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STABILITY ENHANCEMENT OF DFIG WIND TURBINES BY PARAMETERS TUNING OF SHUNT CONNECTED FACTS DEVICES USING ITAE INDEX

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Abstract- In recent years, the doubly fed induction generators (DFIGs) are used in modern wind power plants. These generators have a large impact on the stability of power system. In this paper, we examine the stability of DFIG wind turbines with static synchronous compensator (STATCOM). Optimal tuning of STATCOM control Parameters is very important in order to proper Performance of STATCOM as a stabilizer. To select the best value for STATCOM parameter, *ITAE* criterion as objective function is introduced then optimization process is done by genetic algorithm with the purpose of minimizing the DFIG rotor speed oscillations and with the presence of a three phase short circuit fault. After this process, the stability of DFIG is tested with analyzing the DFIG rotor speed, DFIG active power, and DFIG voltage. Ultimately, static VAR compensator (SVC) as another common compensator is introduced to compare with STATCOM in order to minimize oscillations. Then by doing all the steps of optimization on SVC control system the better performance of STATCOM will be shown. All simulation steps are executed by Matlab software.

Keywords: Doubly Fed Induction Generator (DFIG), Static Synchronous Compensator (STATCOM), Static VAR Compensator, Optimization, Genetic Algorithm, Integral of Time Multiply by Absolute Error (*ITAE*).

I. INTRODUCTION

In last decades with increasing the electricity demand using wind energy and solar energy is taken in to consideration for producing the electricity. Wind generators used in wind power plants are divided in two categories: doubly fed induction generator (DFIG) and squirrel cage induction generators (SCIG). DFIG has many advantages compared to SCIG such as ability to active and reactive power control and voltage control. For this reasons, nowadays this generators are used in modern wind power plants. During the disturbances in power system with the presence of DFIG control system, proposing a proper method for Transient stability improvement of DFIG are very important.

In recent years, flexible AC transmission systems (FACTS) are introduced in order to improve the stability of power systems. FACTS devices use the power electronic for reactive power injection or absorption. The static synchronous compensator (STATCOM) is one of the key FACTS devices based on a voltage-sourced converter. The STATCOM regulates system voltage by absorbing or generating reactive power. Parameters tuning of FACTS devices are very important for better performance of these controllers as a stabilizer.

Therefore, an appropriate objective function and algorithm must be select for optimization process. 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 [1]. Parameters adjustment of DFIG control system for improving the DFIG stability was investigated in [2] and proved that the speed oscillation of wind turbine are reduced perfectly with optimization of DFIG voltage regulator. Dynamic stability improvement of power system connected to DFIG wind power plant with optimal tuning of SVC control parameters was reviewed in [3]. Modeling of wind farms for stability studies using the PSS and Voltage stability improvement using SVC was investigated [4].

In [5, 6] stability of power system includes DFIG have been reviewed. In this work, we review the transient stability of DFIG wind turbines by STATCOM after occurrence of a disturbance. For parameters adjustment of STATCOM and optimization process, the Genetic algorithm is used. Then a method is introduced in order to select the objective function and minimizing the DFIG rotor speed oscillations. After the simulation and optimization process, we will review the DFIG stability such as voltage, active power and rotor speed stability. Matlab software is used for simulation of power system.

II. MODELING OF POWER SYSTEM COMPONENTS

In this section, modeling of the power system components such as DFIG wind generators and static synchronous compensator (STATCOM) will be discussed.

A. Modeling of Wind Power Plant

Wind turbines that are used in modern wind power plants are consist of different parts such as rotor, gearbox, doubly fed induction generator (DFIG), brake mechanism, turbine deviation mechanism, vane and anemometer. In the next sections, modeling of the wind turbine and DFIG is described.

A.1. Modeling of the Wind Turbine

The wind turbine model that is described in this section is based on the characteristics of turbine permanent condition. Output power of Wind turbine describes with Equation (1) [7]:

$$P_m = C_P(\lambda, \beta)\frac{\rho}{2}AV^3 \qquad (1)$$

where P_m is output power, C_P is performance coefficient of the turbine, ρ is the air density, A is turbine swept area, V is wind speed, λ is ratio of the rotor blade tip speed to wind speed and β is blade pitch angle. The C_P-λ characteristics, for different values of the pitch angle β, are illustrated in Figure 1.

