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Dynamic Simulation of Power Systems with Grid Connected Windfarms

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1. Introduction

Wind energy development is consumer and environment friendly, it requires shorter construction time compared to thermal, nuclear generation and is cost competitive. It becomes one of the most competitive sources of renewable energy. However, wind power has some disadvantages. For example, wind power is considered an intermittent power supply because wind does not blow 100% of the time. Besides, the superior wind sites are usually located in remote areas; therefore, it may require substantial infrastructure improvement to deliver the wind- generated power to the load center. There are four major types of wind generators, which are used very widely. (i) Squirrel cage induction generators (ii) Doubly fed induction generators. (iii) Direct driven synchronous generator (iv) Permanent magnet synchronous generator.

2. Literature review

The dynamic stability of a single wind turbine generator supplying an infinite bus through a transmission line was studied by developing the linearized model of the power system under different loading conditions (Abdel magid, 1987).
The effect of wind turbines on the transient fault behavior of the Nordic power system was investigated for different faults (Clemens Jauch, 2004). A novel error driven dynamic controller for the static synchronous compensator (STATCOM) FACTS device was designed to stabilize both a stand-alone wind energy conversion system as well as a hybrid system of wind turbine with Hydro Generators(Mohamed S.Elmoursi, Adel M.Sharaf,2007) . A new definition on rotor speed stability of asynchronous generators is proposed (Olof Samuelsson and Sture Lindahl,2005). A control structure for DFIG based turbines under unbalanced conditions is proposed. (Istvan Erlich.2007). The application of VSC based transmission controllers for Wind energy conversion systems is discussed in (Varma R.K. and Tejbir S.Sidhu, 2006). The dynamic behavior of the power system is analyzed with high wind power penetration is analyzed in (Vladislav Akhmatov, 2003). The impact of FACTS controllers on the rotor speed /rotor angle stability of power systems connected with wind farms is discussed in (N.Senthil Kumar and M.Abdullah Khan, 2008).
The objective of the present chapter is to study the impact of FACTS controllers on the dynamic behavior of a grid connected doubly fed induction generator based wind farm with

and without FACTS controllers. The stability of the system is studied by running time domain simulations without and with FACTS controllers. The following FACTS controllers are considered for the analysis.

i.   Static Var Compensator (SVC)
ii. Static Compensator (STATCOM)
iii. Thyristor Controlled Series Capacitor (TCSC)
iv. Unified Power Flow Controller (UPFC).

This chapter is organized as follows. Section 3 presents the modeling of power system and DFIG along with FACTS controllers. Section 4 presents the dynamic simulation results obtained on the system with and without FACTS controllers. Section 5 presents discussion on the simulation results and conclusion.

3. Doubly Fed Induction Generator

The DFIG is the most commonly used machine for wind power generation. In an induction machine, the rotor is symmetrical, i.e. there is no preferred direction of magnetization. This is in contrast with a salient-pole synchronous machine. Speed of the rotor in an induction machine is not fixed. It varies with load. It impacts selection of the pair of orthogonal axes in which the voltage equations will be written down. Unlike in a synchronous machine, there is no dc excitation supplied to the induction machine rotor. Currents are induced in the rotor windings, idealized or actual depending upon the construction, due to relative speed between the rotor and rotating magnetic field produced by the stator currents. The currents induced are ac with a frequency equal to the slip between the two speeds. They produce magnetic field with the same number of poles as produced by stator currents.

3.1 Modelling of wind energy conversion system

Normally a wind turbine creates mechanical torque on a rotating shaft, while an electrical generator on the same rotating shaft is controlled to produce an opposing electromagnetic torque. The power and torque equations for the wind turbine are as follows. The rotor terminals are fed with a symmetrical three-phase voltage of variable frequency and amplitude. This voltage is supplied by a voltage source converter usually equipped with IGBT –based power electronics circuitry. The basic structure of the DFIG based wind energy conversion scheme is shown in fig. 1.

$$P = \frac{1}{2} C_p . \rho . A V^3 \tag{1}$$

$$T = \frac{P}{\omega} \tag{2}$$

where   P-output power of the turbine (W), T- Mechanical torque (N.m.),
ω -Rotor speed of wind turbine (rad/s), ρ - Density of air (=1.22 kg/m^3),
A - Swept area of the blade (m^2), C_p -Performance Co-efficient, Wind speed (m/s)

The wind farm is represented as an aggregated model of 10 wind turbines of each 2MW. Identical torque input is used for all the wind turbine models.
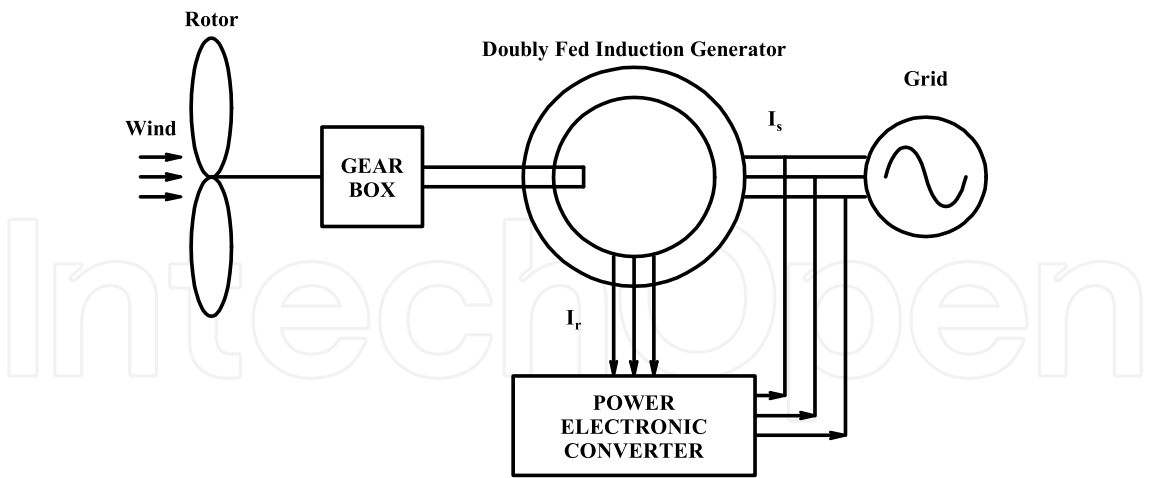
Fig. 1. DFIG Wind Energy Conversion Scheme

The wind energy conversion scheme used for simulation consists of a doubly- fed Induction Generator (Rotor Circuit connected to the grid through power electronic converter). The power electronic converter consists of two-voltage source converters connected through a capacitor.If shaft, turbine and generator damping are neglected, the two-mass model is described by the following equations. (Fig.2) .(Haizea Gaztanaga,2005)

$$T_t = J_t \frac{d\omega_t}{dt} + K_s\theta_s \qquad (3)$$

$$T_e = J_g \frac{d\omega_r}{dt} - K_s\theta_s \qquad (4)$$

$$\frac{d\theta}{dt} = \omega_t - \omega_r \qquad (5)$$

Where T_t is the mechanical torque referred to the generator side [Nm], T_e is the electromagnetic torque [N.m], J_t is the equivalent turbine –blade inertia referred to the generator side [kg m²], ω_t is the turbine's rotational speed (rad/s), ω_r is the generator's rotational speed (rad/s), K_s is the shaft stiffness [N.m/rad] and θ_s is the angular displacement between the ends of the shaft [rad]. Fig 2 gives the two mass representation of the wind turbine
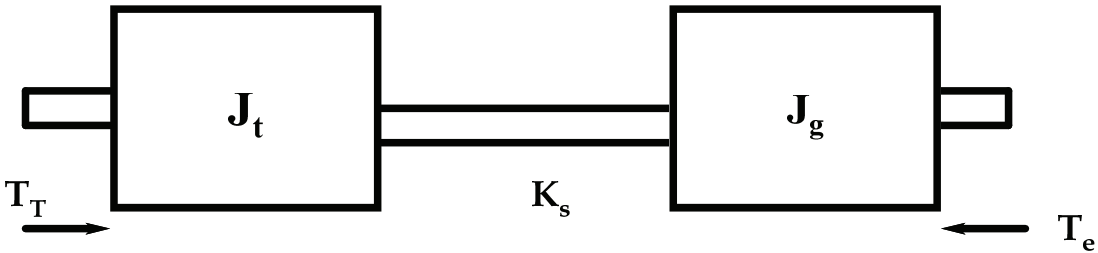

Fig. 2. Two Mass representation of the wind turbine

3.1.1 Doubly fed induction generator model

Equations (6) - (10) represent the complete set of mathematical relationships that describe the dynamic behavior of the machine. The per unit system is adopted as a unit of measurement for all quantities, and the sign convention is chosen in such a way that consumed inductive reactive powers are positive.

Voltage Equations:

$$\frac{d\psi_s}{dt} = r_s I_s + j\omega \psi_s - V_s \tag{6}$$

$$\frac{d\psi_r}{dt} = r_r I_r + j(\omega - \omega_r).\psi_r - V_r \tag{7}$$

Flux Linkages:

$$\psi_s = l_s I_s + l_m I_r \tag{8}$$

$$\psi_r = l_m I_s + l_r I_r \tag{9}$$

Equations of motion:

$$\frac{d\omega_r}{dt} = \frac{1}{\theta_s}(\psi_{sd}i_{sq} - \psi_{sq}i_{sd} + t_m) \tag{10}$$

where

I_s, I_r: stator and rotor currents, V_s, V_r- stator and rotor terminal voltages

ψ_s, ψ_r- stator and rotor flux linkages, L_m-mutual inductance (in per unit it is equal to X_m) r_s, r_r- Stator and Rotor resistances

ω_r, ω- rotor angular speed, synchronous speed

d,q- direct, quadrature axis component

t_m – Mechanical torque

The DFIG model used is a 3rd order model (Equations 6, 7 and 10) the state variables being stator and rotor flux components and rotor speed. Independent control of real and reactive power can be achieved through rotor current control.

