STATCOM for transient stability improvement between wind farm (CSIG/DFIG) and synchronous generator (SG)

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***Abstract*--In this paper we are interested to study the effect of transient stability of generations kind, such as, fixed speed wind turbine (CSIG), variable speed wind turbine (DEIG), synchronous generator (SG) and assigning a fault in the presence of FACTS system. So to increase the transient stability of a power system. The STATCOM is one of the proper element of FACTS system, it provides or absorbs the required reactive power by a power electronics system (VSC). This function is identical to that of synchronous condenser with the rotating mass. In this work, we propose an improvement of transient stability using STATCOM under faults, at first time, we study the transient stability without and with STATCOM for clear advantages in different generator joined to infinite bus, using the PSAT software tool (Power System Analysis Toolbox). some simulation results are presented, commented and discussed.**

***Index Terms*--Transient Stability, FACTS, STATCOM, CSWT, DFIG ,SG, PSAT**

1. Introduction

Today's electricity grid is a complex system allowing the integrated generation, transmission and distribution of electrical power to consumers. But its stability is one of the key in the system operation, this is termed as the synchronous operation of a system. Any disturbance small or large can affect the synchronous operation. The stability of a system determines whether the system can settle down to a new or original steady state after the transient disappears [1]. In power system stability studies the term transient stability usually refers to the ability of the synchronous machines to remain in synchronism during the brief period following large disturbances, such as severe lightning strikes, loss of heavily loaded transmission lines, loss of generation stations or short circuits on buses [2]. The presence of wind farms in such weak transmission network incurs grave about system security and stability. Power system utilities are shifting focus from the power quality issues to the stability problems caused by the wind power integration [3].

In the grid impact studies of wind power integration, the stability issue is a key problem because a large proportion of wind farms are based on fixed speed wind turbines equipped with simple induction generator (IG) [4]-[5]. Induction generators consume reactive power; for that reason, compensating capacitor banks are currently added to provide the induction generator magnetizing current (they can also improve the power factor) [6]-[7]. Also variable speed wind turbines equipped with doubly fed induction generator (DFIG) are becoming more widely used for its advanced reactive power and voltage control capability [8]-[5].

One of the major problem of system stability is the reactive power limit. Such as required reactive power of machine excitation provided by the capacitor banks installed at its terminals. However, improving the systems reactive power handling capacity by a Flexible AC Transmission System(FACTS) devices is a solution for prevention of the voltage instability[3]. such as static VAR compensator (SVC) or STATCOM can represent a more suitable solution. The STATCOM based on a voltage source converter and regulate the system voltage by absorbing or generating reactive power, STATCOM output current can be controlled independent of the alternating current system voltage .The static synchronous compensator (STATCOM) is considered for this application, because it provides many advantages, in particular the fast response time (1–2 cycles) and superior voltage support capability with its nature of voltage source. With the recent innovations in high-power semiconductor switch, converter topology, and digital control technology, faster STATCOM (quarter cycle) with low cost is emerging, which is promising to help integrate wind energy into the grid to achieve a more cost-effective and reliable renewable wind energy [9]-[10].

This paper investigate the application of STATCOM to improve the transient stability of power system including fixed and variable speed wind turbine capability and synchronous generator. To examine the improvement in system performance using STATCOM, with fault at each bus of power system kinds, simulation results of the studied system with and without the connection of STATCOM are presented.

2. Power system modeling

This paper presents the mathematical machine models. Such as synchronous machine, squirrel cage induction machine and double feed induction machine.

A. Synchronous machine model

In general, for transient electromechanical phenomena analysis of a power system, power flow algebraic equations for the transmission network as well as the stator windings of the synchronous machines, along with differential equations for the rotor of the synchronous machines are employed. Therefore, the mathematical model of a power system can be represented by a set of differential and algebraic equations (DAEs). In this paper, the two-axis model is used to describe the synchronous machines. The fourth-order differential equations of the i^{th} synchronous machine of an n-machine system are expressed as follows [2].

$$\frac{d\delta}{dt} = w - w_s \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{M}(P_m - (E_q^{'} - X_d^{'} I_d) * I_q - (E_d^{'} + X_q^{'} I_q) I_d - D(\omega - \omega_s)) \tag{2}$$

Where δ is the angular rotor position, ω is the rotor speed $E_d^{'}$ and $E_q^{'}$ are d-axis and q-axis transient voltages for machine, respectively. ω_s is the synchronous speed, and M is the inertia constant and D is the damping constant for machine. The variables I_d and I_q are the d-axis and q-axis currents respectively P_m is the mechanical input power for machine and it is assumed constant.

