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Evaluation of the DFIG Wind Turbine Built-in Model in PSS/E

Master of Science Thesis in the Programme of Electric Power Engineering

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Abstract

Due to growth of environmental concern, more electricity must be generated from renewable energy sources. One of the most cost efficient alternatives is wind energy. Large wind farms with several hundred megawatts of rated power have been connected to grid. Nowadays, many transmission system operators require wind farms to maintain zero reactive power exchange with the grid during normal operation. Furthermore, like other conventional power plants wind turbines must be able to remain connected to the grid during grid faults. In order to study impact of wind power generation on the power system valid models of wind turbines are needed.

The purpose of this study is to evaluate DFIG wind turbine built-in model in PSS/E. In this report, the responses of the model subjected to grid disturbances are investigated. At first, the typical dynamic model of a DFIG wind turbine is introduced. Secondly the built-in dynamic model for DFIG wind turbine in PSS/E is illustrated and it is used to study the dynamic behavior of DFIG subjected to a symmetrical short circuit at the point of common coupling of a large wind farm. The load flow study for a network where a wind farm consisting 67 numbers of DFIG wind turbines and each one with 1.5MW rated power connected to the grid are presented and the output results from load flow study is used to perform dynamic simulation. The voltage, current, output power, speed and pitch angle profiles are presented in the dynamic study.

The dynamic simulation results shows that the DFIG dynamic model presented in PSS/E is not able to fully represent the limitations of the wind turbine. There are some deficiencies in the model, for example the protection systems for converter and rotor are not included in the model, under/over voltage protection and rotor current limits are not considered. The upper and lower limitation in the voltage control loop will affect the voltage stability and there is no direct relation between the maximum over load on converters and the limitation in voltage control loop.

Keywords: wind turbine, modeling, doubly fed Induction generator, power system stability, voltage stability, aggregated model.

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Contents

1 Introduction

The utilization of wind turbine to produce electricity is increasing rapidly in different parts of the world. It has become one of the main alternatives for non pollutant and environmentally friendly type for power generation in Sweden and a large amount of wind power are connected to the Swedish national grid and some others will be connected in next coming years.

Not until recently, the contribution of wind power generation on the system stability was considered to be small. However with increasing in the wind farm capacity it is clear that disconnecting a large wind farm will result in losing of a big part of power generation in grid, which can aggravate instability problems. Due to increasing portion of wind power, wind turbines have to contribute in reactive power support during steady state as well as during transient conditions. Transmission system operators (TSO) in countries where the amount of wind power generation is significant have established a special regulation and added to the grid codes that specify a number of requirements for wind farms to stay connected to the grid during disturbances.

In order to establish stability and power quality, the Swedish TSO, Svenska Kraftnät (Svk), prescribes performance for production units larger than 1.5 MW. Practically this regulation comprehends all new modern wind power turbines. The grid connection procedure is changing and adaption to a large scale wind power expansion is continually made. This adaption wills most likely lead to requirements of information regarding the wind power units' electrical behavior and then to determine the impact of adding wind generation, and establish how the system can be upgraded, SvK needs adequate wind-turbine generator dynamic models and simulation results. The Svk uses PSS/E as a simulator tool to study the dynamic behavior of the power system. The new version of PSS/E has added a dynamic model for doubly fed induction generator wind turbine. This wind turbine is referred as type 3 per classification of the western electricity coordinating council wind generator modeling group (WECC WGMG) and it is the only model that is publicly available and it is approved by WECC and GE [8]. The model is used for short term voltage stability according to the requirements by SvK which is the basic part of this study.

The mathematical equations for a generic model are presented and some simplifications have been done to get final equations and then the block diagrams of the DFIG which are used in the simulator tool have explained. The fault scenarios according the Svenska Kraftnät's grid code have simulated to evaluate the dynamic behavior of a wind farm model. According to the dynamic simulations results the ride-through capability of the wind farm has evaluated.

After explanation the generic model, the dynamic model of DFIG in PSS/E has introduced and the procedure for controlling active and reactive power in the model has illustrated. The advantages and drawbacks with the model are also discussed.

2 Wind Turbine

The wind turbines are divided into four main types: fixed speed wind turbine with induction generator, variable-speed wind turbine with variable rotor resistance, variable speed wind turbine with doubly fed induction generator (DFIG) and variable speed wind turbine with full converter (FCWT) [3].

2.1 Fixed-Speed Wind Turbine

In fixed speed wind turbine, the generator is a squirrel-cage induction generator which is directly connected to the grid as in Figure 3.1. The rotor of a fixed-speed wind turbine rotates at a fixed speed determined by the frequency of the grid, the gear ratio and the pole pairs of generator. A fixed-speed wind turbine is connected to the grid through a soft-starter. The induction generator absorbs reactive power from the grid, so capacitor bank is necessary to provide reactive power compensation. A gear box is used to transform power from the turbine with lower-rotational speed to the generator rotor with high-rotational speed. The generator terminal voltage is increased with a step-up unit transformer to a medium voltage level.

This type of wind turbines has the advantage of being simple, robust and more cost-efficient compared to the other wind turbine types. However, the reactive power consumption cannot be controlled. Another drawback with the fixed speed wind turbine is that wind speed fluctuation is transmitted into the mechanical torque and it is finally transferred to the electrical power on the grid. The fluctuation in the delivered power to the grid can lead to large voltage fluctuation where the wind farm connected to a weak grid [4].

Risk of loss of synchronism due to over-speed in case of voltage dips and increasing of reactive power consumption**,** especially after fault clearance, is other disadvantages of this type of wind turbine. The Induction generator dynamics cannot be improved. Preventive or corrective measures which can be done are to limit acceleration during voltage dip through improvement of pitch control and to provide reactive power support during and after clearing of fault, via FACTS devices. Compatibility with grid code requirements not satisfied. Installation of FACTS devices, such as SVCs and STATCOMs, is a potential but it can be costly.

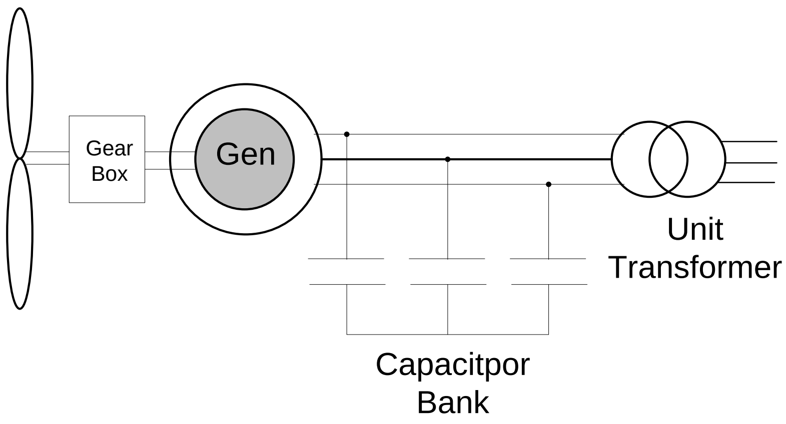


Figure 3.1: Fixed speed wind turbine

2.2 Wind Turbine with Variable Rotor Resistance

In wind turbine with variable rotor resistance the generator is an induction machine with wound rotor and it is directly connected to the grid. Like a fixed-speed wind turbine, a capacitor bank is necessary to provide reactive power for induction machine. By changing the rotor resistance magnitude, the rotor speed can be regulated in a short range up to 10% higher than synchronous speed [5]. The structure of this type of wind turbine is shown in Figure 3.2.

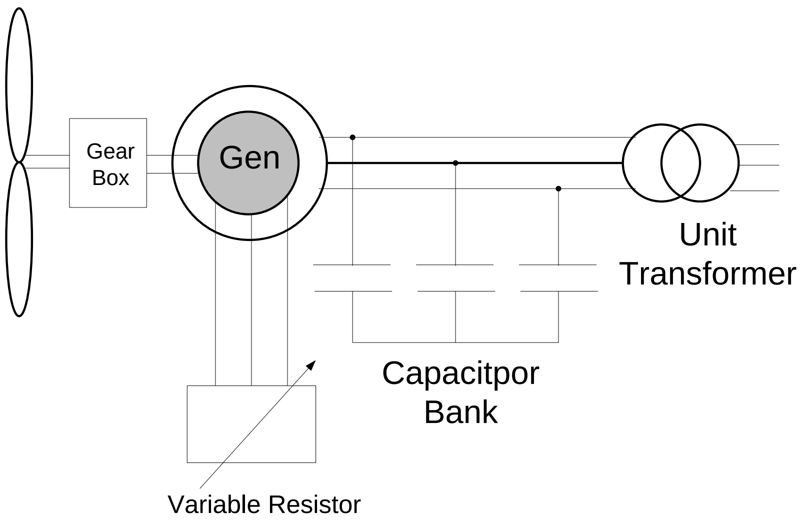


Figure 3.2: Variable-speed wind turbine with variable rotor resistance

2.3 Variable-Speed Wind Turbine with Doubly-Fed Induction Generator

A power electronic converter is used in the variable-speed wind turbine with doubly fed induction generator as shown in Figure 3.3. The converter is connected to the generator rotor and the stator is directly connected to the grid.

Compared to the one with full converter, this type is more suitable for high power wind turbines since only a fraction (typically 20-30%) of the total power goes through the converter. This gives possibility to design the converter with smaller size, and as a result, lower cost and lower power electronic losses.

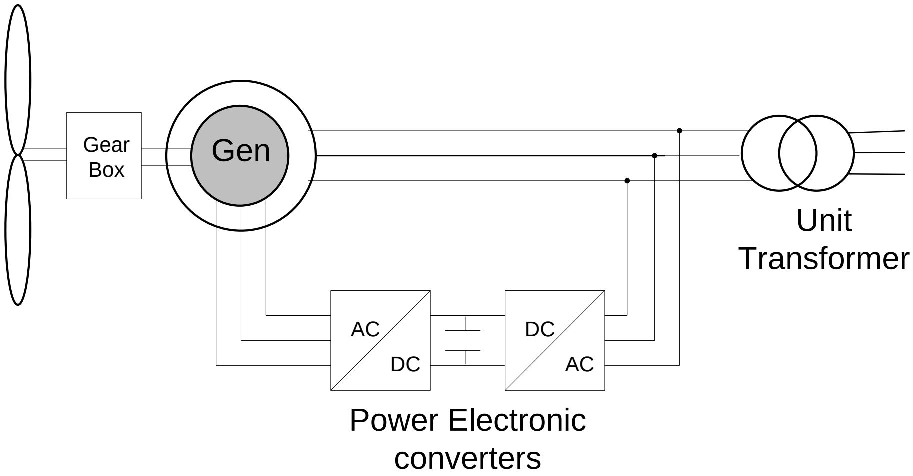


Figure 3.3: Variable-speed with doubly fed induction generator

2.4 Variable-Speed Wind Turbine with Full Converter

In variable-speed wind turbine with full converter, the generator can be a squirrel-cage induction or a synchronous generator which is connected to the grid via a power electronic converter as shown in Figure 3.4. The whole power output from generator goes through the converter and therefore the converter is rated at full power. The voltage level and the reactive power can be regulated by using power electronic converters.

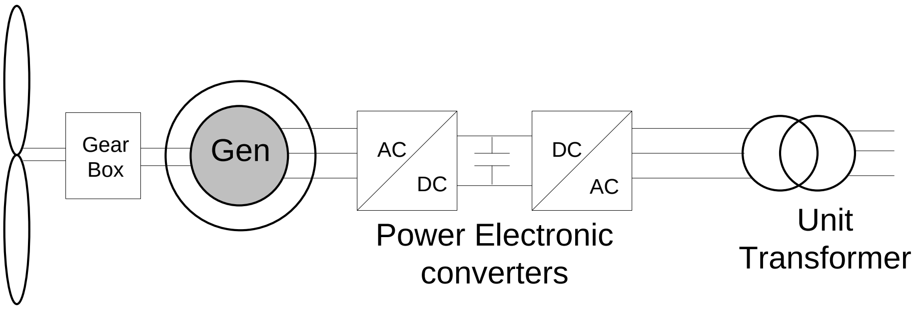


Figure 3.4: Full converter wind turbine

The converter is connected to the stator. This converter has to be able to convert full power from the generator. The gear box can be removed or simplified if a multi-pole synchronous generator is employed. The main advantages of this type of wind turbine are the most favorable dynamic behavior during disturbances, with minimum transients at fault occurrence and clearing. It has also the capability to enhance active and reactive power control and therefore the compatibility with grid code requirements can be satisfied [5].

3 Wind Turbine with Doubly Fed Induction Generator (DFIG)

The objective of this chapter is to provide an overview on the dynamic model of different parts in a DFIG wind turbine. At first, the main mathematic equations, that describe the relationship between voltage and fluxes in an induction machine and they are basic equations for establish dynamic model, are presented with a short description of the other electrical parts. Model of aerodynamic and mechanical parts are also presented. Later, the simplified model which is used in PSS/E software is introduced and the mechanism for controlling active and reactive power in this model is illustrated.

3.1 DFIG and Converter Dynamic Model

An induction generator with power supply on the rotor is a main part of the DFIG wind turbine. The DFIG is modeled by means of an equivalent circuit model. The main components of a DFIG wind turbine are shown in Figure 3.1. In DFIG wind turbine, the stator directly connected to the grid, while the rotor circuit is connected to a power converter by means of slip rings and brushes. The rotor current is regulated by the power converter to control the electromagnetic torque and field current and thus the stator output voltage. The DFIG can operate in either sub-synchronous or in super-synchronous operation modes due to capability of converter to operate in bi-directional operation power mode.