From the basic equations of DFIG, setting all derivatives to zero (steady state) and with stator resistance r_s=0 we get

$$V_r = r_r i_r + js\left(x_m \frac{(v_s - jx_m i_r)}{jx_s} + x_r i_r \right) \tag{11}$$

Considering a coordinate system where the d – axis is located along V_s it follows that

$$V_{rd} = r_r i_{rd} + s(\frac{x_m}{x_s}(V_s) - i_{rq} \sigma x_r) \tag{12}$$

$$V_{rq} = r_r i_{rq} + s i_{rd} \sigma x_r \tag{13}$$

Where leakage coefficient $\sigma = \left(1 - \dfrac{x_m^2}{x_r x_s}\right)$ is introduced. s is the operating slip of the generator. The voltage drops over the rotor resistance in (13) and (14) can be interpreted as auxiliary signals, which are outputs of the intended rotor current controller. PI controllers are introduced to control the rotor voltages and hence rotor currents.

$$V_{rd} = r_r i_{rd} = K_I \left(1 + \frac{1}{pT_1}\right)\left(i_{rd\text{-}ref} - i_{rd}\right) \tag{14}$$

and
$$V_{rq} = r_r i_{rq} = K_I \left(1 + \frac{1}{pT_1}\right)\left(i_{rq\text{-}ref} - i_{rq}\right) \tag{15}$$

The corresponding block diagram of the rotor current controller is shown in Fig.3.
 PI controllers are introduced to control the rotor voltages and hence rotor currents.
The rotor current controller is modeled using the model editor menu of EUROSTAG.
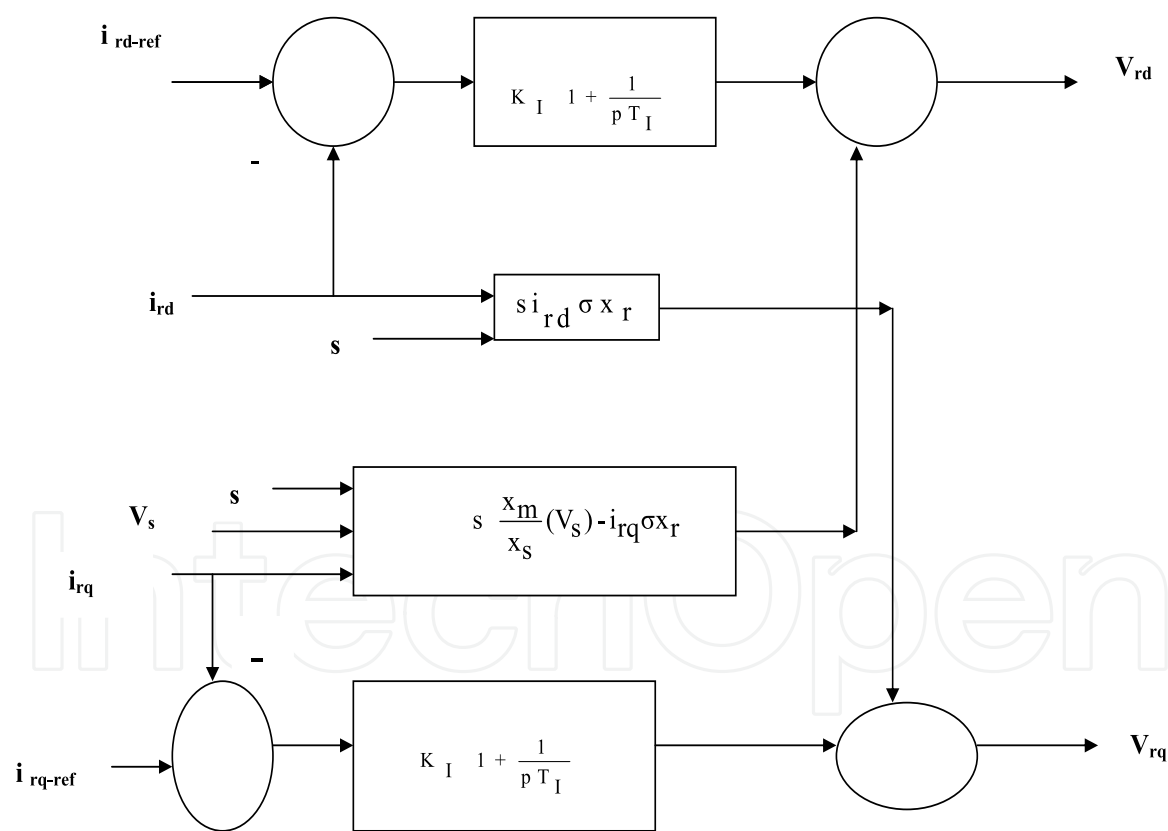
Fig. 3. Rotor Current Controller

3.2 Synchronous generators
The synchronous machine model used for this dynamic analysis is the two axis model with four state variables. (E_d', E_q', δ, ω).

3.3 Static Var Compensators (SVC)

A 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. Typically, the controlled variable is the SVC bus voltage. It is modeled as a variable susceptance controller as shown in Fig. 4 for the execution of the dynamic simulation program. (Nadarajah Mithulananthan, et al.2003)
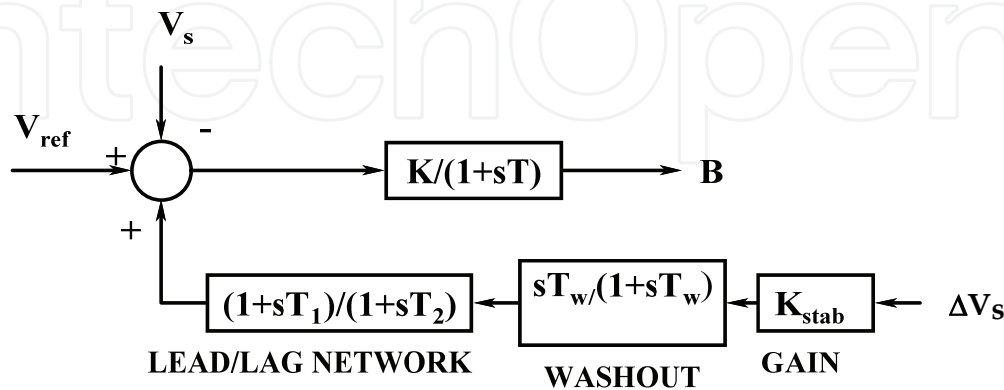

Fig. 4. Dynamic model of Static Var Compensator

3.4 Statcom

The basic electronic block of a STATCOM is the voltage source converter (VSC) which in general converts an input dc voltage into a three-phase output voltage at fundamental frequency, with rapidly controllable amplitude and phase. α is the phase shift between the controller VSC ac voltage and its bus Voltage V_s. V_{ref} is the reference voltage setting.(Claudio Canizares etal ,2003).A phase control strategy is assumed for control of the STATCOM bus voltage, and additional control block and signals are added for oscillation damping as shown in figure 5.
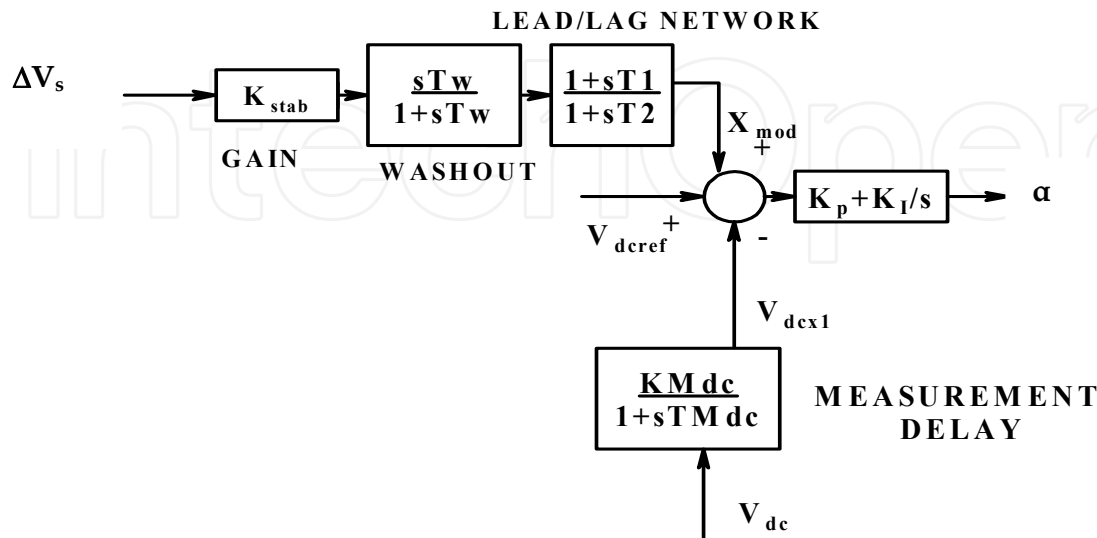
Fig. 5. Dynamic Model of STATCOM