B Automatic voltage regulator

The automatic voltage regulator (AVR) defines the primary voltage regulation of the synchronous machines. Here, we used the simplified IEEE model (I) which can be defined by AVR Type II in PSAT for the excitation system, as shown in Fig. 1. The mathematical model of the AVR is as follows.

$$\frac{dV_r}{dt} = \frac{1}{T_a}(-V_r + K_a(V_{ref} - V - V_f)) \tag{3}$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_e}(V_r - (1 + S_e(E_{fd}))E_{fd}) \tag{4}$$

Where V_{ref} is voltage reference; V_r and V_f are the outputs voltages of AVR and excitation system stabilizer (feedback), respectively. E_{fd} is the voltage applied to the synchronous generator field winding T_a, T_e are the AVR exciter and excitation system stabilizer respectively. $V_{r\min}$ and $V_{r\max}$ are the lower and upper limits of V_r. S_e the exciter saturation [2]-[11].

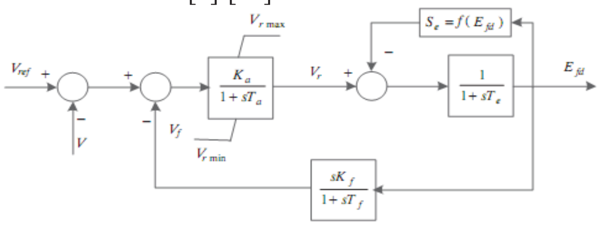

Fig. 1. Simplified model of AVR

C. Wind turbine generator system

C.1. *wind turbine Model*

For capture the maximal wind energy, it is needed to install the power electronics devices between wind turbine and grid where frequency is constant. For a wind turbine, the turbine produce the torque could be described as [12], the mechanical power extracted from the wind P_w the latter is a function of both the wind and the rotor speeds and can be approximated as.

$$p_\omega = \frac{\rho}{2} c_p(\lambda, \beta) A_r v_\omega^3 \tag{5}$$

Where p_ω is a function of the wind speed v_w the rotor speed w_m and the pitch angle β, C_p the performance coefficient or power coefficient λ the tip speed ratio and A_r the area swept by the rotor.

The speed tip ratio λ is the ratio between the blade tip speed v_t and the wind upstream the rotor [13].

$$c_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \tag{6}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{7}$$

C.2. Induction generator model

a. model of Induction generator

In this paper, the equations used for the induction generator as follows.

The power absorptions are.

$$P = v_r i_r + v_m i_m \tag{8}$$

$$Q = v_m i_r - v_r i_m + b_c(v_r^2 + v_m^2) \tag{9}$$

Where b_c is the fixed capacitor conductance.

The equation in terms of the voltage behind the stator resistance r_s are.

$$\frac{dE_r^{'}}{dt} = \omega_s(1 - \omega_m)E_m^{'} - (E_r^{'} - (x_0 - x^{'})i_m)/T_0^{'} \tag{10}$$

$$\frac{dE_m^{'}}{dt} = -\omega_s(1 - \omega_m)E_r^{'} - (E_m^{'} + (x_0 - x^{'})i_r)/T_0^{'} \tag{11}$$

Where $x_0, x^{'}$ and $T_0^{'}$ can be obtained from the generator parameters.

$$x_0 = x_s + x_m \tag{12}$$

$$x^{'} = x_s + (X_{R1} // X_m) \tag{13}$$

$$T_0^{'} = \frac{x_{R1} + x_m}{\omega_s r_{R1}} \tag{14}$$

The mechanical differential equation which take into account the turbine and rotors inertia H_{wr} and H_m respectively, and shaft stiffness K_s are as follows.

$$\frac{d\,\omega_{\omega r}}{dt} = (T_{\omega r} - K_s \gamma)/(2H_{\omega r}) \quad (15)$$

$$\frac{d\,\omega_m}{dt} = (K_s \gamma - T_e)/(2H_m) \quad (16)$$

$$\frac{d\gamma}{dt} = \omega_s(\omega_{wr} - \omega_m) \quad (17)$$

Where the electrical torque is.

$$T_e = E'_r i_r + E'_m i_m \quad (18)$$

And the mechanical torque is.

