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Transient Stability Simulation System with PSS Including Wind Farm

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Abstract. In order to analyze the transient stability of grid connected doubly fed induction generators (DFIG) in wind power generating systems, various mathematical models, including the detailed generator models as well as the one-mass and two-mass shaft system models, are studied in this paper. Based on the different system models, the dynamic behaviors are simulated by using Matlab/Simulink, under the condition that the machine synchronous is subjected to a three-phase short-circuit fault. In addition the power system stabilizer (PSS) is modeled and compared by simulation for different system at the various operation conditions. The models and methods suitable to analyze the transient stability of the power system including wind turbine systems based on DFIG are discussed in detail. Several comparative results have shown that the valid transient stability model of PSS in power systems.

Keywords: Transient Stability, Synchronous Generator, PSS, Wind turbine, Doubly Fed Induction Generator.

1 Introduction

Wind energy is now an energy that cannot be ignored. Because of intrinsic characteristics (scattered primary energy, generators with different technologies, use of power electronics interface), the integration of wind energy system in distribution grids leads to real problems in terms of impacts. With recent standard changes, it is necessary to study the possibilities of each technology of wind turbines to answer or not to these new constraints. In the wind power stations, doubly fed induction generators (DFIG) are commonly used as generators. It is important to analyze the transient stability of power system including wind power farms [l].

PSS is one of the important devices whose effectiveness for voltage control is well known. It has been successfully used to damp out power system oscillations

[2]. Not only small signal but also transient stability can be improved by PSS. Compared with another studies, the PSS can provide control actions continuously and rapidly [3]. Recently, much effort has been directed towards the applications of PSS control in power systems [4;5], however, few papers have considered the application of PSS to power system including wind farms with DFIG [6;7]. It is possible to design PSS controller by taking into account the non-linearity of power system [8]. It can be implemented easily because complicated and time-consuming calculations are not involved.

The purpose of this paper is to present the impact of the PSS to improve the transient stability in power system while using simulation under Matlab-Simulink environment.

2 The transient generator model

Mathematical models of a synchronous machine vary from elementary classical models to more detailed ones. In the detailed models, transient and subtransient phenomena are considered. In this work, transient models are used to represent the machines in the system, according to following equations.[9]

Stator winding equations:

$$v_q = -r_s i_q - x_d^{'} i_d + E_q^{'} \tag{1}$$

$$v_d = -r_s i_d - x_q^{'} i_q + E_d^{'} \tag{2}$$

Where:

r_s Is the stator winding resistance

$x_d^{'}$ Is the d–axis transient reactance

$x_q^{'}$ Is the q–axis transient reactance

$E_q^{'}$ Is the q–axis transient voltage

$E_d^{'}$ Is the d–axis transient voltage.

Rotor winding equations:

$$T_{d0}^{'} \frac{dE_q^{'}}{dt} + E_q^{'} = E_f - \left(x_d - x_d^{'}\right) i_d \tag{3}$$

$$T_{q0}^{'} \frac{dE_d^{'}}{dt} + E_d^{'} = \left(x_q - x_q^{'}\right) i_q \tag{4}$$

Where:

$T_{d0}^{'}$ Is the d–axis open circuit transient time constant.

$T_{q0}^{'}$ is the q–axis open circuit transient time constant.

E_f is the field voltage.

Torque equation:

$$T_{el} = E_d^{'} i_d + E_q^{'} i_q + \left(x_q^{'} - x_d^{'} \right) i_d i_q \quad (5)$$

Rotor equation:

$$2H \frac{d\omega}{dt} = T_{mech} - T_{el} - T_{damp} \quad (6)$$

$$T_{damp} = D \Delta\omega \quad (7)$$

Where:

T_{mech} is the mechanical torque, which is constant in this model; T_{el} is the electrical torque; T_{damp} is the damping torque and D is the damping coefficient.

For time domain simulations, it is necessary to include the effects of the excitation controller. Automatic voltage regulators (AVRs) define the primary voltage regulation of synchronous machines. AVR and exciter for synchronous generator is modeled as the standard IEEE model, Figure1.