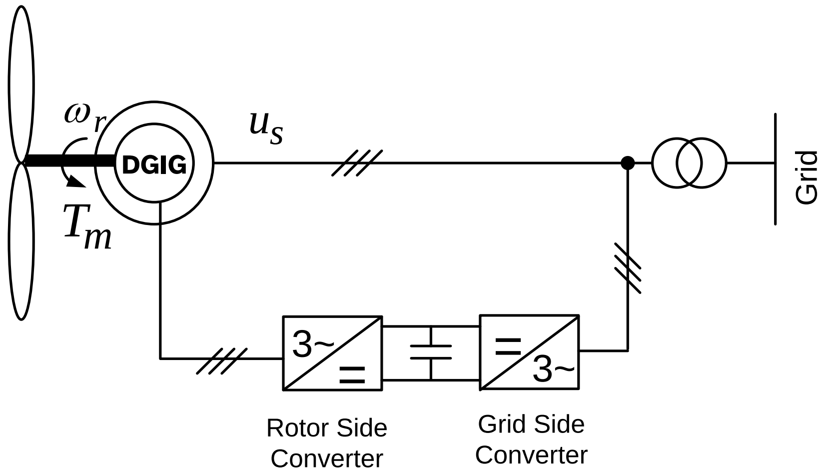


Figure 3.1: Doubly fed induction generator

The general block diagram for controlling a DFIG is shown in Figure 3.2 [3]. The basic parts of model consist of the generator and drive train, the turbine rotor, the grid side converter with dc-link capacitor, the pitch controller and the rotor side controller. The active and reactive power is controlled by the rotor side converter, while the grid-side converter is used to control the dc voltage of dc-link capacitor.

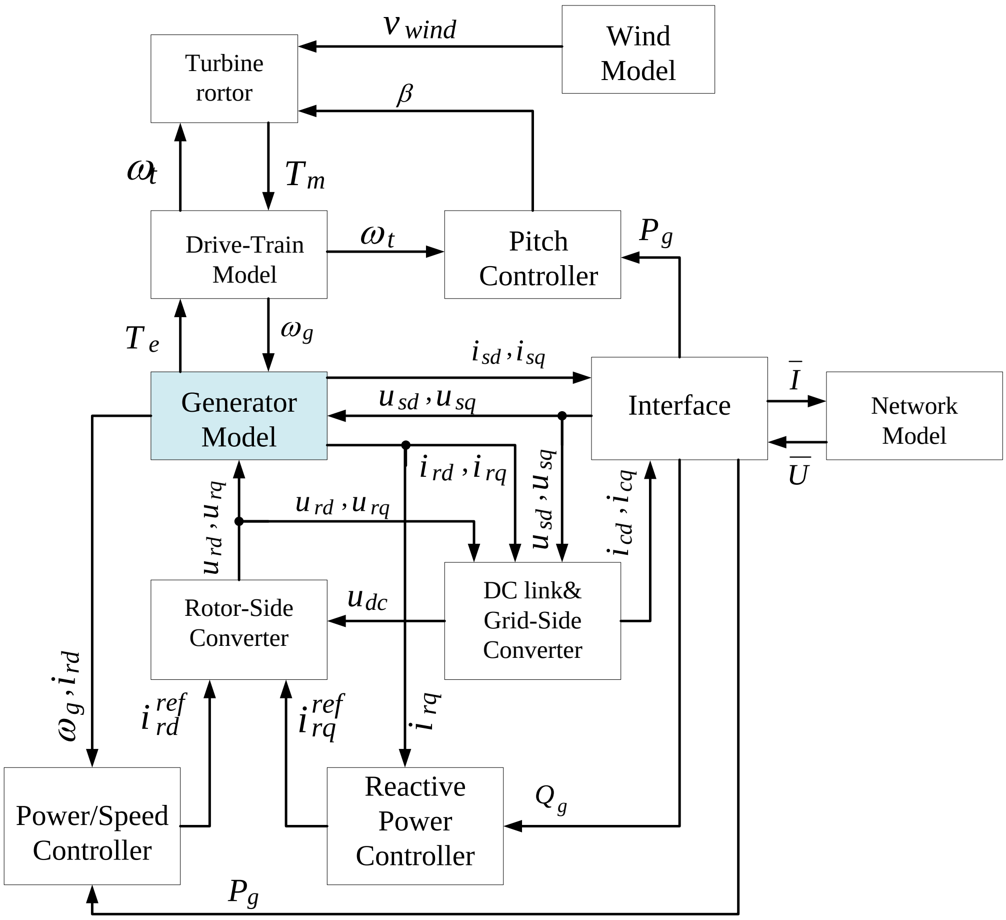


Figure 3.2: Control block diagram of DFIG wind turbine

3.1.1 DFIG Model

The conventional T-equivalent circuit is used to represent the dynamic model of induction generator (IG). This model consists of stator winding and rotor winding with slip rings. The three phase stator windings directly connected to the grid through a step-up transformer. The rotor also has a three phase winding but it is connected to the rotor power supply through slip rings and brushes. The power supply of the rotor comes from the rotor-side converter.

The rotor current is controlled by the rotor-side converter and consequently the active and reactive power can be controlled. The equivalent diagram of the stator and rotor and the grid-side and rotor-side converters is shown in Figure 3.3.

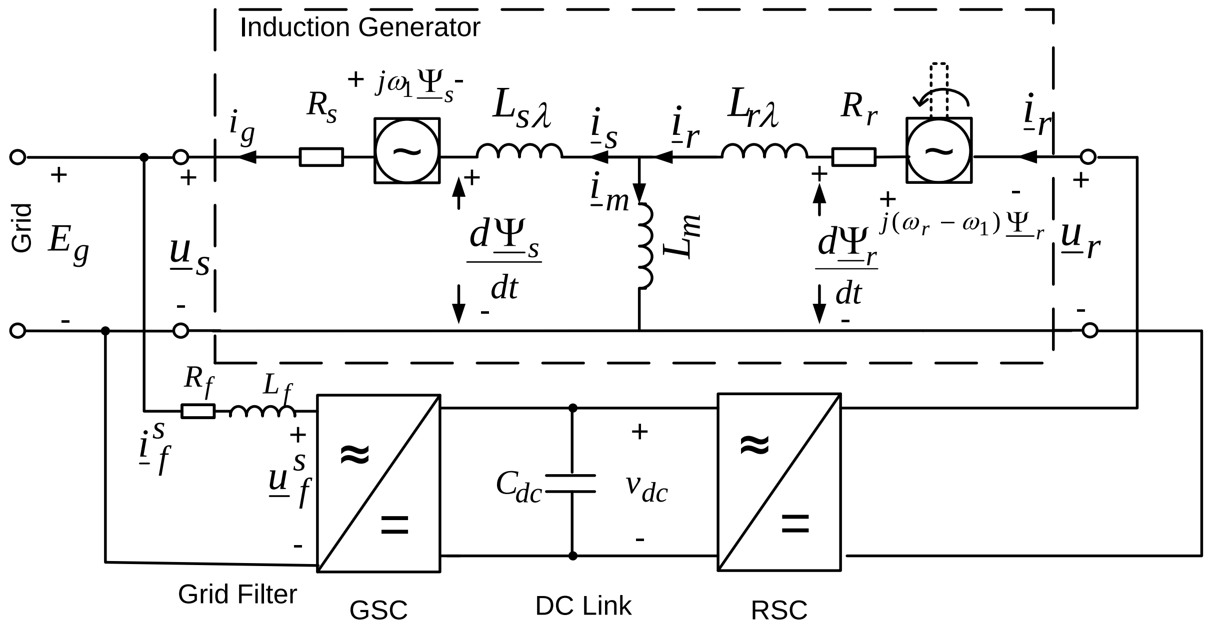


Figure 3.3: Dynamic equivalent circuit of the DFIG and converters

Based on the equivalent circuit presented in Figure 3.3, the electrical dynamics equations using the space vector approach can be derived. By applying Kirchhoff's voltage law in the stator and rotor and in per unit system it can be written as

$$\underline{u}_s = R_s\,\underline{i}_s + \frac{d\underline{\psi}_s}{dt} + j\omega_1\underline{\psi}_s \tag{3.1}$$

$$\underline{u}_r = R_r\,\underline{i}_r + \frac{d\underline{\psi}_r}{dt} - j(\omega_1 - \omega_r)\underline{\psi}_r \tag{3.2}$$

where:

$R_s =$ stator resistance

$L_{s\lambda}$ stator leakage inductance

$R_r =$ rotor resistance

$L_{r\lambda} =$ rotor leakage inductance

$L_m =$ mutual inductance

$(\omega_r - \omega_1)\underline{\psi}_r =$ rotor back emf

$u_s =$ stator voltage

$u_r =$ rotor voltage

$\underline{\psi}_s =$ stator Flux

$\underline{\psi}_r =$ rotor Flux

$\omega_1 =$ synchronous frequency

$\omega_r =$ rotor frequency

$\omega_2 = \omega_1 - \omega_r =$ Slip frequency

$\underline{i}_s =$ Stator current $\underline{i}_r =$ Rotor current

The subscripts *s* and *r* refer to quantities of the stator and rotor, respectively. The dynamic model of an induction machine is usually presented by means of a so called fifth-order model that represents IG by a system of five general differential equations of an idealized induction machine.

$$\underline{\psi}_s = L_s\,\underline{i}_s + L_m\,\underline{i}_r \tag{3.3}$$

$$\underline{\psi}_r = L_r\,\underline{i}_r + L_m\,\underline{i}_s \tag{3.4}$$

where

$$L_s = L_{s\lambda} + L_m$$

$$L_r = L_{r\lambda} + L_m$$

The electromechanical torque is

$$T_e = \mathrm{Im}[\underline{\psi}_s^s\,\underline{i}_s^*] = (\psi_{sd} \cdot i_{sq} - \psi_{sq} \cdot i_{sd}) \tag{3.5}$$

The electrical power will be

$$P_e = \mathrm{Im}\{\underline{\psi}_r\,\underline{i}_r^*\} \tag{3.6}$$

In power system studies, it is desirable to reduce the complexity of the system by using reduced-order models that can be obtained by assuming some of the derivatives as being equal to zero. For example, a third-order model of IG is obtained when we neglect the stator flux transients.

Under balanced network conditions, the amplitude and rotating speed of the stator and rotor fluxes are assumed to be constant. The flux dynamics are canceled to get a fast response to the commands from electric controls of converter. Consequently, in the *dq* reference frame, the stator and rotor fluxes remain constant, i.e.

$$\frac{d\underline{\psi}_s}{dt} = 0 \qquad \frac{d\underline{\psi}_r}{dt} = 0 \tag{3.7}$$

Thus the voltage equations can be written as

$$u_{sd} = R_s i_{sd} - \omega_1 \psi_{sq} \tag{3.8}$$

$$u_{sq} = R_s i_{sq} + \omega_1 \psi_{sd} \tag{3.9}$$

$$u_{rd} = R_s i_{rd} - s\omega_1 \psi_{rq} \qquad (3.10)$$

$$u_{rq} = R_s i_{rq} - s\omega_1 \psi_{rd} \qquad (3.11)$$

If *d*-axis of the synchronous frame is fixed to the stator voltage, then

$$u_{sd} = 0 \qquad (3.12)$$

The flux linkage equations are as follows:

$$\psi_{sd} = L_s i_{sd} - L_m i_{rd} \qquad (3.13)$$

$$\psi_{sq} = L_s i_{sq} - L_m i_{rq}$$

(3.14) $\psi_{rd} = L_r i_{rd} - L_m i_{sd}$ (3.15)

$$\psi_{rq} = L_r i_{rq} - L_m i_{sq} \qquad (3.16)$$

We can also neglect the stator resistance because it is considerably small compared to the stator reactance, hence

$$\psi_{sd} = 0 \qquad (3.17)$$

Subsequently

$$i_{sd} = \frac{L_m}{L_s} i_{rd} \qquad (3.18)$$

$$u_{sd} = -\omega_1 \psi_{sq} \qquad (3.19)$$

The electromechanical torque is calculated as:

$$T_e = \psi_{rq} i_{rd} - \psi_{rd} i_{rq} \qquad (3.20)$$

$$T_e = L_m (i_{sd} i_{rq} - i_{sq} i_{rd}) \qquad (3.21)$$

The active power of stator, rotor, grid-side converter and the injected active power to the grid can be determined as:

$$P_s = Re\left[\, \underline{u_s} . \underline{i_s^*} \,\right] = u_{sd} . i_{sd} + u_{sq} . i_{sq} \qquad (3.22)$$

$$P_r = Re\left[\, \underline{u_r} . \underline{i_r^*} \,\right] = u_{rd} . i_{rd} + u_{rq} . i_{rq} \qquad (3.23)$$

$$P_c = Re\left[\, \underline{u_c} . \underline{i_c^*} \,\right] = u_{cd} . i_{cd} + u_{cq} . i_{cq} \qquad (3.24)$$

$$P_g = P_s + P_c \qquad (3.25)$$

Where $P_{s\,,}$ P_r, P_c, and P_g are the stator, rotor, dc link grid-side converter active power and the total generator active power, respectively .

If the losses in the converter ignored the converter power will be equal to the power injected to the rotor (P_c=P_r), thus it can be written as

$$P_g = u_{sd}.i_{sd} + u_{rd}.i_{rd} + u_{rq}.i_{rq} \qquad (3.26)$$

The reactive power can be calculated as:

$$Q_s = -u_{sq}.i_{sq} \qquad (3.27)$$

$$P_c = u_{rq}.i_{rd} - u_{rd}.i_{rq} \qquad (3.28)$$

By assuming the grid-side converter reactive power is zero, the generated reactive power will be

$$Q_g = Q_s + Q_r \qquad (3.29)$$

$$Q_g = -u_{sd}.i_{sq} + u_{rd}.i_{rd} - u_{rq}.i_{rq} \qquad (3.30)$$

3.1.2 Frequency Converter Model

The induction machine of a DFIG wind turbine operates in a generating mode at sub-synchronous and super-synchronous speeds where the speed range is limited by the maximum voltage of the rotor-side frequency converter [6]. The rotor winding is supplied from a converter consisting of back-to-back connected converter bridges with a dc link, as shown in Figure 3. 4.

