STUDY OF WIND TURBINE DRIVEN DFIG USING AC/DC/AC CONVERTER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS OF THE DEGEREE OF

Bachelor of Technology

In

Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled, "**Study Of Wind Turbine Driven Induction Generator Using AC/DC/AC converter"** submitted by Ashish Kumar Agrawal, Bhaskar Munshi and Srikant Kayal in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision.

And to the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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An assemblage of this nature could never have been attempted with our reference to and inspiration from the works of others whose details are mentioned in references section. We acknowledge our indebtedness to all of them. Further, we would like to express our feeling towards our parents and God who directly or indirectly encouraged and motivated us during this dissertation

ABSTRACT

In recent years, wind energy has become one of the most important and promising sources of renewable energy, which demands additional transmission capacity and better means of maintaining system reliability. The evolution of technology related to wind systems industry leaded to the development of a generation of variable speed wind turbines that present many advantages compared to the fixed speed wind turbines. These wind energy conversion systems are connected to the grid through Voltage Source Converters (VSC) to make variable speed operation possible. The studied system here is a variable speed wind generation system based on Doubly Fed Induction Generator (DFIG). The stator of the generator is directly connected to the grid while the rotor is connected through a back-to-back converter which is dimensioned to stand only a fraction of the generator rated power.

To harness the wind power efficiently the most reliable system in the present era is grid connected doubly fed induction generator. The DFIG brings the advantage of utilizing the turns ratio of the machine, so the converter does not need to be rated for the machine's full rated power. The rotor side converter (RSC) usually provides active and reactive power control of the machine while the grid-side converter (GSC) keeps the voltage of the DC-link constant. The additional freedom of reactive power generation by the GSC is usually not used due to the fact that it is more preferable to do so using the RSC. However, within the available current capacity the GSC can be controlled to participate in reactive power generation in steady state as well as during low voltage periods. The GSC can supply the required reactive current very quickly while the RSC passes the current through the machine resulting in a delay. Both converters can be temporarily overloaded, so the DFIG is able to provide a considerable contribution to grid voltage support during short circuit periods. This report deals with the introduction of DFIG, AC/DC/AC converter control and finally the SIMULINK/MATLAB simulation for isolated Induction generator as well as for grid connected Doubly Fed Induction Generator and corresponding results and waveforms are displayed.

NOMENCLATURE

Pm Mechanical power captured by the wind turbine and transmitted to the rotor

Ps Stator electrical power output

Pr Rotor electrical power output

Pgc Cgrid electrical power output

Qs Stator reactive power output

Qr Rotor reactive power output

Qgc Cgrid reactive power output

Tm Mechanical torque applied to rotor

Tem Electromagnetic torque applied to the rotor by the generator

Wr Rotational speed of rotors

p derivative symbol

Vqs ,Vds are the three-Phase supply voltages in d-q reference frame, respectively

iqs ,ids are the three-Phase stator currents in d-q reference frame, respectively

λqs ,λds are the three-Phase stator flux linkages in d-q reference frame, respectively

Vqr ,Vdr are the three-Phase rotor voltages in d-q reference frame, respectively

iqr ,idr are the three-Phase rotor voltages in d-q reference frame, respectively

λqr ,λdr are the three-Phase rotor voltages in d-q reference frame, respectively

Rs ,Rr are the stator and rotor resistances of machine per phase, respectively

Lls ,Llr are the leakage inductances of stator and rotor windings, respectively

θ s ,θ r are the stator and rotor flux angle, respectively

Te ,Tm are the electromagnetic and mechanical torques, respectively

Ps ,Qs are the stator-side active and reactive powers, respectively

Pr ,Qr are the rotor-side active and reactive powers, respectively

RON ,ROFF are the IGBT ON and OFF resistances, respectively

D, J are the moment of inertia and damping coefficient, respectively

P are the Number of poles

M1,M2 are the stator and rotor modulation depths, respectively

Vtri is the triangular Voltage Signal

R,L are the resistance and inductance of input filter, respectively

V1, I1 are the input filter line voltage and current, respectively

E is the DC-link voltage

s is the Laplacian Operator

C is the DC-Link capacitance

PDC is the DC-link active power

J Combined rotor and wind turbine inertia coefficient

Ws Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles

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List of Diagrams

CONTENTS

Chapter 1

INTRODUCTION

INTRODUCTION

With increased penetration of wind power into electrical grids, DFIG wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. This has created an interest in developing suitable models for DFIG to be integrated into power system studies. The continuous trend of having high penetration of wind power, in recent years, has made it necessary to introduce new practices. For example, grid codes are being revised to ensure that wind turbines would contribute to the control of voltage and frequency and also to stay connected to the host network following a disturbance.

In response to the new grid code requirements, several DFIG models have been suggested recently, including the full-model which is a 5th order model. These models use quadrature and direct components of rotor voltage in an appropriate reference frame to provide fast regulation of voltage. The 3rd order model of DFIG which uses a rotor current, not a rotor voltage as control parameter can also be applied to provide very fast regulation of instantaneous currents with the penalty of losing accuracy. Apart from that, the 3rd order model can be achieved by neglecting the rate of change of stator flux linkage (transient stability model), given rotor voltage as control parameter. Additionally, in order to model back-to back PWM converters, in the simplest scenario, it is assumed that the converters are ideal and the DC-link voltage between the converters is constant. Consequently, depending on the converter control, a controllable voltage (current) source can be implemented to represent the operation of the rotor-side of the converter in the model. However, in reality DC-link voltage does not keep constant but starts increasing during fault condition. Therefore, based on the above assumption it would not be possible to determine whether or not the DFIG will actually trip following a fault.

In a more detailed approach, actual converter representation with PWM-averaged model has been proposed, where the switch network is replaced by average circuit model, on which all the switching elements are separated from the remainder of network and incorporated into a switch network, containing all the switching elements. However, the proposed model neglects high frequency effects of the PWM firing scheme and therefore it is not possible to accurately determine DC-link voltage in the event of fault. A switch-by-switch representation of the back-to-back PWM converters with their associated modulators for both rotor- and stator-side Converters has also been proposed. Tolerance-band (hysteresis) control has been deployed. However, hysteresis controller has two main disadvantages: firstly, the switching frequency does not remain constant but varies along the AC current waveform and secondly due to the roughness and randomness of the operation, protection of the converter is difficult. The latter will be of more significance when assessing performance of the system under fault condition.

In order to resolve the identified problems, a switch-by-switch model of voltage-fed, current controlled PWM converters, where triangular carrier-based Sinusoidal PWM (SPWM) is applied to maintain the switching frequency constant. In order to achieve constant switching frequency, calculation of the required rotor voltage that must be supplied to the generator is adopted. Various methods such as hysteresis controller, stationary PI controller and synchronous PI controller have been adopted in order to control current-regulated induction machine. Among which, synchronous PI controller has been acknowledged as being superior.

Power quality is actually an important aspect in integrating wind power plants to grids. This is even more relevant since grids are now dealing with a continuous increase of non-linear loads such as switching power supplies and large AC drives directly connected to the network. By now only very few researchers have addressed the issue of making use of the built-in converters to compensate harmonics from non-linear loads and enhance grid power quality. In, the current of a non-linear load connected to the network is measured, and the rotor-side converter is used to cancel the harmonics injected in the grid. Compensating harmonic currents are injected in the generator by the rotor-side converter as well as extra reactive power to support the grid. It is not clear what are the long term consequences of using the DFIG for harmonic and reactive power compensation. some researchers believe that the DFIG should be used only for the purpose for which it has been installed, i.e., supplying active power only .

