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Investigating the effect of high level of wind penetration on voltage stability by quasi-static time-domain simulation (QSTDS)

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Abstract- In this paper, the impact of increasing in wind energy penetration level on voltage stability is studied by utilizing quasi-static time domain simulation (QSTDS). Connecting a squirrel cage induction generator (SCIG)-based wind farm has an undesirable effect on the voltage stability in power system, especially when this connection is accompanied through the increase of wind penetration level. Due to the asynchronous operation of induction machine, the increment of wind power generation will be possible only by absorption of more reactive power. Increasing in the power reactive consumption of induction generator leads to reduction of voltage in that bus which connect the wind farm to the grid. In such conditions, if the reactive power absorption of wind farm is not managed efficiently it cause to the voltage instability. In this paper, it is shown that using static var compensator (SVC) and static synchronous compensator (STATCOM) has improved the voltage stability of the system, which is improve the wind power generation delivery and leads to desirable performance of the wind farms.

Keywords Voltage Stability; Induction Generator; Reactive Power; Quasi-Static time domain simulation (QSTDS).

1. Introduction

In recent years, with the development of renewable energies, wind energy has gained a considerable share of power generation in grid. The increasing growth of price of Oil and petroleum products together with the environmental concerns have caused the share of renewable energy and especially wind generation in supplying energy to maintain its ascending trend and have convinced experts to plan for its further development. By growth rate of sharing of wind energy generation in supplying the load demand, studying the effect of wind farms on power system stability is getting more emphasis.

One of the important issues in connection of large scale wind farms to power grid is their effects on the power system satbility that includes voltage, angle, and frequency stability [1], [2]. The squirrel cage induction wind turbine generators (SCIGs) are widely used in power systems because of their simple design, robust and cost-effective performance [1]. In addition to the mentioned benefits, it should be considered that the induction generator as a reactive power consumer will have a significant effect on the voltage stability of system.

In this paper, the impact of SCIG-based wind farm on grid and their effect on increasing of voltage stability with regards to the inability of reactive power generation in SCIG are investigated. The results of carried out wide researches indicate that supplying the reactive power has great importance for supplying the reactive power demand of induction generator and also for improving system stability [3]. So far several methods have been presented for studying system voltage stability in presence of wind farms. Most of these researches such as [4], have focused on static voltage stability by utilizing the continuation mthods. Refrence [5] presents time-domain nonlinear dynamic simulations for voltage stability analysis by continuation power flow (CPF). In fact, in CPF method the results remain well-behaved in the proximity of point which voltage would collapse, and it is the most important feature of CPF. This method prevents the Jacobian matrix from becoming singular at the critical point [6], this feature considered as an advantage of this method. Also, in references [7]-[9], several continuation and convergent algorithms such as optimal power flow (OPF) and maximum loading margin (MLM) have been used for investigating and determining the static stability margin of voltage. So far in most of carried out studies the induction generator has been modeled based on PQ and PV models. However, in this paper, besides using the dynamic model of induction generator, the quasi-static time domain simulation (QSTDS) method is used to model the increase in penetration of wind energy generation and to investigate the voltage stability of wind farm. It is shown that by using this method for simulating of increasing in the penetration of wind energy acceptable results are obtained. In following, the role of the stability of wind farm bus and the role of supporting reactive power by means of equipments such as SVC and STATCOM in improving voltage stability is investigated. In [4] and [10], in addition to explaining the bases of QSTDS, have compared the results of QSTDS with the results of methods that are based on continuation algorithms and they have even concluded that the QSTDS has a more acceptable performance.

2. Voltage Stability

Voltage stability of a power system in steady state is defined as its capability to keep the bus voltages in a certain acceptable range after the occurrence of a disturbance. In other words, the voltage profile in different buses of system would be acceptable [11]. Voltage instability and significantly voltage collapse occur in such systems that they are not able to supply the reactive power demand of loads under fault or overloading conditions [3]. Impact of reactive power on fault and overloading conditions have been the subject of many studies [11], [12]. The voltage collapse could be defined as a successive process of events which leads to voltage instability results in black out or a low and unacceptable voltage profile in a major part of system.