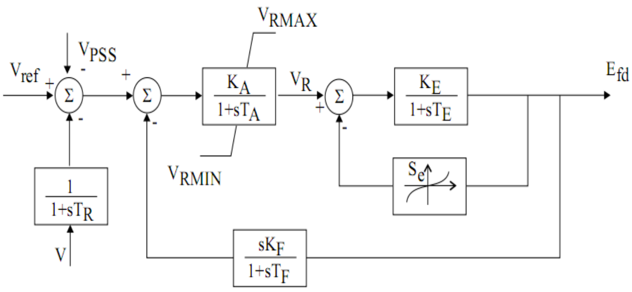

Fig. 1. AVR and exciter model for synchronous generator

3 Power system stabilizer model

Using Matlab/Simulink, a PSS can be viewed as an additional control block used to enhance the system damping. This block is added to AVR. The three basic blocks of a typical PSS model, are illustrated in Figure 2. The first block is the stabilizer Gain block, which determines the amount of damping. The second is the Washout block, which serves as a high-pass filter, with a time constant that allows the signal associated with oscillations in rotor speed to pass unchanged, but does not allow the steady state changes to modify the terminal voltages. The last one is the phase-compensation block, which provides the desired phase-lead characteristic to compensate for the phase lag between the AVR input and the generator torque.

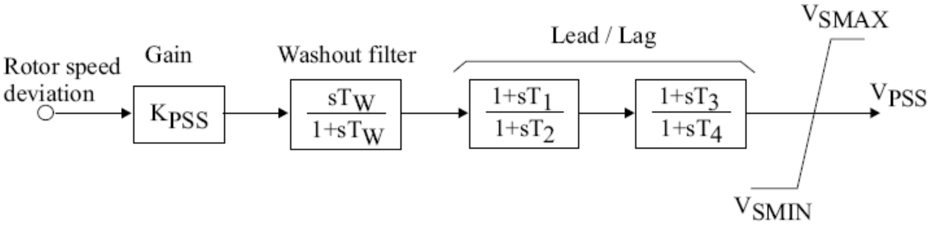

Fig.2. PSS block diagram

4 Variable speed wind turbine model

A typical DFIG configuration (Figure. 3) consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back partial scale power converter. The back-to-back converter is a bi-directional power converter consisting of two conventional pulse width modulation (PWM) voltage source converters (rotor side/grid side converter) and a common DC-bus. The transformer connecting the system to the grid has two secondaries; one winding connecting the stator and the other connecting the rotor. The voltage reduction on the rotor side makes possible to operate at a lower DC bus voltage.

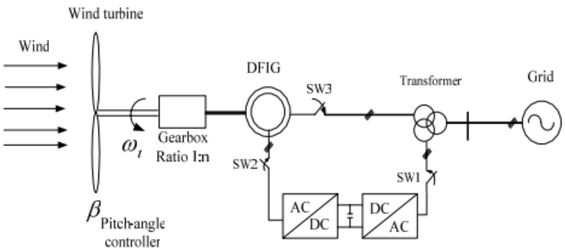

Fig. 3. Wind Turbine with DFIG

4.1 Mechanical component models

- Wind model

The wind model has been developed at RISØ National Laboratory based on the Kaimal spectra [10]. The wind speed is calculated as an average value of the fixed-point wind speed over the whole rotor, and it takes the tower shadow and the rotational turbulences into account. A main component in this model is the normally distributed white noise generator. Therefore, in order to obtain the same wind time series in all considered simulation tools used in the simulation platform, some investigations have been done. It has been found that the built-in white noise generator from different simulation tools uses a different algorithm and thus a different wind time series is obtained. In order to validate the new white noise generator model some comparisons have been done. A wind time series for 3600 sec with 0.05 sec sample time.

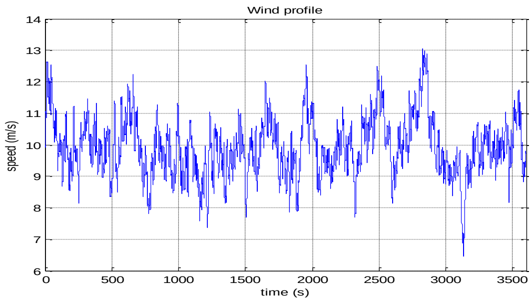

Fig. 4. The wind profile

- Wind turbine rotor model

The aerodynamic model of the wind turbine (WT) rotor is based on the torque coefficient C_Q or the power coefficient C_P. The torque coefficient C_Q is used to determine the aerodynamic torque directly by using:

$$T_{wt} = 0.5\pi\rho R^3 V_\infty C_Q \tag{8}$$

Where ρ is the air density, R is the blade radius, V_∞ is the wind speed, C_Q is the torque coefficient.