3.5 Thyristor Controlled Series Capacitors (TCSC)

Thyristor controlled series Capacitor schemes typically use a thyristor-controlled reactor in parallel with a capacitor to vary the effective compensating reactance. The variable reactance model of TCSC used for dynamic simulation is shown in Fig.6. (R.Mohan Mathur and Rajiv K.Verma, 2003).
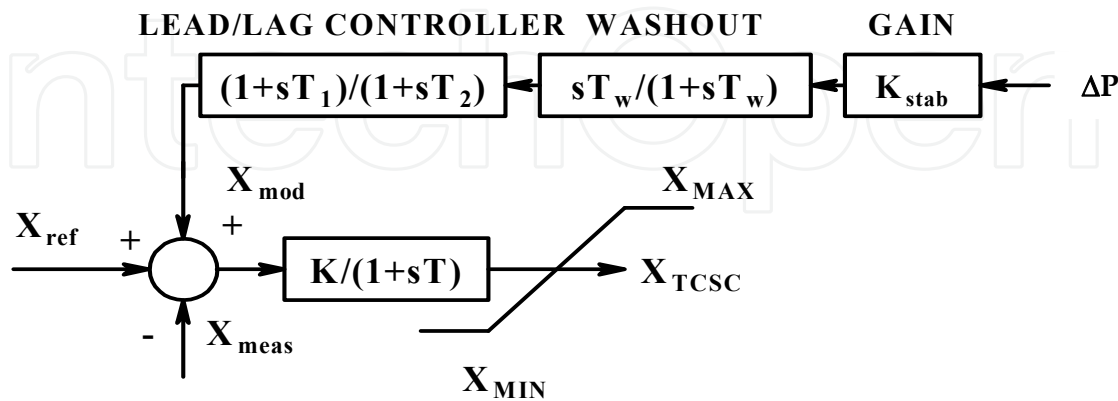
LEAD/LAG CONTROLLER WASHOUT   GAIN

$$(1+sT_1)/(1+sT_2) \quad\longleftarrow\quad sT_w/(1+sT_w) \quad\longleftarrow\quad K_{stab} \quad\longleftarrow\quad \Delta P$$

X_{mod} X_{MAX}

X_{ref} +   + $K/(1+sT)$ X_{TCSC}

- X_{meas}

X_{MIN}

Fig. 6. Dynamic Model of TCSC

3.6 Unified power flow controllers

The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting. It comprises two Voltage Source Converters coupled through a common dc link.

The UPFC is modeled in the power flow program using the power injection model with two real and reactive power injections at two nodes of the system. The power injections at both the nodes are selected such that the base case power flow with doubly fed induction generator is maintained. The active and reactive power flow control loops of the UPFC are shown in fig.7 and 8.

P_{flow}

-

+

$P_{flow-ref}$ $K_p+(K_i/s)$ V_{seq}

+

u-stabilizing signal
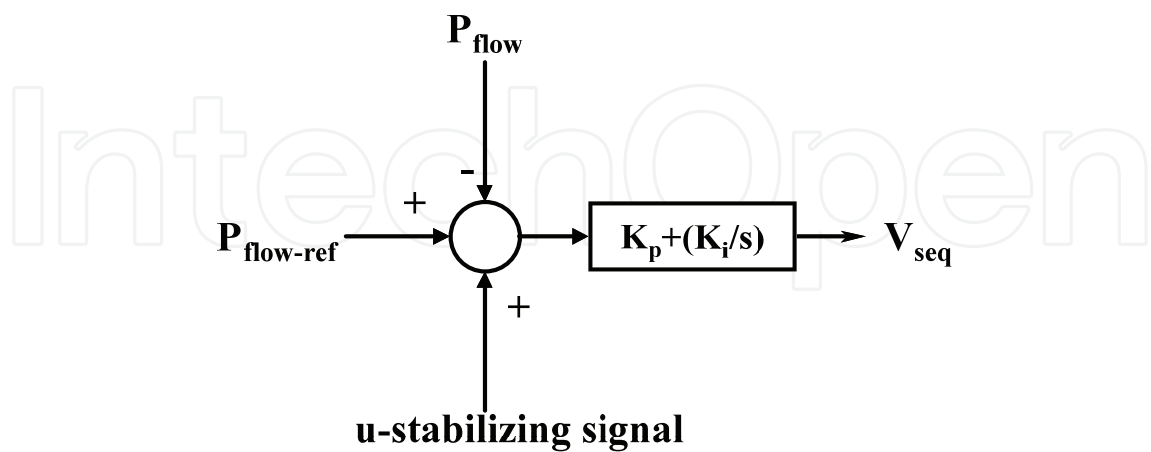
Fig. 7. Active Power Control Loop

V_{seq} is the component of series injected voltage in quadrature with the line current.
Q_{ref} from Fig.8 is the reference value of reactive power flow in the UPFC controller. V_{sep} is the component of A.C. voltage injected in phase with the line current.
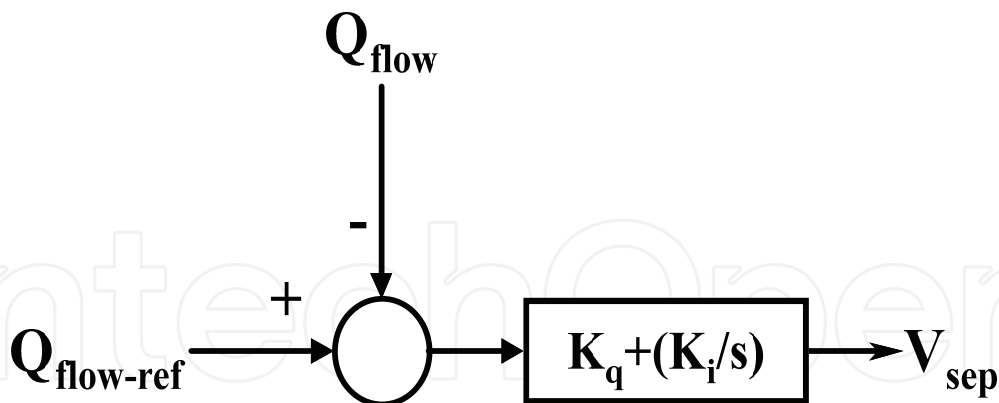
Fig. 8. Reactive Power Control Loop

3.6.1 Parameter tuning

The gains of the FACTS controllers in the forward path of the transfer function are tuned by using an optimization algorithm which minimizes the voltage oscillations of the induction generator bus. The tuning is posed as an optimization problem with the objective as minimizing the oscillations of Point of Common Coupling (PCC) voltage from the desired value and is given by,

Minimize:

$$PI = \sum_k \left[(V_{ref} - V_k)^2 + (\omega_{ref} - \omega_k)^2 \right] \tag{16}$$

$$K_{min} \leq K \leq K_{max}$$

where V_{ref} = 1.0 per-unit and PI is the sum squared deviation index of the PCC voltage. For the test system chosen ST is the point of common coupling (Fig. 9.The optimization problem is solved using sequential quadratic programming. The optimization problem is solved iteratively with pre selected initial guess of gain.

4. Dynamic simulation results and stability investigation

The single line diagram of the test system with the doubly fed induction generator connected is shown in Fig 9. The test system consists of a 7 bus system with two synchronous generators G1 and G2.The doubly fed induction generator (DFIG) is connected to the grid through a three winding transformer. IG denotes the stator of the doubly -fed induction generator. At Node ST the stator of induction generator is connected and at node RT the rotor of the doubly fed induction generator is connected. At bus 5 the load is represented as a combination of Impedance and voltage frequency dependant load in the dynamic simulation. . The shunt connected FACTS controllers (SVC and STATCOM)are located at bus 3 and the series connected FACTS controllers are located in one of the lines in grid wind farm line (2-3). The total MW loads on the two load buses 5 and 4 of the test system are 500 MW and 5000 MW respectively.The steady state active power generated by generator G1 is 800 MW and that of G2 is 5000 MW.The wind genertor (DFIG) supplies 2.5. MW in the steady state.

This specific test system is chosen for the dynamic simulation study as this system has two synchronous machines which is good enough for conducting a stability investigation on a wind farm. The doubly fed induction generator is modelled as two active power injections in the load flow program of EUROSTAG at nodes ST and RT.The FACTS controllers are modelled as power injections in the load flow program. The SVC is modelled as a shunt reactive current in the load flow program.The TCSC and UPFC are modelled with two power injections between buses 2 –3 .
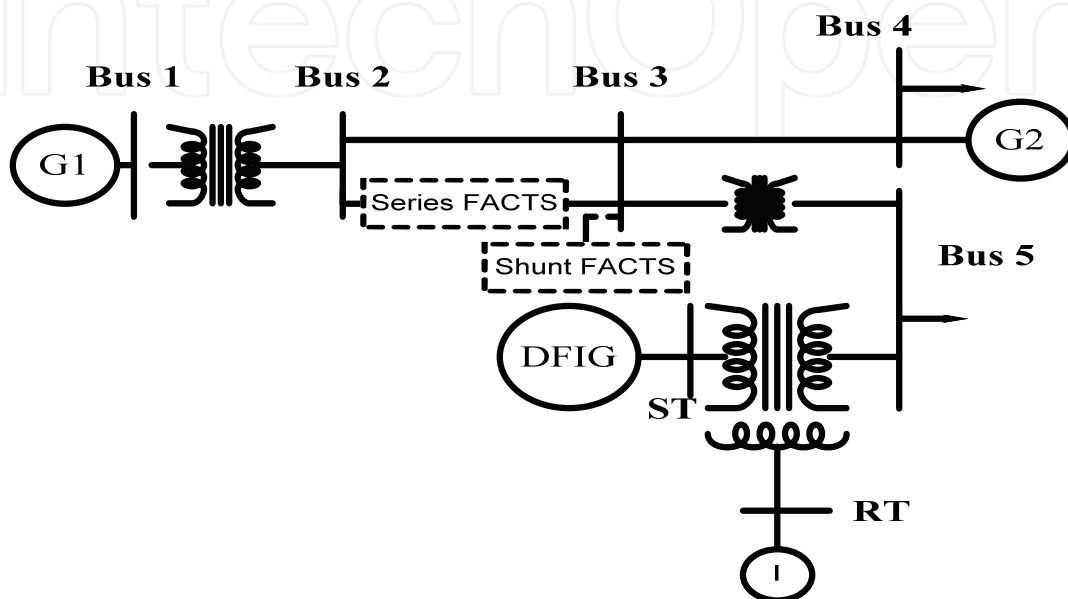
Fig. 9. Single Line Diagram of the power system with Wind Turbine stator connected to Node ST and Rotor Connected to Node RT.

