## Dynamic Stability Improvement of a Power System Incorporating DFIG Wind Power Plant Using Optimized Control Parameters of a SVC

M. Mohammadi<sup>1</sup>, M. Gitizadeh<sup>2</sup>, and A. Roosta<sup>3</sup>

<sup>1</sup>Dept. of Electrical Engineering, Dezful Branch, Islamic Azad University, Dezful, Iran, msc.mohammadi@yahoo.com <sup>2</sup>Dept. of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran, gitizadeh@sutech.ac.ir <sup>3</sup>Dept. of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran, roosta@sutech.ac.ir

Abstract--Since the penetration of wind power in power system is increasing greatly it is urgent to study the impact of wind power on the dynamic stability of power system. Doubly fed induction generator (DFIG) is widely utilized in large wind power plants. Therefore the dynamic behaviors of DFIG wind turbines is necessary to be studied. This paper presents the impact of static VAr compensator (SVC) on the dynamic stability of power system connected to DFIG. In order to improve the dynamic stability, control parameters of SVC need to be set optimally. In this article, we offer a suitable choice of objective function and then be optimized by genetic algorithm. The dynamic simulation results give us information such as the impact of SVC on the performance of DFIG and synchronous generators dynamic performance. MATLAB is used for executing the dynamic simulation.

*Index Terms* -- Doubly fed induction generator, Dynamic stability, Optimization, Static VAr compensator, Sum of absolute deviation index.

### I. INTRODUCTION

Wind energy is one of renewable energy sources. Given the common characteristics of renewable energy with the low concentration (low density) provide for human. The attention toward using of new energy such as solar and wind energy is growing because of consumption of fossil fuels and reducing the sources of these fuels. As increasing use of wind power capacity in the power system, sudden discontinuation of wind power during a large disturbance in the system cause instability in the power system and moreover occurrence of a small disturbance in the power system associated with wind power, investigation of the dynamic stability of the system must be considered. Doubly fed induction generators (DFIGs) used in wind farms have many benefits such as reactive power control capability and power improvement [1]. These generators have the ability to keep the voltage in the steady state when they are exposed to a small disturbance. Due to these characteristics and the control ability of capacity, utilizing of such generators in power system stability control is very useful. If a power system disturbance occurs with the presence of power plant controllers such as power system stabilizer (PSS), frequency control system (governor) and control system of DFIG, presenting of proper method is very essential in order to improve system stability. In several recent decades, FACTS devices have

been introduced in the network in order to solve problems such as voltage instability and reactive power limits. Static VAr compensator (SVC) can be considered as a pioneer of FACTS devices. For the first time, SVC was used for compensating in electric arc furnaces. This type of compensator is connected to the point where compensation is required in parallel. One of the most important applications of SVC is to improve the power system stability. In this study, with providing a proper method to optimize the SVC control system, we investigate the stability of power system including wind power plant. In recent years, great attention has been on the power system stability studies dependent on the wind power. The dynamic stability of a single wind turbine generator supplying an infinite bus through a transmission line was studied by developing the linear model of the power system under different loading conditions [2]. The effect of wind turbines on the transient fault behavior of the Nordic power system was investigated for different faults in [3]. Modeling wind farms for stability studies using the PSS and Voltage stability improvement using SVC are investigated [4]. The research has also examined the dynamic behavior of DFIG and effects of fault on wind turbines [5]. The purpose of this research is investigate the stability of power systems include DFIG by SVC and SVC control system optimization. In section 2, the dynamic modeling of power system, wind power plant and SVC are performed. In section 3, appropriate method is proposed to select the objective function for minimizing oscillations, and then with the help of genetic algorithm, optimization process is done. In section 4, we review the simulation and evaluate results on a multi-machine power system including wind power plant. In section 5, we review the summary and discussion on the results. Simulation process and optimization performed by MATLAB software.

