Assessing the Effective Parameters on Operation Improvement of SCIG based Wind Farms Connected to Network

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Abstract-As the penetration level of wind energy in power system increases, stable operation of the power system is impacted by the wind turbine's characteristics. The stability issue is derived from the fact that the squirrel cage induction generators used in these turbines would potentially cause a voltage drop and voltage stability problems in the network, in relation to its reactive power absorption tendency. The detection of effective parameters in increment and reduction of instability occurrence probability could make squirrel cage induction generator based wind farm predictable and lead to improvement in the voltage stability margin of the entire power system. In this paper, the effective factors of wind farm operation connected to the network are assessed and studied in two sections. The first section includes parameters which depend upon substantive and functional characteristics of induction generators and could affect the stability of the power system. The second section contains parameters and characteristics of the power system that affect the stable operation of squirrel cage induction generators and can lead to instability of the entire power system. Reactive power has been identified as the more effective option in system design. The studies concentrate on voltage stability and small signal stability. In order to make the results more practical, the 660 kW induction generator which is widely used in Iran is studied in this paper.

Keywords SCIG, voltage stability, wind farm, reactive power.

1. Introduction

Due to the increase in renewable energy resources utilization, wind turbines equipped with squirrel cage induction generators (SCIG), with advantages of firm connection, cheap and easy generation, stable frequency control and constant speed operation, are widely used [1]. The disadvantages of SCIGs include voltage control and the need for reactive power absorption for continuous operation [2, 3]. The active power generation has caused these generators to appear as a voltage fluctuating resource in power system [4].

As penetration of wind energy in the power system increases, the stable operation of power system is affected by wind turbine characteristic. These turbines usually use SCIGs to transform mechanical moment to electricity. The inherent tendency of SCIGs to absorb reactive power causes a voltage drop and instability problem on the network. As wind turbines are usually connected to distribution networks at weak points (from a voltage stability point of view) [4], considerable amounts of reactive current would be absorbed during the unstable period [5-8], causing small signal instability or large signal instability.

Network connection of SCIG type wind turbines according to wind speed random characteristics can lead to fluctuation of voltage and instability [9], especially when the network is weak. Hence providing reactive power compensation as close as possible to the loads is necessary [10]. FACT's device usage for the stable operation of wind farms has been subject of much research [9, 11]. Recognizing the affecting parameters on exacerbation or alleviation of the possibility of an instability occurrence allows for a more predictable behaviourof the SCIG-based wind farms. Forecasting of the wind turbine treatment leads to reformation of the voltage stability margin of the power system and allows for better monitoring. In this research, the effective parameters of wind farms operation integrated to network have been studied in two sections:

Section 1: consists of those parameters related to substantive and operational characteristics of SCIGs which threaten the stable operation of the whole of system.

Section 2: consists of those parameters and characteristics of the power system that affect the stable operation of SCIG and eventually lead to instability on the entire power system.

In this context table 1 shows the parameters studied with the classification of parameters.

Table 1. Classification of studied parameters in mentioned sections

First section parameter	Second section parameters
Wind speed	Topology of studied system
Slip of induction machine	Length of Transmission line
Active power of SCIG	$\frac{X}{R}$ ratio for transmission line
Reactive power of SCIG	Penetration of wind energy in power system

Therefore, the main contributions of this study can be summarizing as follows. First, precise evaluation of the parameters that can affect power system stability by injection of the wind energy to the power grid. Second, an accurate investigation of the selected parameters and their associated characteristics that have direct impacts on the smooth operation of SCIGs grid connected wind turbines.The power system stability can be categorized and studied from different point of views. First, it can be studied through small signal stability like steady and continuous load increment which eventually can cause to the voltage collapse in the entire system. Second, it can be investigated from large signal stability which can leads to sudden transmission lines outages, probability of loss of load and generation capacity.

2. First Section Parameters:

These parameters are related to substantive and operational characteristics of induction generators which could provoke instability on the entire power system by affecting the stable operation of the power system.