4.1 Rotor angle deviations of synchronous generators without wind farm, with wind farm and with FACTS controllers

Fig.10 shows the rotor angle response of the synchronous generators without the wind farm in the network. From the figure it can be observed that after the fault the generator rotor angle of G1 deviates slightly but after the fault clearance the system returns to a new post equilibrium rotor angle value. Generator G2, which supplies a local load, lies far away from the transient fault and hence is left unperturbed. Fig.11 shows the rotor angle response of the synchronous generators with wind farm included in the network.

From Fig. 11 it can be observed that the rotor angle of synchronous generator G1 oscillates indefinitely. This leads to dynamic instability (sustained oscillations of rotor angle) in the system.Fig.12 and 13 show the rotor angle response of synchronous generators with shunt and series controllers included in the transmission line network. The controller parameters of the static var compensator/STATCOM are tuned to stabilize the oscillations as given by the objective function of equation (16).

From Fig. 12 it can be observed that rotor angle oscillations settle down after 4 seconds with the SVC controller included in the network. The oscillations settle down in 2 seconds with STATCOM. This may be attributed due to the fact that STATCOM (A voltage source converter based FACTS controller) has a faster transient response compared to Static Var compensator (a passive thyristor switched reactor/capacitor).
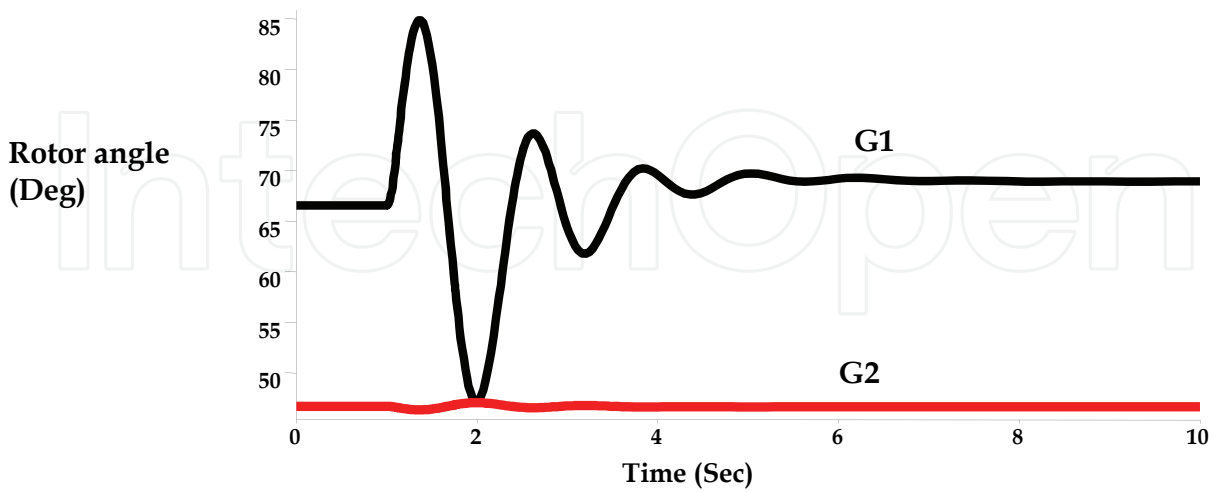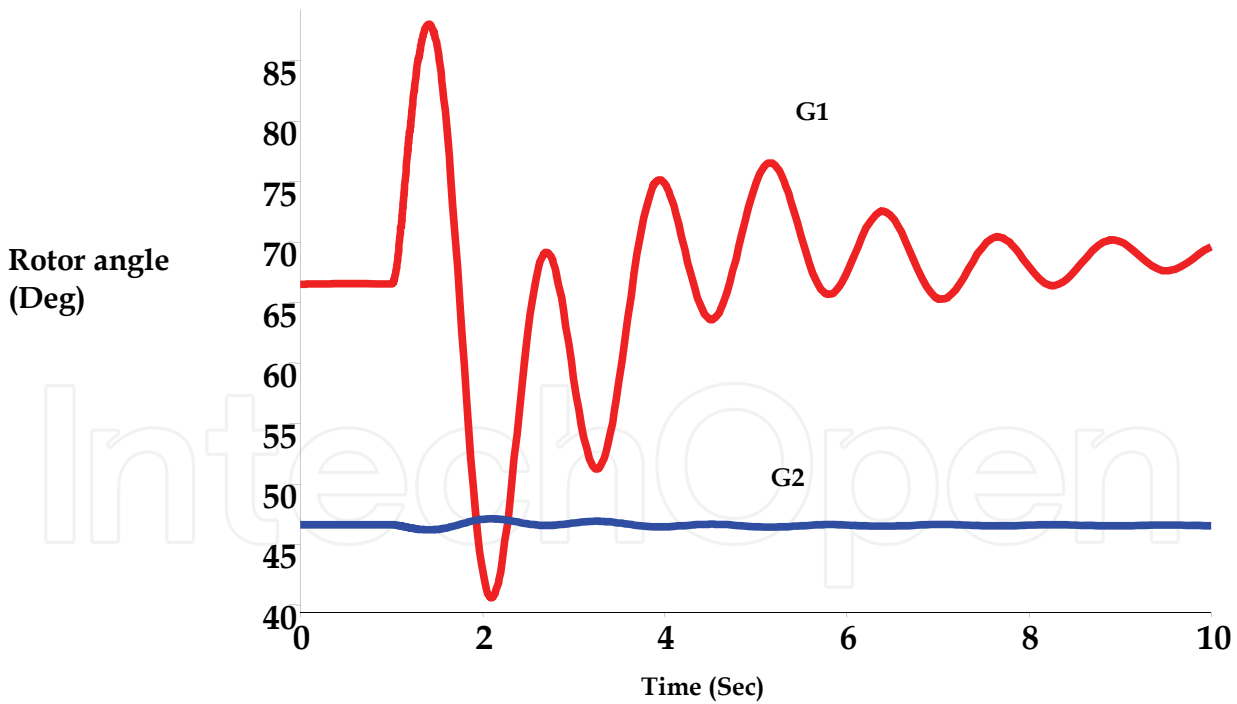
Fig. 10. Rotor angle response without Wind farm

Fig. 11. Rotor angle response with Wind Farm- without FACTS controllers in the network

From fig. 13 it can be observed that there are no oscillations in the rotor angles of synchronous generator with UPFC in the network.
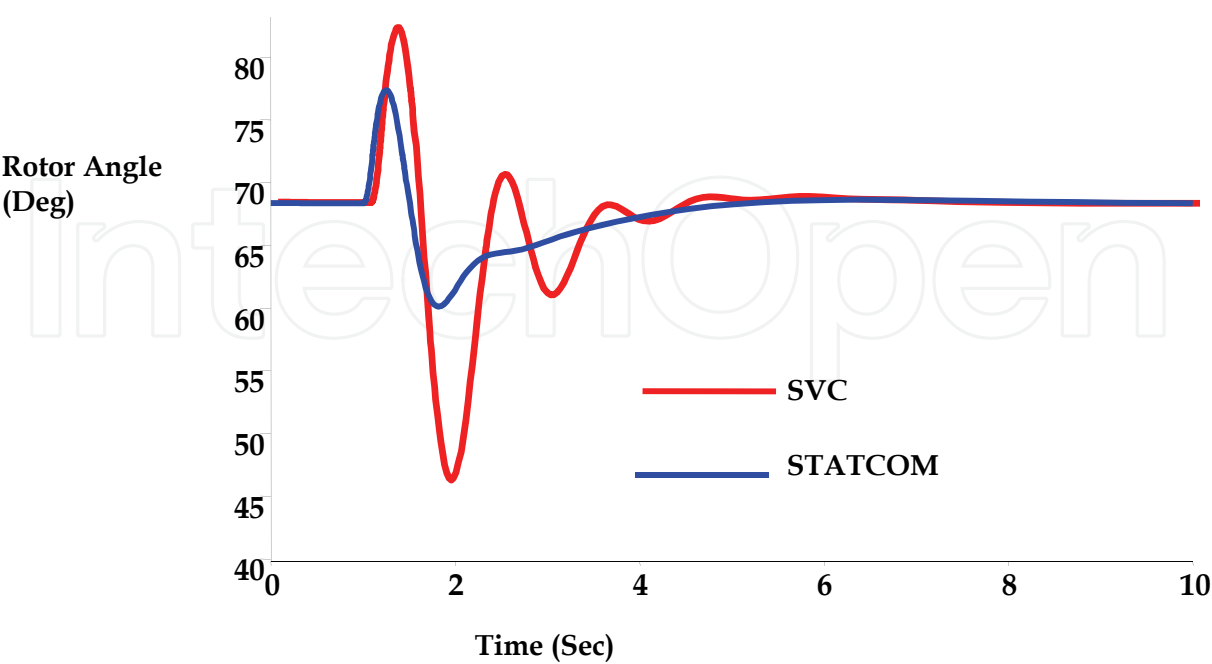
Fig. 12. Rotor angle response of synchronous machine G1 with windfarm – Effect of SVC and STATCOM
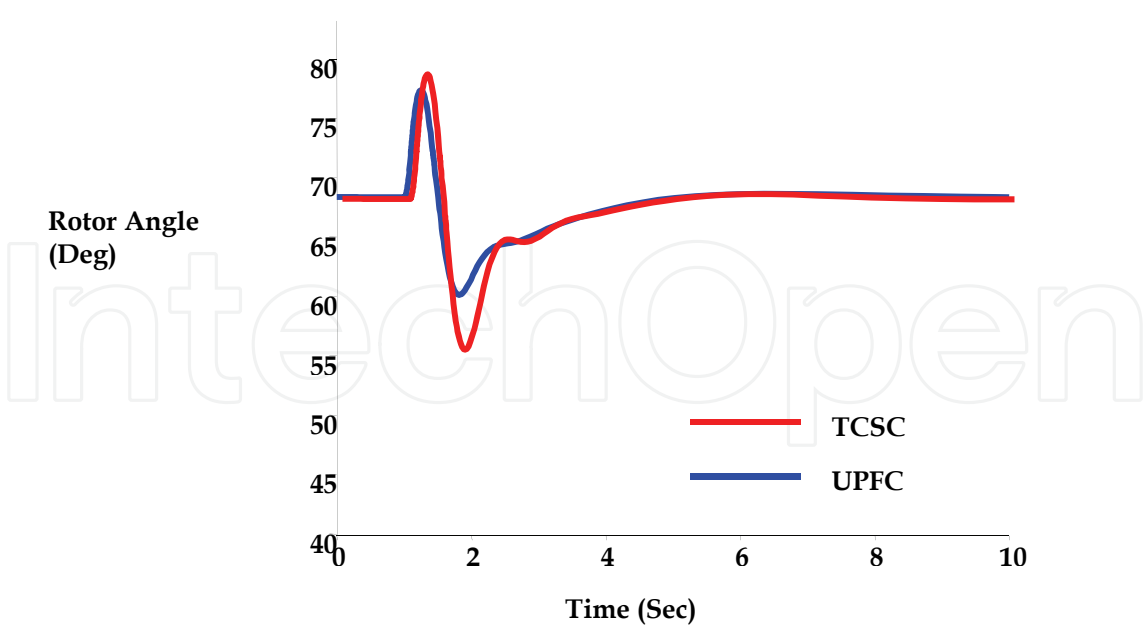