$$T_{\omega r} = \frac{P_\omega}{\omega_{\omega r}} \quad (19)$$

b. Model Of DFIG

The equation used for doubly feed induction generator are in terms of the direct (d) and quadrature (q) axis.

$$v_{ds} = -r_s i_{ds} + ((x_s + x_m) i_{qs} + x_m i_{qr}) \quad (20)$$

$$v_{qs} = -r_s i_{qs} - ((x_s + x_m) i_{ds} + x_m i_{dr}) \quad (21)$$

$$v_{dr} = -r_r i_{dr} + (1-\omega_m)((x_r + x_m) i_{qr} + x_m i_{qs}) \quad (22)$$

$$v_{qr} = -r_r i_{qr} - (1-\omega_m)((x_r + x_m) i_{dr} + x_m i_{ds}) \quad (23)$$

The active and reactive powers injected into the grid depend on the stator currents and the grid side currents of the converter, as follows.

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dc} i_{dc} + v_{qc} i_{qc} \quad (24)$$

$$Q = v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qc} i_{dc} - v_{dc} i_{qc} \quad (25)$$

whereas, on the rotor side.

$$P_r = v_{dr} i_{dr} + v_{qr} i_{qr} \quad (26)$$

$$Q_r = v_{qr} i_{dr} - v_{dr} i_{qr} \quad (27)$$

The generator motion equation is modeled as a single shaft, as it is assumed that the converter controls are able to filter shaft dynamics. For the same reason, no tower shadow effect is considered in this model. Thus one has.

$$\frac{d\,\omega_m}{dt} = (T_m - T_e)/2H_m \quad (28)$$

$$T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \quad (29)$$

$$T_m = \frac{P_\omega}{\omega_m} \quad (30)$$

Where T_e and T_m are electrical and mechanical torques.

D.STATCOM model

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage source converter (VSC). This function is identical to the synchronous condenser with rotating mass, but its response time is extremely faster than of the synchronous condenser. This rapidity is very effective to increase transient stability, to enhance voltage support, and to damp low frequency oscillation for the transmission system [14].

The schematic representation of the STATCOM and its equivalent circuit are shown in fig .2.

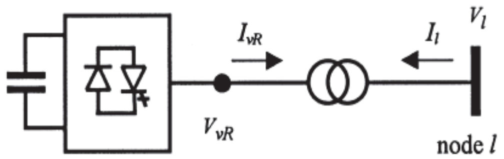

Fig. 2. STATCOM, VSC connected to the AC network via a shunt transformer

The STATCOM has the ability to either generate or absorb reactive power by suitable control of the inverted voltage $|V_{vR}| \prec \theta_{vR}$ with respect to the AC voltage on the high-voltage side of the STATCOM transformer, say node l, $|V_l| \prec \theta_l$.

In an ideal STATCOM, with no active power loss involved, the following reactive power equation yields useful insight into how the reactive power exchange with the AC system is achieved.

$$Q_{vR} = \frac{|V_l|^2}{x_{vR}} - \frac{|V_l||V_{vR}|}{x_{vR}} \cos(\theta_l - \theta_{vR}) \quad (31)$$

$$Q_{vR} = \frac{|V_l|^2 - |V_l||V_{vR}|}{x_{vR}} \quad (32)$$

Where $\theta_l = \theta_{vR}$ for the case of a lossless STATCOM; if $|V_{vR}| \prec |V_l|$ the STATCOM absorbs reactive power. On the other hand, if $|V_{vR}| \succ |V_l|$ and the STATCOM generates reactive power.

In power flow studies the STATCOM may be represented in the same way as a synchronous condenser, which in most cases is the model of a synchronous generator with zero active power generation. It is adjusts the voltage source magnitude and phase angle using Newton's algorithm to satisfy a specified voltage magnitude at the point of connection with the AC network as presents at the fig .2.

$$v_{vR} = |v_{vR}|(\cos\theta_{vR} + j * \sin\theta_{vR}) \quad (33)$$

It should be pointed out that maximum and minimum limits will exist for $|V_{vR}|$ which are a function of the STATCOM. Capacitor rating. On the other hand, θ_{vR} can take any value between 0 and 2π radians but in practice it will keep close to θ_l.

STATCOM is capable of providing capacitive reactive power for network with a very low voltage level near $0.15pu$. It also is able to generate its maximum capacitive power independent of network voltage. This capability will be very beneficial in time of a fault or voltage collapse or other restrictive phenomena, as presents at the fig .3.