Alternatively, the aerodynamic torque can be determined using the power coefficient C_P based on:

$$T_{wt} = 0.5\pi\rho R^2 V_\infty^3 C_P \tag{9}$$

It is important to underline that both coefficients C_P and C_Q can be function of the tip speed ratio λ for passive-stall wind turbines or function of tip speed ratio λ and pitch angle θ for active stall and variable pitch/speed wind turbines. The parameters for this model are: blade radius, air density, cut-in and cut-out wind speeds, as shown in appendix. Using a reduced look-up table in respect with the variation of the torque coefficient/power coefficient with the pitch angle $(-10° \le \theta \le 10°)$, the model for the active-stall wind turbine is obtained. Imposing a zero value for the pitch angle θ the model for passive stall wind turbine can be obtained.

- Drive train model

The equivalent model of a wind turbine drive train is presented in Figure. 5. The masses correspond to a large mass of the wind turbine rotor, masses for the gearbox wheels and a mass for generator respectively. [11]

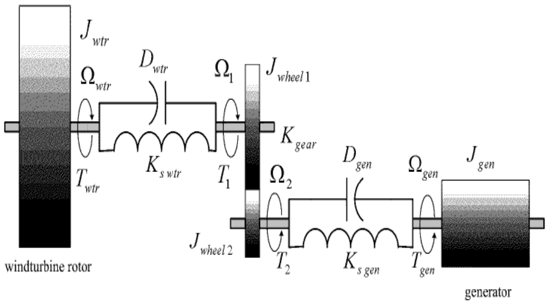

Fig.5. Model of a wind turbine drive train

Taking into account the stiffness and the damping factors for both shafts, the dynamic equations can be written as follows:

$$T_{wtr} = J_{wtr}\frac{d\Omega_{wtr}}{dt} + D_{wtr}\Omega_{wtr} + K_{swtr}\left(\theta_{wtr} - \theta_1\right) \tag{10}$$

$$T_1 = J_1\frac{d\Omega_1}{dt} + D_{wtr}\Omega_1 + K_{swtr}\left(\theta_1 - \theta_{wtr}\right) \tag{11}$$

$$T_2 = J_2\frac{d\Omega_2}{dt} + D_{gen}\frac{d\Omega_2}{dt} + K_{sgen}\left(\theta_2 - \theta_{gen}\right) \tag{12}$$

$$-T_{gen} = J_{gen}\frac{d\Omega_{gen}}{dt} + D_{gen}\Omega_{gen} + K_{sgen}\left(\theta_{gen} - \theta_2\right) \tag{13}$$

$$T_2 = \frac{1}{K_{gear}}\cdot T_1 \tag{14}$$

Such as:

$$\Omega_{wtr} = \frac{d\theta_{wtr}}{dt}, \Omega_{gen} = \frac{d\theta_{gen}}{dt};\ \Omega_i = \frac{d\theta_i}{dt}; i = 1,2;\ \Omega_2 = K_{gear}\cdot\Omega_1, \tag{15}$$

Where: T_{wtr} is the wind turbine torque, T_1 is torque that goes in the gearbox, T_2 is the torque out from the gearbox, J_{wtr} is the WT moment of inertia, Ω_{wtr} is the WT mechanical speed, K_{swtr} is the spring constant indicating the torsion stiffness of the shaft on wind turbine part, T_{gen} is the generator torque, J_{gen} is the generator moment of inertia, Ω_{gen} is the generator mechanical speed, K_{sgen} is the spring constant indicating the torsion stiffness of the shaft on generator part.

4.2 Doubly-Fed-Induction model

Some of the machine inductances are functions of the rotor speed, whereupon the coefficients of the state-space equations (voltage equations), which describe the behavior of the induction machine, are time varying (except when the rotor is at stand-still). A change of variables is often used to reduce the complexity of these state-space equations. There are several changes of variables, which are used but there is just one general transformation [8]. This general transformation refers the machine variable to a frame of reference, which rotates at an arbitrary angular velocity ω_g. In this reference frame, the machine windings are replaced with some equivalent windings as shown in Figure. 6.