## II. MODELING OF THE POWER SYSTEM AND WIND POWER PLANT

In general for the purpose of dynamic analysis power systems are modeled by a set of differential and algebraic equations, that is:

$$\dot{x} = f(x, y, \lambda, p) \tag{1}$$

$$0 = g(x, y, \lambda, p) \tag{2}$$

Where  $x \in \mathbb{R}^n$  is a vector of state variables associated with the dynamic states of generators, loads and other system controllers.  $y \in \mathbb{R}^m$  is a vector of algebraic variables associated with steady state variables resulting from neglecting fast dynamics (e.g., most load voltage phasor magnitudes and angles);  $\lambda \in \mathbb{R}^1$  is a set of uncontrollable parameters, such as variations in active and reactive power of loads;  $p \in \mathbb{R}^k$  is a set of controllable parameters such as transformer tap, AVR setting and FACTS controller reference voltages.

### A. Synchronous Generator

The synchronous generator model used for this dynamic analysis is the two axis model with four state variables [6]:

$$\dot{E}'_{di} = \frac{1}{\tau'_{q0i}} \left( -E'_{di} - \left( x_{qi} - x'_{qi} \right) I_{qi} \right)$$
(3)

$$\dot{E}'_{qi} = \frac{1}{\tau'_{doi}} \left( E_{Fdi} - E'_{qi} + (x_{di} - x'_{di}) I_{di} \right)$$
(4)

$$\dot{\omega}_{i} = \frac{1}{\tau_{ji}} (T_{mi} - D\omega_{i} - T_{ei})$$
(5)

$$\dot{\delta}_i = \omega_i \quad i = 1, 2, \dots, n \tag{6}$$

Where the state variables are  $E'_d$  is the direct axis component of voltage behind transient reactance,  $E'_q$  is the quadrature axis component of voltage behind transient reactance,  $\omega$  is the angular velocity of rotor,  $\delta$  is rotor angle.

## B. Aerodynamic Model of the Wind Turbine

For a pitch controlled wind turbine, The wind turbine mechanical power output is function of rotor speed as well as wind speed and is expressed as [7]:

$$P = (\rho/2)C_p(\lambda,\theta)AV^3 \tag{7}$$

$$T_m = P/\omega \tag{8}$$

Where  $\rho$  is the density of air (1.22 kg/m3); A is swept area of the blade in  $m^2$ . C<sub>P</sub> is the performance co-efficient which represents the rotor efficiency of the turbine (captured power/wind power); V is the wind speed (m/s); P is the output power of the turbine;  $\omega$  is the rotor speed of wind turbine;  $\lambda$  is the tip speed ratio V<sub>t</sub>/V, the ratio between blade tip speed V<sub>t</sub> and wind speed upstream the rotor V (m/s);  $\theta$  is the pitch angle in degrees. The wind turbine and its associated controls modeled are shown in Fig. 1, The wind energy conversion scheme used for simulation consist of a doubly fed induction generator (rotor circuit connected to the grid through power electronic converter). The converter adjusts the frequency of the rotor feeding current to enable variable speed operation (Fig. 2)



Fig. 1. Wind energy conversion scheme and its associated controls.



Fig. 2. Structure of doubly fed induction generator based wind turbine system.

## C. Doubly Fed Induction Generator

Doubly fed induction generator is the most commonly used machine for wind power generation. The rotor terminals are fed with a symmetrical three-phase voltage of variable frequency and amplitude. Using the generator convention, the following set of dynamic equations results:

$$V_{ds} = -R_s i_{ds} - \omega_s \psi_{as} + d\psi_{ds}/dt \tag{9}$$

$$V_{qs} = -R_s i_{qs} + \omega_s \psi_{ds} + d\psi_{qs}/dt \tag{10}$$

$$V_{dr} = -R_r i_{dr} - s\omega_s \psi_{qr} + d\psi_{dr}/dt \tag{11}$$

$$V_{qr} = -R_r i_{qr} + s\omega_s \psi_{dr} + d\psi_{qr}/dt$$
(12)