The grid-side converter operates at a network frequency and controls the voltage level in the dc link circuit. If required, it is possible assign the grid-side converter to deliver reactive power to the grid. The rotor-side converter operates at different frequencies (slip frequency), depending on the rotor speed, and controls the flux of the DFIG and thus the active and reactive power [6].

The rotor-side converter has an over-current protection called crowbar. The crowbar protects the rotor-side converter, as well as the rotor circuit of the DFIG, against high currents during grid disturbances. The location of crowbar resistor is shown in Figure 3.4, where RSC is the rotor-side converter, GSC is the grid-side converter, CH is the chopper circuit and CR is the crow bar circuit.

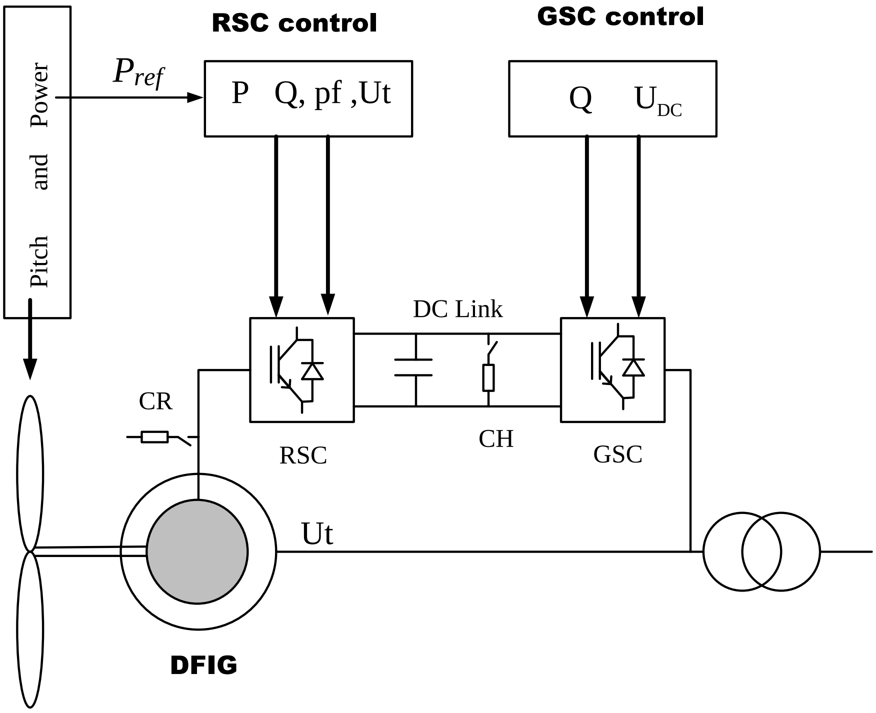


Figure 3.4: Typical layout of a DFIG

3.1.2.1 Rotor-side Converter

The power rating of the rotor-side converter is determined according the maximum slip power and reactive power control capability. The rotor-side converter can be simplified as a current-controlled voltage source converter.

Rotor Control Mode

The reference rotor speed is obtained from power-speed characteristic curve as shown in Figure 3.5. The rotor speed is then used as an input for a PI controller to get the stator active power reference P_s^{ref} . The rotor reference current in dq reference frame is then calculated by the following expression [3]

$$i_{rd}^{ref} = -\frac{L_s.P_s^{ref}}{L_m.u_{sd}} \tag{4.31}$$

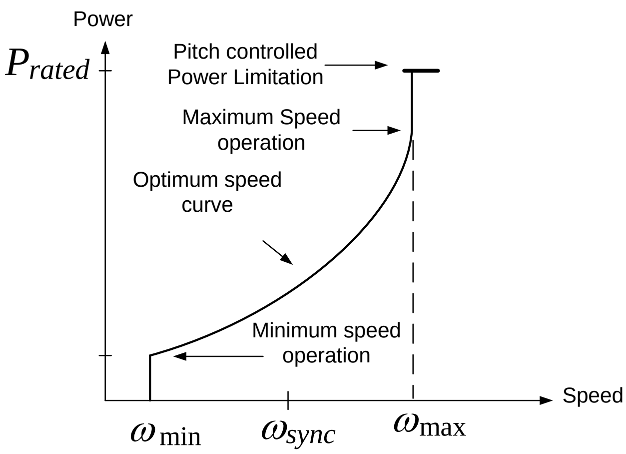


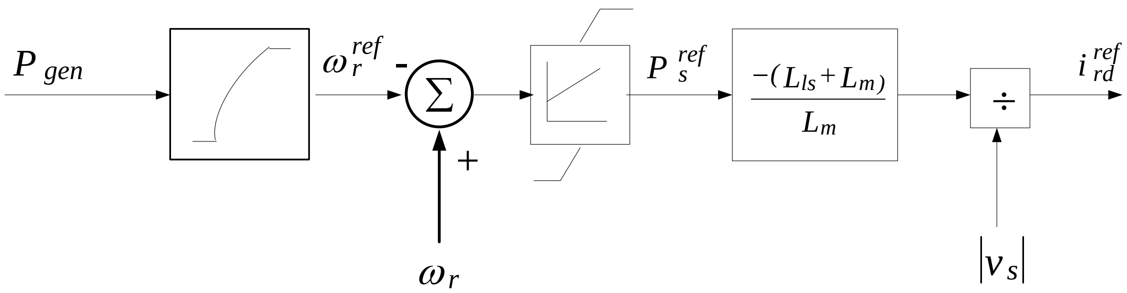
Figure 3.5: Power-speed curve

It can be found from above equation that the stator active power is controlled by controlling the rotor current in *d* direction. The magnitude of reference rotor current in *q* direction is calculated as:

$$i_{rq}^{ref} = -\frac{\omega_1 L_s \, i_{sq} + u_{sd}}{\omega_1 L_m} \tag{3.32}$$

The control diagram for active and reactive power controls is shown in Figure 3.6.

a) Active power control



b) Reactive power control

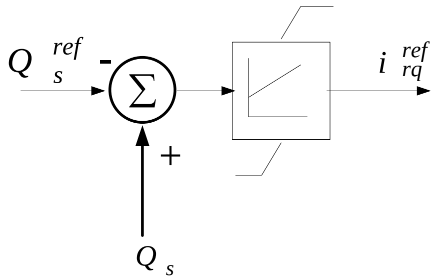


Figure 3.6: Rotor current controller: (a) active and (b) reactive power control

Over-Current Protection (Crowbar)

The new Swedish grid code requires grid connected wind turbines to remain connected to the network even when there is a short-term power network disturbance. In other words, the wind farm should have fault-ride-through capability. However, riding through grid faults with DFIG will lead to high peak currents in the rotor and high power into the DC circuit. Thus the rotor and rotor-side converter need to be protected against over-current and over voltage. In order to protect against over current and over voltage, a DC-chopper parallel with DC-link and an AC-crowbar installed in the rotor circuit are used.

When there is a short circuit in the grid, the voltage at the terminal of DFIG goes down almost immediately and it will cause high transient rotor current. One possible solution to avoid over-current is to use a rotor over-current protection, a so-called crowbar. The crowbar is connected in parallel with the rotor-side converter as shown in Figure 3.7. The crowbar deactivates the rotor-side converter and short-circuits the rotor winding, whenever the rotor current exceeds the maximum limit value. When the grid fault is cleared, the rotor-side converter is restarted.

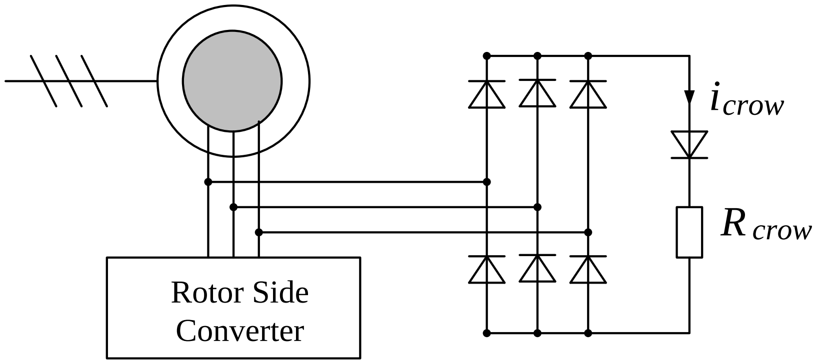


Figure 3.7: The crowbar connected between the rotor of the DFIG and the rotor-side converter.

3.1.2.2 Grid-side Converter

The grid-side converter (GSC) is usually represented by a simplified model, a so-called generic control scheme based on a set of PI controllers. The voltages in *d* and *q* direction are calculated according the active and reactive power reference values. In a simplified model, the switching dynamics of converter is neglected and an ideal control is assumed, meaning that the converter is able to follow its demanded value at any time [6].

The converter can also be utilized to support grid reactive power during a fault and it can also be used to enhance grid power quality. However, these abilities are seldom utilized since they require a larger converter rating [6].

In some studies, such as in [9], the detailed model of GSC for dynamic simulation is recommended. The author argued that if the detailed model is not used, the results for rotor current calculation and dc link voltage are not accurate enough. Nevertheless, the majority of DFIG studies use the simplified dc-link voltage controller. The dc-link capacitor voltage can be calculated as a function of the input power to the dc link [6]. Accordingly, the main objective of the GSC is to control the dc-link voltage assuming that the power factor is unity. The equivalent circuit of the dc-link model is shown in Figure 3.8 where i_r and i_g are the dc currents flowing from dc-link to the rotor-side converter and from dc-link to the grid-side converter, respectively.

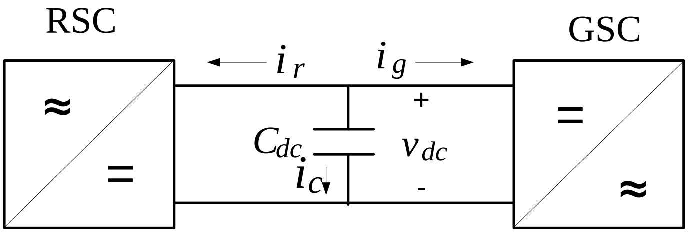


Figure 3.8: dc-link equivalent circuit

The energy stored to the dc-link capacitor can be written as

$$E_c = \int P.dt = \frac{1}{2} C v_{dc}^2 \quad (3.33)$$

Where P is the net power flow into the capacitor C_{dc} is the dc-link capacitor value and v_{dc} is the capacitor voltage. P equals to P_r-P_g, where P_r is the power to the rotor and P_g is the power from grid. The aim of the grid-side converter control is to maintain the level of dc link voltage v_{dc} at a pre-set value v_{dc-ref} by means of a PI controller. . In Figure 3.9 the simplified model of dc-link and grid-side converter is represented.

$$v_c = \int i_c.dt \quad (3.34)$$

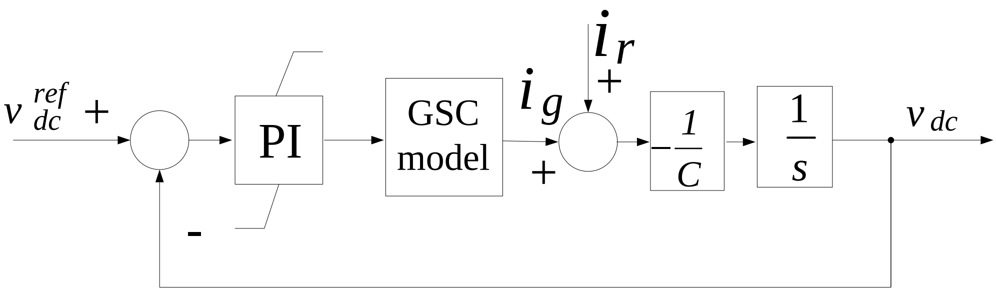


Figure 3.9: Simplified model of the dc-link and the grid-side converter.

3.2 Mechanical Model and Turbine Control

The mechanical model of a DFIG wind turbine and its control in dynamic studies of power systems usually consists of wind speed model, aerodynamic model; drive train model and rotor speed and pitch angle controller subsystems. The mechanical model and control of the wind turbine is simplified in this study. The input and out powers to the different parts of a wind turbine is shown in Figure 3.10.

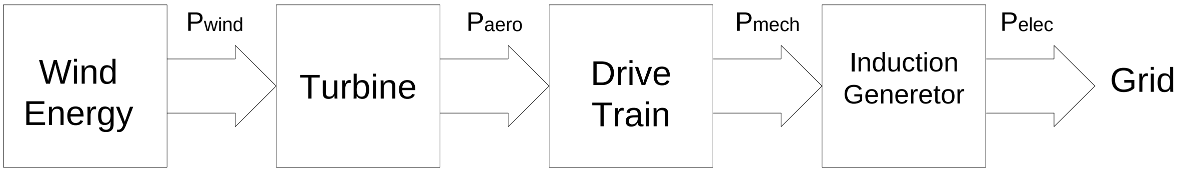


Figure 3.10: The input and out powers in WT

3.2.1 Turbine Speed Control Model

The basic strategy for the wind turbine control system is to get the maximum power from the wind. The limiting factor that affects the amount of energy from wind is the equipment power ratings. Accordingly, the mechanical input power has to be limited when the input power from wind is higher than the equipment power ratings. Otherwise, it may destroy the mechanical parts. To reduce the amount of input mechanical power the turbine blades must be turned. This ability of controlling the mechanical input power is called pitch control of turbine blades. The dynamics of the pitch control are moderately fast, and can have significant impact on dynamic simulation results.