2.1. Wind speed

The wind turbine generated power has a close relationship with wind speed. So that any trivial fluctuations at wind speed could affect the generated power. Extractable power of an air mass can be calculated by follow equation [1]:

$$P_{wind} = \frac{1}{2}.\rho_{air}.A.\vartheta^3 \tag{1}$$

Where, ρ_{air} is air density, v is wind speed and A is area swept by blades. Wind energy can not, however, be utilized fully. The extractable optimum power discovered by Betz for the first time in 1962 [12], gives the maximum extractable power as:

$$P_{Betz} = \frac{1}{2}\rho A\vartheta^3 C_{Betz} = \frac{1}{2}\rho A\vartheta^3 \times 0.59 \tag{2}$$

The percentage of wind power extracted by the wind turbine is determined by coefficient of power (CP) which practically does not exceed 48%:

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

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6 \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{5}$$

$$\lambda = \frac{R\omega}{v} \tag{6}$$

Figure 1 depicts the mechanical power of turbine as the function of wind speed variations vs. generator shaft speed in β=0 (the pitch angle controller has been ignored).

According to Fig.1 the producedmechanical power changes by variation of the wind speed in the range of 5 m/s to 12 m/s. In addition these variations can cause harmonic fluctuation and voltage flicker [13].

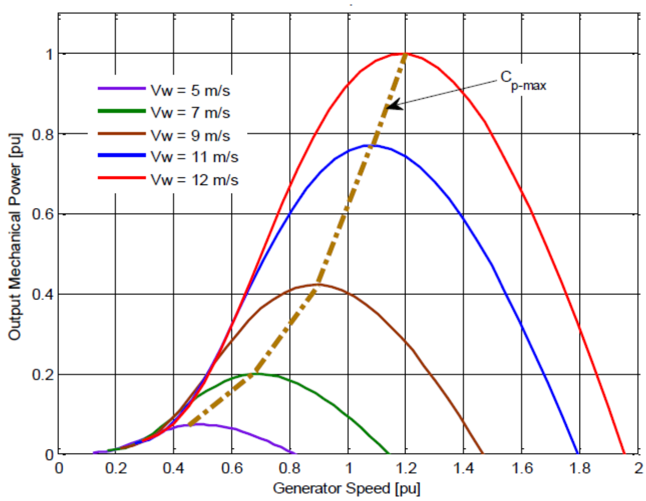

Fig. 1. The mechanical power of wind turbines in comparison with rotor speed (Dotted lines show operational zone of Maximum Point of Power Tracking)

2.2. Active and Reactive Power of SCIG

In this section the describing equations of active and reactive power, by using steady state equivalent circuit of SCIG shown in Fig. 2, are obtained [14].

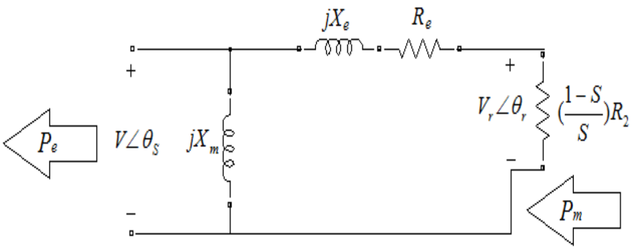

Fig.2. Equivalent circuit of SCIG type induction generator

According to equivalent circuit, the active and reactive power are described as follows:

$$|V_r| = \frac{|V_S|\left(\frac{1-s}{s}\right)R_2}{\sqrt{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2}} \tag{7}$$

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

$$P_e = P_m - R_e\frac{P_m^2}{V_r^2} \tag{9}$$

$$Q_e = -X_e\frac{P_m^2}{V_r^2} - \frac{V_S^2}{X_m} \tag{10}$$

By substitution of equations (7) and (8) into equations (9) and (10), the final form of active and reactive power will be:

$$P_e = \frac{|V_S|^2\left[\left(\frac{1-s}{s}\right)R_2-R_e\right]}{\left[\left(\frac{1-s}{s}\right)R_2+R_e\right]^2+{X_e}^2} \tag{11}$$

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

According to equations (11) and (12), there is a close relationship of active power with slip of machine and voltage. Looking at the relationship for reactive power, reveals that the reactive power controlling has a direct impact on active power generation of induction machine and even could have a monitoring role. The Fig.3.a and 3.b show the power characteristics of SCIGs vs. slip variations. These pictures are schematic description of the above equations.