The problem of voltage stability could be studied in two domains; static and dynamic. In static voltage stability, the reason for the occurrence of instability lies in gradual growth of load. Therefore, it is also called the small disturbance voltage stability. While, in dynamic voltage stability, the main reasons of instability can be the occurrence of large and sudden disturbances such as unforeseen loss of generation, sudden loss of load, and other system faults.

3. Squirrel Cage Induction Generator (SCIG)

The instantaneous power produced by the movement of air masses that blow to the area *Ar* Which is equivalent to the area swept by turbine blades, which could be calculated using the following equation:

$$P_{wind} = \frac{1}{2}\rho_{air}.A_r.v_w^3 \quad (1)$$

Where, ρ_{air} is the air density and v_w is the wind speed. The portion of wind power which is absorbed by the wind turbine is given by a coefficient C_p known as coefficient of power. Eventually, the output power of turbine is calculated as follows:

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}v_{wind}^3 \quad (2)$$

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \quad (3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (4)$$

$$\lambda = \frac{R\omega}{v} \quad (5)$$

As it is observable from the equation (2), the power generated by the wind turbines has a direct relation to the wind speed so that the smallest change in wind speed would result in a great change in the generated power. Fig. 1 shows the mechanical power generated by the turbine as a function of generator shaft speed, for different values of wind speed and a pitch angle of β=0.

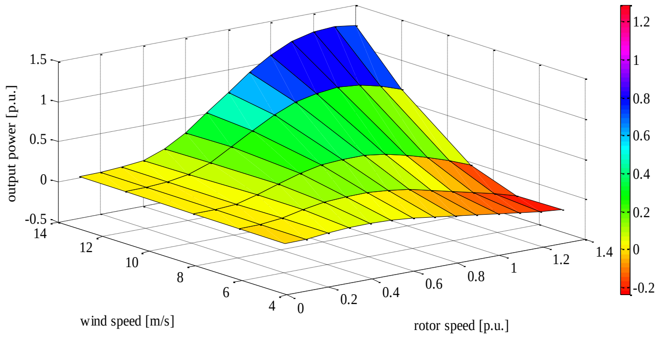

Fig. 1. The mechanical power of wind turbine versus changes in wind speed and rotor speed.

In voltage stability studies, with the decrease of voltage, the power that delivered form induction generator to grid also decreases because of its dependency on the power delivered to the bus voltage. In this section, a simple model of induction generator with regards to its steady state equivalent circuit, is presented in Fig. 2 in order to show the dependency of the active and reactive powers of induction generator on voltage and slip.

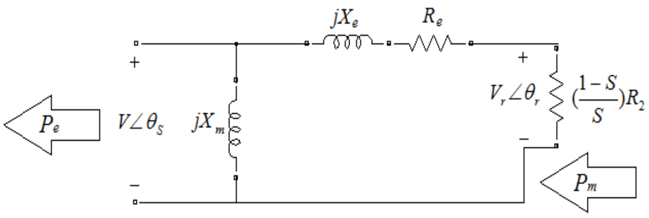

Fig. 2. The equivalent circuit of squirrel cage induction generator.

By referring the rotor parameters to stator side we obtain:

$$-V_r - \left(\frac{1-s}{s}\right) R_2 I_r = 0 \Rightarrow I_r\angle\theta_r = \frac{-V_r\angle\theta_r}{\left(\frac{1-s}{s}\right)} \tag{6}$$

$$-V_r\angle\theta_r + I_r\angle\theta_r(R_e + jX_e) + V_s\angle\theta_s = 0 \tag{7}$$