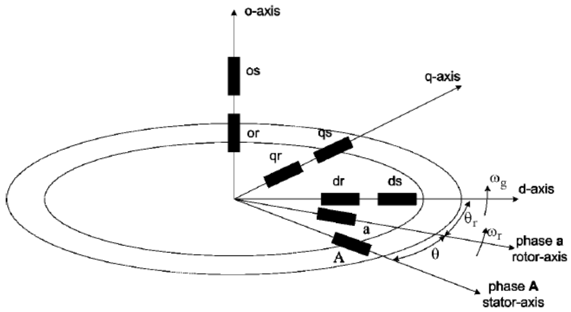

Fig.6. Induction machine windings in the dq0- reference frame

The basic equation of the machine is:

$$[V]=[R]\cdot[I]+\frac{d[\psi]}{dt} \tag{16}$$

Based on eq. (16) and using the general transformation, the voltage equations in the arbitrary reference frame can be written as:

$$[V]=[R][I]+\frac{d}{dt}[\psi]+[\Omega][\psi] \tag{17}$$

The relation between the linkage fluxes and currents is given by:
Or in compact form:

$$[\psi]=[L][I] \tag{18}$$

The electromagnetic torque can be obtained starting from eq. (16) and multiplying it from the left with the transpose of the currents vector:

$$[I]^t[V]=[I]^t[R][I]+[I]^t\frac{d}{dt}[\psi]+[I]^t[\Omega][\psi] \tag{19}$$

Where:

$P_i=[I]^t[V]$ is the instantaneous power.

$P_{copper}=[I]^t[R][I]$ are the copper losses in the machine windings.

$P_{mag}=[I]^t\frac{d[\psi]}{dt}$ is the magnetic power stored in machine (due to the variation in time of the magnetic energy).

$P_m=[I]^t[\Omega][\psi]$ is the mechanical power.

The electromagnetic torque is then:

$$T_e = \frac{P_m}{\Omega_r} = p\frac{P_m}{\omega_r} = \frac{3}{2}p\left(\psi_{sd}i_{sq} - \psi_{sq}i_{sd}\right) \tag{22}$$

With p is the number of pole pairs and Ω_r is the mechanical speed of the rotor.

4.3 Power converter model

Currently, in wind turbine applications the back-to-back voltage source converter (VSC) is mainly used. A block diagram of this power converter is shown in Figure. 7. This topology comprises a double conversion from AC to DC and then from DC to AC. Both converters can operate in rectifier or inverter mode.

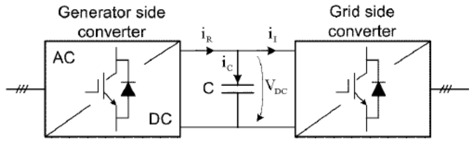

Fig.7. Structure of the back-to-back voltage source converter

A voltage source converter can be implemented in several ways: six-step, pulse amplitude modulated (PAM) or pulse width modulated (PWM). Moreover, the implementation of a PWM VSC may be performed by three methods: harmonic elimination, "sinusoidal" PWM or space vector strategy (SV-PWM). The DC-link voltage, which is the voltage at the capacitor terminals, is given by:

$$V_{DC} = \frac{1}{C}\int i_C dt = \frac{1}{C}\int \left(i_R - i_I\right)dt \tag{23}$$

Where i_R is the current of the generator in side converter and i_I is the current of the grid side converter

5 Case study and simulation

In order to validate the presented models, the results of simulating a heavy and a relatively weak disturbance in the system shown in Figure 8 are described. The system is modeled by a source behind an impedance that is connected to a synchronous generator through a transmission line. A wind farm consisting of doubly-fed induction generators with a rating of 2 MW is connected to the mid-point of the transmission line. Each doubly-fed induction generator is modeled according to Figure 5, including a three winding transformer, the induction generator, the grid-side and the rotor-side converter and the intermediate DC circuit Figure 9.
Time domain simulations under Matlab-Simulink environment are performed for a strong three-phase fault of 0.1 sec applied to the grid impedance in several times.

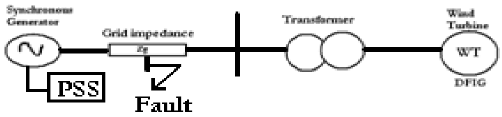

Fig.8. Case study

Figure 9 illustrates voltage terminal, rotor angle oscillations, active and reactive powers of synchronous machine respectively without and with integration of PSS.

The PSS controller model used in this case is shown in Figure 2. The gain and various time constants of the PSS were selected from [12] based on the rating of the machine. A complete set of data for the PSS controller parameters are given in Appendix.

The performance of the test system without and with PSS is shown in figure 9. Although the system is stable, there is a damped oscillation that could be improved by retuning the controller of PSS.