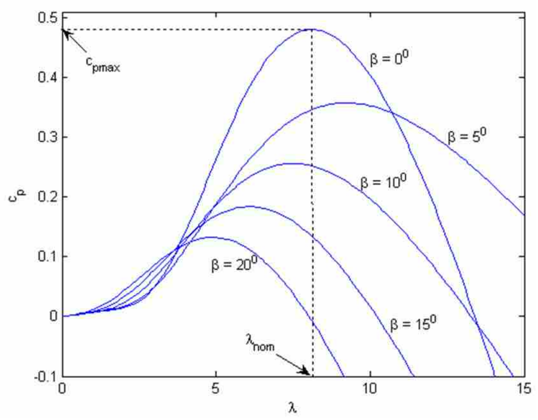

Figure 1.The C_P-λ characteristics for different values of the pitch angle β

A.2. Modeling of DFIG

Doubly fed electric machines have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and electrical system. Doubly fed machines are used in applications that require varying speed of the machine's shaft for a fixed power system frequency. The wind turbine and the doubly fed induction generator (DFIG) are shown in the Figure 2. The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). The C_{rotor} and C_{grid} are voltage-sourced converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source.

A coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings.

The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals [7].

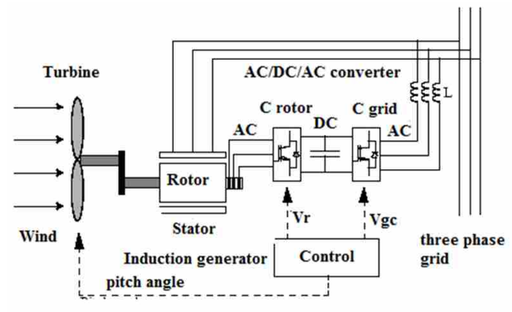

Figure 2. DFIG structure

B. Modeling of STATCOM

The Static Synchronous Compensator (STATCOM) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids. Based on a voltage sourced converter, The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. Contrary to a thyristor based Static VAR Compensator (SVC), STATCOM output current (inductive or capacitive) can be controlled independent of the AC system voltage.

Depending on the power rating of the STATCOM, different technologies are used for the power converter. High power STATCOMs (several hundreds of MVARs) normally use GTO based, square-wave voltage sourced converters (VSC), while lower power STATCOMs (tens of MVARs) use IGBT based (or IGCT based) pulse-width modulation (PWM) VSC. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive).

The variation of reactive power is performed by means of a Voltage Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V_2 from a DC voltage source. The principle of operation of the STATCOM is explained on the Figure 3 showing the active and reactive power transfer between a source V_1 and a source V_2. In this figure, V_1 represents the system voltage to be controlled and V_2 is the voltage generated by the VSC. Diagram of STATCOM control system is shown in Figure 4.

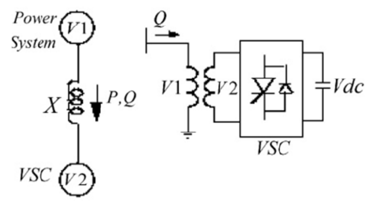

Figure 3. Operating principle of the STATCOM

The control system consists of: A phase-locked loop (PLL) which synchronizes on the positive sequence component of the three-phase primary voltage V_1. The output of the PLL is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltage and currents (labeled as V_d, V_q or I_d, I_q on the diagram). Measurement systems are measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage V_{dc}.

An outer regulation loop consists of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current I_{qref} for the current regulator. The output of the DC voltage regulator is the reference current I_{dref} for the current regulator. An inner current regulation loop consists of a current regulator. The current regulatory controls the magnitude and phase of the voltage generated by the PWM converter (V_{2d} V_{2q}) from the I_{dref} and I_{qref} reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is assisted by a feed forward type regulator, which predicts the V_2 voltage output (V_{2d} V_{2q}) from the V_1 measurement (V_{1d} V_{1q}) and the transformer leakage reactance [8].