And by carrying out some calculations and some simplifications:

$$|V_r| = \frac{|V_s|\left(\frac{1-s}{s}\right)R_2}{\sqrt{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2}} \tag{8}$$

$$P_m = \frac{|V_s|^2\left(\frac{1-s}{s}\right)R_2}{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2} \tag{9}$$

$$P_e = P_m - R_e\frac{P_m^2}{V_r^2} \tag{10}$$

$$Q_e = -X_e\frac{P_m^2}{V_r^2} - \frac{V_s^2}{X_m} \tag{11}$$

By substituting equations (8) and (9) into equations (10) and (11), the output active and reactive powers could be obtained as follows:

$$P_e = \frac{|V_s|^2\left[\left(\frac{1-s}{s}\right)R_2-R_e\right]}{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2} \tag{12}$$

$$Q_e = -\frac{|V_s|^2}{X_m} - X_e\frac{|V_s|^2}{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2} \tag{13}$$

These two equations express that how the active and reactive powers are related to voltage and slip implicitly. Fig. 3(a) and (b) show the active and reactive powers of the induction generator described by the above equations.

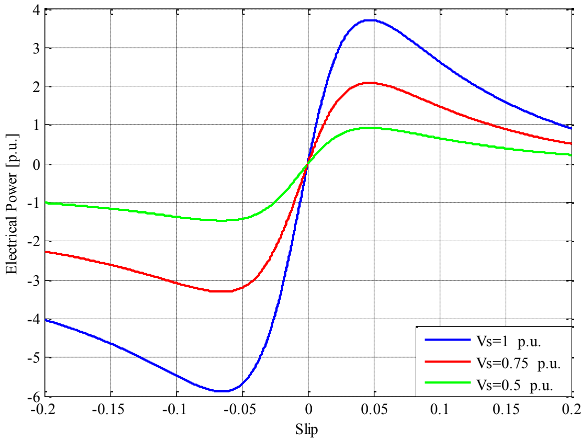

Fig. 3 (a) The power-slip characteristics of induction machine.

Previous researches have shown that the faults occurring in a power system could be related instability (over speed) of induction generator and consequently result in voltage instability of the network [13], [14]. As a matter of fact the decrease in bus voltage which the wind farm is connected through, it cause to reduction of active power output of induction generator. As it is shown in Fig.4 (a), at a fixed wind speed i.e. at a fixed input mechanical torque, the reduction of the output power of generator creates unbalance between the input and output powers of induction generator. This unbalance emerge as increase of speed and finally increase of slip. With the increase of slip, the induction generator absorbs more reactive power and this increment in the consumption of reactive power decreases the voltage of bus that wind farm is connected to it more and worsens voltage instability (Fig. 4 (b)).

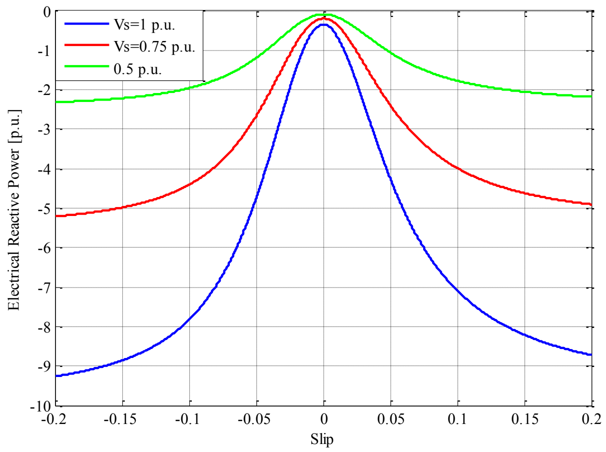

Fig. 3. (b) The reactive power-slip characteristics of induction machine.

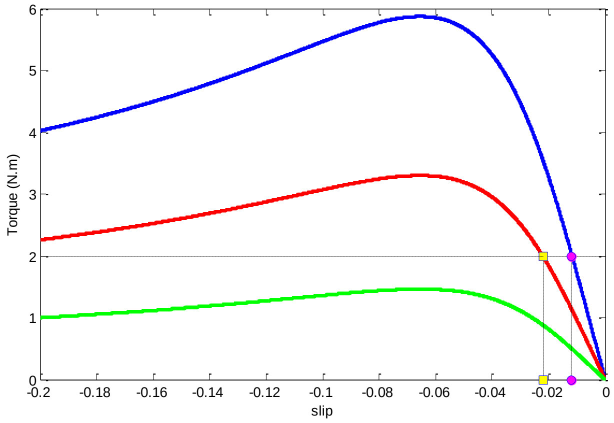

Fig. 4. (a) The power-slip characteristics of induction generator.