Chapter 2

Doubly fed induction generator

Doubly Fed Induction Generator

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

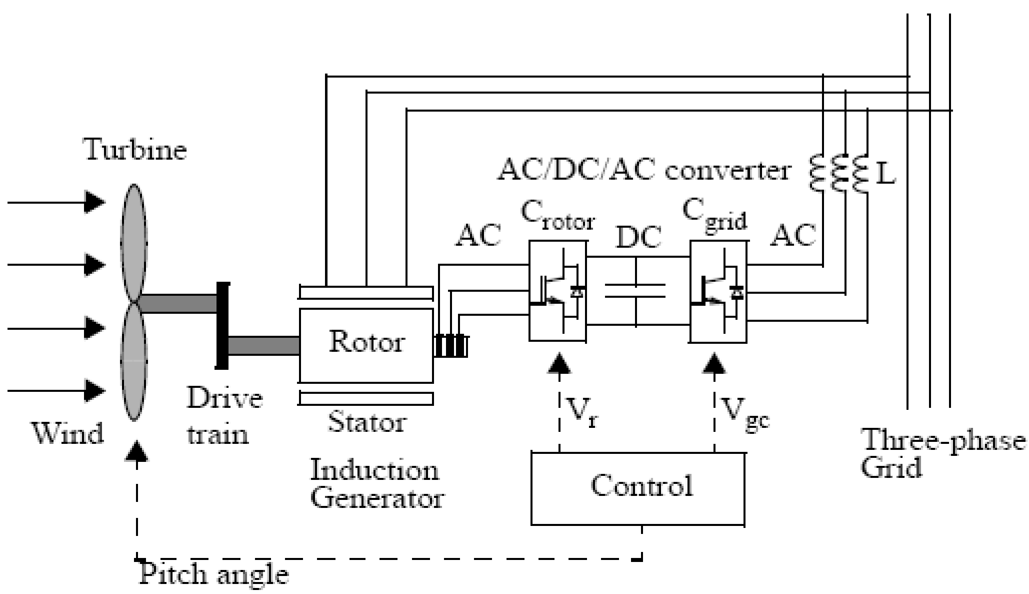


Fig 2.1 basic diagram of Doubly fed induction generator with converters

Where Vr is the rotor voltage and Vgc is grid side voltage. The AC/DC/AC converter is basically a PWM converter which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system. Here Crotor is rotor side converter and Cgrid is grid side converter. To control the speed of wind turbine gear boxes or electronic control can be used.

2.1 Operating Principle of DFIG

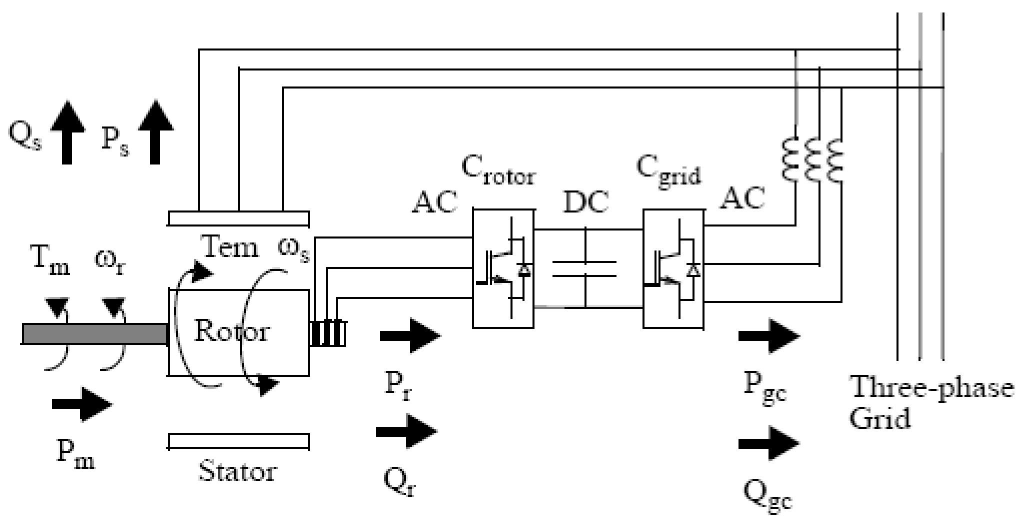


Fig. 2.2 Power flow diagram of DFIG

The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DIFG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator-side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m * \omega_r$$

$$P_s = T_{em} * \omega_s$$

For a loss less generator the mechanical equation is:

$$J \frac{d\omega_r}{dt} = T_m - T_{em}$$

In steady-state at fixed speed for a loss less generator

$$T_m = T_{em} \text{ and } P_m = P_s + P_r$$

and It follows that:

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s = -sP_s$$

where

s= $(\omega_s - \omega_r)/\omega_s$ is defined as the slip of the generator

Generally the absolute value of slip is much lower than 1 and, consequently, Pr is only a fraction of Ps. Since Tm is positive for power generation and since ωs is positive and constant for a constant frequency grid voltage, the sign of Pr is a function of the slip sign. Pr is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For supersynchronous speed operation, Pr is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, Pr is taken out of DC bus capacitor and tends to decrease the DC voltage. Cgrid is used to generate or absorb the power Pgc in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter Pgc is equal to Pr and the speed of the wind turbine is determined by the power Pr absorbed or generated by Crotor. The phase-sequence of the AC voltage generated by Crotor is positive for sub-synchronous speed and negative for supersynchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. Crotor and Cgrid have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

2.2 Dynamic simulation of DFIG in terms of dq-winding

The general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows :

1. Voltage equations:

   Stator Voltage Equations:

   $$v_{qs} = p\,\lambda_{qs} + \omega\lambda_{qs} + r_s i_{qs} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

   $$v_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

   Rotor Voltage Equations**:**

   $$v_{qr} = p\,\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r\, i_{qr} \ldots\ldots\ldots\ldots (3)$$

   $$v_{dr} = p\,\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} + r_r\, i_{dr} \ldots\ldots\ldots\ldots\ldots (4)$$

2. Power Equations:

   $$p_s = 3/2(v_{ds}\, i_{ds} + v_{qs} i_{qs}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

   $$Q_s = 3/2(v_{qs}\, i_{ds} - v_{ds}\, i_{ds}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

3. Torque Equation:

$$T_e = -3p/4(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \ldots\ldots\ldots\ldots\ldots \quad (7)$$

4. Flux Linkage Equations:

Stator Flux Equations:

$$\lambda_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \ldots\ldots\ldots \quad (8)$$

$$\lambda_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \ldots\ldots\ldots \quad (9)$$

Rotor Flux Equations:

$$\lambda_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs} \ldots\ldots\ldots \quad (10)$$

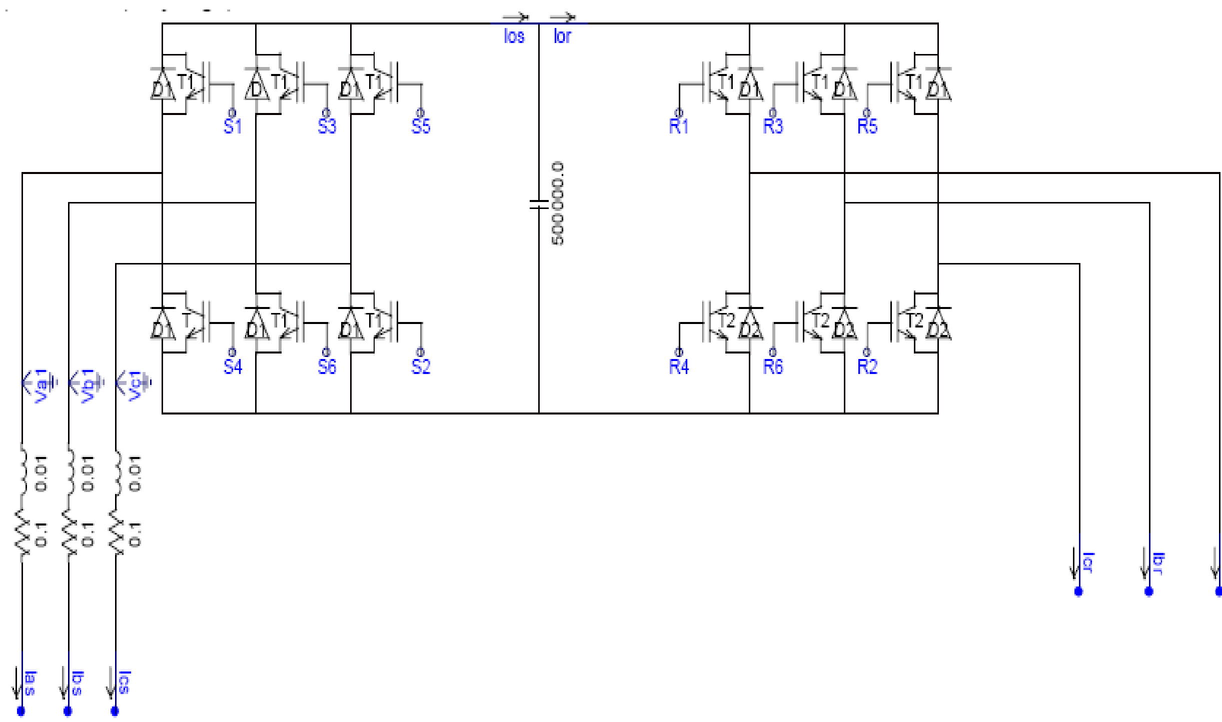
$$\lambda_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds} \ldots\ldots\ldots \quad (11)$$