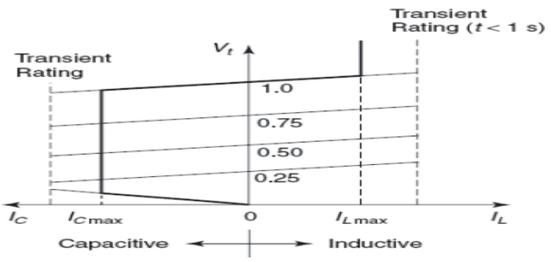

Fig. 3. Voltage current characteristic of STATCOM[15].

3. Power System Implementation

In this paper we analyze the effect of squirrel cage, double feed induction generator and synchronous generator respectively on transient stability including STATCOM applied in [16]. The test system is employed as three kinds of power system, to demonstrate the proposed test for analyzing how the three kinds of machine studied in transient stability. Test systems where implemented using the software tool Power System Analysis Toolbox (PSAT); PSAT Simulink library.

In this section, a test system implementation in PSAT is completely described in fig.4. In PSAT, the synchronous machine, squirrel induction machine and double feed induction machine are initiated after power flow computations. A PV or a slack generator is necessary to require the desired voltage and active power at the machine bus. the voltage ratings of all system equipments in kV need to be specified in PSAT.

Thus, we chose one voltage level for the system equipments. The voltage ratings for all machines where decided to be 69 kV. Then, the voltage ratings of the other equipments where chosen to be 69 kV, according to the existing transformer ratio equal one in the system. But, the slack bus (i.e., buses 3,6 and 9), are directly connected to the system without any transformer. Therefore, based on the voltage rating chosen for the system equipment, the slack bus should be connected to the 69 kV bus.

- Each wind farm has thirty equal wind turbine.
- Buses 1, 4 and 7 , where taken as the generator with a constant speed wind turbine with third order induction generator, a variable speed wind turbine with doubly feed induction generator and a forth order synchronous generator, respectively where considered as PV bus.
- Buses 2, 5 and 8 ,where taken as a fault appear at 1 s and clear at $t = 1.07s$ where the breaker installed at lines 2-3, 5-6 and 8-9, opened at $t = 1.07s$.
- Buses 3, 6 and 9 considered as slack buses.

As shown in fig. 4. a sample contingence is applied to the test system. This contingency is a three-phase short-circuit ground fault at buses 2, 5 and 8.

It is assumed this fault is eliminated by opening the transmission line connected between buses 2 and 3, buses 5 and 6, buses 8 and 9 in the post-fault system; as look in fig.4.

A STATCOM device was placed at buses 2, 5 and 8 for increasing a transient stability of power system.

The first objective of this paper is to evaluate the specific need of the system to restore to its initial state as quickly as possible after fault clearing.

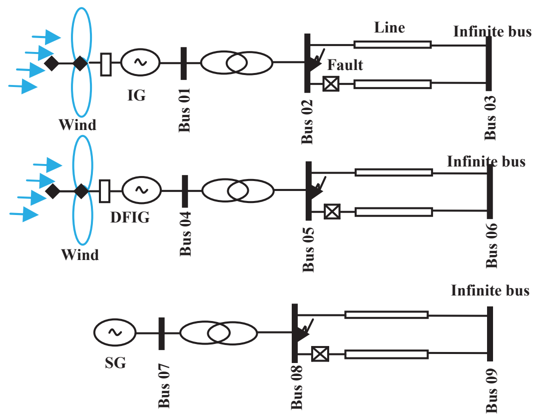

Fig .4. Test system

A. Without STATCOM

The effect of a three phase short circuit fault at the buses 2,5 and 8 are studied. The ground fault is initiated at $t = 1s$ and cleared at $t = 1.07s$ .The system is studied under different kinds of power generation.

Fig .5, show the angular speed of synchronous machine, constant speed induction machine and doubly feed induction machine. We can see the angular speed of a constant speed wind turbine curve reached $t = 1.7s$ in transient state operation and a doubly feed generator curve reached $t = 1.3s$ of speed angular, except, the synchronous generator curve return near $1.0 pu$ in the steady state mode even with fault presence at $1.0s$ and cleared at $t = 1.07s$.

Fig. 6, show the voltage amplitude of each kind power generation, such as, $V_{bus\,2}$, $V_{bus\,5}$ and $V_{bus\,8}$ are the voltage where a fixed speed induction generator connected, the voltage where a doubly feed induction generator connected and the voltage where a synchronous generator connected, respectively.