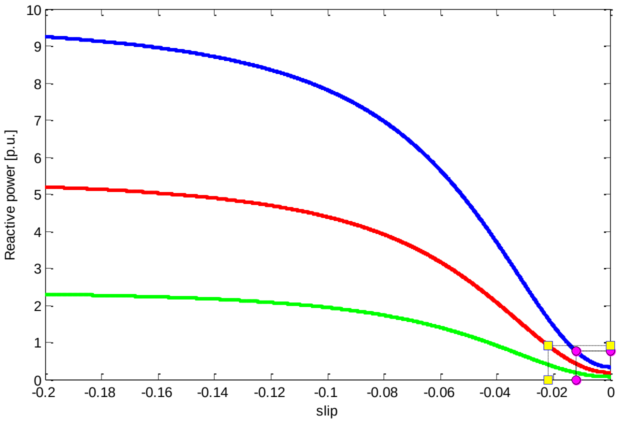

Fig. 4. (b) The reactive power-slip characteristics of induction generator.

4. Quasi-Static Time Domain Simulation (QSTDS)

Using conventional CPF which is based on PQ or PV model of generator could lead to wrong results in determining the static voltage stability status especially in the case of SCIG, so that in practical systems the voltage collapse might occur at a point before what is predicted by static analysis [4]. QSTDS provides desirable results with high accuracy which are nearly as same as those obtained by continuation approaches such as dynamic continuation power flow (DCPF) [4].

In QSTDS, the wind power generation level increases slowly as a function of time. In this approach, in contrast with continuation approaches, the total consumption and generation of the system are fixed and only an increase in generation of wind farm will be observed. This increase will be modeled as an increase in wind speed by a time-dependant ramp function. Increase in wind speed would occurs with increase in slip of SCIG and the reactive power, also has impact to decrease in the voltage of wind farm bus.

According to Fig. 5 which is obtained by overlaying of Fig.4 (a) with the *x* and *z* axes of Fig. 1, the increase in wind speed which happening simultaneously with the decrease in voltage, especially for voltages less than $0.5^{p.u.}$ and wind speeds higher than 16 m/s, prevents the forming a stable operating point in the slip-power characteristics of induction generator. Under these conditions, the SCIG becomes instable (over speed) and constitute an unwanted increase in reactive power and creating voltage instability.

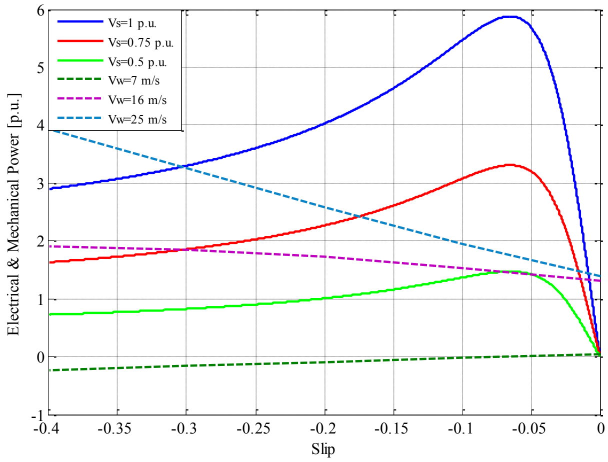

Fig. 5. The characteristics of slip versus active power of induction generator (the output power of SCIG) and mechanical power of turbine (the input power of SCIG).

5. Reactive Power Compensation Using SVC and STATCOM

In the real systems, reactive power compensation is provided for each turbine independently. In other words, as the power increases a power factor correction (PFC) capacitor gradually enters to the circuit by means of mechanical switches [15]. However, due to the fixed impedance nature of capacitor banks, these systems are not capable to supplying reactive power under transient conditions that result in instability. Therefore, SVC and STATCOM are used as tools for controlling the reactive power when a wind farm is connected to a power system. SVC and STATCOM by using power-electronic devices are capable to continuously supplying variable susceptance, also they are fast reaction components.