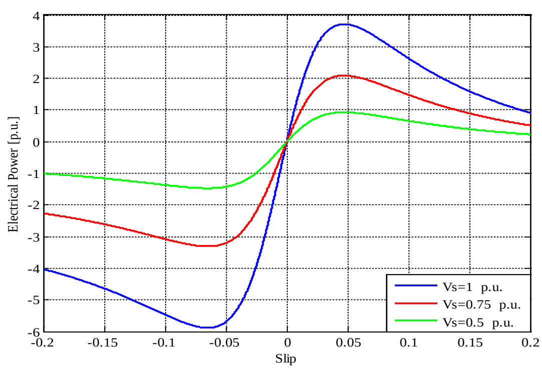

Fig.3.a. Active power-slip characteristic of induction machine

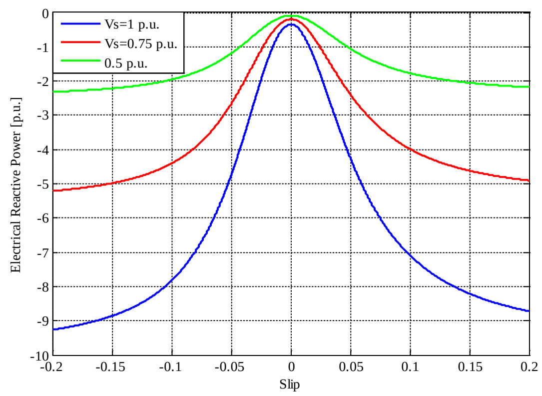

Fig.3.b. Reactive power-slip characteristic of induction machine

2.3. Slip of Induction Machine

Increasing the wind speed leads to increase in slip which in turn causes more reactive power absorption and could endanger the stability of the grid[10]. The following equation resulted from some calculations on equations (9) and (11), and describes the close relationship of voltage and wind speed with slip of induction generator:

$$\frac{1-s}{s} = \frac{(R_2|V_S|^2-\rho AC_P\vartheta^3R_2R_e)\pm\sqrt{(\rho AC_p\vartheta^3R_2R_e-R_2|V_S|^2)^2-2(\rho AC_PV^3)^2{R_2}^2({X_e}^2+{R_e}^2)}}{\rho AC_P\vartheta^3{R_2}^2} \tag{13}$$

Faults occurring on the power system could cause over speed and voltage instability in induction generator [15, 16].

The voltage drop at the point of common connection of the wind farm to the grid could cause active power reduction in the induction machine. In the case of fixed wind speed or a constant mechanical moment, the reduction of generator outgoing active power means a lack of balance between input and output powers of the induction machine, shown in Fig.4.a . The input and output power unbalance appears as an acceleration of the turbine and increase in slip. Increasing slip increases the reactive power absorption of the induction machine which would cause subsequent reduction of the wind farms bus voltage, and voltage instability may follow (Fig.4.b).

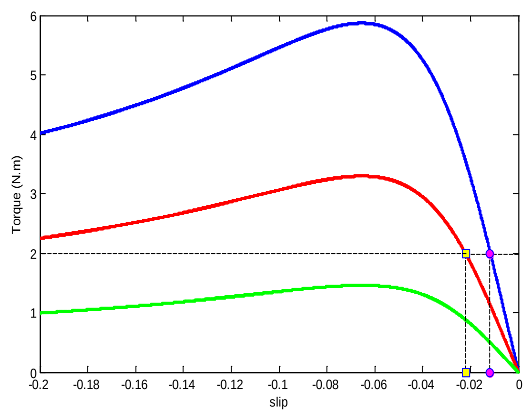

Fig.4.a. The characteristic of torque-slip of induction machine

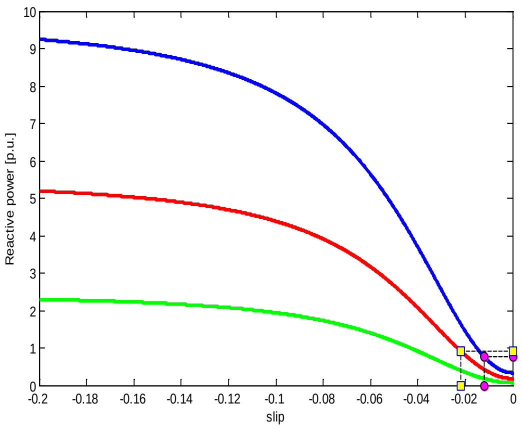

Fig.4.b. The characteristic of reactive power-slip of induction machine.

The rotor's speed would continuously increase if voltage regulation did not execute rapidly and in proper time [17, 10]. If speed exceeds a determined critical value, the generator would go into an unstable zone. The use of over speed protection device to interrupt the turbine operation is necessary [18].