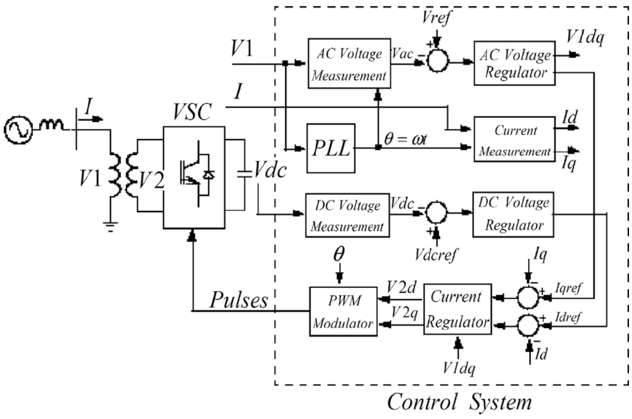

Figure 4. Control system block diagram of STATCOM

III. OPTIMIZATION PROCESS

In this paper, optimization process is done in order to select the best value for the voltage regulator gain of STATCOM control system. Appropriate choice of this parameter has a large influence on the performance of STATCOM as a stabilizer. STATCOM Voltage regulator can be seen in Figure 5. As is clear from Figure 5, a multiplier is used to access the integrator gain of voltage regulator. Then with selecting K_i = 1 and with proper selection of K, the integrator gain is selected appropriately.

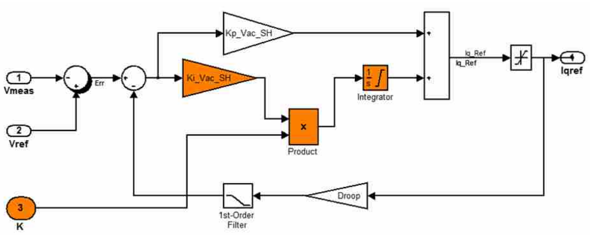

Figure 5. STATCOM voltage regulator with changes

A. Proposing a Method for Selecting the Objective Function

Choosing of objective function depends on the aim of study on the power system [9]. In this paper, given that, the type of power system disturbance is a symmetrical three-phase short circuit for 0.1 seconds and the rotor speed stability of DFIG must be considered. Thus, the desired objective function is considered to minimize the rotor speed oscillations of DFIG. 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 power system with DFIG wind power plant. During these 10 seconds, a certain number of points on the chart of DFIG rotor speed are considered and then the deviation of these points with reference value of DFIG rotor speed can be obtained. Therefore, the objective function value is determined as follows:

$$ITAE = \int_0^\infty t|e|dt = \int_0^\infty t\left|\omega_{DFIG\ ref} - \omega_{DFIG\ K}\right|dt \quad (2)$$

Equation (2) is the integral of time multiply by absolute error ($ITAE$) index that is a popular performance criterion used for control system design. This index was proposed by Graham and Lathrop in 1953, who derived a set of normalized transfer function coefficients from 2nd to 8th order to minimize the $ITAE$ criterion for a step input [9]. $ITAE$ is commonly referred to as a good performance index in designing PID controllers.

As an advantage, the search of controller parameters can be obtained for particular types of load and/or set point changes and as this criterion is based on error calculation, it can be applied easily for different processes modeled by different process models. In this paper, $ITAE$ objective Function is used to minimize the deviation of DFIG rotor speed. K is the gain of STATCOM voltage regulator that must be adjusted optimally.

The t is the simulation time. $\omega_{DFIG\ ref}$ is the reference value of rotor speed and $\omega_{DFIG\ K}$ is the value of DFIG rotor speed during fault with different values 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 stability improvement.

B. The Genetic Algorithm

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation.

Over successive generations, the population "evolves" toward an optimal solution. We can apply the genetic algorithm to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, no differentiable, stochastic, or highly nonlinear. The genetic algorithm uses three main types of rules at each step to create the next generation from the current population.

1) *Selection rules*: select the individuals, called *parents* that contribute to the population at the next generation.
2) *Crossovers rules:* combine two parents to form children for the next generation.
3) *Mutation rules*: apply random changes to individual parents to form children. Flowchart of genetic algorithm can be seen in Figure 6 [10].

The genetic algorithm differs from a classical, derivative-based, optimization algorithm in two main ways: generates a population of points at each iteration. The best point in the population approaches an optimal solution and Selects the next population by computation, which uses random number generators. In this research, genetic algorithm is used for executing the optimization process.