5.1. *Static Var Compensator (SVC)*

SVC consists of controllable thyristor switches, capacitor banks, and shunt reactors which is able to compensate reactive power continuously. The thyristor controlled reactor with fixed capacitor (TCR/FC) could be mentioned as a member of this family of compensators. the single line diagram of TCR/FC is shown in Fig. 6.

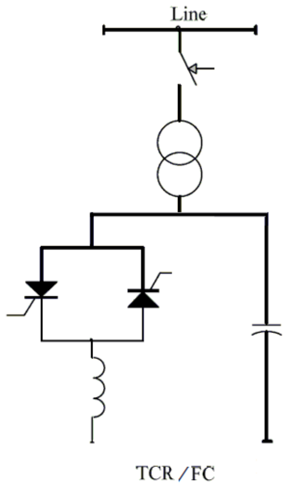

Fig. 6. The single line diagram of SVC.

Fig. 7 shows the voltage-current characteristics of TCR/FC. According to Fig. 7 , by adding capacitor banks to TCR causes the control area can make progress towards leading side (the left side of voltage axis where usually there is a capacitive current).

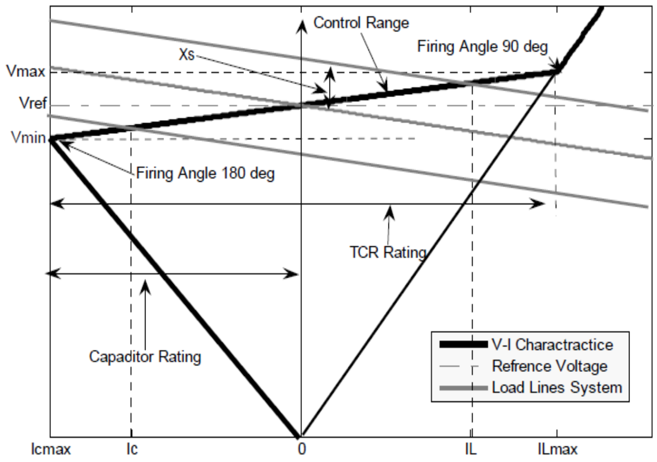

Fig. 7. The voltage-current characteristics of TCR/FC.

The control area of voltage-current characteristic in lagging side is limited by the maximum power that could be absorbed by the reactor (the current that could be absorbed by TCR at a firing angle of 90 degrees). In the leading side, control area is limited by the current generated by capacitor banks when reactor absorbs no current (the purely capacitive current which is obtained for TCR at a firing angle of 180 degrees). Outside this region, the compensator will not be able to control system parameters.

5.2. Static synchronous Compensator (STATCOM)

This compensator is a shunt compensator Similar to SVC. In this type of compensator a voltage source converter is used instead of capacitors and the shunt reactor. This converter is also known as GTO-SVC or advanced SVC. Fig. 8 shows the single line diagram of STATCOM.

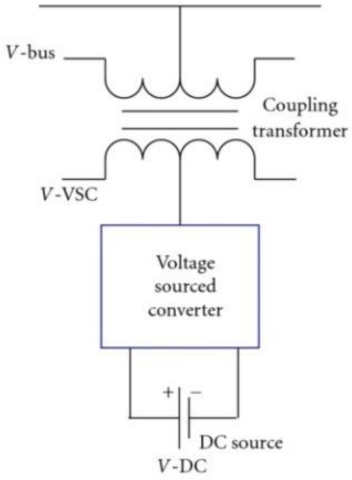

Fig. 8. The single line diagram of STATCOM.

According to Fig.9 which shows the voltage-current characteristics of STATCOM, if the system voltage (V_{bus}) is equal to V_{ref} , no reactive power is absorbed or injected. If in case, the voltage drop is smaller than V_{ref} , ($V_{bus}<V_{ref}$), the current will be capacitive otherwise, it will be inductive.