3. Parameters of Second Section:

These parameters and characteristics of power system impact stable operation of SCIG and eventually cause instability in the entire power system.

3.1. Topology of studied system:

To investigate the impact of system topology connected to wind farm the 9-bus and 14-bus IEEE standard systems are studied (Fig.5 and Fig.6). In order to verify the reaction of system and the wind farm integration against small signal or in the other word gradual continuous load increments, two sample 9 and 14 IEEE bus systems are connected to a wind farm consists of 43 units of 660 kW SCIG type wind turbines through a transmission line with 5.25×10^{-7}+ j 9.23×10^{-3} line impedance and a transformer with 100 MW capacity.

Wind farms are usually connected to the parts of system which inherently have instability problems [19], as such in this simulation the wind farm is connected to the weakest bus with the highest risk of occurrence of voltage collapse [20]. After continuation power flow (CPF) implementation, the 5th bus in 9 bus system and the 14th bus in 14 bus system have been recognized as weakest bus standpoint of voltage stability and have been chosen for wind farm connection (Figures 7 and 8). In CPF algorithm, the loads of system will be increased after each power flow step by λ loads coefficient which called load parameter [21].

The small signals stability state has been verified through executing CPF for different wind speeds at the weakest bus as PCC. The stability margin of voltage has been compared for each of 2 mentioned systems by calculating the load parameters and drawing the voltage collapse curve.

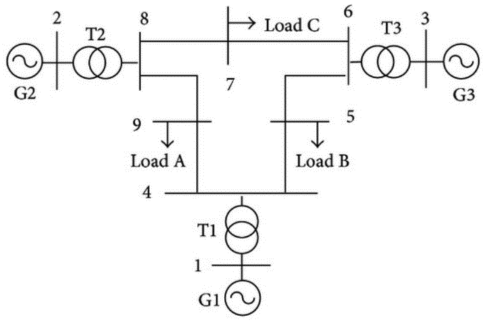

Fig.5. IEEE 9 bus system single line diagram

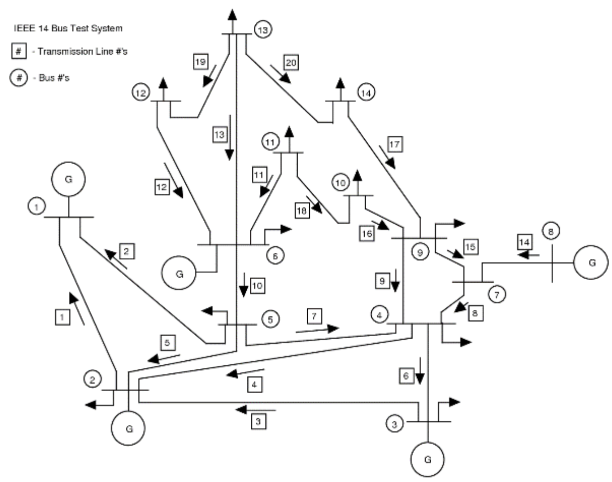

Fig.6. IEEE 14 bus system single line diagram

In the case of the wind farm connections in both of the systems, it is obvious that wind speed increment would have different results. So that the loading margin (maximum load parameter) for 9 bus system would decrease and for 14 bus system would increase which means that margin of voltage stability for each mentioned system gets worse and better, respectively (Fig.7 and 8) .

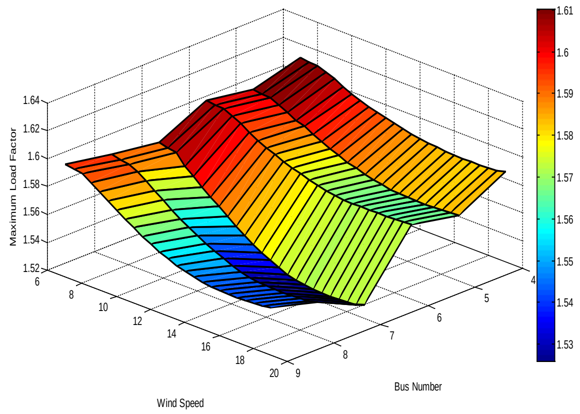

Fig.7. Variation of λ_{max} as a function of wind speed at different buses as PCC (9 bus system)