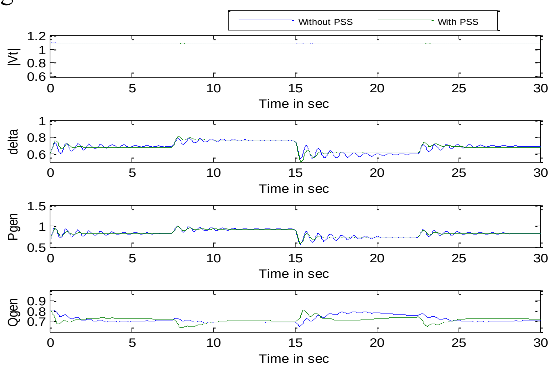

Fig.9. Simulation results of synchronous machine

Figure 10 depicts the simulation results of mechanical parts of the wind turbine; speed, torque and the wind variation during the time of simulation. The wind turbine speed varies approximately between 0.7 pu and 1.8 pu and presents a pick during the integration of wind turbine similarly to torque as shown in Figure. 12.

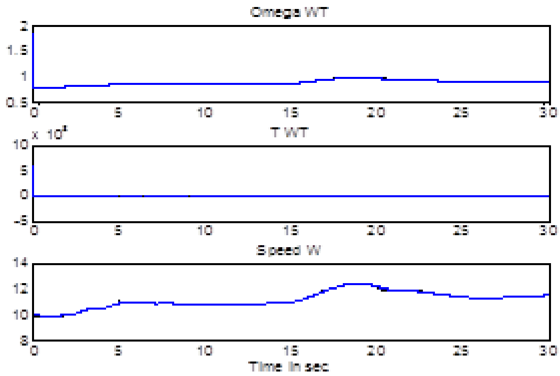

Fig.10. Simulation results of wind turbine with DFIG (Mechanical parts)

The electromagnetic torque is is equal to 0 between the time simulation 0 to 10 sec then it builds a envelope signals, the speed electromagnetic of wind turbine varies between 156.5 and 155 rad/s. On the other hand, the torque of the drive train varies between 1000 and 2000 N.m during the all time of simulation as shown in Figure 11.

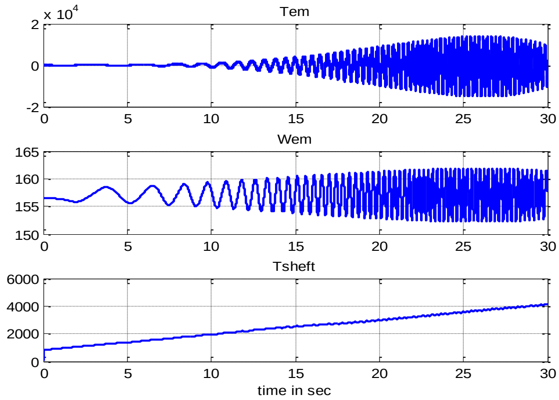

Fig.11. Simulation results of wind turbine with DFIG (Mechanical parts)

Several simulation results have been presented in this study under Matlab-Simulink environment by considering wind generator connected to infinite bus. These results show the reactions of the wind turbine during given disturbances such as wind fluctuation of and the short circuit three-phase.

Figures 12 and 13 present respectively the simulation results of the stator and the rotor currents following the d−axis, q−axis and homopolar axis.

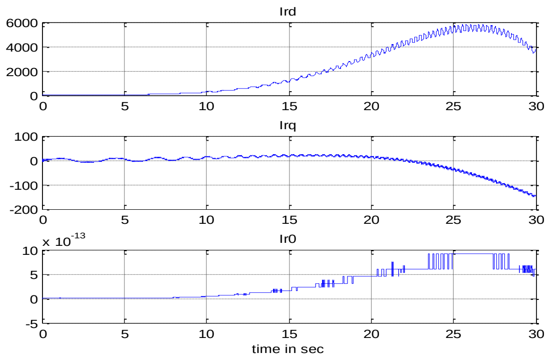

Fig.12. Simulation results of wind turbine with DFIG (Electrical parts)

The electric quantities (power or currents) are also very disturbed by the fluctuations of wind and the short circuit applied: the statorique or rotorique currents values is 4 times higher than the rated current, even more significant, is its consequence of the asynchronous machine demagnetization.