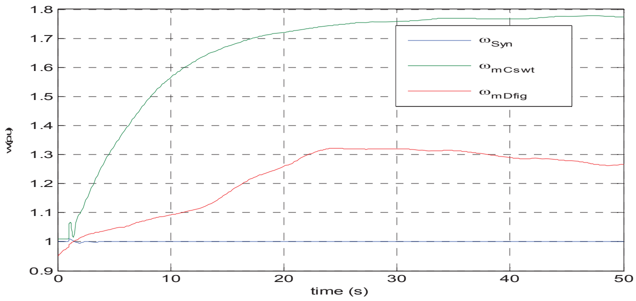

Fig.5. Angle speed generators

We can see, the voltages curve of buses 2, 5 and 8 are drops near zeros during a fault and are under its initial values reach $0.38pu$ at bus 2, and reach $0.75pu$ at bus 8 in post-fault. the voltage curve of bus 5, where a DFIG connected.

we can see its voltage drop to zeros during a fault and return in the steady state operation in the post fault.

Fig.7, show the voltage curve, where a power sources connected. It is clear according to these results where the fault appears who the voltage drop near $0.1pu$ for DFIG bus, $0.35pu$ for synchronous generator bus and $0.2pu$ for CSIG bus during a fault and $0.24pu$ voltage value of CSIG for post-fault, because the reactive power is insufficient for system exciter of machine when the fault appears, but the DFIG and SG voltages return near initial values.

The wind turbine equipped with simple induction generator are not provided with reactive power regulation capability. Voltage stability deterioration is mainly due to the large amount of reactive power absorbed by the wind turbine generators during the continuous operation and system contingency.

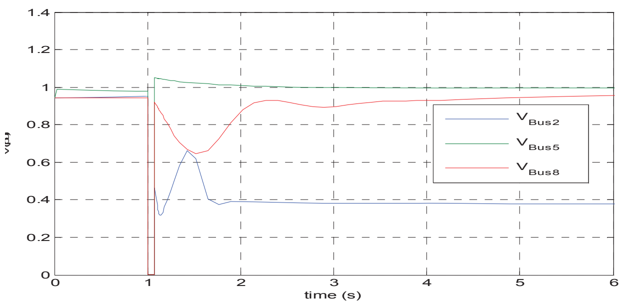

Fig.6. Bus fault voltage

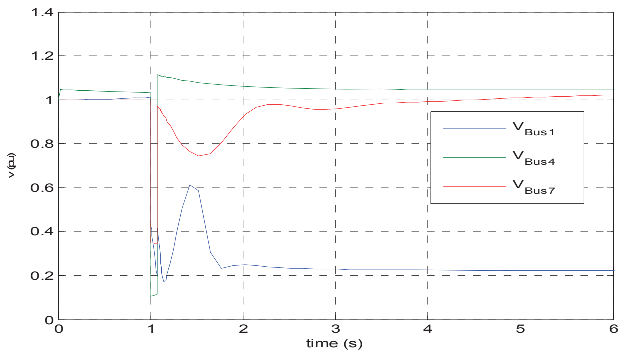

Fig.7. Voltage bus of power source

The wind turbine equipped with doubly fed induction generator (DFIG) controlled by the PWM converter is provided with reactive power regulation capability; can absorb or supply reactive power during normal operation. The adverse affect on local network voltage stability is mitigated, so that more wind power installed capacity can be incorporated into grid, and the transient voltage characteristic of wind turbine with DFIG is better than wind turbine with induction generator because of the voltage control capability of the DFIG based wind turbine. The DFIG based wind turbines have a better voltage recovery performance than the IG based wind turbine with same rating. as like at buses 2 and 5 voltages respectively.

B. With STATCOM

According to the previous simulation results, we added the STATCOM at buses 2, 5 and 8 for view the STATCOM effect.

Fig.8, show the angular speed of synchronous machine (SG), constant speed induction generator (CSIG) and doubly feed induction generator (DFIG). We can see the angular speed of constant speed wind turbine curve return at initial state after a fault, because the reactive power of STATCOM react the unsuccessful energy for machine exciter. and a doubly feed generator curve reached $1.3pu$ of speed angular, because its wind is changeable and its protection is limited. The synchronous generator curve return near $1.0pu$ in the steady state mode even with the presence of a fault at $1.0s$ and cleared at $1.07s$. However, the reactive power injected or absorbed by STATCOM play its aim.