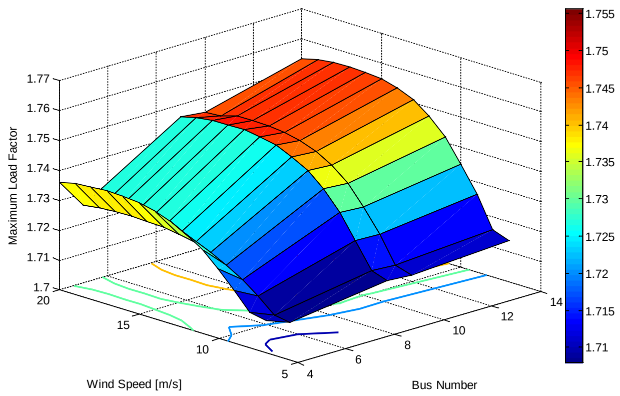

Fig.8. Variation of λ_{max} as a function of wind speed at different buses as PCC (14 bus system)

In the other word, although connecting the 9 bus system to the wind farm leads to exacerbation of voltage collapse occurrence (Fig.9), the lag occurred in the oltage collapse of 14 bus system is due to the system design (Fig.10). This indicates significant role of proper reactive power supporting on voltage stability improvement of 14 bus system, which obtained via 2 synchronous condensers, when wind farm as a reactive power consumer is integrated to system. Since the topology of system would be reacted by operation of breakers protective equipment and subjected to change [22], thus the system stability should be taken under consideration before and after occurrence of common faults.

3.2. The length transmission line

The impedance of a transmission line, including capacitance, inductance and resistance, are represented in $\frac{F}{km}$, $\frac{H}{km}$, $\frac{\Omega}{km}$, which show effect of the length of transmission line on increase or decrease of these parameters. In assessing how the length of the line impacts on voltage stability, the length of connecting line to 5th bus of 9 bus system have been set to 30 km, 60 km and 90 km. The CPF has been implemented. Figure 11 shows the effect of the length of line on voltage stability in different wind speed.

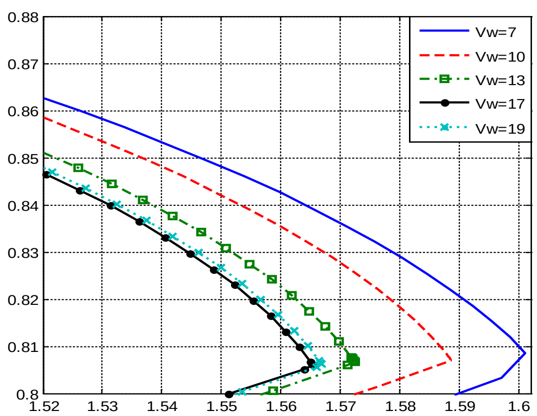

Fig.9. Voltage collapse against load parameter for different wind speed at 5th bus (9 bus system)

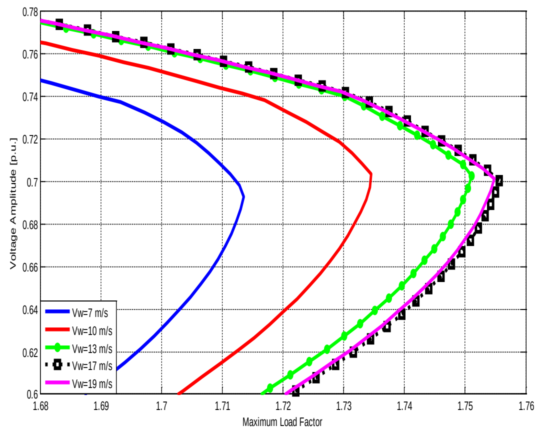

Fig.10. Voltage collapse against load parameter for different wind speed at 14th bus (14 bus system)