Chapter 3

Back to Back AC/DC/AC Converter modeling

Back-to-Back AC/DC/AC Converter Modeling

Mathematical modeling of converter system is realized by using various types of models, which can be broadly divided into two groups: mathematical functional models and Mathematical physical models (either equation-oriented or graphic-oriented, where graphic-oriented approach is actually based on the same differential equations).



Functional model describes the relationship between the input and output signal of the system in form of mathematical function(s) and hence constituting elements of the system are not modeled separately. Simplicity and fast time-domain simulation are the main advantages of this kind of modeling with the penalty of losing accuracy. This has been a popular approach with regard to DFIG modeling, where simulation of converters has been done based on expected response of controllers rather than actual modeling of Power Electronics devices. In fact, it is assumed that the converters are ideal and the DC-link voltage between them is constant. Consequently, depending on the converter control, a controllable voltage (current) source can be implemented to represent the operation of the rotor-side of the converter in the model. Physical model, on the other hand, models constituting elements of the system separately and also considers interrelationship among different elements within the system, where type and structure of the model is normally dictated by the particular requirements of the analysis, e.g. steady-state, fault studies, etc. Indeed, due to the importance of more realistic production of the behavior of DFIG, it is intended to adopt physical model rather than functional model in order to accurately assess performance of DFIG in the event of fault particularly in determining whether or not the generator will trip following a fault. This paper proposes a graphic-oriented switch-by-switch representation of the back-to-back PWM converters with their modulators for both rotor- and stator-side converters, where both IGBT and reverse diode devices are represented as a two-state resistive switch.The two-state switch can take on two values, RON (close to zero) and ROFF (very high).

Chapter 4

Converter control system

Converter control system

The back to back PWM converter has two converters, one is connected to rotor side and another is connected to grid side. Control by both converters has been discussed here,

4.1 Rotor side converter Control System

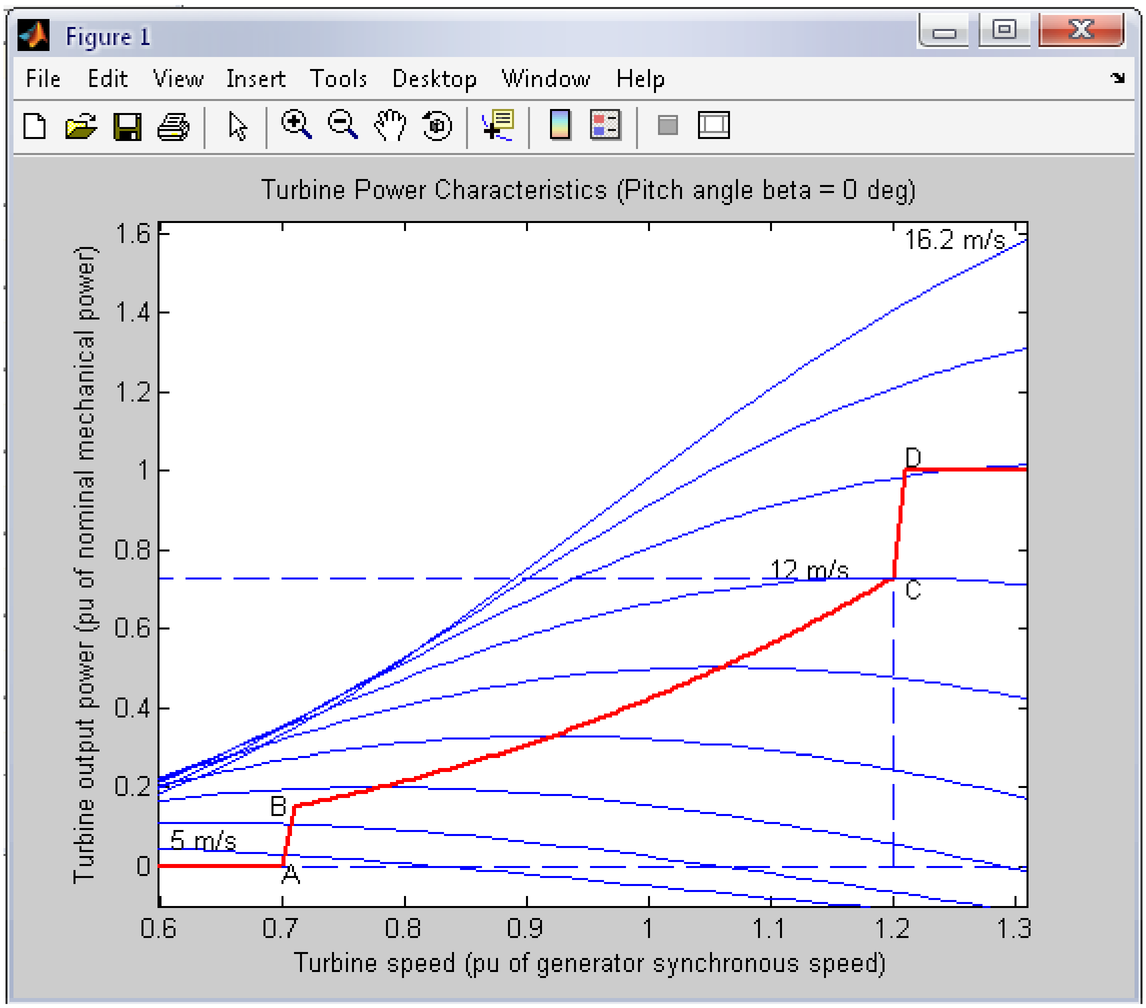


Fig 4.1 turbine power characteristics

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ωr is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line.

Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit. Beyond point D the reference power is a constant equal to one per unit.