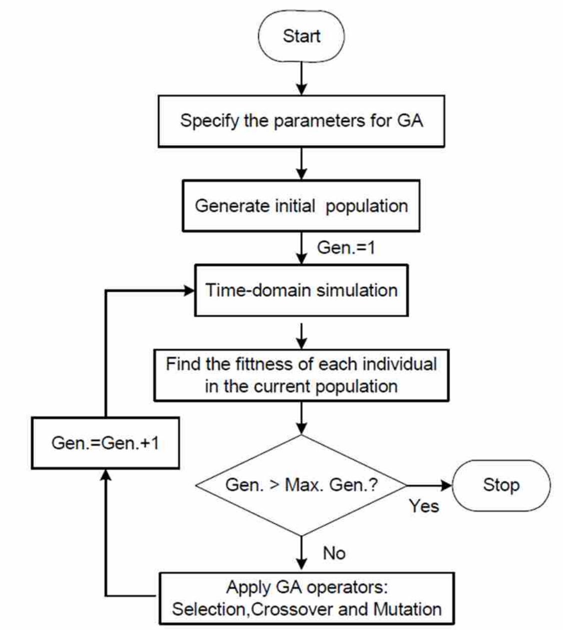

Figure 6. Flowchart of genetic algorithm

IV. SAMPLE NETWORK AND SIMULATION RESULTS

In this article, an actual grid including DFIG wind farms is considered. Its geographical diagram is shown in Figure 7. In this grid, the equivalent model is used DFIG wind farm that is entire wind farm is replaced by one DFIG turbine with identical capacity. The synchronous generators use 6th order model and all the power plants are including the control systems such as governor, excitation system and power system stabilizer (PSS).

According to Figure 7, the static synchronous compensator is installed on Bus 1 and the three-phase short circuit fault occurs on bus 3. Fault time is 0.1 sec (1-1.1 sec) and the simulation time is 10 sec.

A. Optimization Results

The *ITAE* value without the presence of STATCOM is 1.4522 while with STATCOM and after the optimization process *ITAE* value is obtained at amount of 0.5279 and the best value of $K_{STATCOM}$ is 68.4722. The process of optimization by genetic algorithm in successive generations is shown in Figure 8.

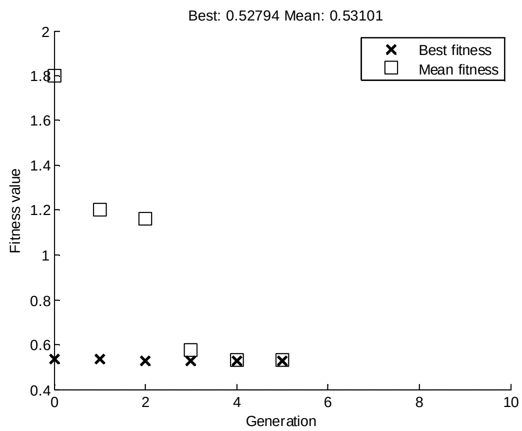

Figure 8. The process of optimization in successive generations

From above figure, it is concluded that the genetic algorithm reaches to optimal value in 5th generation and mean value for objective function is 0.53101. The score histogram of optimization process can be seen in Figure (9). In this figure, the range of objective function value in latest generation is shown. It is obvious that in the latest generation, amount of objective function for 6 individual (parameter) is in the range of 0.525 to 0.530.