On the hand if the available wind power is less than the equipment ratings, the blades is set at a certain pitch angle to get maximum power from wind. The turbine control model sends a power order to the electrical control according the available wind speed, requesting the converter to deliver this amount of power to the grid

3.2.2 Drive Train Model

The two-mass model is commonly used to model the rotor dynamic simulation. This model, the drive-train consists of two inertias, i.e. turbine and generator inertias. The two inertias are connected through a spring as shown in Figure 3.11. The mechanical power from the wind power model and the electrical power from the generator/converter model are used as inputs to calculate the rotor speed. The block diagram of the system is shown in Figure 3.12.

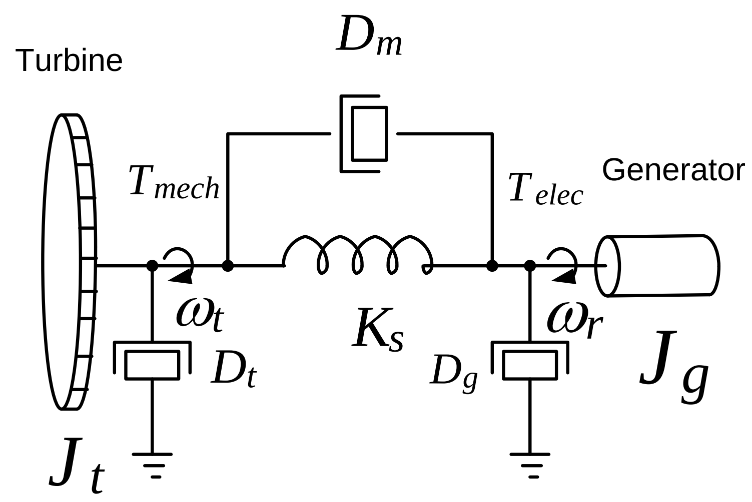


Figure 3.11: Drive Train of Wind Turbine

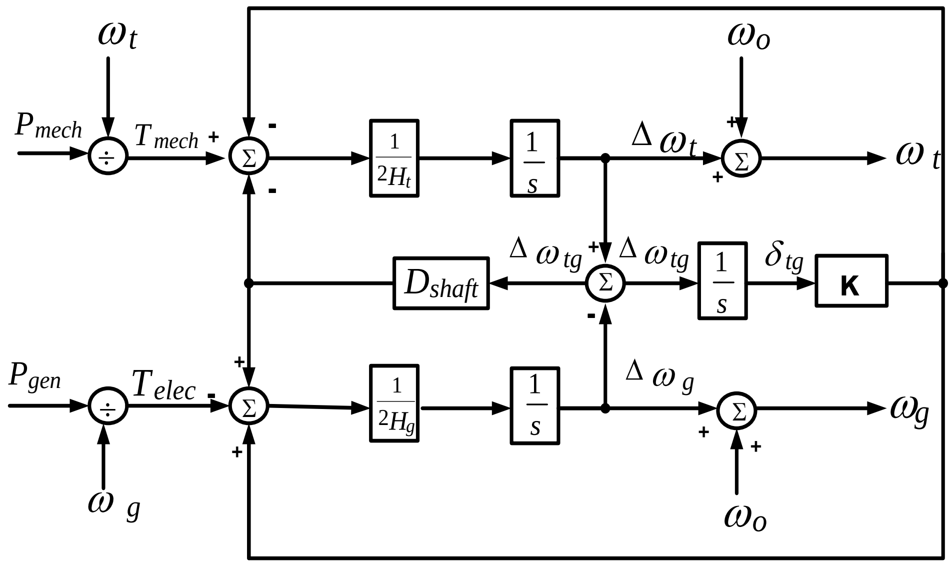


Figure 3.12: Two-mass torsional model

H_t	Turbine inertia constant	[MW.sec/MVA]
H_g	Generator inertia constant	[MW.sec/MVA]
K	Gain factor	
$H = H_t + H_g$	Total inertia constant	[MW.sec/MVA]
D_{shaft}	Shaft damping factor	[pu]
Freq1	First shaft torsional resonant frequency	[Hz]
K_s	Shaft stiffness	

3.2.3 Aerodynamic and Pitch control Model

For a power system simulation involving grid disturbances and fault-ride through capability, it is important to include the aerodynamic model. In this model, the mechanical power to the turbine is a function of wind speed, blade pitch angle and shaft speed.

The function of the wind power module is to compute the wind turbine mechanical power (shaft power) from the energy contained in the wind using the following formula:

$$P_{mech} = \frac{\rho}{2} A_r V_w^3 C_p(\lambda, \theta) \tag{3.35}$$

P_{mech} is the mechanical power extracted from the wind, ρ is the air density [kg/m^3], A_r is the area swept by the rotor blades [m^2] or $A = \pi r^2$, V_w is the wind speed [m/sec], and Cp is the is the power coefficient, which is a function of λ and θ. λ is the ratio of the rotor blade tip speed and the wind speed *(v tip/v_w)*, θ is the blade pitch angle in degrees.

The relationship between blade tip speed and generator rotor speed is a constant (λ) and it is defined as

$$\lambda = \frac{r*\omega}{V_w} \tag{3.36}$$

Where r is the rotor blade radius; ω is turbine angular speed; and V_w is wind speed.

C_p is a characteristic of the wind turbine. There are different methods to calculate C_p, for instance, like blade element method,$C_p(\lambda, \theta)$ look-up table and analytical approximation.
In this project, the second method is used. C_p is provided as a set of curves relating Cp to λ, with θ as a parameter. The Cp curves for the GE wind turbine are shown in figure 3.13.

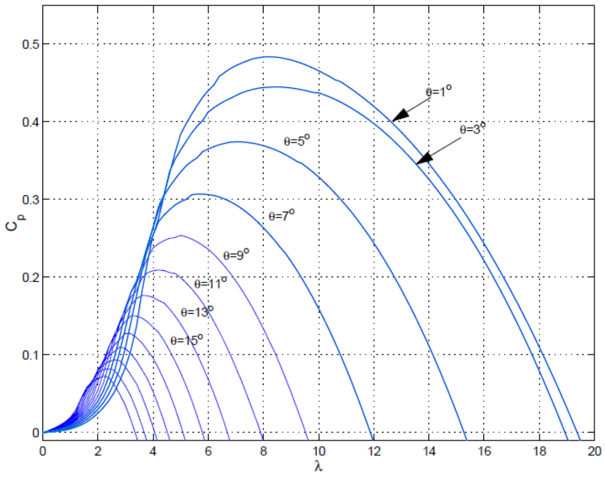


Figure 3.13: Wind power C_p curves

For power levels below rated, the turbine speed is controlled primarily by the electric power order to specify speed reference. For power levels above rated, the rotor speed is controlled primarily by the pitch control, with the speed being allowed to rise above the reference transiently.

Typically high wind speed threshold is 25 [m/sec]. The measured rotating turbine speed is compared with the reference speed and the difference is integrated and if this value is higher than a specified value, the unit is tripped. It has also the ability to trip the machine if turbine speed falls below a specified value.

The pitch angle controller is shown in figure 3.14 including the pitch control and pitch compensation. The block diagram to control of active power is illustrated in figure 3.15. The pitch controller, pitch compensator and drive train models are included in the block diagram. In the diagram V_{term} is the voltage measured at the terminal of wind turbine, I_{inj} is the current injected from the wind turbine to the grid, ω_{wt} is the wind turbine rotating shaft speed, ω_{wt} is the wind speed, P_e is the output electrical power measured at the terminal of wind turbine, P_{mech} is mechanical input power to the shaft , P_{cmd} P_{cmd} is the command power and β is the pitch angle.

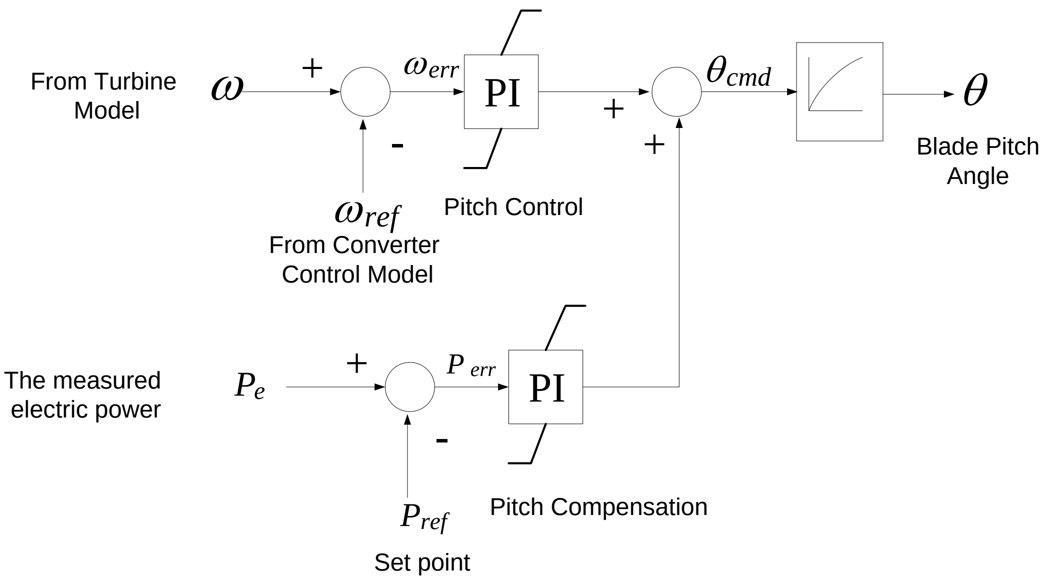


Figure 3.14: Pitch control and pitch compensation block diagram

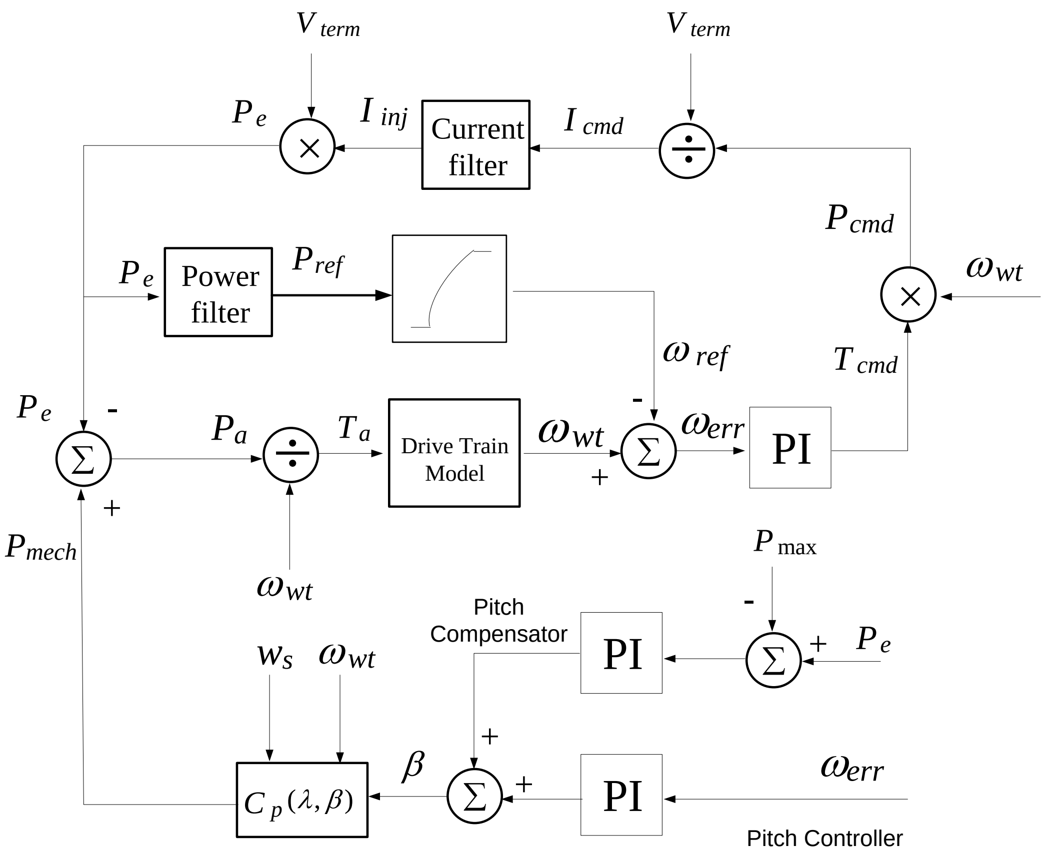


Figure 3.15: The block diagram for active power control in wind turbine

3.3 PSS/E Simulation Software

PSS/E stands for Power System Simulator/Engineering and is mainly used for power system studies. It can perform both phase vector and electromechanical simulations and has become one of the most commonly used software within the power system industry. Many wind turbine manufacturers provide PSS/E models that are e.g. used for verification of grid codes however most of them are bound with non-disclosure agreements. Therefore, only one wind turbine model is so far available publicly. PSS/E is developed by Siemens Power Technologies International (PTI).

Power System Simulation for Engineering (PSS/E) is composed of a comprehensive set of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. PSS/E can be utilized to facilitate calculations for a variety of analyses, including: Power flow and related network functions, optimal power flow, balanced and unbalanced faults, network equivalent construction, dynamic simulation. In addition to the steady-state and dynamic analyses, PSS/E also provides the user with a wide range of auxiliary programs for installation, data input, output, manipulation and preparation.

Power Flow

A power flow study (also known as load-flow study) is an important tool involving numerical analysis applied to a power system. Unlike traditional circuit analysis, a power flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (i.e.: reactive, real, and apparent).

Power flow studies are important because they allow for planning and future expansion of existing as well as non-existing power systems. A power flow study also can be used to determine the best and most effective design of power systems.