Fig. 13. Rotor angle response of Synchronous Machine G1 with Windfarm–Effect of TCSC and UPFC

4.2 Rotor speed deviation of DFIG- Effect of FACTS controllers

Fig. 14 demonstrates the effect of FACTS devices on the rotor speed response of DFIG after the disturbance**.** The speed of the induction generator tends to increase towards its maximum value set (1.22 per unit) in the dynamic simulation without FACTS controllers in the network After the clearance of the fault it is observed that the speed of the wind turbine does not reach its prefault steady state value of 1.1 p.u.This post fault rotor speed deviation of the asynchronous generator causes rotor speed instability.
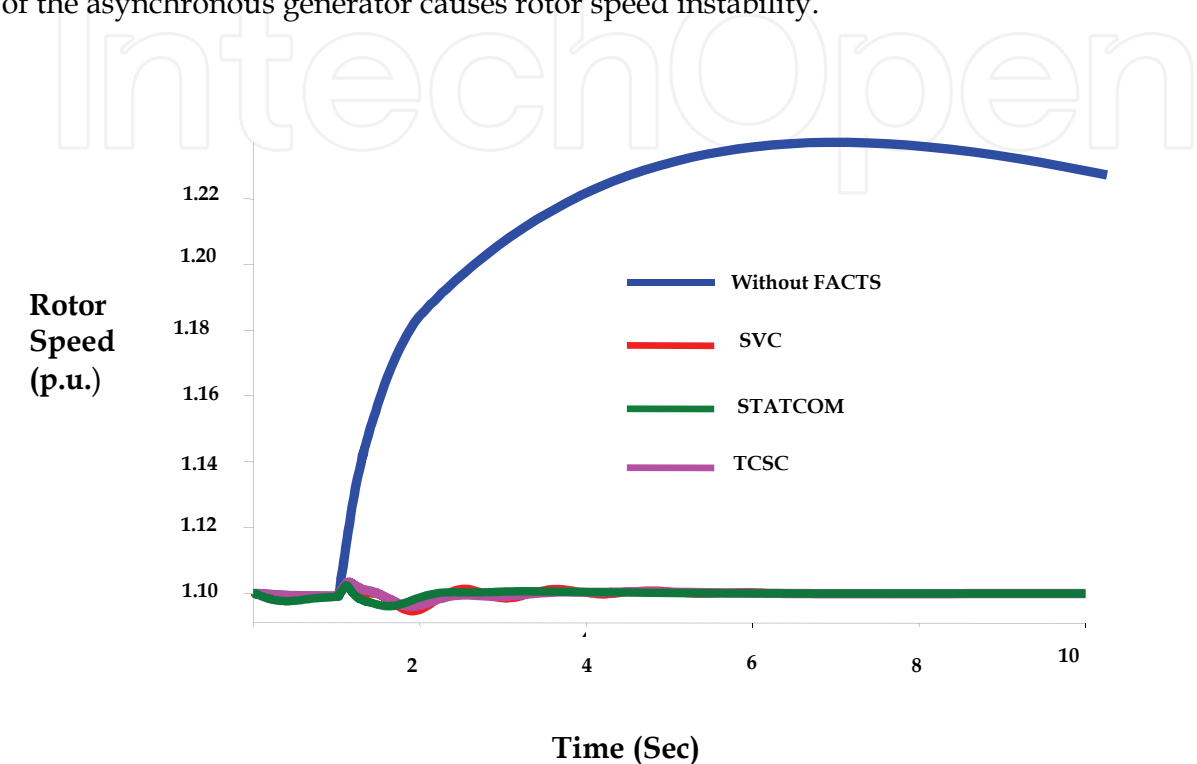
Fig. 14. Rotor Speed Deviation – Effect of FACTS devices

The rotor speed response of DFIG with SVC /STATCOM is displayed in Fig.15. It can be noticed that due to the additional dynamic reactive power support of SVC and the damping signal provided suppresses the rotor speed oscillations of the asynchrnous generaotors. From Fig 16 it can be inferred that there are no appreciable rotor speed deviations with UPFC controller in the network. This is due to the effectivenss of UPFC damping controller attached with its power flow controller and also due to the shunt reactive support provided by the UPFC.Hence it can be concluded that UPFC damps out rotor speed /rotor angle oscillations of asynchronous and synchrous generators more effectively.

4.3 Active power injected by the DFIG –effect of FACTS controllers

Fig. 17 shows the active power injected by the wind turbine into the grid folloiwng the three phase fault carried on one of the lines near bus 3.The stator protection system associated with the induction generator disconnects the stator from the grid if the terminal voltage of the induction generator is less than 0.75 p.u. for a period of 0.08 seconds, hence the stator active power delivered comes down to zero after the fault. The active power injected comes down to zero from its initial value of 5.5. Megawatts specified in the load flow.
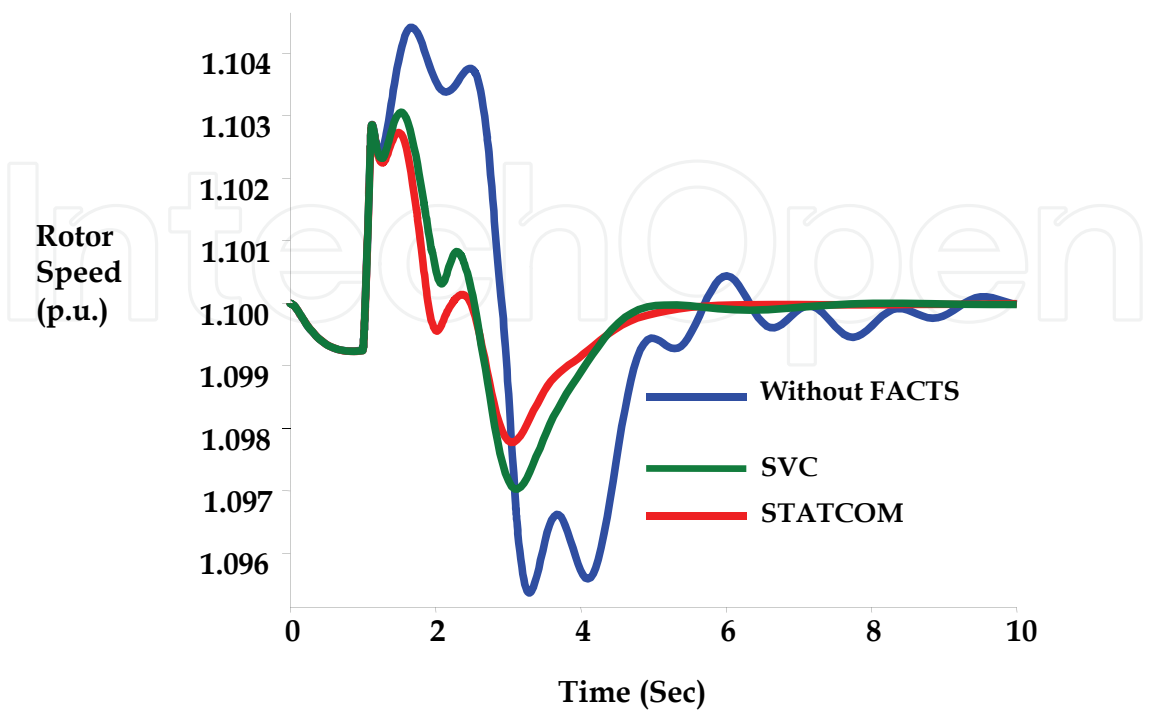
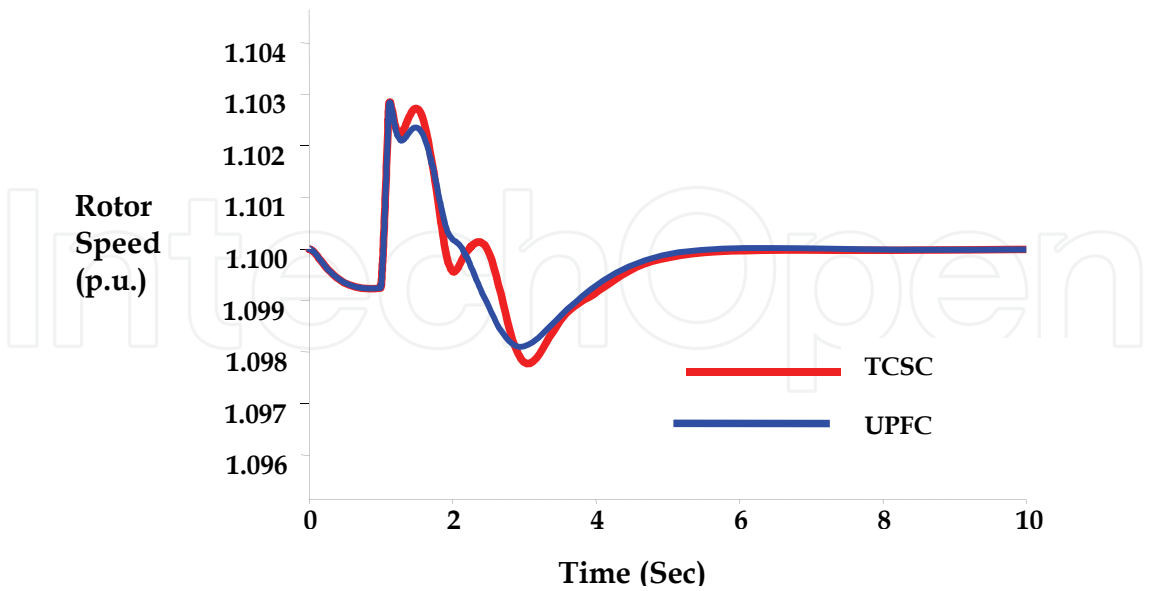Fig. 15. Rotor Speed Deviation – Effect of Shunt FACTS devices –