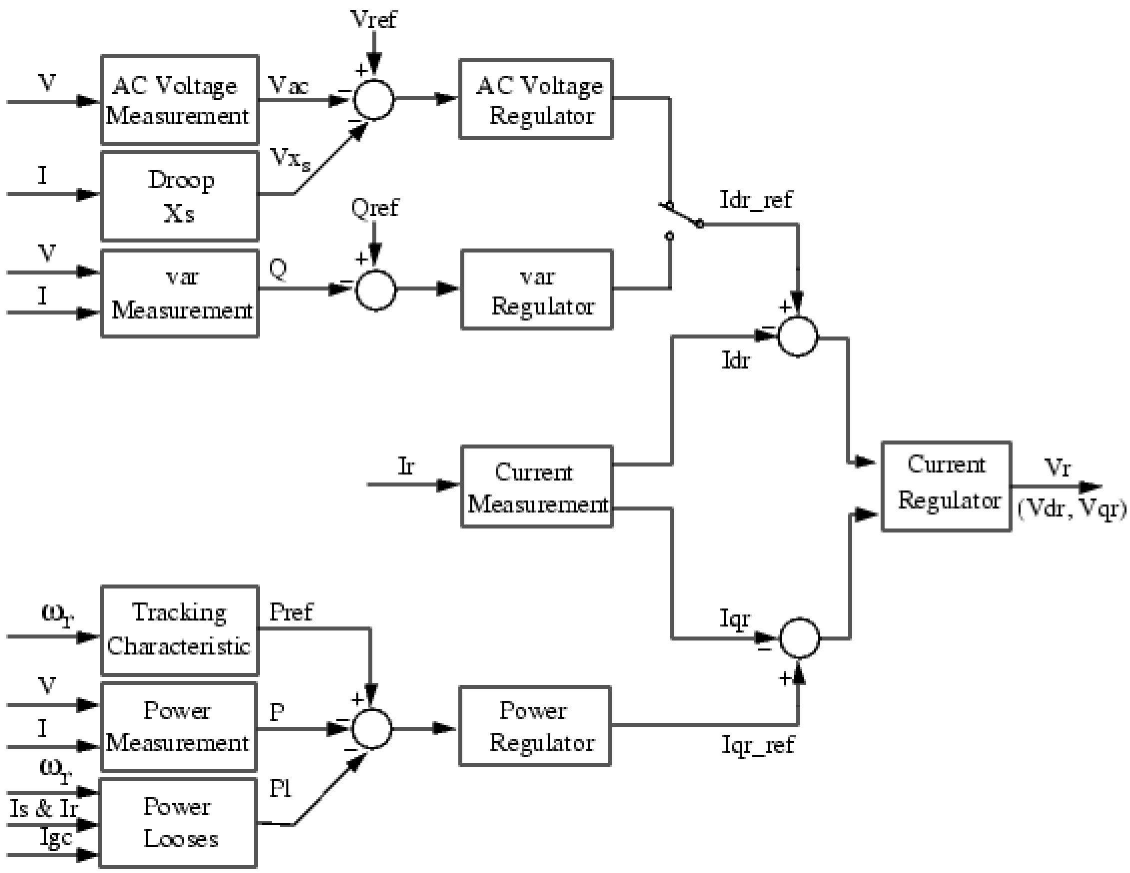


Fig 4.2. Rotor converter control block diagram

For the rotor-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with air-gap flux. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current Iqr_ref that must be injected in the rotor by converter Crotor. This is the current component that produces the electromagnetic torque Tem. The actual Iqr component is compared to Iqr_ref and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage Vqr generated by Crotor. The current regulator is assisted by feed forward terms which predict Vqr. The voltage at grid terminals is controlled by the reactive power generated or absorbed by the converter Crotor. The reactive power is exchanged between Crotor and the grid, through the generator. In the exchange process the generator absorbs reactive power to supply its mutual and leakage inductances. The excess of reactive power is sent to the grid or to Crotor.

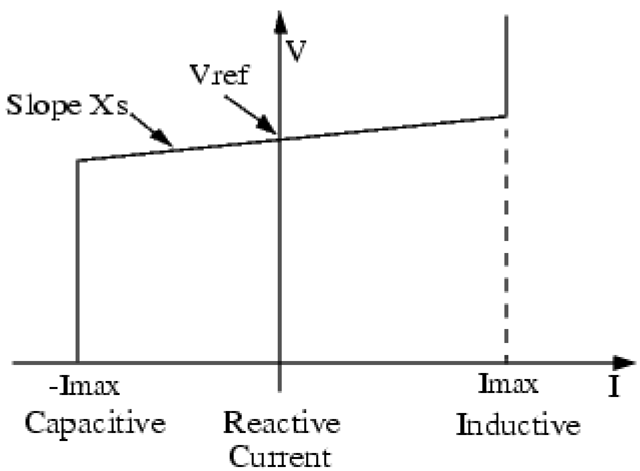


Fig 4.3. V-I characteristics of turbine

The wind turbine control implements the V-I characteristic illustrated in Fig.. As long as the reactive current stays within the maximum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. A voltage droop is used for the V-I characteristic shown in Fig. (3% at maximum reactive power output).

$$V = Vref. + I^{*} Xs$$

where ,

V Positive sequence voltage (p.u.)

I Reactive current (p.u./Pnom) (I > 0 indicates an inductive current)

Xs Slope or droop reactance (p.u./Pnom)

Pnom Three-phase nominal power of the converter specified in the block dialog box

When the wind turbine is operated in var regulation mode the reactive power at grid terminals is kept constant by a var regulator. The output of the voltage regulator or the var regulator is the reference d-axis current Idr_ref that must be injected in the rotor by converter Crotor. The same current regulator as for the power control is used to regulate the actual Idr component of positive-sequence current to its reference value. The output of this regulator is the d-axis voltage Vdr generated by Crotor. The current regulator is assisted by feed forward terms which predict Vdr. Vdr and Vqr are respectively the d-axis and q-axis of the voltage Vr.

4.2 Grid side converter control system

The Grid side converter is used to regulate the voltage of the DC bus capacitor. For the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage. This controller consists of:

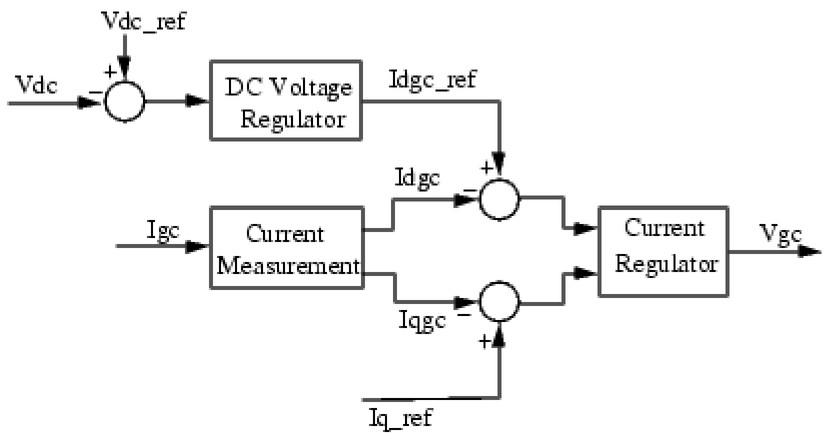
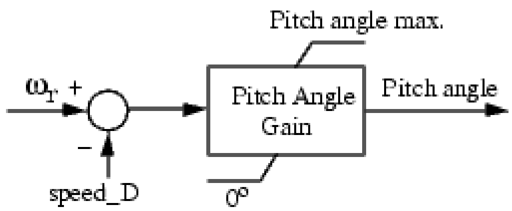


Fig. 4.4 Grid side converter control

1. A measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage Vdc.
2. An outer regulation loop consisting of a DC voltage Regulator.
3. An inner current regulation loop consisting of a current Regulator.

The current regulator controls the magnitude and phase of the voltage generated by converter Cgrid (Vgc) from the Idgc_ref produced by the DC voltage regulator and specified Iq_ref reference. The current regulator is assisted by feed forward terms which predict the Cgrid output voltage.

4.3 Pitch angle control system



The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. For electromagnetic transients in power systems the pitch angle control is of less interest. The wind speed should be selected such that the rotational speed is less than the speed at point D.