Dynamics

The dynamic simulation program includes all the functionality for transient, dynamic and long term stability analysis. The purpose of the dynamics is to facilitate operation of all dynamic stability analytical functions.

The dynamic modeling simulation is used to ensure the reliability of electricity supply and to predict the performance of the system under a wide range of conditions and to identify any problems and scope measures needed for reliability. The testing and validation of models will enable the performance of wind turbine on the power system on their own and interacting with other turbines, to be predicted [1]. The PSS/E version number 31 has a dynamic model for doubly fed induction generator wind turbine in the library. The wind turbine is referred to as Type 3 per classification of the Western Electricity Coordinating Council Wind Generator Modeling Group (WECC WGMG). [8]

3.4 Built-in Wind Turbine Model in PSS/E

The dynamic model for DFIG in PSS/E model is according to the recommendation by GE Energy. In the following section, the main strategy of the model will be explained. There are three considerations when the model is used for dynamic simulations

1. The model is mainly appropriate for bulk power system studies. The model is for positive sequence phasor time-domain simulations.
2. The model assumes that the analysis is mainly focused on how the wind turbine-generator (WTG) reacts to grid disturbances, such as faults on transmission system.

To construct a complete WTG model, four device models are used: generator/converter model (WT3G), electrical control model (WT3E), mechanical control (wind turbine) module (WT3T) and pitch control module (WT3P). These models are represented as four boxes in Figure 3.16.

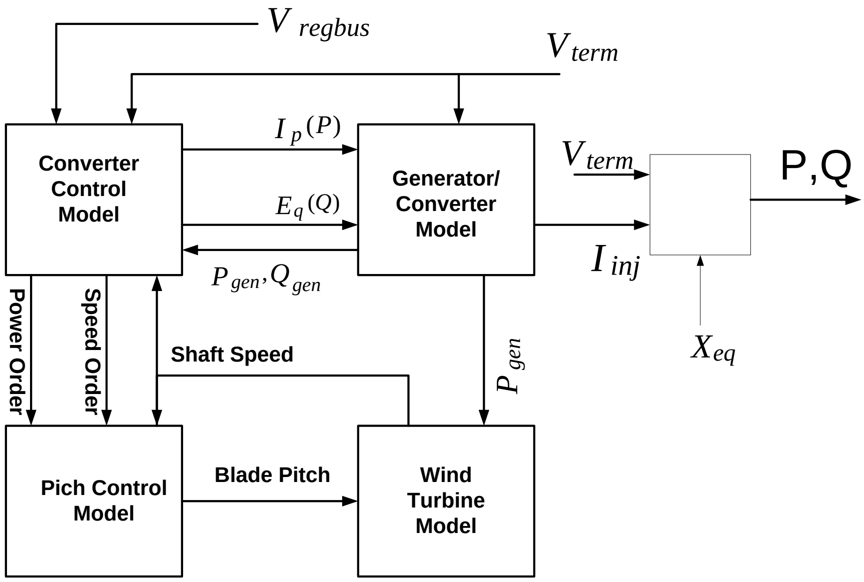


Figure 3.16: GE WTG dynamic model

3.4.1 Generator/Converter Model

The generator/converter model (WT3G1) is the equivalent of the generator and the field converter and provides the interface between the WTG and the network. The difference between this model and conventional models is that this model has no mechanical variables for the machine rotor. These variables are included in the turbine model, instead. The flux dynamics have been neglected in order to get a faster response to the higher level commands from the electrical controls through the converter.

The generator is modeled as a controlled-current source as shown in Figure 3.17. This current controller delivers the amount of required current that must be injected to the grid in response to the flux and active current commands which are generated by the converter control model [3]. This part represents DFIG and rotor converter model.

In case of over voltage, the amount of injected current to the grid is reduced to mitigate over voltage. The two first-order low-pass filters represent the electronic control systems. They have a time constant of 20 msec. There is a phase locked loop (PLL) in the actual converter controls to synchronize the generator rotor currents with stator, however due to extremely fast response of PLL dynamics relative to the generator/field converter time frame; it is not shown in the model.

The input in the upper part is the excitation current, which adjusts the output voltage. The input in the lower part is the active current, which specifies the amount of active power which should be delivered to the grid. X'' in the model represents the effective equivalent reactance of generator and T represents the transfer function of generator-network. The vector diagram of the voltages and currents is shown in Figure 3.18

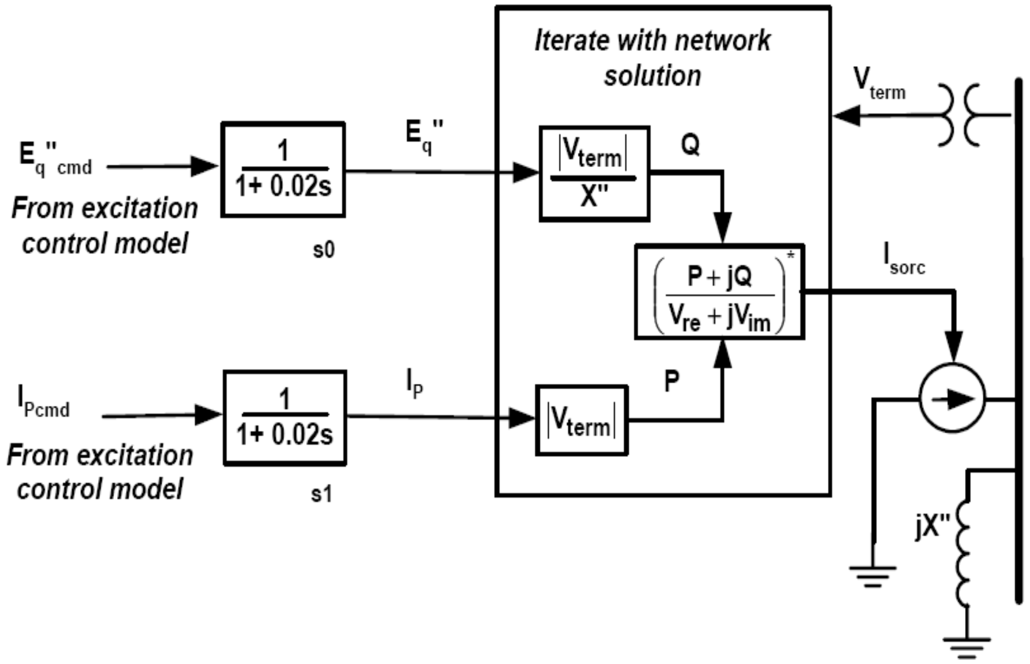


Figure 3.17: Generator and rotor converter model

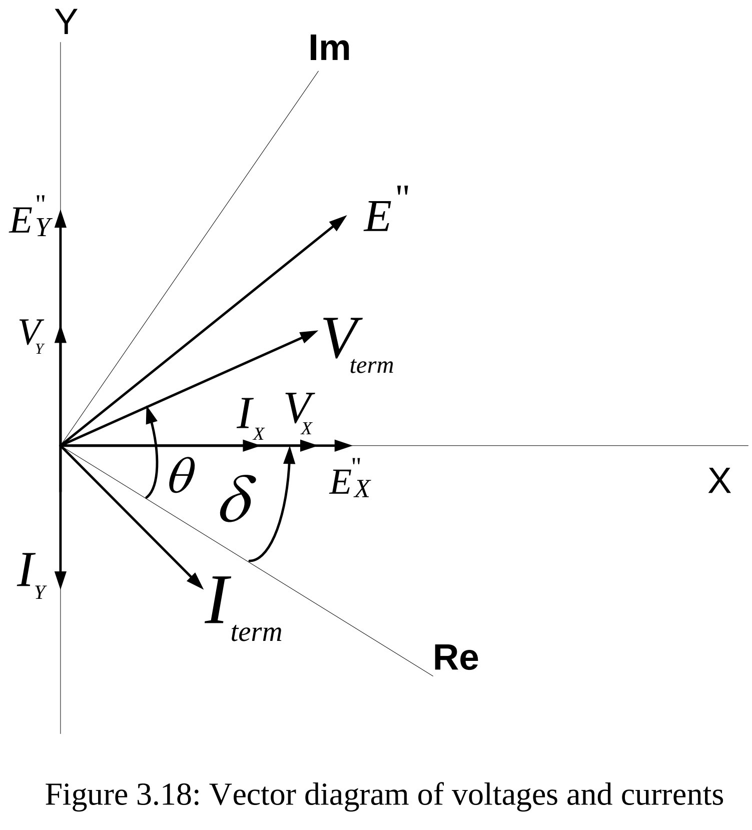


Figure 3.18: Vector diagram of voltages and currents

3.4.2 Electrical (Converter) Control Model

The electrical control model determines the amount of active and reactive power that must be delivered by the generator to the grid. It compares the measured active power (P_{gen})(with the ordered active power from turbine model (P_{cmd})(and the measured reactive power at the wind turbine terminal (Q_{gen})(with the ordered reactive power (Q_{cmd})(from the reactive power control model. The electrical control model provides the voltage and current commands and sends them to the generator model by comparing the measured active and reactive power with the required amount of the active and reactive power.

The control procedure for active power is specified in the turbine model. The model for reactive power control is shown in Figure 3.19. Three different options are provided in the model for reactive power control. These options can be selected by changing *varflg* switch position. When the switch is in position 1, the voltage magnitude at a particular bus, often the point of common coupling (PCC) with the transmission system is compared with the voltage reference magnitude, and this voltage is regulated by sending a reactive command to all of the WTGs.

The reference voltage magnitude is specified during data entering in load flow study. In position -1 the reactive power command comes from power factor regulation and in position 0 the reactive power command is set to follow a certain amount of reference magnitude for reactive power [7]. The reactive power command is compared with reactive power measured at the terminal of wind turbine in another model that is shown in Figure 3.20. The output of PI controller is the reference voltage. The reference voltage compared with voltage magnitude at the terminal point of WTG to make the voltage command (E''_{qcmd})(for the generator model. The overall electrical model is presented in simplified model of Figure 3.21

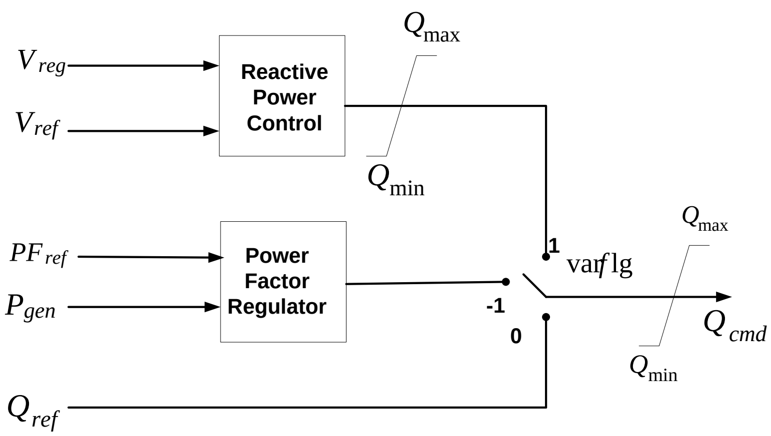


Figure 3.19: Converter control model

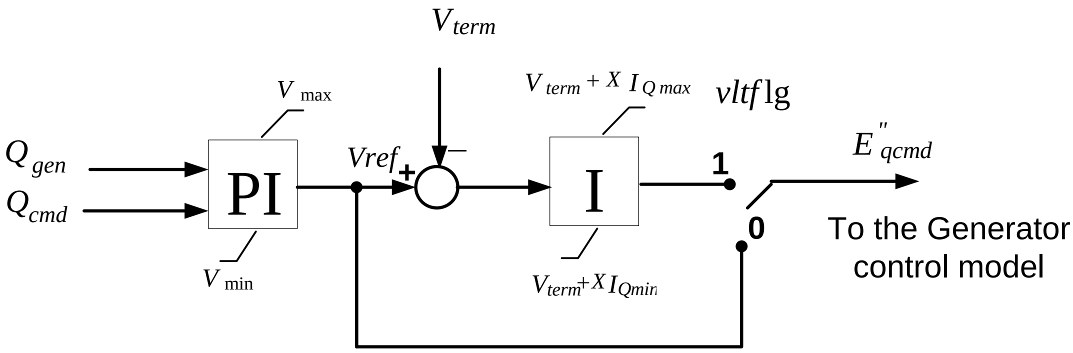


Figure 3.20: Voltage control model

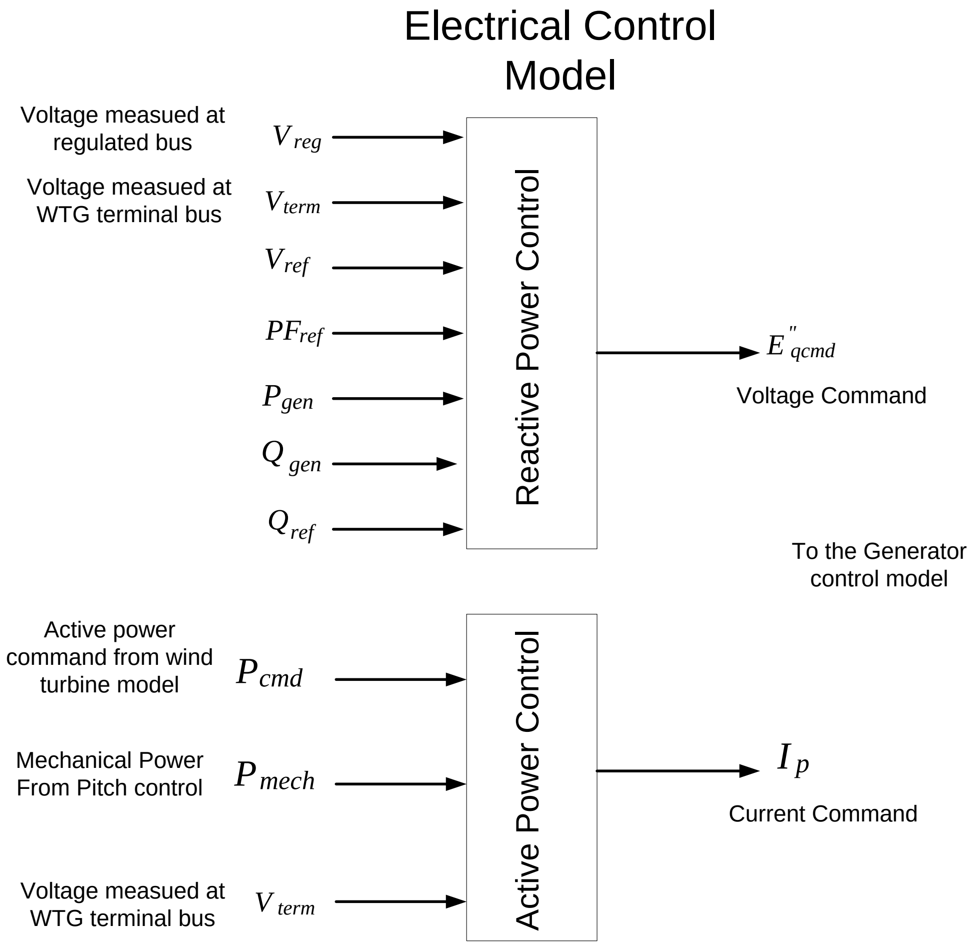


Figure 3.21 Overall DFIG electrical control model

4 Model Simulation

In this section, the load flow and dynamic simulation of a DFIG wind turbine model in PSS/E subjected to a grid fault is presented.