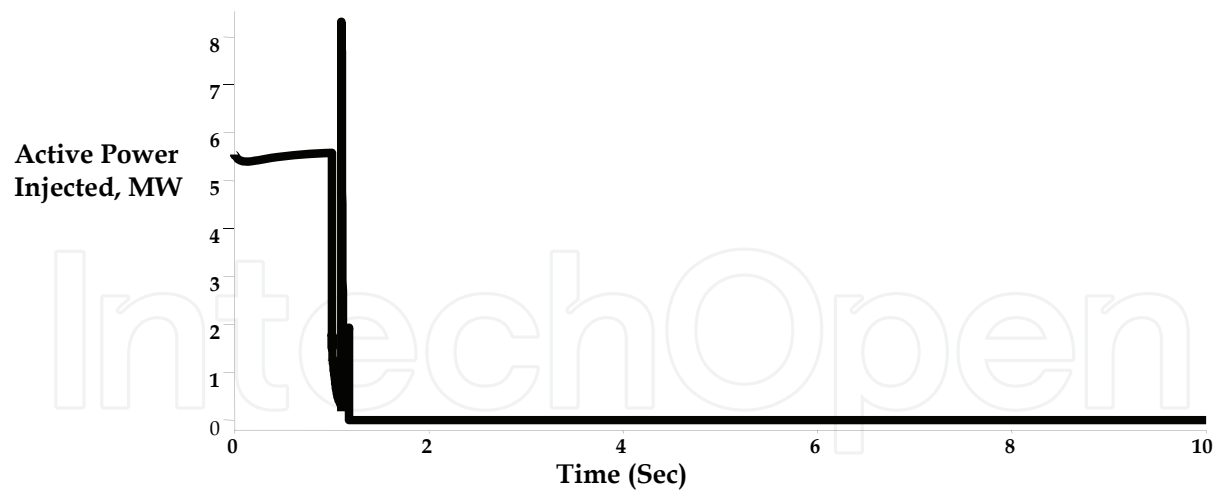Fig. 16. Rotor Speed Deviation – Effect of Series FACTS devices – TCSC & UPFC

Fig. 17. Active Power Injected by the wind farm without FACTS

The power calculation according to equation (1) is based on a single wind speed. However, in reality, the wind speed may differ slightly in direction and intensity across the area traversed by the blades. To consider this effect, the wind speed is supplied through a lag block to the power conversion equation. This creates a slight change in the active power delivered to the grid before the disturbance at 1 second.

4.4 Induction generator terminal voltage –effect of FACTS controllers

The response in induction generator terminal voltage following the transient fault is shown in Fig. 18, without FACTS controllers in the network. The under voltage protection system associated with the wind turbine disconnects the stator from the network if the voltage at its stator terminals is less than 0.75 p.u. for a period of 0.08 seconds.
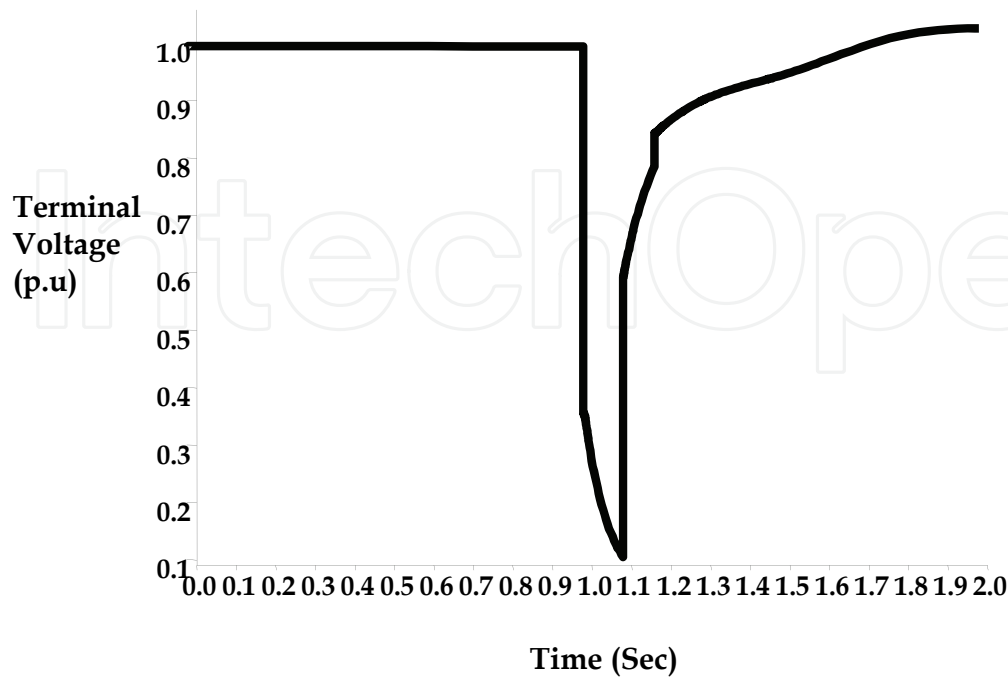
Fig. 18. Induction Generator Terminal Voltage without FACTS

Fig. 19 and 20 show the response of the induction generator terminal voltage with SVC/TCSC and STATCOM. /UPFC.

It can be concluded that terminal voltage of the DFIG is above 0.75 p.u. after 0.1 seconds. Comparing Fig. 18, 19 and 20 it can be concluded that the UPFC improves the fault ride through capability of the DFIG very effectively.
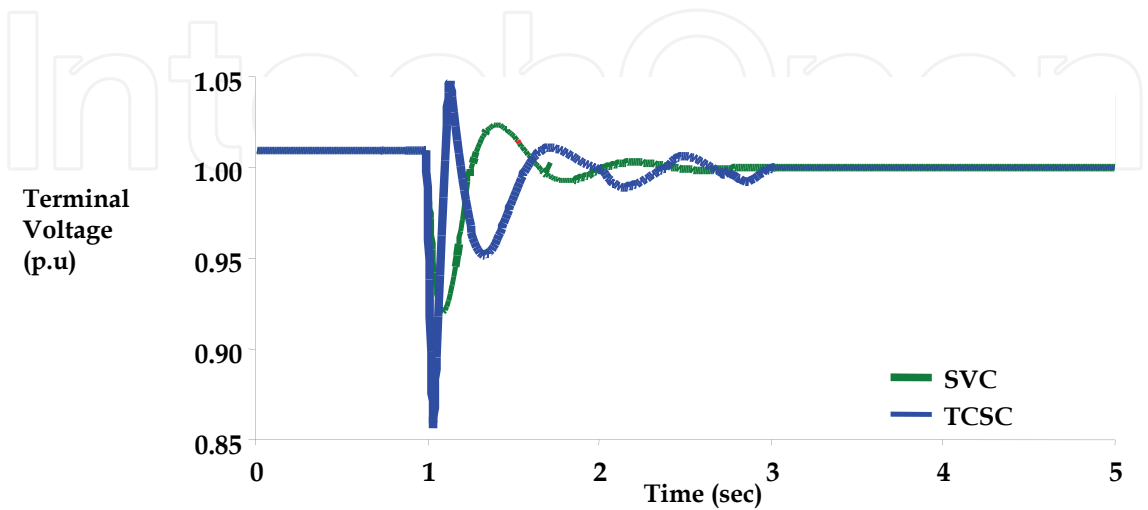