Chapter 5

Wind turbine driven Isolated Induction Generator model Simulation in SIMULINK

Wind turbine driven Isolated Induction Generator model Simulation in SIMULINK

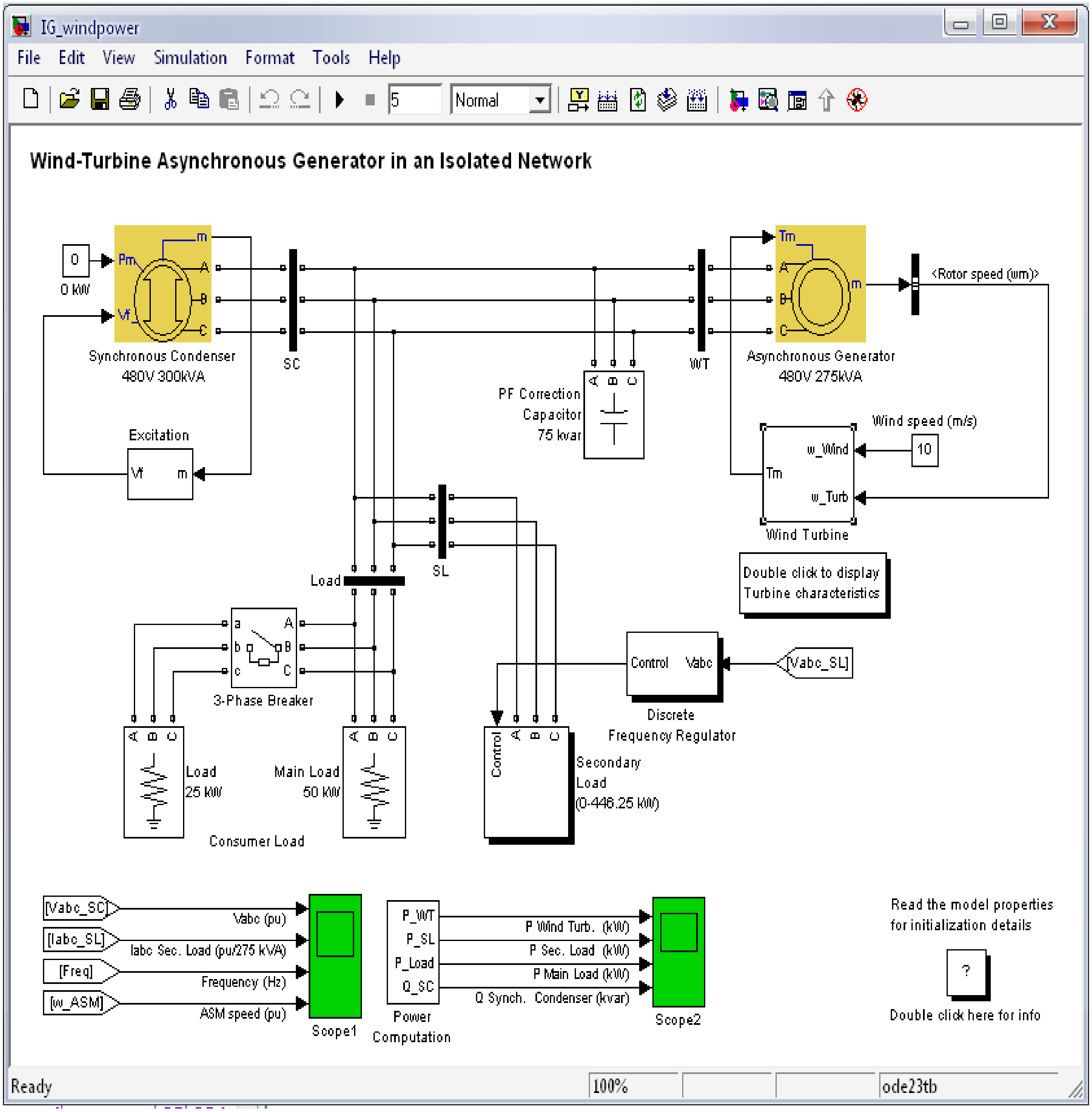


Fig. 5.1 simulink diag. for wind turbine driven isolated squirrel cage induction generator.

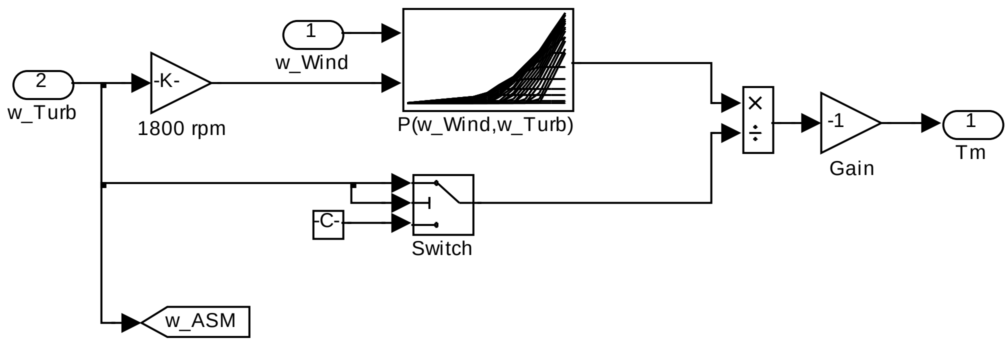


Fig. 5.2 of Wind turbine simulink block diagram

Operation of Induction Generators (IG) Driven by Variable-Pitch Wind Turbines. A wind farm consisting of six 1.5-MW wind turbines is connected to a 25-kV distribution system exports power to a 120-kV grid through a 25-km 25-kV feeder. The 9-MW wind farm is simulated by three pairs of 1.5 MW wind-turbines. Wind turbines use squirrel-cage induction generators (IG). The stator winding is connected directly to the 60 Hz grid and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.

Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 kvar for each pair of 1.5 MW turbine) and the rest of reactive power required to maintain the 25-kV voltage at bus B25 close to 1 pu is provided by a 3-Mvar STATCOM with a 3% droop setting.

5.1 Output Characteristics

Turbine response to a change in wind speed

We Started simulation and observed the signals on the "Wind Turbines" scope monitoring active and reactive power, generator speed, wind speed and pitch angle for each turbine.