4.1 Grid Codes and fault-ride through capability

In the past the wind farms were disconnected from the grid following a grid fault and then there were no requirements for wind farms to contribute in voltage stability [1]. Such wind farms usually had small power ratings. Recently, wind turbines grow in size. Big wind farm consisting several units of wind turbines are connected together to make wind farms with high power rating. As the wind farm power rating is higher disconnection of large wind farms from the grid during disturbance will lead to loss of large amount of power from the grid [1].

Transmission system operators in the countries where the wind power is a part of main electricity source added some regulations to grid codes, which require the wind farms to continue their operation during a grid fault for a certain time period.

Accordingly during a grid fault, wind turbines should be able to stay connected to the power network and. The Swedish technical document which specifies the requirements for connecting wind farms to grid is SvKFS 2005:2. The fault-ride-through on the low voltage is a basic part the specification.

This grid code states the wind turbine must not be disconnected from the grid when there is a three-phase fault in the closest bus in the 400 KV grids and for fault duration of 250 milliseconds with voltage recovery to 90% of rated voltage. Therefore the wind farm must stay connected to the grid as long as the voltage of the grid where the farm is connected is above the criteria limit. There are different requirements for wind parks with a rated active power more than 100 MW and medium size ones with rated power between 1.50 and 100 MW. This study is focused on the medium sized wind parks in which a three phase short circuit fault at point of common coupling causes a 75% voltage dip at the terminal of wind turbine. The voltage profile is depicted if Figure 4.1.

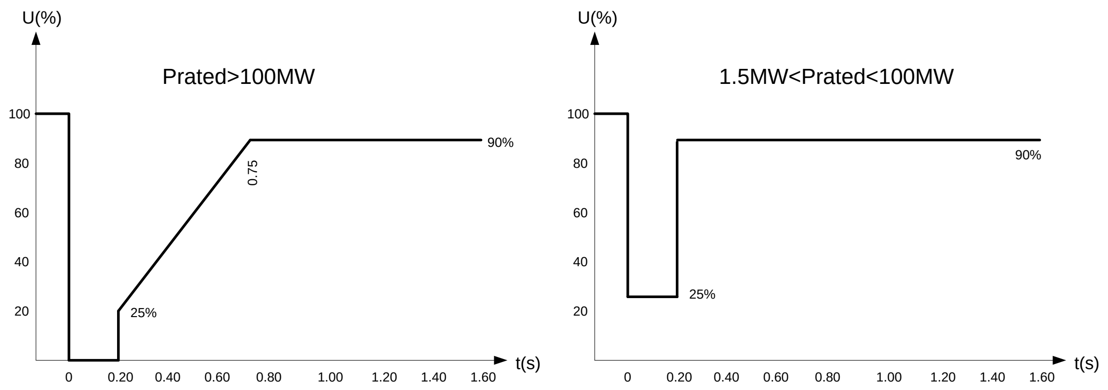


Figure 4.1: Voltage profile for wind farm to perform fault-ride through

4.2 Test System

A test power system configuration for load flow and dynamic simulation studies consist of a wind farm with several wind turbines. In this study, however, the wind farm is presented by a single equivalent machine connected to a single equivalent unit of transformer. This representation is called aggregated model of wind farm. The aggregated model is considered to be sufficient for analyzing the response of the wind park to grid disturbances and for performance evaluation of wind turbine fault ride-through capability. The high voltage side of unit transformer connected to a wind farm transmission line to transfer power to a wind farm substation. The voltage level is stepped-up in the substation to a level that is proper for connecting to the grid.

The rated active and reactive power of the single machine which represents the wind farm is the sum of rated active and reactive power of wind turbines inside the wind farm. In the same way, the rated active power and reactive power for single unit transformer obtained by multiplying the number of individual unit transformers and the rated active and reactive power of each unit transformer. A single bus represents the bus collector. The wind farm has an active power rating of 100 MW, which consists of 67 wind turbines; each of them has rated power of 1.5 MW. The configuration of the power system is shown in Figure 4.2. The connection between wind farm and main substation is through more than one line in case of disconnecting of one line the wind farm dose not disconnected from the grid. However in this test system it is assumed the disturbance is on the PCC and not on the transmission line between wind farm and the main substation and therefore it is shown as a single line.

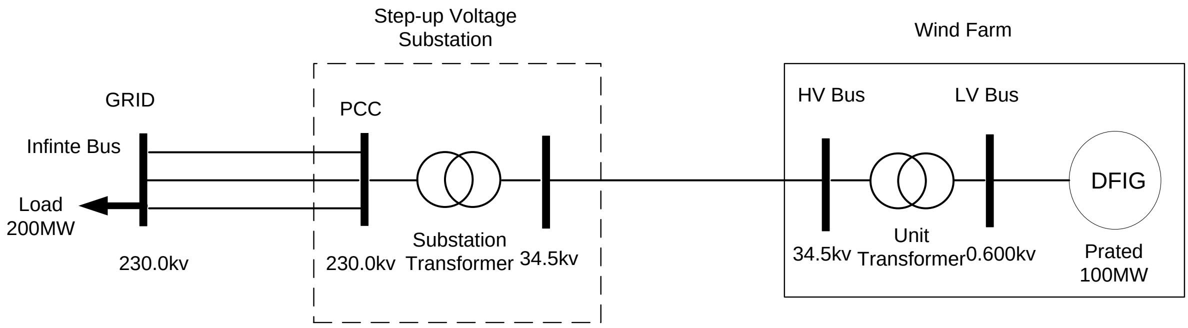


Figure 4.2: Power system configuration

4.3 Load Flow

The load flow provides the initial conditions for dynamic simulation. The load flow model of a wind farm serves two purposes: First, it serves as the basis for load flow studies including thermal, voltage, and other analyses. Second, it serves as initial conditions for stability analysis. The quantities that can be obtained from load flow study are the bus voltage magnitudes, bus voltage angle, active and reactive powers that flow through transmission lines.

The maximum and minimum active and reactive power limits according to the capability curve of generators are among the most important input data that must be specified during data preparation. The capability curve for a 1.5 MW GE wind turbine generator is shown in Figure 4.3[7]

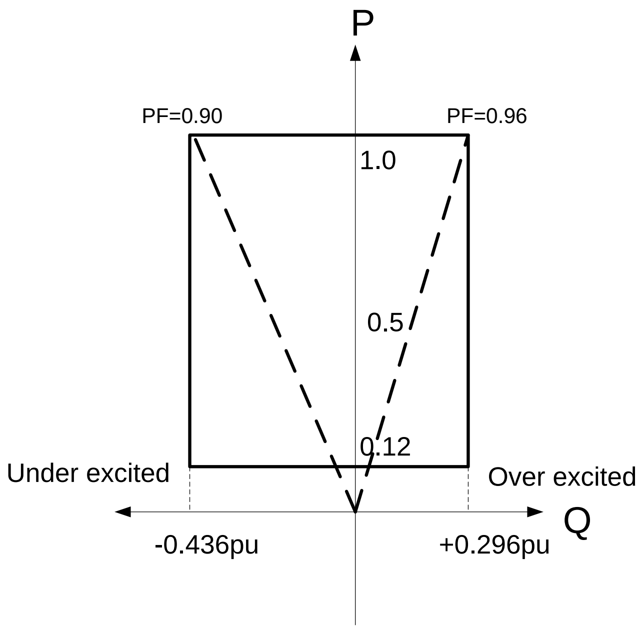


Figure 4.3: GE 1.5 MW DFIG capability curve

A wind turbine generator in load flow is treated as a conventional generator and is specified on the existing generator record of the power flow raw data file. In the end of this data record, a wind control mode must be specified, as follows:

- 0 for a non wind turbine generator.
- 1 for a wind turbine generator that participates in voltage control provided with upper and lower reactive power limits.
- 2 for a wind turbine generator with a constant power factor.
- 3 for a wind turbine generator that operates at a fixed active and reactive power.

The load flow diagrams of the test system are shown in Figure 4.4

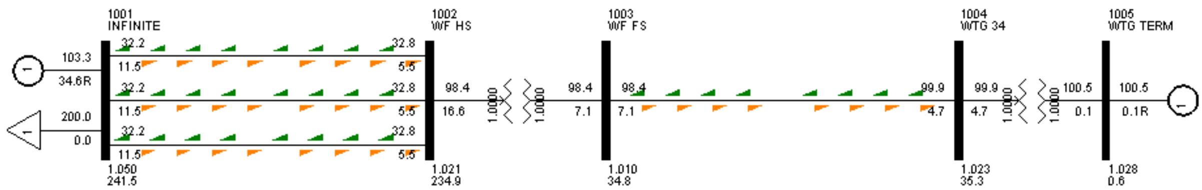


Figure 4.4: The active and reactive power flow (MW,MVAr)

4.4 Dynamic Simulation

The first step in dynamic simulation is to enter the dynamic model data, which is saved in a file. This file contains a group of records, each of which defines the location of a dynamic equipment model in the network along with the constant parameters of the model. As it was mentioned in previous chapter, the PSS/E version 31 provides a dynamic model for a DFIG wind turbine. The model includes generator, electrical control, and wind turbine and pitch control. In this simulation, the infinite grid is represented by a constant internal voltage generator model (GENCLS). GENCLS is the classical constant voltage behind transient reactance generator model in PSS/E. Appendix 1 contains model parameters that are used in this simulation.

Dynamic simulation is performed based on the load flow data that provide the transmission network, load, and generator data. In this study, a number of simulations are performed to investigate the model response subjected to grid disturbances. The disturbance in the simulation study is a three-phase symmetrical short-circuit fault on one of the lines connecting PCC bus and grid bus. The fault lasts for 250 milliseconds and is cleared by disconnecting the faulted line. During the fault the voltage at PCC is dropped to zero and thus no electrical power transfer from wind turbine to the grid.

4.4.1 Constant reactive power without closed-loop terminal voltage control

When the reactive control mode of the model is set to a constant reactive power (*varflg*=0), the current in q-direction is also constant during the fault. Figure 4.5 shows that during the fault on PCC voltage drops to zero. After fault clearing, the voltage gradually recovers to around 0.95 pu. The wind turbine terminal voltage has a similar pattern, except that during the fault the retaining terminal voltage is 0.25 pu, which is considerably higher that the PCC voltage. When faulted line is disconnected from the network, the total impedance between the turbine terminal and PCC increases and therefore the voltage drop will increase and the recovered voltage will be less than its pre-fault magnitude.