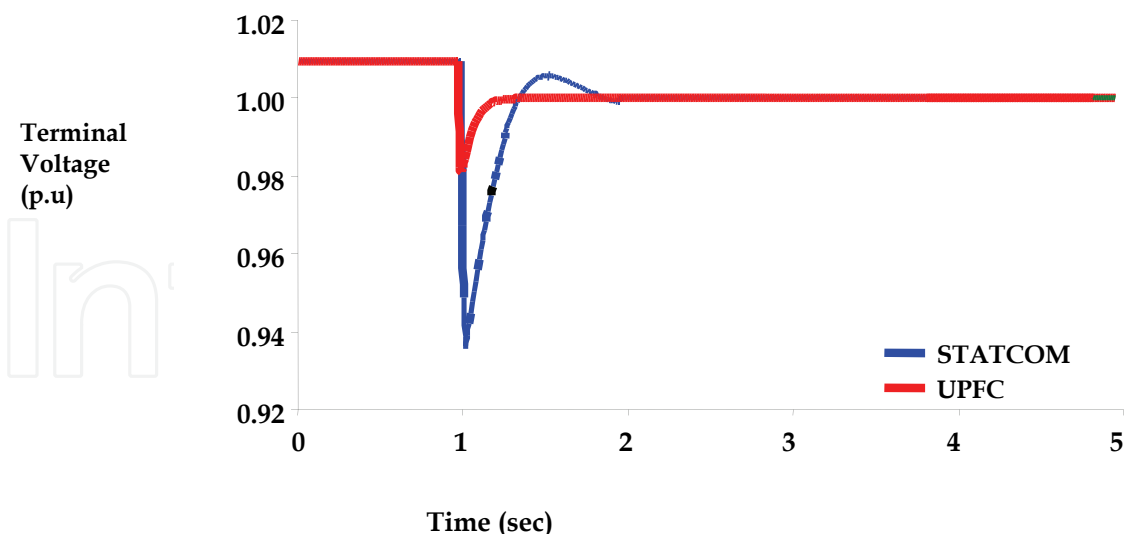Fig. 19. Induction Generator Terminal Voltage – Effect of SVC and TCSC

Fig. 20. Induction Generator Terminal Voltage – Effect of STATCOM and UPFC

4.5 Effect of wind speed variations

The dynamic performance of the FACTS controllers with doubly fed induction generator (DFIG) based wind farm is investigated using the wind speed model shown in Fig. 21.[7]
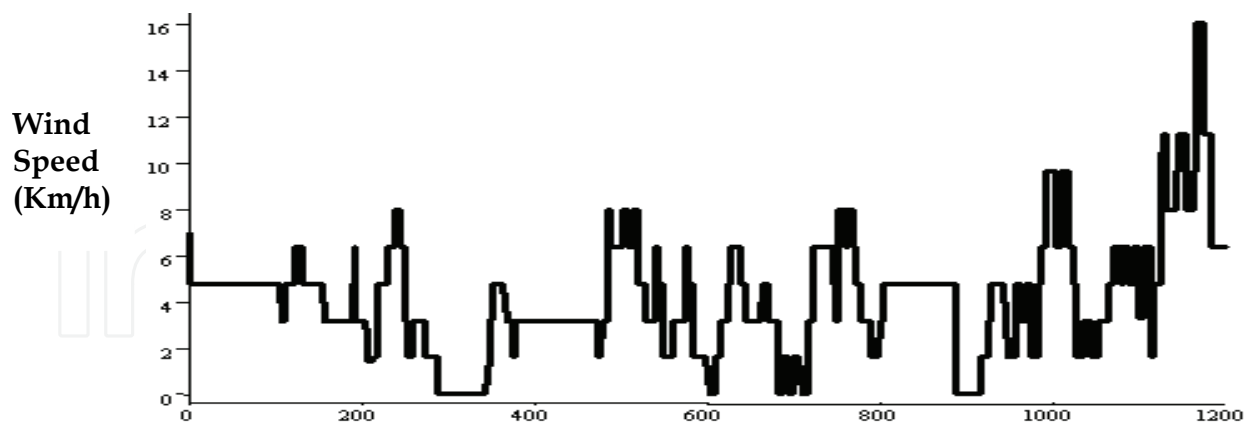
Fig. 21. Wind speed Model considered for long term dynamic simulation

The average wind speed is around 5 Km/h approximately. The wind speed data are obtained by measuring the wind speed changes over an hour from the regional meteorological website.

It can be observed that during the time period from 0- 1000 sec the wind speed fluctuates around an average wind speed of 5 Km/h. But the wind speed reaches 16 Km/h around 1,200 seconds. The corresponding rotor speed variation by the induction generator is shown in Fig 22. It can be observed that the rotor speed changes from its initial value to 1.25 p.u. following wind speed increase at 1200 seconds.

Time (Sec)
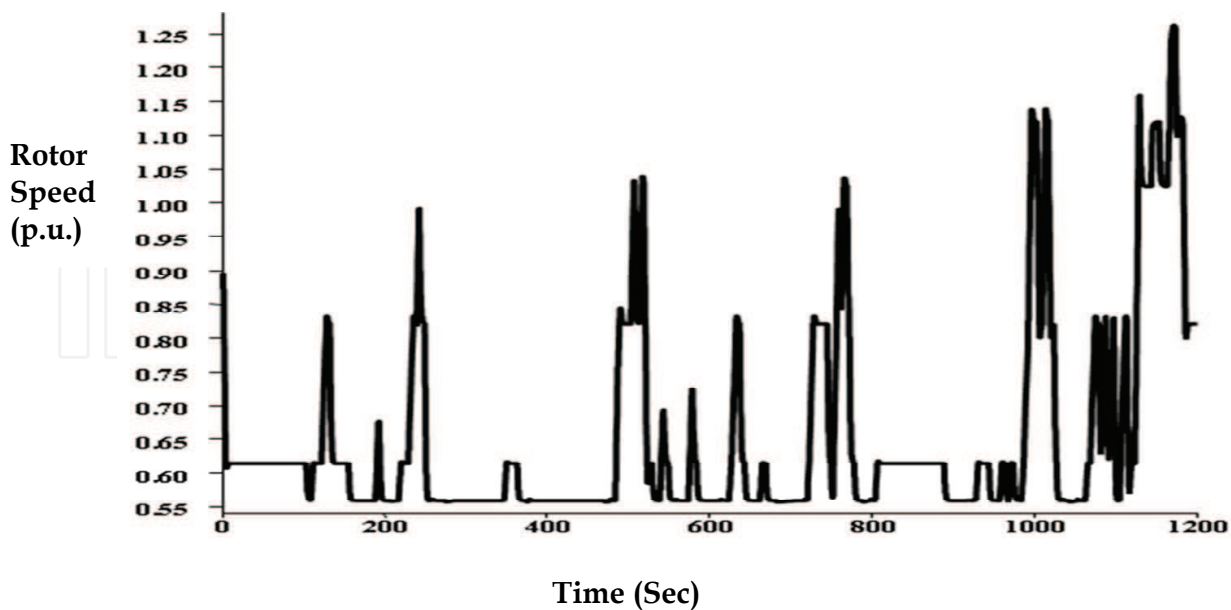
Fig. 22. Rotor Speed response of DFIG

The corresponding active power variations are shown in Fig.23.

Active Power Injected MW

Time (Sec)
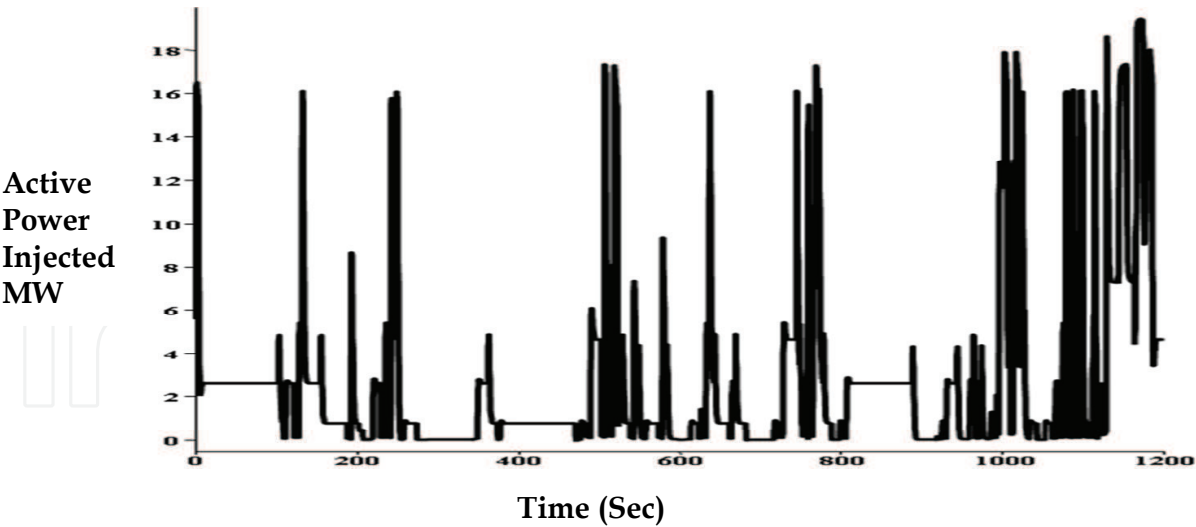
Fig. 23. Active Power Injected by the wind farm

The active power variations following the wind speed changes are highly fluctuating from the steady state load flow level to the grid. The performance coefficient C_p of the wind turbine is kept as 0.48 in the algebraic equation $P = \dfrac{1}{2}C_p.\rho.AV^3$. Fig. 24 shows the impact of an SVC/STATCOM controller on the rotor speed response of the DFIG.
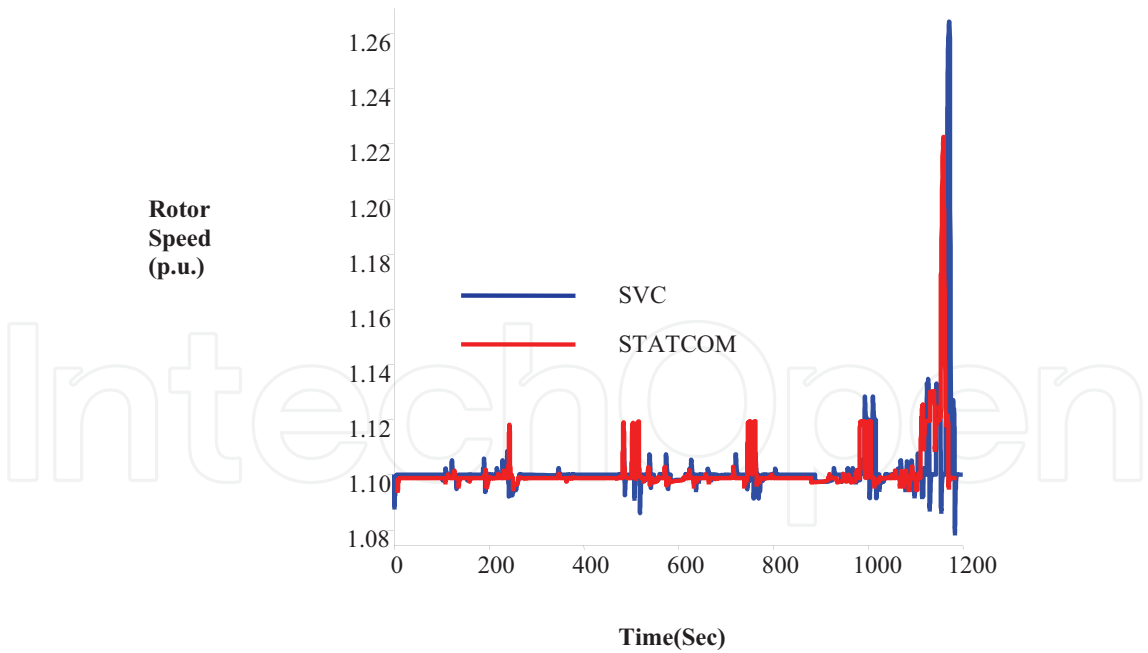

Rotor Speed (p.u.)