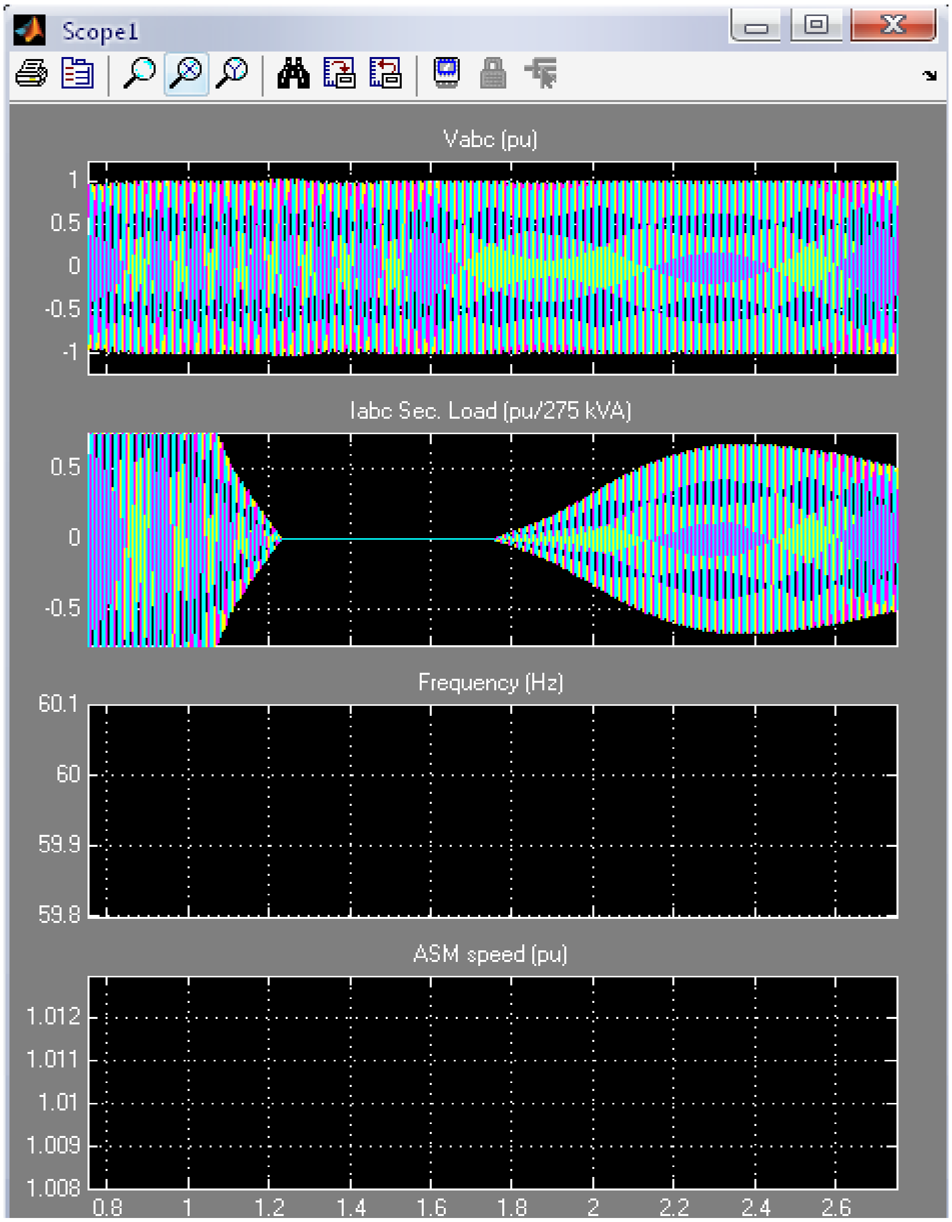


Fig.- voltge and current characteristic of loa

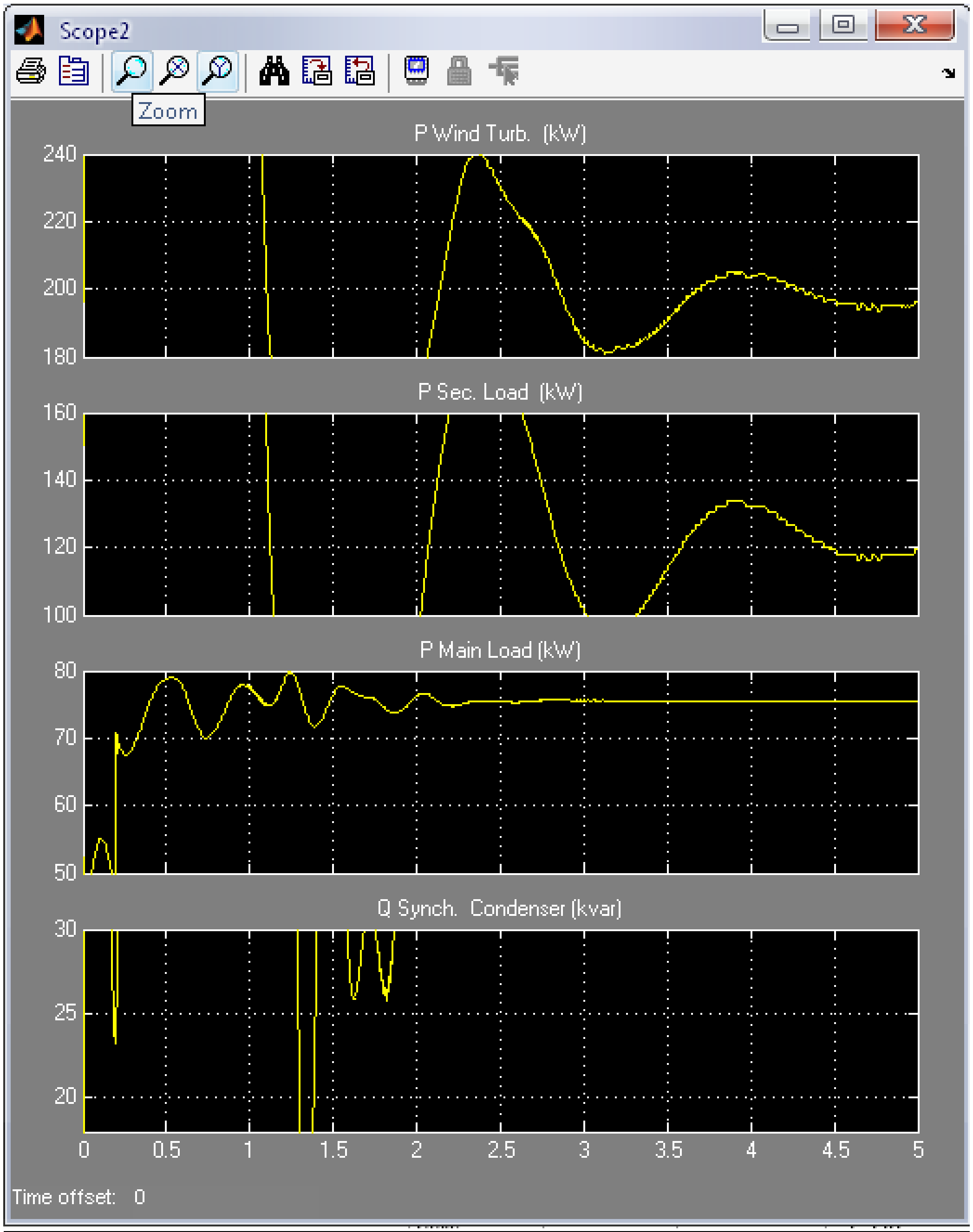


Fig. 5.2 active power of wind turbine ,loads and reactive power of synchronous condenser

For each pair of turbine the generated active power starts increasing smoothly (together with the wind speed) to reach its rated value of 3 MW in approximately 8s. Over that time frame the turbine speed will have increased from 1.0028 pu to 1.0047 pu. Initially, the pitch angle of the turbine blades is zero degree. When the output power exceed 3 MW, the pitch angle is increased from 0 deg to 8 deg in order to bring output power back to its nominal value. Observe that the absorbed reactive power increases as the generated active power increases. At nominal power, each pair of wind turbine absorbs 1.47 Mvar. For a 11m/s wind speed, the total exported power measured at the B25 bus is 9 MW and the statcom maintains voltage at 0.984 pu by generating 1.62 Mvar (see "B25 Bus" and "Statcom" scopes).

5.2 Operation of protection system

At t=15 s, a phase to phase fault is applied at wind turbine 2 terminals, causing the turbine to trip at t=15.11 s. If you look inside the "Wind Turbine Protections" block you will see that the trip has been initiated by the AC Undervoltage protection. After turbine 2 has tripped, turbines 1 and 3 continue to generate 3 MW each.

Chapter 6

Operational Characteristics of a Doubly-Fed Induction Generator (DFIG) Driven by a Wind Turbine