When, the length of line increased, at 12 $\frac{m}{s}$ wind speed and upper, the maximum load parameter abates and result in the voltage collapsing will occur at lower loading or demand. For this test, transmission line parameters are as follow:

$$R = 5.25e\text{-}7 \quad \Omega/km$$

$$X_L = 9.2300e\text{-}3 \quad H/km$$

$$Y_C = 9.8710e\text{-}9 \quad F/km$$

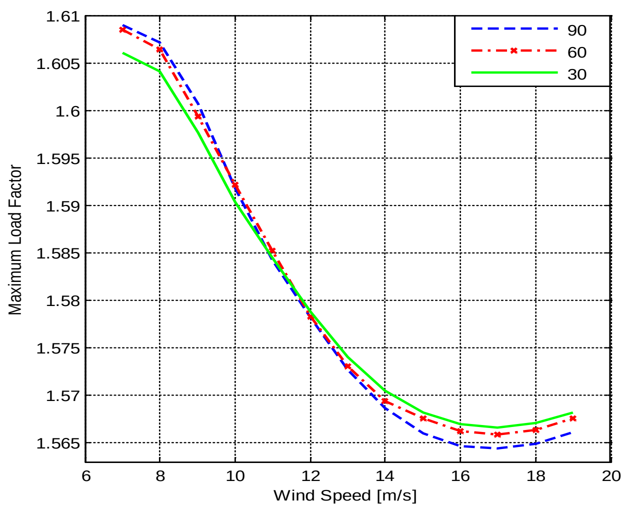

Fig.11. Maximum load parameter vs. wind speeds for different length of transmission line (km)

3.3. Transmission line $\frac{X}{R}$ ratio

If the $\frac{X}{R}$ of transmission line increases, the loading factor (maximum load parameter) decreases which leads tovoltage collapse and voltage stability weakness in the power system (Fig.12).

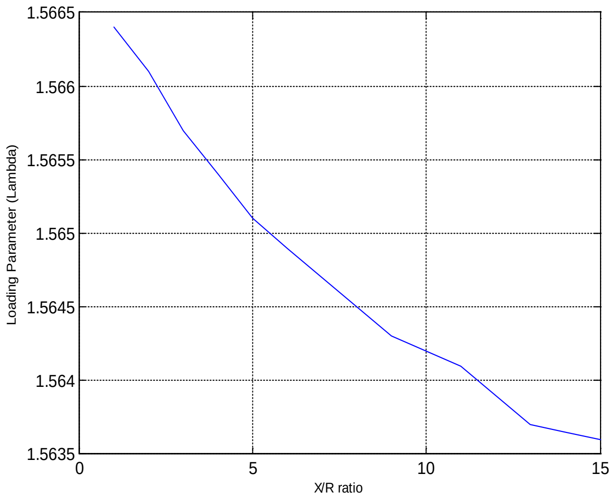

Fig.12. Maximum load parameter (loading factor) vs. variations of $\frac{X}{R}$

3.4. Increase of wind energy penetration in power system

In this paper, in order to model the increase of wind energy penetration in the power system and to study how the power system affects stable operation of wind turbines, the quasi static time domain simulation (QSTDS) is used. In QSTDS scenario the level of wind power generation increases gradually as a function of time.In power system analysis toolbox (PSAT) in order to simulate the impact of wind penetration increment, we increased the active power via increasing the wind speed variation instead of increasing and switching the wind turbine units. This assumption may not be correct practically, but we can achieve to the mentioned idea through this method. This method has been comprehensively illustrated in ref [14, 23].

The main difference of this approach is about the characteristics of the continuation power flow for voltage stability studies, where the state of power generation and consumption in the entire the power system is assumed to be constant and only the wind farms generation would be increased.The increment is in form of a wind speed increment which could be expressed as a time dependent ramp function [23].

When studying a wind farm consisting 43 turbine units, subjected to QSTDS implementation with an increasing wind speed from nominal (15 m/s), the wind farm will lose its stable operation at even less than 20 m/s as seen in Fig.14. This is referred to inability of case study system to provide reactive power demand of induction generators, which eventually pushes the system towards voltage collapse. By reducing the number of units from 43 to 25 units, along with the increase in wind speed the system under study was responsible for supplying reactive power (Fig.15). As seen in this figure, the depletion of active power level emanates of this characteristic of wind turbines that in a constant terminal voltage the wind turbine's *Cp* would be decreased in high wind speed. In this simulation, in order to simulating the higher wind speeds, cut-out limitation has been ignored.