Time(Sec)

Fig. 24. Rotor Speed Response of induction Generator with SVC/STATCOM

There are no significant rotor speed oscillations in the rotor speed of the induction generator with SVC in the network; however the rotor speed increases to 1.26 p.u. with SVC in the network following wind speed increase of 16 Km/h near 1200 seconds. The rotor speed response of induction generator with TCSC/UPFC is shown in Fig 25.

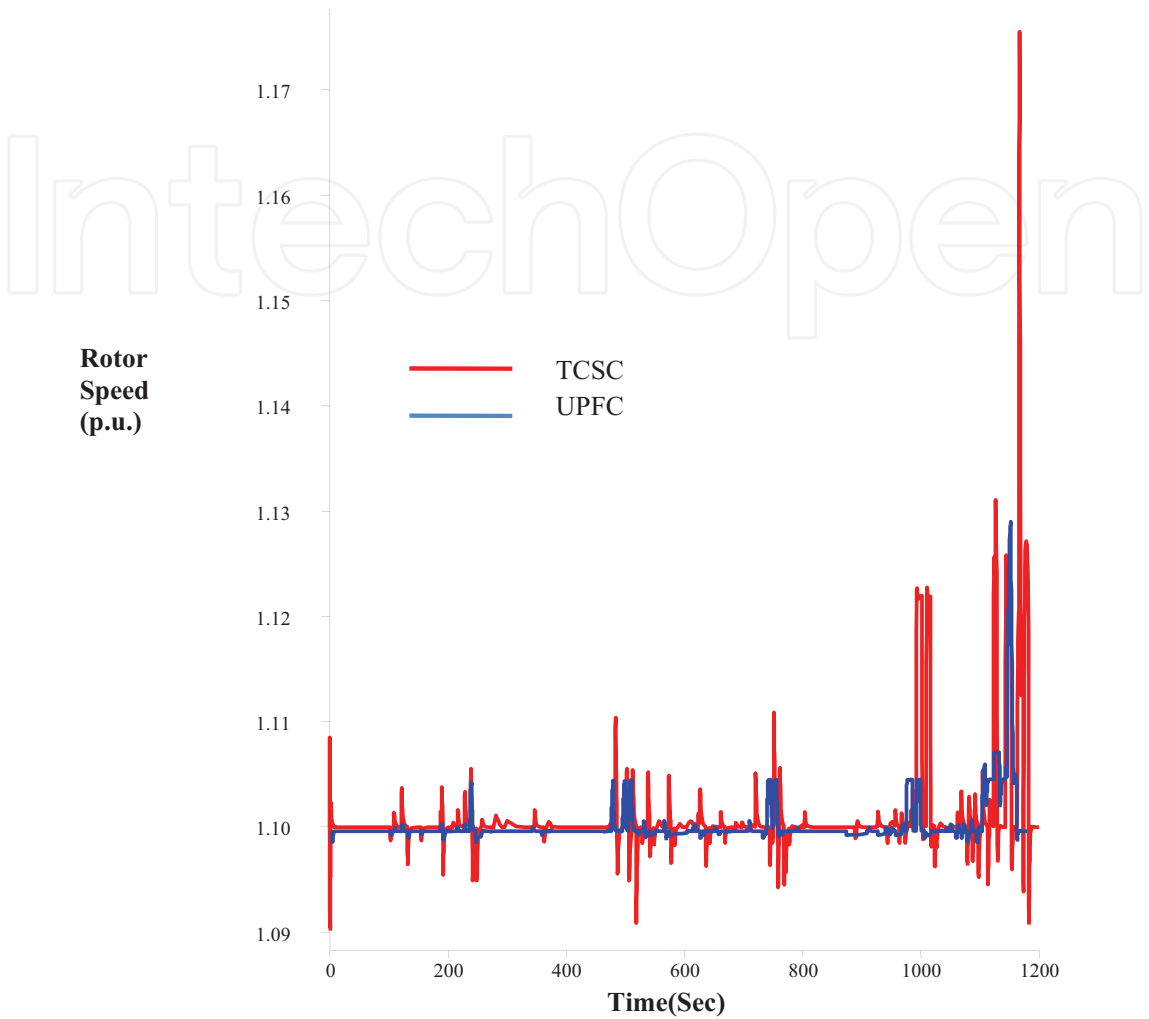It can be noticed that the rotor speed oscillations are damped effectively with UPFC in the network.

Fig. 25. Rotor speed Response of Induction generator with TCSC/UPFC.

5. Conclusion

For the simulation study the gains and time constants of the FACTS controllers are tuned using a conventional optimization program, which minimizes the voltage /rotor speed oscillations of the induction generator. Among series connected FACTS controllers the UPFC damps both rotor angle oscillations of synchronous generators and rotor speed oscillations of induction generator very effectively when compared with TCSC. This is due to the reactive support provided by the shunt branch of the UPFC following the disturbance. However the reactive power rating of UPFC is very high compared to that of the TCSC .It is suggested that a STATCOM of suitable rating may be installed at the point of common coupling (PCC) with or without a capacitor may be used for stabilizing rotor speed oscillations associated with doubly fed variable speed induction generators following transient faults and disturbances.

The development of wind turbine and wind farm models is vital because as the level of wind penetration increases it poses dynamic stability problems in the power system. For the

present work we have taken a taken a doubly fed induction generator model and illustrated the presence of sustained oscillations with wind farms. Suitable Flexible A.C.Transmission Systems controllers are modeled using the non-linear simulation models and the transient ratings of the FACTS controller are obtained to stabilize the rotor speed/rotor angle oscillations in a DFIG based wind energy conversion scheme. The rotor speed stability of the DFIG based system following a generator outage is studied. It can be observed that the effect of low voltage ride through (LVRT) is very minimum following the contingency and the presence of a FACTS device like the SVC improves the rotor speed stability.

This chapter also presented the results of a long term dynamic simulation of a grid connected wind energy conversion system which simulated wind speed changes. From the results it is observed that STATCOM and UPFC are effective candidates for damping the rotor speed oscillations of the induction generator.

6. Appendix

a.   Parameters

Base values for the per unit system conversion.

Base Power: 100 MVA, Base Voltage: 0.69 KV for low voltage bus bar, 150 KV for high voltage busbar.

b.   Doubly- Fed Induction Generator

Rated apparent power MVA: 2 MVA, Rotor inertia: 3.527 MW s/MVA

R_s (p.u.) = 0.0693,X_s (p.u.) = 0.080823,R_r (p.u.) =0.00906,X_r (p.u)= 0.09935,

X_m (p.u) = 3.29, Minimum Rotor Speed: 0.56 p.u., Maximum Rotor Speed: 1.122 p.u.

c.   Transformers

Three winding transformer (150 KV: 0. 69 KV), Primary rated apparent power=25 MVA, Secondary rated apparent power = 25MVA,Tertiary rated apparent power = 6 MVA.

7. Acknowledgement

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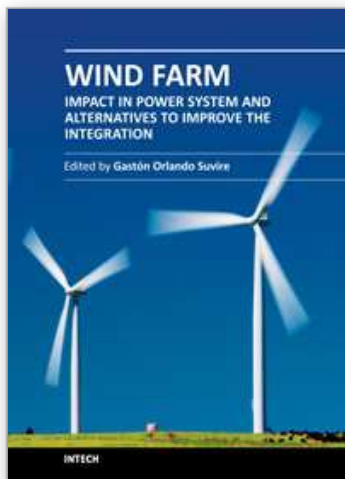
Wind Farm - Impact in Power System and Alternatives to Improve the Integration

Edited by Dr. Gastón Orlando Suvire

During the last two decades, increase in electricity demand and environmental concern resulted in fast growth of power production from renewable sources. Wind power is one of the most efficient alternatives. Due to rapid development of wind turbine technology and increasing size of wind farms, wind power plays a significant part in the power production in some countries. However, fundamental differences exist between conventional thermal, hydro, and nuclear generation and wind power, such as different generation systems and the difficulty in controlling the primary movement of a wind turbine, due to the wind and its random fluctuations. These differences are reflected in the specific interaction of wind turbines with the power system. This book addresses a wide variety of issues regarding the integration of wind farms in power systems. The book contains 14 chapters divided into three parts. The first part outlines aspects related to the impact of the wind power generation on the electric system. In the second part, alternatives to mitigate problems of the wind farm integration are presented. Finally, the third part covers issues of modeling and simulation of wind power system.

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