Where v is the voltage in (V), R is the resistance in  $(\Omega)$ , i the current in (A) and  $\omega_s$  the stator electrical frequency in (rad/s),  $\psi$  the flux linkage (Vs) and s the rotor slip. From the above set of dynamic equations d and q indicate the direct and transverse axis components and s and r indicate stator and rotor quantities. The d - q reference frame is rotating at synchronous with the q-axis 90° ahead of the d-axis. Flux linkages in above Equations can be calculated using the following set of equations in per unit:

$$\psi_{ds} = -(L_s + L_m)i_{ds} - L_m i_{dr} \tag{13}$$

$$\psi_{qs} = -(L_s + L_m)i_{qs} - L_m i_{qr} \tag{14}$$

$$\psi_{dr} = (L_r + L_m)i_{dr} - L_m i_{ds} \tag{15}$$

$$\psi_{qr} = -(L_r + L_m)i_{qr} - L_m i_{qs} \tag{16}$$

Where  $L_m$  is the mutual inductance and  $L_s$  and  $L_r$ , are the stator and rotor leakage inductances respectively in equations. the changes in generator speed that result from a difference in electrical and mechanical torque can be calculated using generator equation of motion:

$$d\omega_s/dt = \frac{1}{2h}(T_m - T_e) \tag{17}$$

Where H is the inertia constant (seconds) and  $T_m$  is the mechanical torque.  $T_e$  is the electro mechanical torque generated by the DFIG:

$$T_e = \psi_{dr} i_{qr} - \psi_{qr} i_{dr} \tag{18}$$

The converters are represented as current sources, and therefore the current set points equal rotor currents. The current set points are derived from the set points for active and reactive power. The active power set point is generated by the rotor speed controller, based on the actual rotor speed value. The reactive power set point is generated by the terminal voltage controller or power factor controller, based on the actual value of the terminal voltage or the power factor.

### D. Static VAr Compensator (SVC)

SVC is basically a shunt connected static VAr generator/ absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables [8], typically, the controlled variable is the SVC bus voltage. One of the major reasons for installing an SVC is to improve dynamic voltage control, and thus, increase Loading capability of the system. An additional stabilizing signal, and supplementary control superimposed on the voltage Control loop of an SVC can provide damping of system oscillations during transient faults and disturbances (Fig. 3). The state equation for SVC can be written as:

$$\dot{B}_{svc} = \frac{\kappa}{T} \left( V_{ref} - V_{meas} + u \right) - \frac{1}{T} B_{svc}$$
(19)

Where  $B_{svc}$  is the SVC susceptance, u is the stabilizing loop output. here,  $V_{ref}$  is chosen as 1.0 perunit and  $V_{meas}$  is the PCC voltage.



Fig. 3. Structure of SVC controller with stabilizing loop.

## III. OPTIMIZATION

In this paper, optimization process is done in order to select the best value for the gain of SVC. At first, objective function and then a suitable algorithm is selected to minimize oscillations.

## *A.* The Proposed Method for Selecting the Objective Function

Choosing of objective function depends on the aim of study on the power system. In this paper, Given that the type of power system disturbance is a symmetrical threephase short circuit for 0.1 seconds, the dynamic stability of the system must be considered. Thus the desired objective function is considered to minimize the rotor speed and load angle oscillations of the synchronous generators which is in the system. Then, with minimizing these oscillations, we examine the stability of wind power plant. Considering that the time required to study and simulation of the system is 10 seconds and the system studied is a multi-machine system with two synchronous generators. During these 10 seconds, a certain number of points on the chart of synchronous generators rotor speed is considered and then the deviation of these points with the rotor speed reference value of both of production units can be obtained. So, The objective function value is determined as follows:

$$SADI = \sum_{k} \left| \left( \omega_{ref} - \omega_{1k} \right) \right| + \left| \left( \omega_{ref} - \omega_{2k} \right) \right|$$
(20)

Above equation is the sum of absolute deviations index (SADI) used to minimize the deviation of synchronous generators rotor speed. K is the gain of the SVC that must be adjusted optimally.  $\omega_{ref}$  is the rotor speed reference value.  $\omega_{1k}$  and  $\omega_{2k}$  are the synchronous generators rotor speed value during fault with SVC and with different value of k. After selecting the appropriate algorithm to minimize the objective function and the best value for the objective function and for the most appropriate value for k, best conditions can be obtained for improvement of the dynamic stability of power system.

## B. Genetic Algorithm

Genetic algorithm is a method for optimization of limited and unlimited problems that is based on the optimal selection in the nature. Genetic algorithm improve the population of solutions repeatedly. At each stage, the genetic algorithm selects individuals from the current population randomly so that the population get parents for children. In successive generations, population goes towards the optimal solution [9]. In this paper, we use genetic algorithm in order to optimize and select the best appropriate value for K. The range of  $k_{svc}$  is from 1 to 300.