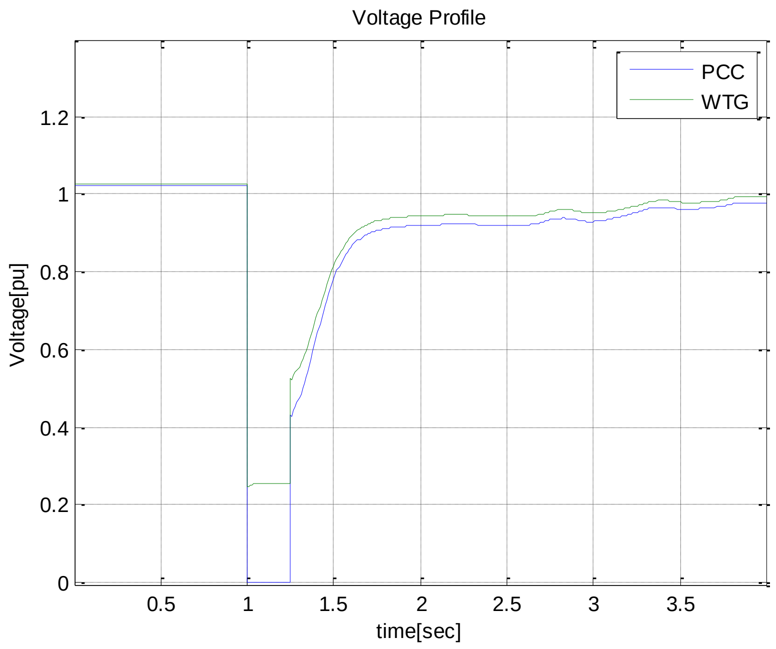


Figure 4.5: Voltage profile

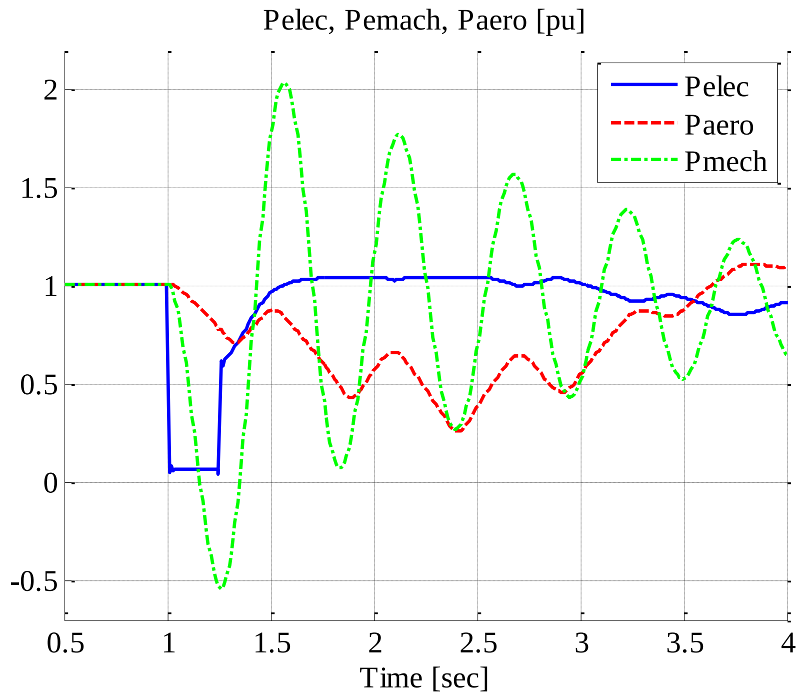


Figure 4.6: Electrical, mechanical and aeromechanical power

As seen in figure 4.6, when the fault occurred the electrical power suddenly decreases to a very low value (0.06433pu or 6.433 MW) and the difference between mechanical input power and electrical output power make an increasing in the rotor speed and therefore the rotor starts to accelerate. The torsional oscillation in the drive-train model is reflected in the output power of the wind turbine. The frequency of the oscillation is 1.8 Hz in this particular case.

The peak of the mechanical power is considerably high, which is up to 2 pu during the first cycle of the oscillation. The scale of this magnitude indicates that the mechanical stress in the drive train is quite high.

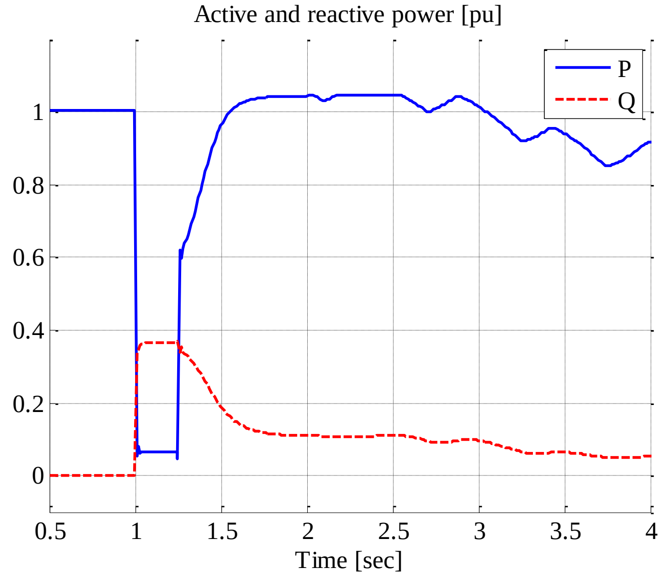


Figure 4.7: Active, reactive and mechanical power profile

During the fault, the mechanical input power is reduced by pitch control mechanism. The P_{mech} plot shows the damped mechanical power output of the wind turbine due to the pitch controller action. It is assumed that the wind turbine works at its rated power at the fault instant. As the fault duration and the transient of voltage recovery is short, the wind speed can be assumed constant in the grid fault simulations. It can be seen in figure 4.7 prior to the fault, the reactive power is zero and the wind farm operated at unity power factor. During the fault, the wind turbine inject reactive power of 0.3671 pu (36.71 MVAr) to the grid.

The output current profile is shown in figure 4.8. It can be seen the current level during fault is around 1.5 pu and as the magnetizing impedance of generator is much bigger than its stator and rotor impedances it can be assumed whole current goes through the rotor-side converter and rotor winding. The converters are normally designed for a 10% overload and therefore flowing of the high current during fault will likely violate the rotor converter current limit and can damage the IGBTs inside converters.

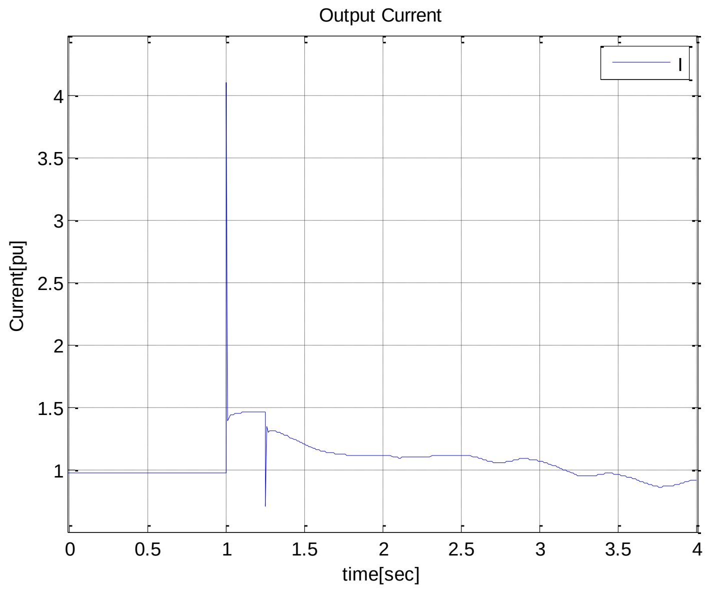


Figure 4.8: Current profile

The performance of the model for longer fault duration time has also been investigated. The simulation results, which is not presented here, show that even when the fault occurs in much longer time period, in this case up to 3 seconds, the turbine is able to ride through the fault despite the fact that the current injected by the generator and hence the converter is considerably high i.e. up to 1.5 pu. This may raise a question regarding the validity of the model to realistically simulate the limitation of the rotor-side converter. In other words, the model seems to produce too optimistic simulation results.

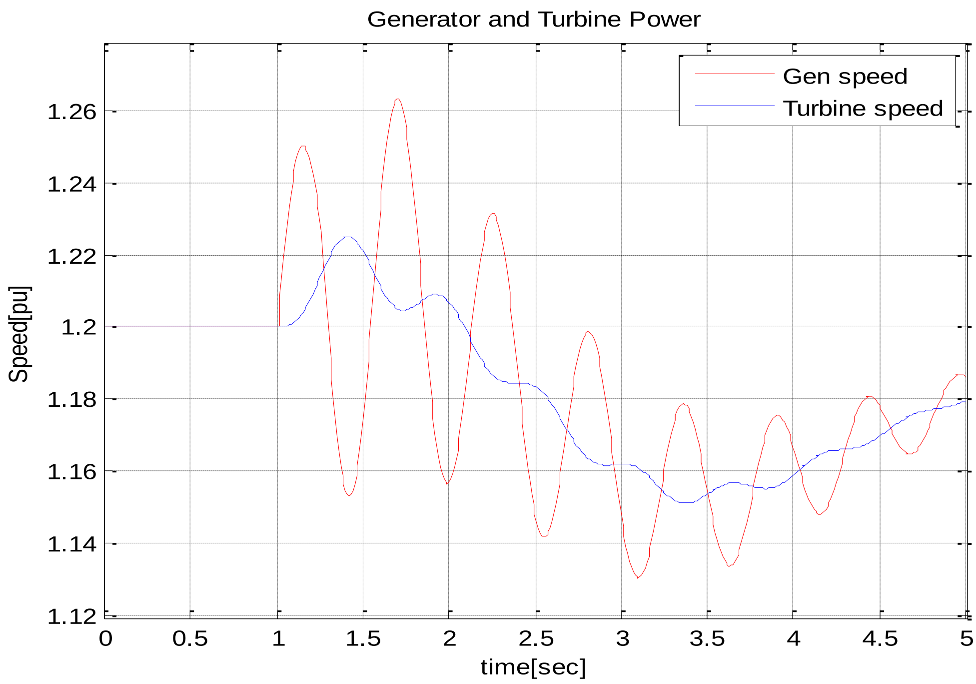


Figure 4.10: Wind turbine and generator speed profile

It can be seen from figure 4.10 in the two mass model for drive train the speed of generator is oscillating and it is not identical with the turbine speed.

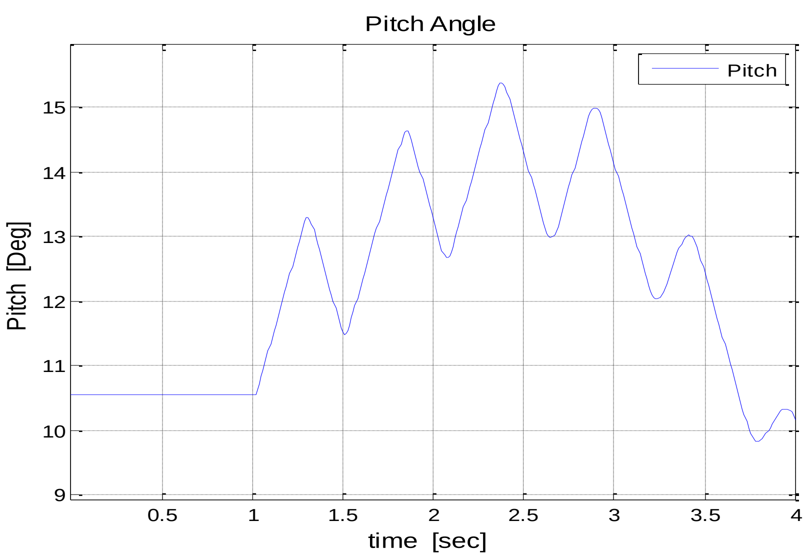


Figure 4.11: Pitch angle profile

It can be seen in Figure 4.11, the pitch angle is increased during the fault in order to reduce the power input from wind turbine. The pitch angle is oscillating; this is because the pitch angle is controlled by the speed of the turbine. After fault clearing, the turbine speed goes down (see Figure 4.10), however the pitch angle continuously increases until few seconds. This is due to the effect of the pitch compensation. The pitch compensation tries to reduce the input power to the turbine by increasing a little more in pitch angle.

4.4.2 Constant reactive power with closed-loop terminal voltage control

In the second simulation study, the *varflg* is set to 0 (constant reactive power) and *vltflg* is set to 1. This means that the terminal voltage control is enabled. The reactive power command is equal to the reference value and the internal voltage magnitude is limited in the closed loop controller. The upper and lower limits of the internal voltage magnitude are Vterm+XI_{Qmax} and Vterm+XI_{Qmin}, respectively. In the simulation, the voltage drop limits XI_{Qmax} and XI_{Qmin} must be set by user. It was found that using the typical voltage drop limit values given in PSS/E, i.e. XI_{Qmax}=0.4, the voltage is not able to recover following a grid fault (see Figure 4.12 and Figure 4.13). This is probably due to numerical instability since the upper and lower limits of the voltage controller are not fixed; rather it is dependent on the terminal voltage level (Vterm).

In order to avoid such a numerical instability, the maximum voltage drop limit value must be increased. Figure 4.14 shows simulation result where the voltage is successfully recovered with maximum voltage drop limit set at 0.55.