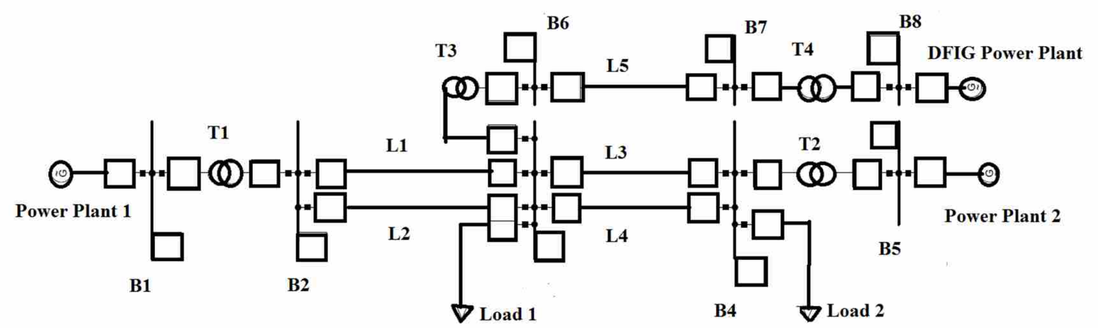

Figure 7. The single line diagram of the studied power system

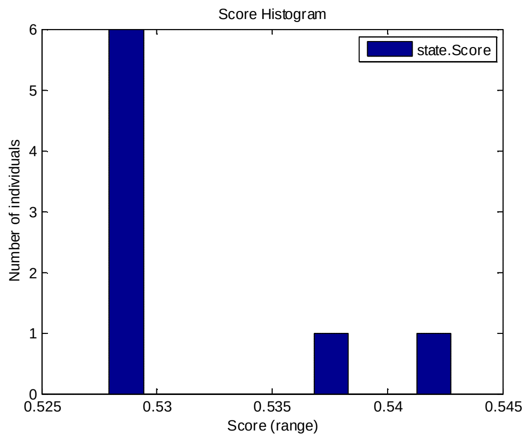

Figure 9. The score histogram for latest generation

Best, worst, and mean values of objective function in successive generations are shown in Figure 10. From figure can be seen that after successive generations distance between Best, worst and mean values become less.

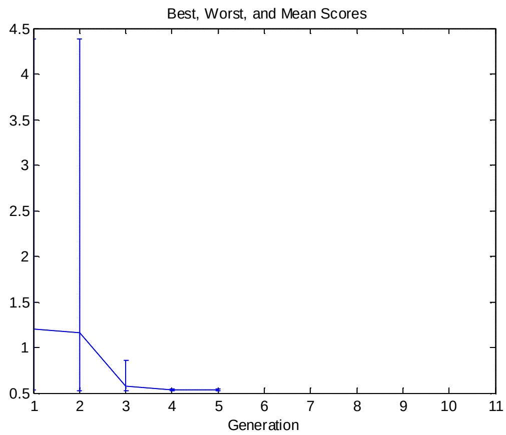

Figure 10. Best, worst, and mean values of objective function in successive generations

B. Investigation the Transient Stability of DFIG Wind Power Plant

Doubly fed Induction generator rotor speed without STATCOM and with STATCOM tuned is shown in Figure 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 Figure 11, low level of instability of DFIG rotor speed can be observed. It is for this reason that Compared with a constant speed wind turbine (SCIG), a variable-speed wind turbine (DFIG) has additional controllers, such as the rotor speed controller and the pitch angle controller.

From Figure 11 we conclude that after occurrence of short circuit in the system and clearing the fault, damping of oscillations are better with STATCOM tuned. Without STATCOM maximum of oscillations is 0.8005 pu whereas with STATCOM tuned, this value is 0.8001 pu. It goes without saying that the rating of oscillations and amplitude of oscillations without STATCOM is far more intense than tuned case.

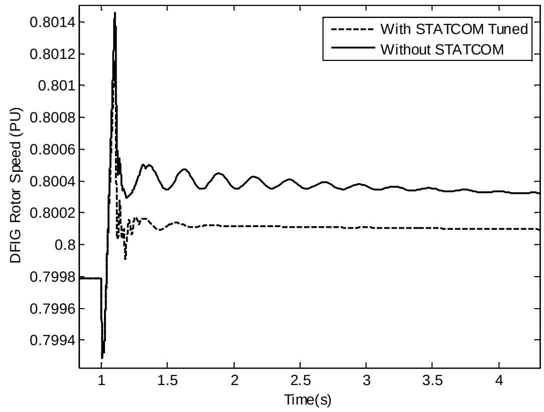

Figure 11. DFIG rotor speed

From Figure 12, it can be observed that the DFIG active power is 1.56 MW in steady state. During the disturbance, oscillations are very severe. The range of amplitude of oscillations is from +8 MW to -1 MW. With STATCOM tuned it can be seen that after 1.4 second this oscillation are damping and the amplitude of oscillations and the number of oscillations are very less.