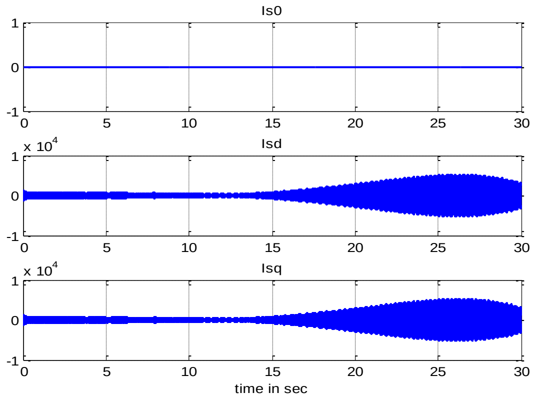

Fig.13. Simulation results of wind turbine with DFIG (Electrical parts)

5 Conclusion

In order to investigate the models and methods for the transient stability analysis of DFIG based wind turbines system, some methods to improve the power system stability including PSS are presented. Several system models with different generator models and drive train models of wind turbines are established in this paper.

Under Matlab-Simulink environment, simulations have been done when the synchronous is subjected to the three-phase short circuit fault. The application of the proposed model demonstrates the effect of the PSS on the grid. Using this model, the dynamic characteristics of power system stability can be estimated. Moreover, for future work, the transient stability of the multi-machine power system including wind farms and the system FACTS combined with this model should be studied.

5 Appendix

The generator parameters in per unit are as follows:

$X_d = 1.790$, $X_q = 1.660$, $X_d^{'} = 0.355$, $X_q^{'} = 0.570$,
$R_a = 0.0048$, $X_l = 0.215$, $T_{d0}^{'} = 7.9$, $T_{q0}^{'} = 0.410$, $H = 3.77$, $D = 0$.

The PSS Parameters are as follows:

$K_{PSS} = 120$ $T_w = 1.0$ $T_1 = 0.024$ $T_2 = 0.002$ $T_3 = 0.024$ $T_4 = 0.24$

The exciter parameters in per unit are as follows:

$K_A = 50$, $T_A = 0.06$, $V_{RMax} = 1$, $V_{RMin} = -1$, $T_E = 0.052$, $K_E = -0.0465$,
$T_F = 1.0$, $K_F = 0.0832$, $A_{Ex} = 0.0012$,
$B_{Ex} = 1.264$.

The wind turbine parameters:

Stator parameters [Rs (Ω), Lsgm_s(H)] =[3.67, 9.2 10^{-3}].
Rotor parameters [Rr (Ω) Lsgm_r (H)] =[2.32 ,12.29 10^{-3}].
Magnetizing inductance [H]: Lm=0.235.
Number of poles pair: pw=2.

References

[1] T. Petru and T. Thiringer, “Modeling of wind turbines for power system studies,” *IEEE Trans. Power Syst.*, vol. 17, no. 4, pp. 1132–1139, Nov. 2002.

[2] J. L. Rodriguez-Amenedo, “Automatic Generation Control of a Wind Farm With Variable Speed Wind Turbines,” *IEEE Transactions on Energy Conversion*, Vol 17, No. 2, June 2002.

[3] Claudio L.Souza et. al., "Power System Transient Stability Analysis including Synchronous and Induction Generator," *IEEE Porto Power Tech Proceedings*, Vol.2, pp.6, 2001.

[4] P. Ledesma, J. Usaola, J.L. Rodriguez, "Transient stability of a fixed speed wind farm", *Elsevier Science*, 5 August 2002.

[5] A.Sanai Sabzevaty, Manabu Sakata, Yam0 Tamura: "Robust Quadratic Stabilization of Power System", The Fourth h u a l Conference of Power

[6] J. G. Slootweg, S. W. H. de Haan, H. Polinder, W. L. Kling, "Aggregated Modelling of Wind Parks with Variable Speed Wind Turbines in Power System Dynamics Simulations," Proc. of the 14th Power Systems Computation Conference, Sevilla, 2002.

[7] J. B. Ekanayake, L. Holdsworth, X. G. Wu, and N. Jenkins, "Dynamic modeling of doubly fed induction generator wind turbines," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 803–809, May 2003.

[8] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Convers.*, vol. 18, no. 2, pp. 194–204, Jun. 2003.

[9] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc.1993

[10] Sorensen, P., Hansen, A.D., Rosas, P.A.C. – Wind models for simulation of power fluctuations from wind farms, *Journal of Wind Engineering*, 90, 2002, pp. 1381-1402.

[11] Shaltout, A. "Analysis of torsional torques in starting of large squirrel cage induction motors," *IEEE Trans. on Energy Conversion*, Vol. 9, No. 1. March 1994, pp. 135-141.

[12] N. Dizdarevic, Uni_ed Power Flow Controller in Alleviation of Voltage Stability Problem , Doctoral thesis, Zagreb,2001.