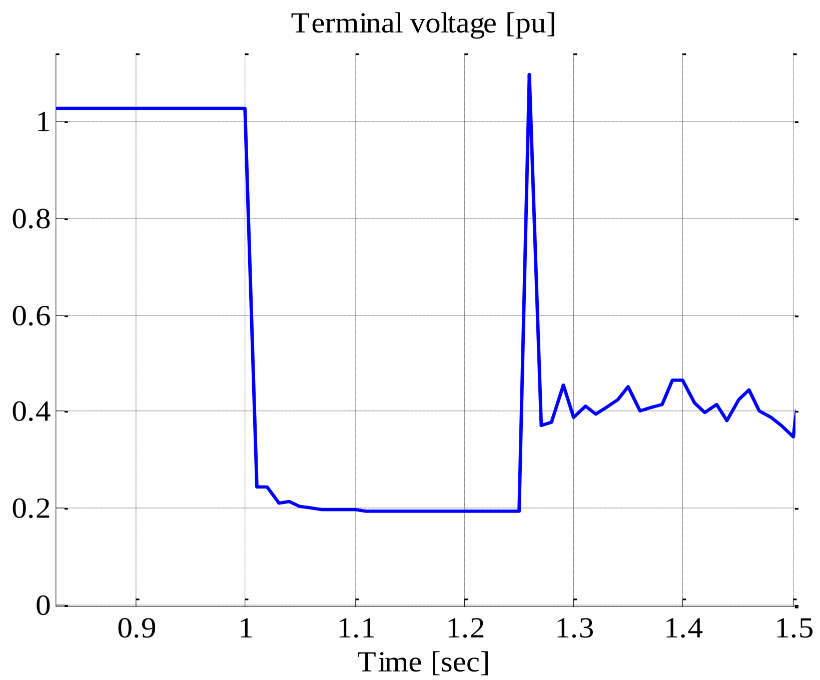


Figure 4.12: Voltage profile for upper limit value of 0.4pu

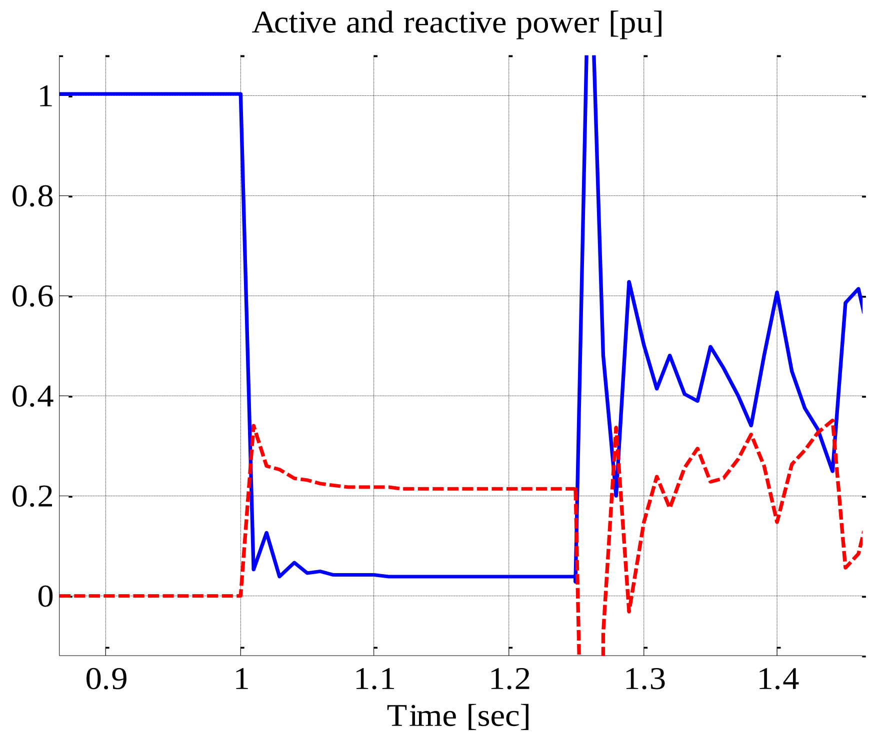


Figure 4.13: Active and reactive power profile for upper limit value of 0.4pu

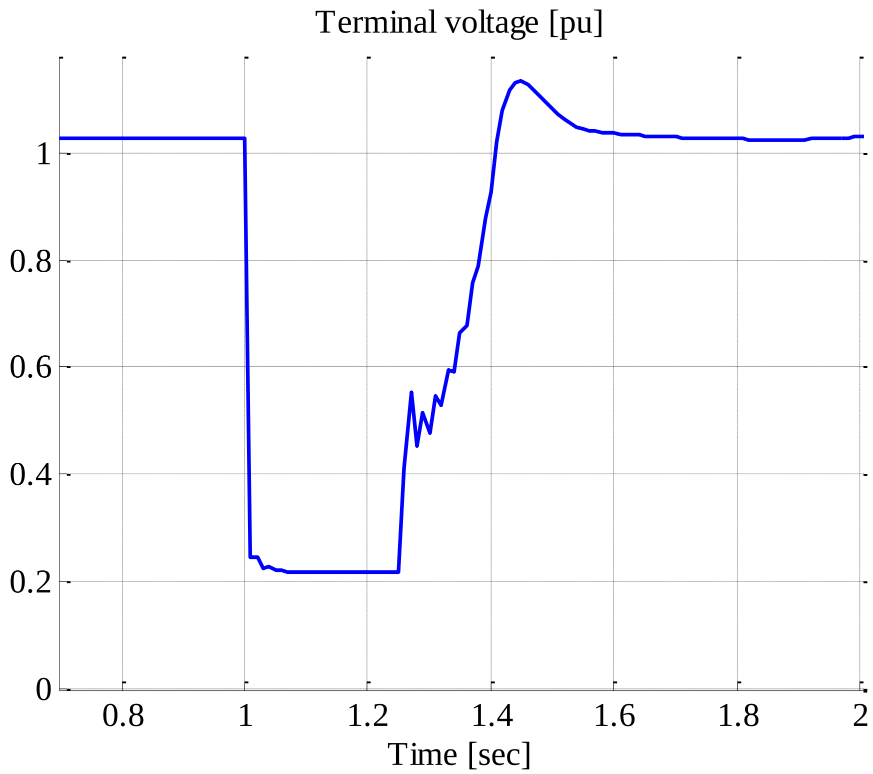


Figure 4.14: Voltage profile for upper limit value of 0.55pu

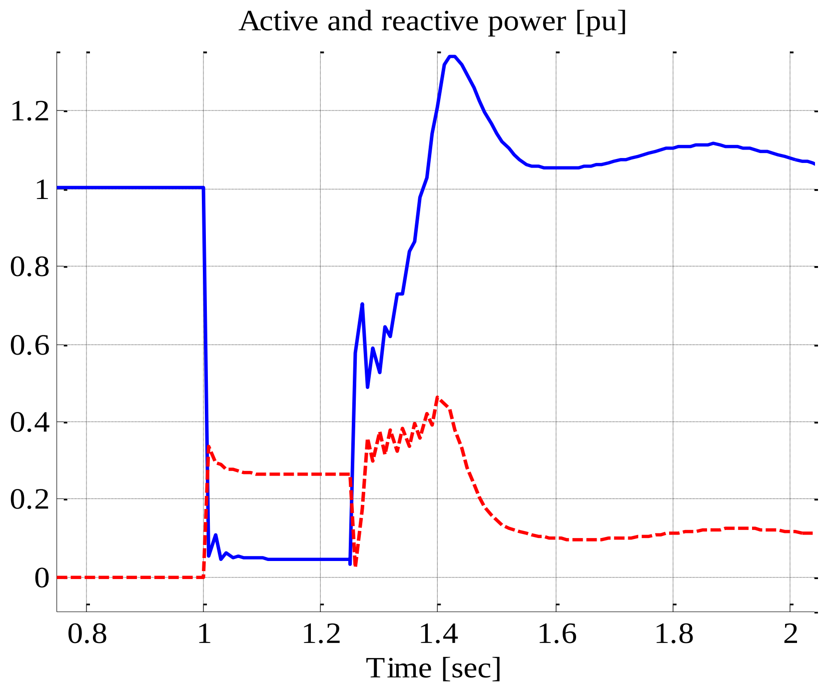


Figure 4.15: Active and reactive power profile for upper limit value of 0.55pu

4.5 Simulation result summary

It was found from the simulations that the model has advantages and some drawbacks. The advantages with the model are summarized as follows:

- The drive-train model is presented in two-mass model representation. The influences of this model on the dynamic response of the wind turbine model are clearly shown in the simulations. The magnitude of the mechanical power oscillation during the fault indicates the scale of mechanical stress in the drive train. Thus, the impacts of frequent expose of voltage dip on the lifetime of the drive train components need to be investigated further.
- The pitch angle controller and its function for decreasing the aerodynamic power during and following a grid fault are considered in the wind turbine model. The simulation results emphasize the importance of the pitch controller model in fault responses of a DFIG wind turbine. Without appropriate representation of the pitch controller the aerodynamic input power would be constant and thereby would result in less accurate predictions.
- The time step required to run the model is compatible with the standard time step in PSS/E simulator. Consequently, this model does not require time step reduction in order to avoid numerical instability during simulations.

- The procedure for controlling voltage and reactive power is included in the model. There are three different options provided in the model to control reactive power/voltage i.e. constant voltage, constant power factor and constant reactive power.
- There is possibility to define the power-speed curve in the model. This provides flexibility for users to adjust the power-speed characteristic of the turbine according to the wind turbine being investigated.

The main drawbacks with the model can be explained as follows:

- The generator is modeled as a simple voltage source behind transient reactance. As a consequence, the generator losses are not included in the model.
- The rotor current and voltage are not represented in the model and therefore the influence of rotor current limits on the wind turbine response during and following a disturbance on the grid cannot be investigated.
- There is high risk for voltage instability following a grid fault when the closed loop terminal voltage control is used. This is probably due to numerical instability in the controller limiters which are not fixed; rather it is dependent on the terminal voltage level (Vterm). To avoid such a problem, the upper limits must be increased with the consequence of much higher reactive current during fault.
- The FRT is not included in the model. Therefore, regardless the fault duration and the magnitude of voltage dip during grid fault, wind turbine remains intact. It has been observed that during grid faults the generator/converter current can be very high, while in reality such a high current magnitude are not permitted due to the limited capability of the converter. That means the model provide too optimistic results and therefore it does not depict realistic behavior of a typical wind turbine.
- Wind speed is assumed to be constant throughout simulations and thereby the effect of wind speed changes on the turbine response cannot be simulated using this model.

5 Conclusion and Future Works

5.1 Conclusions

The modeling of wind turbine generators for power system studies is an important aspect and it is in a rapid evolution state. More accurate model can help the power system operators to study the dynamic performance of the gird under disturbances and predict its behavior in a more realistic way.

The PSS/E built-in model investigated in this study emphasizes a detailed representation of reactive power and voltage control, while the generator model of the wind turbine is simply modeled as a voltage source behind transient impedance. In this study the model has been evaluated by simulating the model subjected to grid disturbances.

The simulation results show that the behavior of the DFIG wind turbine model in PSS/E is dependent on the parameters used in the model. One of the most important parameters is the closed loop terminal voltage control limits. This parameter has a significant effect on voltage stability of the wind turbine after fault clearing. It was found that the under voltage and over current protection is not implemented in the model. It is observed that there no limitation in fault time duration and severity. The model does not differentiate between short and long-term/permanent faults. While in reality, the wind farm must be disconnected from the grid when disturbance is permanent otherwise it can be damaged by high amount of short circuit current and also the under voltages.

On the other hand the model the model has number of advantages such as the possibility to control the reactive power and voltage using different mode of operation. In general, the model can be used to study dynamic simulation when it is connected to bulky power system, however some considerations related with the model must be take into account. Accordingly the model is applicable with care.

5.2 Future works

The results of this work can be basic point for future studies. Some basic parts of DFIG same as rotor crowbar can be added to the dynamic model. The under/over voltage protection can be considered. The dynamic model for the full converter and fixed-speed wind turbines also can be introduced. Another subject that could be of interest is evaluation of the model for islanding operation.

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Appendices

A .Wind Turbine and Network Parameters

A.1 Doubly-fed induction generator (WT3G1)

Symbol	Description	Value
X_{eq}	Equivalent reactance for current injection(pu)	0.8
$K_{p}ll$	PLL first integrator gain	30
$K_{ip}ll$	PLL second integrator gain	0
PLLMX	PLL maximum limit	0.1
Prated	Turbine MW rating	1.5

A.2 Doubly-fed induction generator electrical control (WT3E1)

Symbol	Description	Value
Tfv	Filter time constant in voltage regulator(sec)	0.15
K_{pv}	Proportional gain in voltage regulator(pu)	18
K_{iv}	Integrator gain in voltage regulator(pu)	5
X_{c}	Line drop compensation reactance(pu)	0.05
Tfp	Filter time constant in torque regulator(sec)	0.05
K_{pp}	Proportional gain in torque regulator(pu)	3
K_{ip}	Integrator gain in torque regulator(pu)	0.6
PMX	Max limit in torque regulator(pu)	1.12
PMN	Min limit in torque regulator(pu)	0.10
QMX	Max limit in voltage regulator (pu)	0.296
QMN	Min limit in voltage regulator(pu)	-0.436
IP_{max}	Max reactive current limit(pu)	1.10
T_{rv}	Voltage sensor time constant(sec)	0.05
RPMX	Max power order derivative(pu)	0.45

RPMN	Min power order derivative(pu)	-0.45
T_Power	Power filter time constant(sec)	5.0
K_{qi}	MVAR/Voltage gain	0.0
VMINCL	Min voltage limit	0.90
Symbol	**Description**	**Value**
VMAXCL	Max voltage limit	1.20
K_{qv}	Voltgae/MVAR gain	40
XIQmin	Min limit of diff. between Vterm and $E_q^{''}$cmd	-0.50
XIQmax	Max limit of diff. between Vtrem and $E_q^{''}$cmd	0.40
T_v	Lag time constant in WindVar controller(sec)	0.05
T_p	Pelec filter in fast PF controller	0.05
Fn	A portion of online wind turbines	1.0
WPMIN	Shaft speed at Pmin(pu)	0.69
W_p20	Shaft speed at 20% rated power(pu)	0.78
W_p40	Shaft speed at 40% rated power(pu)	0.98
W_p60	Shaft speed at 60% rated power(pu)	1.12
Pwp	Minimum power for operation at W_p100 speed (pu)	0.74
W_p100	Shaft speed at 100% rated power(pu)	1.20

A.3 Turbine (WT3T1)

Symbol	Description	Value
VW	Initial wind, pu of rated wind speed	1.25
H	Total inertia constant, MW*sec/MVA	4.95
DAMP	Machine damping factor , pu P/pu speed	0.00
Kaero	Aerodynamic gain factor	0.0070
Theta2	Blade pitch at twice rated wind speed (deg)	21.98

Htfrac	Turbine inertia fraction (Hturb/H)	0.875
Frec1	First shaft torsional resonant frequency(Hz)	1.80
DSHAFT	Shaft damping factor (pu)	1.50

A.4 Pitch control (WT3P1)

Symbol	**Description**	**Value**
Tp	Blade response time constant(sec)	0.30
Kpp	Proportional gain of PI regulator(pu)	150
Kip	Integrator gain of PI regulator(pu)	25
Kpc	Proportional gain of the compensator(pu)	3.0
Kic	Integrator gain of the compensator(pu)	30
TetaMin	Lower pitch angle limit(deg)	0.0
TetaMax	Upper pitch angle limit(deg)	27.0
RTeta	Upper pitch angle rate limit(deg/sec)	10.0
PMX	Power reference(pu on MBASE)	1.0