## IV. DYNAMIC SIMULATION RESULTS AND STABILITY INVESTIGATION

The single line diagram of the test system with the wind turbine connected is shown in Fig. 4. The test system consists of a six bus system with two synchronous generators G1 and G2. The doubly fed induction generator (DFIG) is connected to the grid through a two winding transformer. The synchronous generators capacity is 750 MVA for each of them. The wind farm is represented by aggregated model consisting of 6 wind turbines of each 1.5 MW. The induction generator is injecting 1.68 MW in the steady state. The wind power plant is connected to the transmission system by 20 KV distribution system. All available load in the system is 900 MW and 394 MVAr. The voltage is 500 KV for high voltage buses and 13.8 KV for low voltage buses. The dynamic simulation is carried out for a three phase fault on line 1-2 in the second line near bus No.1. The three phase fault is cleared after 0.1 seconds (1s - 1.1s). SVC is installed on bus No. 2. Simulation time is 10 seconds.



Fig. 4. Single line diagram of power system.

## A. Synchronous Generators Rotor Speed with and without SVC

After the simulation process, in order to improve the system dynamic performance, the best value for  $K_{svc}$  can be obtained at amount of 32.2 to minimize the objective

function. The objective function value (SADI) can be obtained at amount of 3.108 without SVC in disturbance condition. Whereas with the SVC and optimal adjustment of  $K_{svc}$  the objective function value is 2.595 in disturbance condition. From Fig. 5 and 6, the rotor speed of synchronous generators (G1 and G2) can be seen with the presence of SVC and without the presence of SVC, respectively. Due to occurrence of short circuit on bus No.1, the instability of the rotor speed of synchronous generator No.1, is more than other synchronous generator. So impact of SVC on reduction and damping of oscillations is more than other generator.



## B. Synchronous Generators Rotor Angle with and without the Presence of SVC

Fig. 7 and 8, shows the synchronous generators rotor angle with and without SVC, respectively. The rotor angle of G1 is 47.1 and the rotor angle of G2 is 38.9 in the steady state. From Fig. 7, it can be observed that the rotor angle oscillations of G1 are stable after 2/5 seconds with the presence of SVC, and following that the way amplitude of this oscillations is reduced to appropriately. It is also clear from Fig. 8, that the rotor angle oscillations of G2 do not exist in the system with the presence of SVC after 2 seconds. Due to occur the symmetrical three phase short circuit near G1, it goes without saying that the rating of oscillations and amplitude of oscillations in this production unit is far more intense than G2.



Fig. 7. G1 Rotor angle with and without SVC.



Fig. 8. G2 Rotor angle with and without SVC.

C. SVC Bus Bar Voltage and Compensation of SVC

From Fig. 9, voltage of SVC installed on bus No. 2, and amount of reactive power compensation by the SVC can be seen.



Fig. 9. SVC compensation and SVC voltage.

From Fig. 9, we conclude that with the presence of SVC and setting of gain of SVC optimally by genetic algorithm due to capacitive and inductive performance of SVC, the amount of reactive power compensation of SVC is from + 0.3pu (capacitive) to - 0.2pu (inductive).

### D. Voltage Stability of Wind Power Plant

Fig. 10, demonstrates voltage of wind power plant with and without the presence of SVC.



Fig. 10. Wind power plant voltage with and without SVC.

From Fig. 10, it is clear that with the presence of SVC, voltage fluctuations of wind power plant are stable after 2.5 seconds and The range and number of these fluctuations have reduced significantly.

## E. Rotor Speed Stability of DFIG

Doubly fed Induction generator rotor speed without SVC and with the SVC is shown in Fig. 11. The rotor speed is 0.8 pu in steady state, wind speed is 8 m/s and turbine blades pitch angle is zero degrees. From Fig. 11, we conclude that after occurrence of short circuit in the system and clearing the fault, despite the low level of instability of the rotor speed, damping of oscillations are better with the presence of SVC.



Fig. 11. DFIG rotor speed with and without SVC.