Fig .9, show the voltage curve, where the fault injected. It is clear according to these results where the fault appear. We can see, the voltages curve of buses 2,5 and 8 are drops near zeros during fault and are return near its initial values in post-fault. The same for the voltage curve show in fig .9, increased their amplitude after a fault.

Fig .7, and fig.10 show the voltage buses when the power generation are connected , we can note that in the figure.10. the voltages also stabilized faster with less oscillation compared with the figure .7, in the transient state and even after the fault.

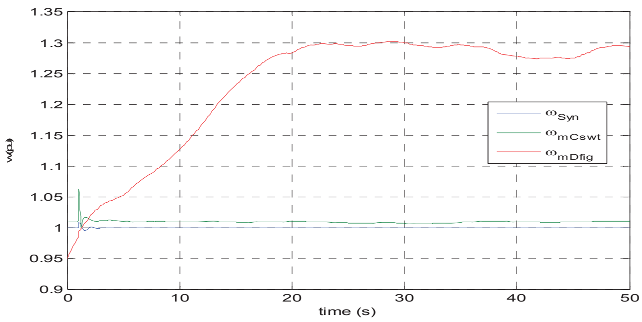

Fig.8. Angle speed generators

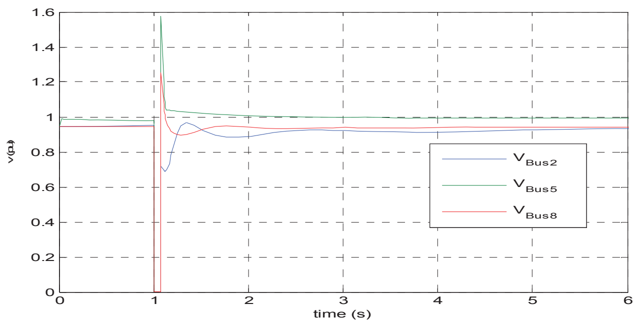

Fig.9. Bus faults voltage

Fig.11, show the current injected by a STATCOM when appear faults and post fault of different generator kinds.

According to the simulation results, the curves presented above, show the importance of the compensation when the power system consist of constant speed induction generator, doubly feed induction generator and synchronous generators recovers its operation after a fault appears and take its stability with some oscillation by intervention of STATCOM which connected.

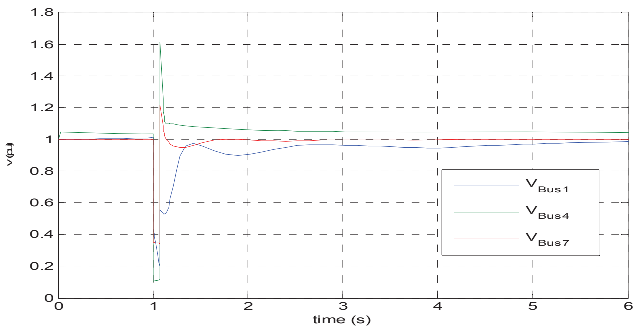

Fig.10. Voltage bus of power source

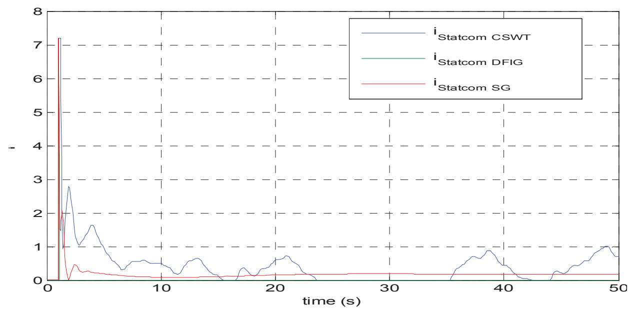

Fig.11.Current STATCOM of CSWT,DFIG and SG

4 .CONCLUSIONS

The increasing penetration of renewable energy sources in the grid, high demand, drive a destabilized the electrical network, so the researchers must be finding and master a new techniques for produced more power, better quality and higher reliability at lower cost. In first section a global description of system was presented, for each; its component a brief presentation are given, modeled and simulated.

In the second section, the dynamics of the fixed speed, variable speed and synchronous generator grid infinite bus connected are compared with and without STATCOM under fault.

According to the simulation results, it clearly illustrates the main between sources generation kinds and the need of STATCOM improvement when the power system recover its operation after the fault and take its stability.

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