is connected to Suichatar bus is different than Pokhara bus and M. Marshyangdi bus, and hence the result is shown in separate figures.

7. Discussion

Integration of wind farm of different technologies in three different buses in INPS showed that the Pokhara bus of INPS is weaker among the three buses as the penetration limit is the lowest and wind integration has noticeable impact on the voltage level, even for small penetration. Suichatar bus as POI is the best location for wind penetration in INPS among the three locations. VQ curves of various location showed that the reactive power margin of the POI is largely affected by FSIG whereas DFIG has lesser impact.

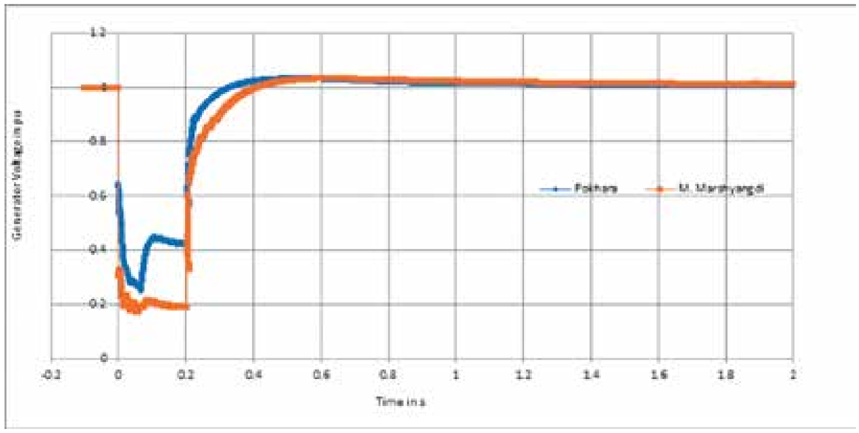

Figure 15: Voltage recovery characteristic of DFIG

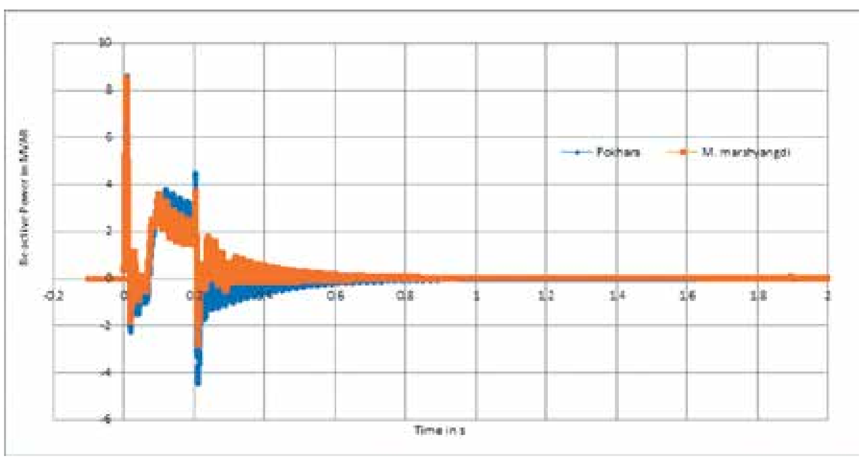

Figure 16: Reactive power consumption of DFIG

Fig. 15 and Fig. 16 shows the voltage recovery characteristics and reactive power response of DFIG connected to Pokhara bus and M. Marshyangdi bus. The installed capacity of the wind farm is 90 MW and 66 MW for Pokhara and M. Marshyangdi respectively. The system fails to converge for DFIG of larger installed capacity.

The steady state voltage stability limit showed that the limit for wind penetration in a network is large but such penetration was not possible due to transient voltage stability. In case of Suichatar bus the steady-state limit is 374 MW and 614 MW for wind farm-1 and wind farm-3 respectively. However, the transient voltage limit is only 96 MW for wind farm-1 and 120 MW for wind farm-3. Similarly, for other buses, the transient voltage limit is significantly lower than steady state limit. The voltage recovery characteristics of the wind farm are lost if the wind penetration is higher than the transient voltage limit. The transient voltage limit for M. Marshyangdi bus is 36 MW for wind farm-1 and 66 MW for wind farm-3, which is the lowest among the four buses.

8. Conclusions

The study demonstrated the voltage stability limit of wind penetration of INPS. The wind power penetration capacity at locations with high power potential was determined for different kind of wind turbines in existing INPS system. Further study on the impact of the wind turbines on the frequency stability and control coordination of active and reactive power for stability enhancement can be done.

Conflict of Interests

Not declared by authors.

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