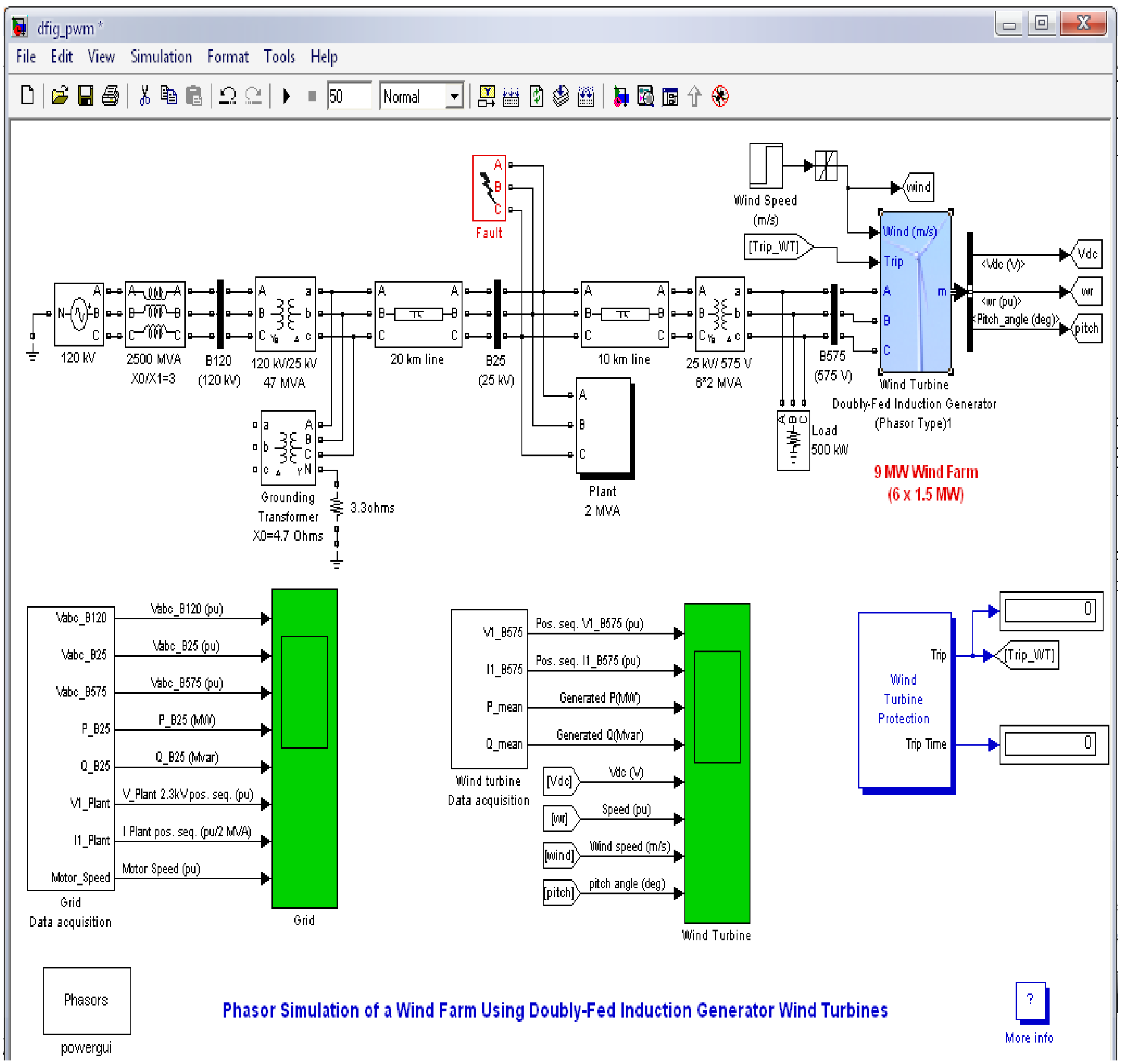
Operational Characteristics of a Doubly-Fed Induction Generator (DFIG) Driven by a Wind Turbine

A 9-MW wind farm consisting of six 1.5 MW wind turbines connected to a 25-kV distribution system exports power to a 120-kV grid through a 30-km, 25-kV feeder. A 2300V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder at bus B25. Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed. The DC link voltage of the DFIG is also monitored.

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. For wind speeds lower than 10 m/s the rotor is running at sub synchronous speed . At high wind speed it is running at hyper synchronous speed. Open the turbine menu, select "Turbine data" and check "Display wind-turbine power characteristics". The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 5 m/s to 16.2 m/s. The DFIG is controlled in order to follow the red curve. Turbine speed optimization is obtained between point B and point C on this curve. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generators.

6.1 SIMULINK DIAGRAM

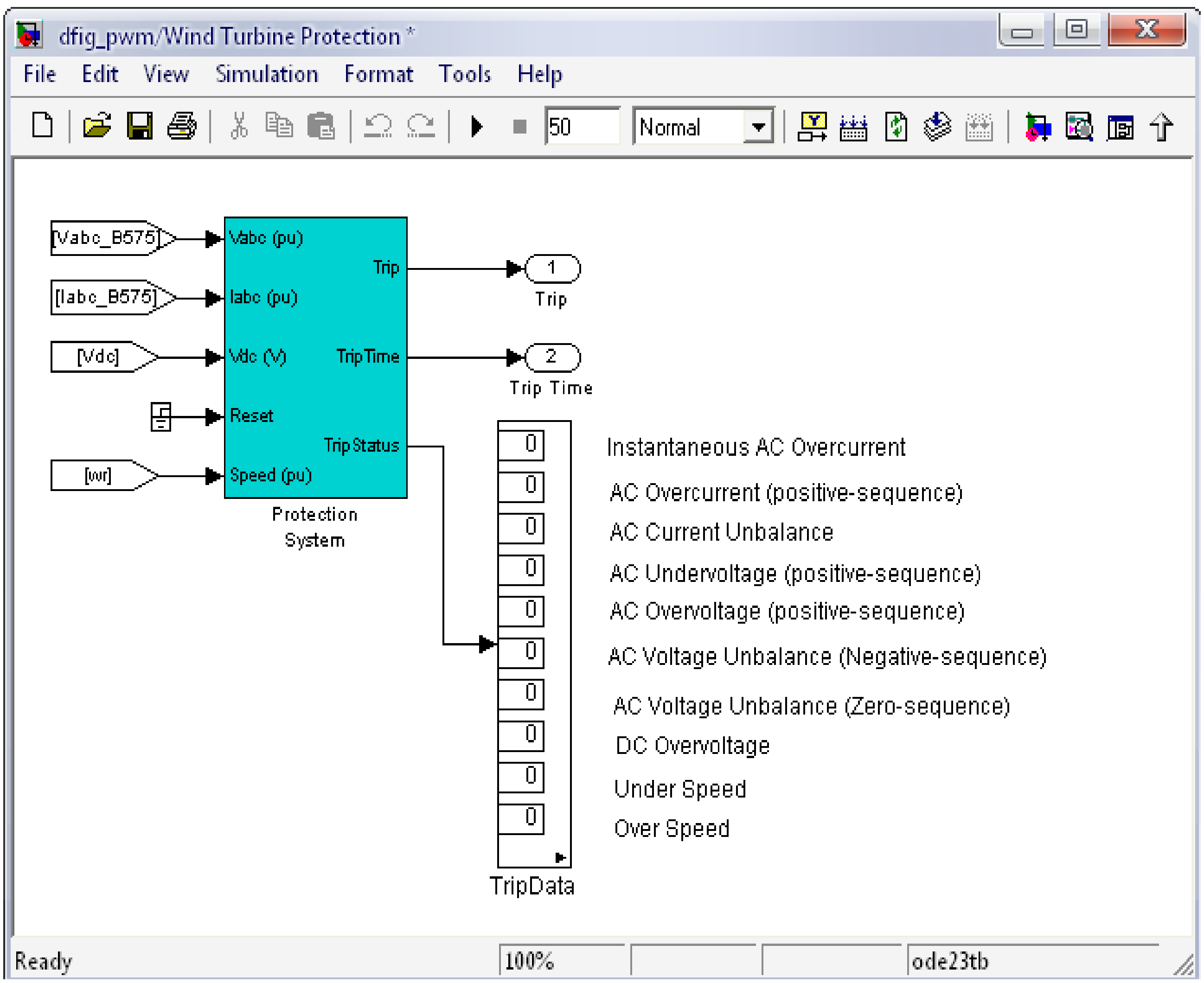
This is the Simulink diagram for a doubly fed induction generator connected to grid side with wind turbine protection schemes involved for protection from single phase faults and ground faults. The system is connected to a 120 KV, 3 phase source which is connected to a 9MW wind farm (6 of 1.5 MW each) via. Step down transformers, fault protection and pi- transmission line.



The wind-turbine model is a phasor model that allows transient stability type studies with long simulation times. In this demo, the system is observed during 50 s.