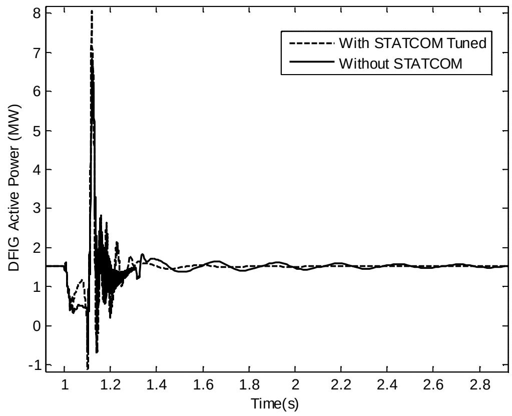

Figure 12. DFIG active power

Figure 13, shows the voltage of DFIG wind power plant following the three-phase short circuit fault. From Figure 13, it is clear that, with STATCOM tuned, voltage fluctuations of wind power plant are stable after 2 sec and the range and number of these fluctuations has reduced significantly, whereas in not tuned case voltage oscillations are stable after 4.5 sec.

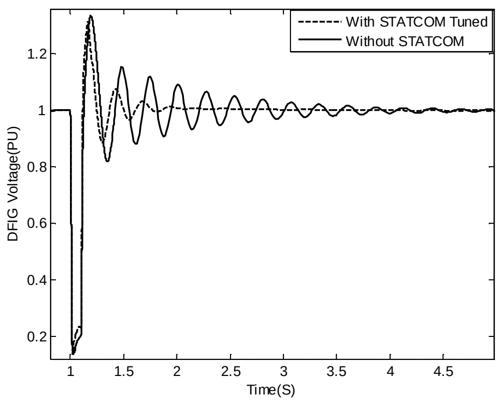

Figure 13. DFIG voltage

C. Comparison between the Performance of Tuned STATCOM and Tuned SVC in order to DFIG Stability Enhancement

The Static VAR Compensator (SVC) is a shunt device of the flexible AC transmission systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer [8]. SVC voltage regulator with changes in order to select the optimal value of *K* is shown in Figure 14.

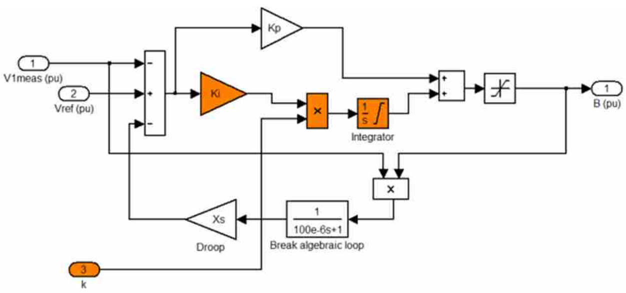

Figure 14. SVC voltage regulator with changes in order to select the optimal value of *K*

In this section, parameter tuning of SVC is done by expressed methods. Then the performance of SVC and STATCOM is compared with each other in order to enhance the DFIG stability. Optimization results of SVC control parameter with *ITAE* objective function and genetic algorithm can be seen in Figure 15. From figure, it is concluded that the genetic algorithm reaches to optimal value in 6th generation also in this case optimal value of K_{SVC} is 99.2 whereas with STATCOM the genetic algorithm reaches to optimal value in 5th generation according to previous results. As can be observed with SVC tuned, the *ITAE* value can be obtained at amount of 1.3224 whereas with STATCOM, the *ITAE* value was obtained at amount of 0.5279.