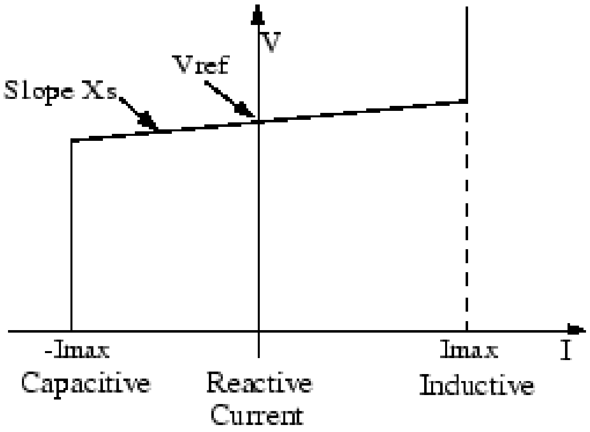

Fig. 9. The voltage-current characteristics of STATCOM.

6. Simulation results

All simulation which presented in this paper are carried out in Matlab software using PSAT toolbox. The 9-bus IEEE system is used as a case study with double-circuit lines.

The 5th bus by using load flow analysis is recognized as the weakest bus from voltage point of view and the wind farm is connected to this bus. The wind farm includes 43 wind turbine generators equipped with SCIGs with total capacity of 28.38 MW. Fig. 10 shows the topology of this system. The wind farm under study is connected to 5th bus through a transmission line with a line impedance of $5.25 \times 10^{-7}+j9.23\times10^{-2}$ (p.u.) and a transformer with a capacity of 100 MVA.

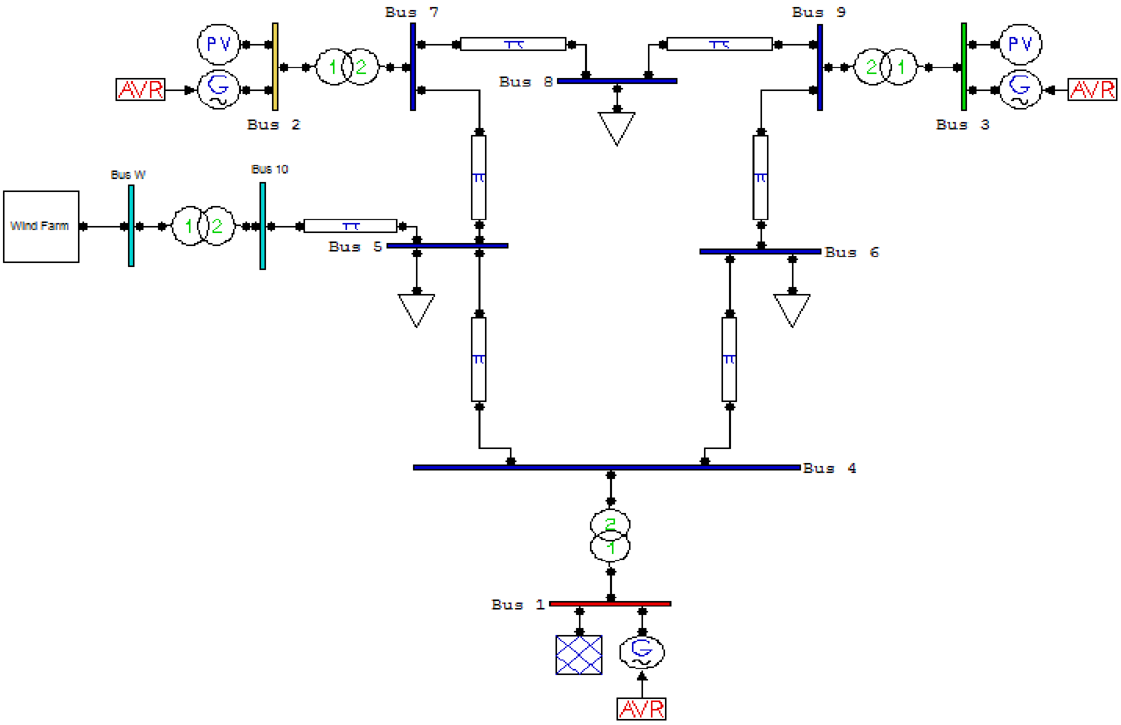

Fig. 10. Connecting the wind farm to the 5th bus of 9-bus IEEE system via a transmission line.