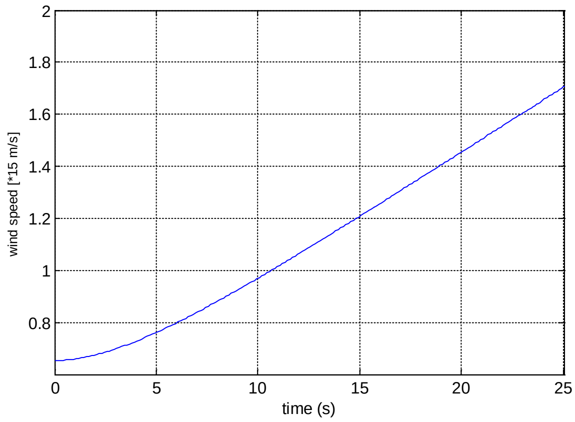

Fig.13. Ramp function of wind speed increasing

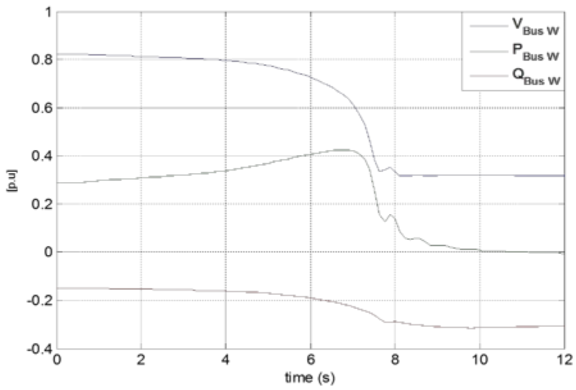

Fig.14. Voltage, active and reactive powers of wind farm consisting 43 units of wind turbine.

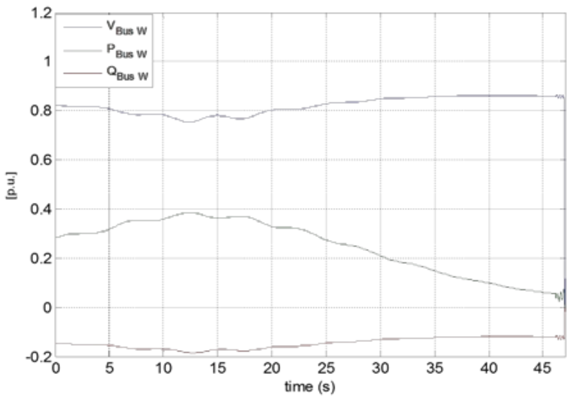

Fig.15. Voltage, active and reactive powers of wind farm consisting 25 units of wind turbine.

4. Conclusion

In this investigation, effective parameters of wind farm connected to the network have been studied in two sections (all of studies are based on voltage stability). The first section consisted of operational and inherent characteristics of induction generators which are capable to of worsening the stable operation of the system. The second section was included the parameters and characteristics of power system which could impact stable operation of SCIG and could cause unstable operation of wind farm.

The results demonstrate that the reactive power has had significant impact on the almost all of parameters. Parameters such as slip of induction machine, wind speed, system's topology and also length of transmission line directly or indirectly are affected by reactive power. This relation can be bivariate, and these parameters effect on the absorption amounts of reactive power. The control of reactive power is dominant in comparison with others one. The effect of reactive power injection in different voltage levels is related to the short-circuit capacity and impedance of the power system. These two factors are the main characteristics of the topology of the power system which show the bivariate relation of the reactive power and the power system topology. In studying each of the effective parameters of wind power operation separately and imagining the others as static parameters could lead to incorrect results.

The present research could obtain functional and accurate information about wind farms and wind power plant development to the companies which are active in field of designing or development of power plants.

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Nomenclature

P_{wind}	Extractable power of an air mass
ρ_{air}	Air density (kg/m3)
A	Turbine swept area (m2)
ν_{wind}	Wind speed (m/s)
P_m	Mechanical output power of the turbine (W)
C_p	Performance coefficient of the turbine
β	Blade pitch angle (degree)
λ	Tip speed ratio of the rotor blade tip speed to wind speed
R	the length of wind turbine blades (m)
ω	Rotational speed of rotor (rad/sec)
V_s	grid side voltage (p.u)
V_r	rotor side voltage (p.u)
s	slip of induction machine (p.u)
R_2	rotor side equivalent resistor (p.u)
R_e	equivalent resistance of induction machine (The total resistance of the rotor and the stator)
X_e	equivalent inductance of induction machine (The total inductance of the rotor and the stator)
P_e	generated active electrical power (p.u)
Q_e	generated reactive electrical power (p.u.)

The coefficients $c1$ to $c6$ are: $c1 = 0.5176$, $c2 = 116$, $c3 = 0.4$, $c4 = 5$, $c5 = 21$ and $c6 = 0.0068$