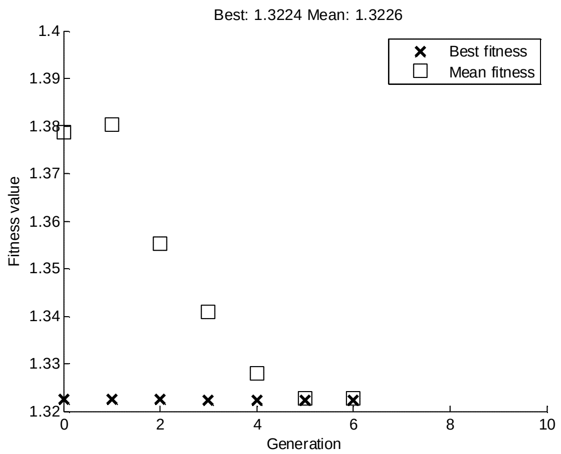

Figure 15. Process of optimization in successive generations with SVC

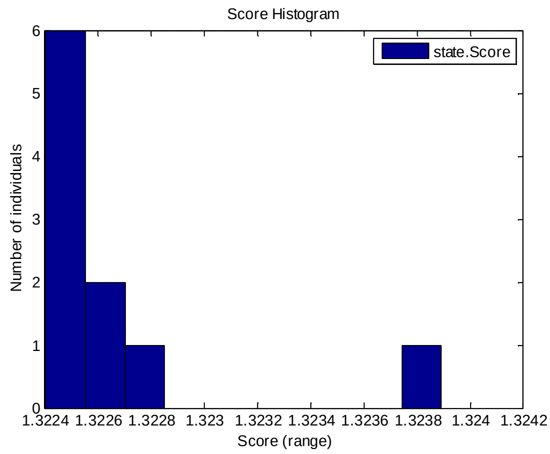

Figure 16. The score histogram for latest generation with SVC tuned

The score histogram of optimization process values in latest generation can be seen in Figure 16. It is obvious that the dispersion of objective function values is more in comparison with STATCOM. Figure 17 shows the oscillations of DFIG rotor speed with STATCOM and SVC tuned and without compensators. It is observed that the performance of STATCOM is better than SVC and with STATCOM oscillations are in the range of 0.8 pu to 0.8002 pu whereas with SVC tuned this value is from 0.8004 pu to 0.8006 pu.

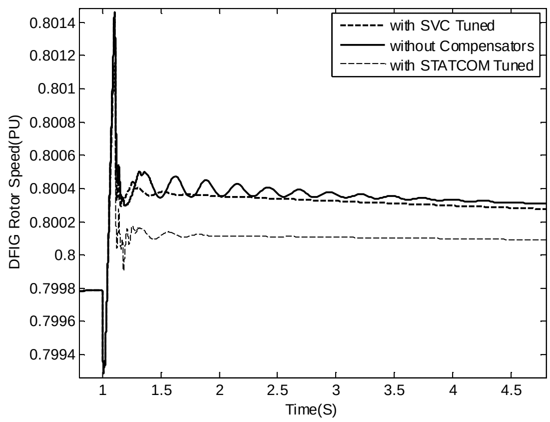

Figure 17. DFIG rotor speed with SVC and STATCOM tuned

The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. This is due to the fact that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). This ability to provide more capacitive reactive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the VSC, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for a SVC).

V. CONCLUSIONS

In this article, our purpose was improving the DFIG stability with tuning of STATCOM control parameters. In order to select the objective function, we proposed a method with the name of integral of time absolute error index or *ITAE* then optimization process was done by genetic algorithm. Optimization results showed that the speed of genetic algorithm response was good and after 6th generation, the algorithm reaches to optimal value. The large difference between *ITAE* values in the case of STATCOM tuned ($K_{STATCOM}$ = 68.47) and without STATCOM ($K_{STATCOM}$ = 1.45) proved that the performance of *ITAE* objective function is very good to find the minimum of values.

With executing the simulation, we observed that although DFIG speed oscillations is not very intensive during short circuits that can be solved in little times but with the STATCOM tuned, DFIG speed oscillations were damped sufficiently. About the DFIG active power oscillations and DFIG voltage oscillation it can be said that this oscillation is very sever and with the STATCOM tuned, oscillations damping time and stability of oscillation were enhanced properly. Then SVC is selected in order to show the better performance of STATCOM in comparison with each other.

Optimization results showed that with STATCOM the *ITAE* objective function value was obtained at amount of 0.52 whereas with SVC this value was in the range of 1.32 also was observed that DFIG rotor speed with STATCOM was very stable in comparison with SVC. results show that optimized STATCOM is more effective than other the conventional shunt connected FACTS devices (SVC) in damping of DFIG oscillations. The results of the simulation show the capability of the proposed method (*ITAE* criterion) and its validity.

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BIOGRAPHIES

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