Fig. 11 illustrates the voltage status of system buses versus the increase in wind speed. As it can be seen in Fig. 11, with increasing of wind speed which leads to increment in generated active power and increasing in reactive power absorbed by the SCIGs of wind farm, the voltages in different buses move towards instability.

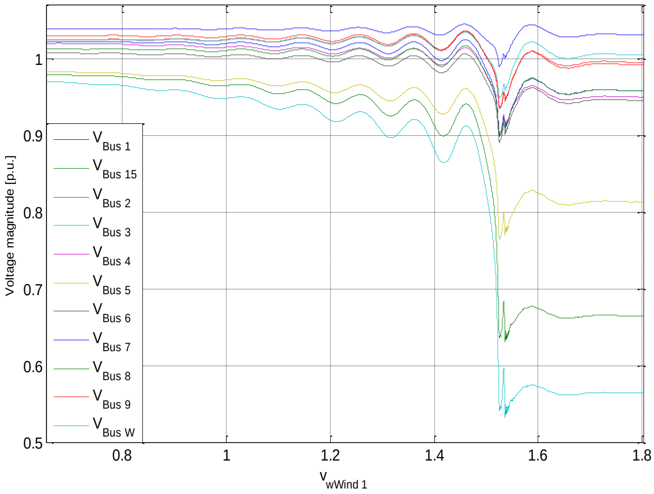

Fig. 11. The voltage status of different buses for different wind speeds in QSTDS method.

Figures 12 (a) and (b) properly show the effect of wind speed increment on the level of injected active power into the network and on the absorbed reactive power from the system as a function of time. Also, the increasing reduction of voltage is shown in these figures.

According Fig. 12 (a) and (b), developing wind farms by increasing their generation level without considering a proper reactive power support pushes the power system towards voltage instability and finally voltage collapse.

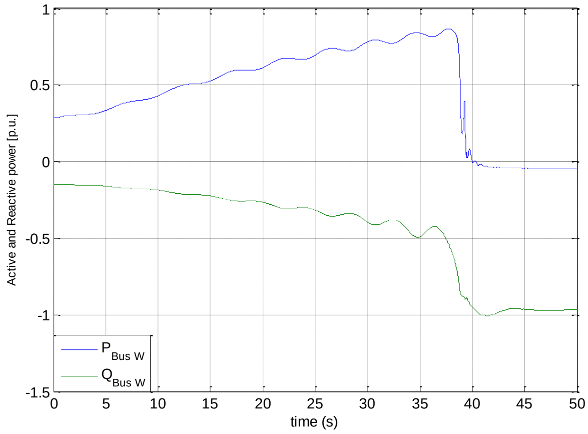

Fig. 12. (a) The active and reactive powers of wind farm in QSTDS approach.

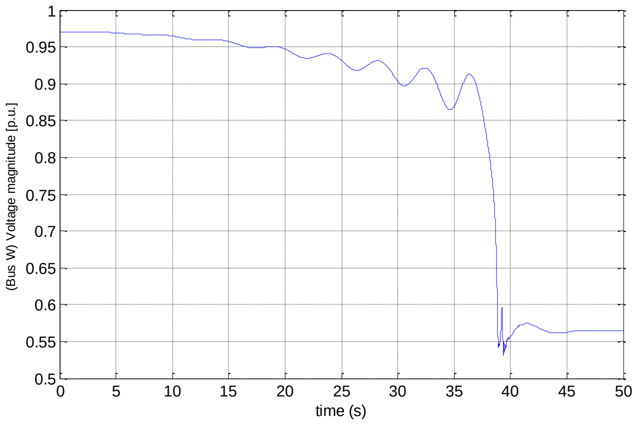

Fig. 12. (b) The voltages of wind farm bus in QSTDS approach.