# F. Active Power Stability of DFIG With and Without SVC

From Fig. 12, it can be observed that active power oscillations in the wind power plant is very severe during the disturbance. The range of amplitude of oscillations is from + 6.5 MW to -1.5 MW. With the presence of SVC can be seen that after 1.7 second, this oscillation are damping and The amplitude of oscillations and the number of oscillations are very less with the presence of SVC.



Fig. 12. DFIG active power with and without SVC.

## V. CONCLUSION

In order to study the dynamic stability of power system and wind power plant and also investigate the stability under small disturbance, choosing the SVC need to select the best value of K<sub>svc</sub>. Choosing the appropriate objective function has a very important role in improving stability by SVC. In this paper, the proposed objective function, SADI or the sum of absolute deviations of synchronous generator rotor speed was considered. Proper choosing of different variables of power system to minimize the objective function such as voltages of buses, the rotor angle, the speed of wind turbine, the synchronous generators rotor speed have a very significant impact on improving sustainability. For the dynamic studies, use of synchronous generators rotor speed deviation in objective function is the best choice to improve the dynamic stability and both synchronous generators load angle are influenced by selecting the rotor speed deviation, were damped sufficiently. The simulation proved that small disturbances such as short circuits that can be solved during little time have little effect on wind turbine speed. However, the presence of SVC has a salient effect on improving the stability of wind power plant rotor speed after disturbance. The presence of SVC has a great effect on the voltage stability of wind power plant. During the simulation, it is proved that the effect of small disturbances on active power

oscillations in the wind power plant is very intensive and the number and amplitude of these oscillations are much less with the presence of SVC.

#### VI. REFERENCES

- S. Muller, M. Dieke and R. W. D. Oncker, "Doubly fed induction generator systems", *IEEE Industry Applications Magazine*, May/june,2002.
- [2] Abdel. Majid and El. Amin, "Dynamic stability of wind turbine generators under widely varying loading conditions", Int J Electric Power Energy Syst, 9(3), pp.180-188, 1987.
- [3] Jauch. Clemens, Poul. Sorensen, Ian. Norheim and Carsten. Rasmussen, "Simulation of the impact of wind power on the transient fault behavior of the nordic power system", *Electric Power Syst Res*, 77, pp. 35-144,2007.
- [4] Akhmatov. Vladislav, Knudsen. Hans, Nielson. Arne. Hejde, Pederson. Jorgen. Kass and Poulsen. Niels. Kjolstad, "Modeling and transient stability of large wind farms", *Int J Electric Power Energy Syst Res*, 25(2), pp.123-144,2003.
- [5] Hansen. Anca and Michalke. Gabriele, "Fault ride through capatibility DFIG wind turbines", Int J Renewable Energy, 32,pp. 1594-1610, 2007...
- [6] Paul. M. Anderson, A. A. Fouad, Power System Control and Stability, IEEE Press Power engineering series. New York: Wiley, 2002.
- [7] Thomas. Ackermann, Wind Power In Power Systems, John Wiley and Sons. New York: 2005.
- [8] Narain. G. Hingorani, Laszlo. Gyugyi, Understanding FACTS, IEEE Press,2000.
- [9] Randy. L. Haupt, S. E. Haupt, *Practical Genetic Algorithms*, John Wiley and Sons. New York: 2004.



## BIOGRAPHIES

Morteza Mohammadi was born in Shiraz, Iran, on July 17, 1984. He obtained the B.S degree in 2008 from Kazeroon Islamic Azad University, Iran. He is M.S student in Islamic Azad University Dezful Branch, Iran now. His current research interests include, power system dynamics, FACTS devices and impact of DFIGs on power system.

Mohsen Gitizadeh was born in February, 1976 in Shiraz, Iran. He received his B.S degree in Electrical Engineering from Shiraz University in 1999, and his M.S and PhD degrees from Iran University of Science and Technology in 2001 and 2009, respectively. Currently, he is an assistant professor with the Shiraz University of Technology. His research interests are in the areas of power system evices.

operation and FACTS devices.



Alireza Roosta was born in Iran. He received his B. S. and M.S degree in control Eng. from Tehran University and PhD degree in Electrical Eng. from France University. Currently, he is an Assistant Professor with the Shiraz University of Technology. His research interests include stability and control and impact of DGs on power system.

### 421