Next, the effect of connecting the wind farm to different buses of case study system with regards to their voltage stability status is investigated. The obtained results show that the increase in wind energy penetration has more undesirable effect on weak buses from voltage point of view. Fig. 13 shows the results of using QSTDS for connecting the sample wind farm to different buses of the under study system. According Fig. 13, since the 4th bus is in the proximity of slack bus, it has shown higher stability when it is connected to wind farm and generation of wind farm is increased.

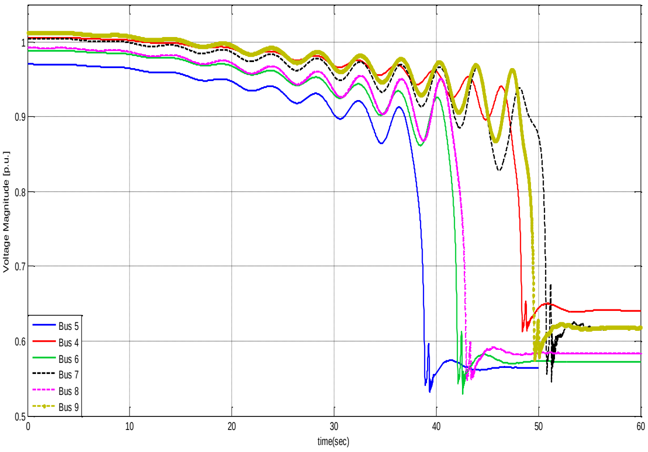

Fig. 13. Voltages of different buses when a wind farm is connected to each of these buses in QSTDS.

The capability of providing dynamic reactive power compensation by utilizing of SVC and STATCOM can increase the voltage of network when the share of wind generation or the penetration of wind energy, increases in the power system. Utilization of these compensators can even provide appropriate support at the time that a fault occurs as well as after that. It also decreases the generation of electric torque by SCIG and as a result of reduction the possibility of over speed. Fig. 14 shows the comparison of voltage status of wind farm bus without compensator and in presence of different compensators. Using PFC, SVC, and STATCOM has improved the system voltage stability, but as it was mentioned before, PFC has had smaller effect on stability considering its fixed impedance operation. It is significant to mention that in PFC modeling the switching of numerous capacitor banks is ignored and only a capacitor bank with a capacity of 14.8 MVar is considered in this study.

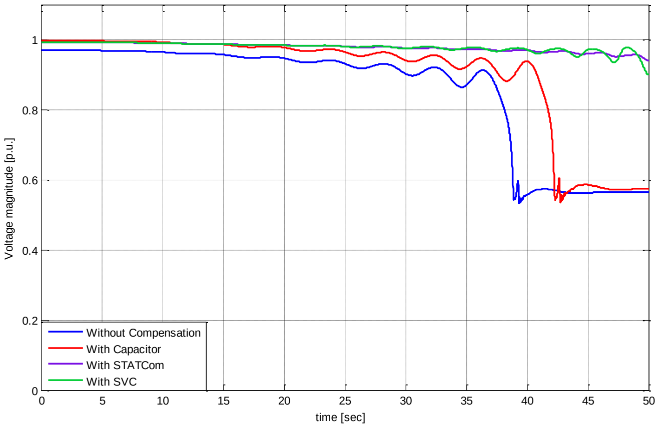

Fig. 14. The voltage of wind farm bus in presence of different compensators in QSTDS approach.

7. Conclusion

In this paper, the issue of increase in wind energy share in total generation of the network also it's impact on voltage stability of the network was investigated. Using the QSTDS as the basis of studies, it was shown that the increase in the generation of SCIG-based wind farms will have an undesirable effect on voltage stability of whole network and it will decrease the voltage stability margin. On the other hand, if the bus of common connection between wind farm and the grid would be weaker in aspect of voltage stability, the impact of connecting wind farm to grid would be more undesirable.

Considering the problem of absorbing reactive power by the induction generator which is the main reason of voltage instability, reactive power compensators were used. Simulation results show that the performance of STATCOM was much better than that of SVC. This superiority rises from the fact that the maximum reactive power capacity of SVC is proportional to the square of network voltage while the maximum reactive power capacity of STATCOM depends on the difference between the voltages of network and the DC converter.

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