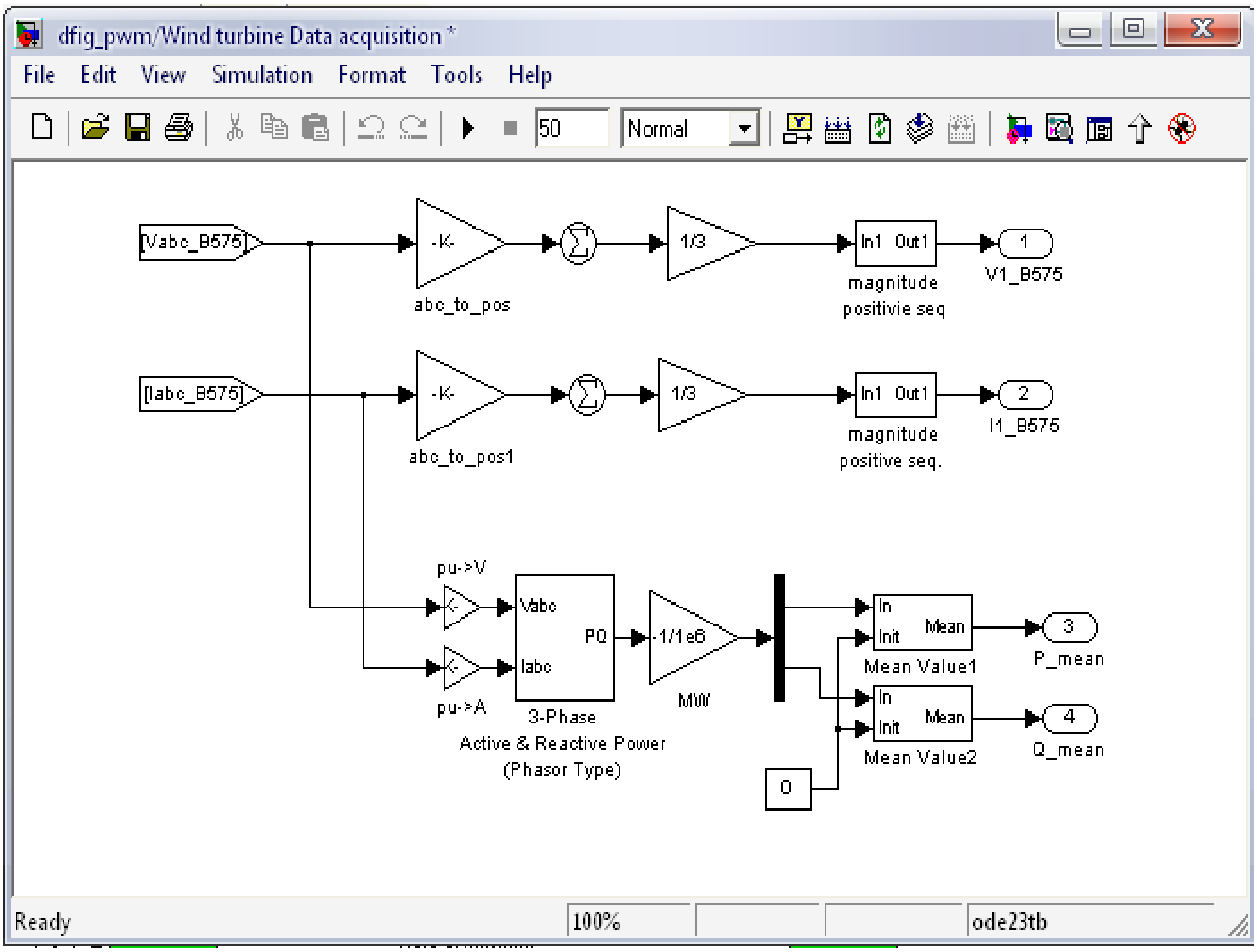
6.2 Wind Turbine Protection Block

This is the block for wind turbine protection in which the positive sequence voltage and current and DC voltage are given as input and for their corresponding values trip data is used to see whether it should be tripped or not. The different reasons for tripping may be AC over voltage, under voltage, over current, undercurrent, DC overvoltage, over speed, under speed.



Depending on the reasons stated above the trip signal is given to trip the circuit with in the trip time.

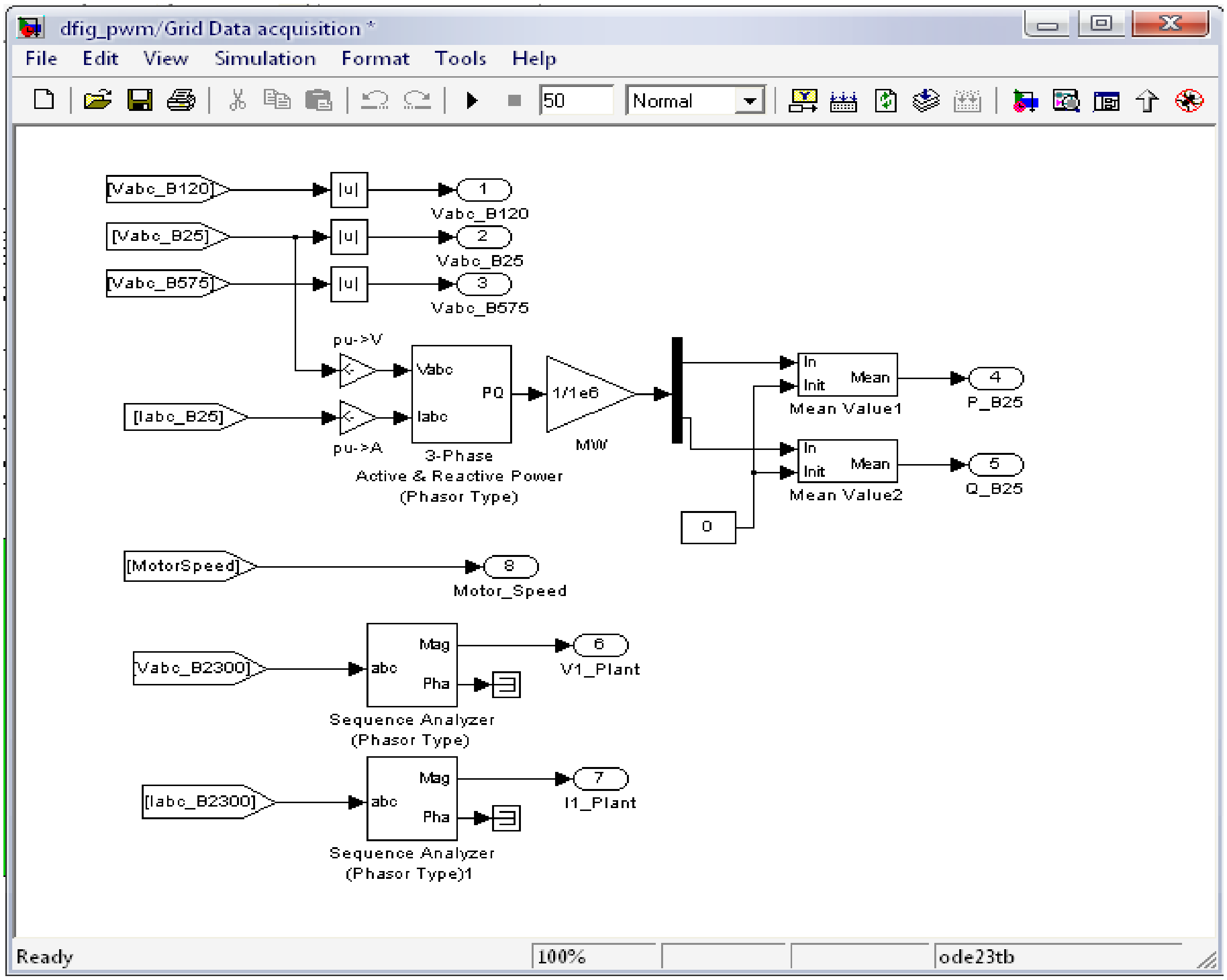
6.3 Wind Turbine Data Acquisition



This is the Block diagram for generator data acquisition. In this the input signal are voltage and current which are passed through gains and finally the outputs provided are positive sequence current, voltage and active and reactive power mean values. Where the value of gain is K= [1 exp(j*2*pi/3) exp(-j*2*pi/3)]. The values of active and reactive power calculated are in Per Unit.

6.4 Grid Data Acquisition

This is the block diagram for Grid data acquisition. The voltage, current, and speed are input to various blocks giving PU active and reactive power outputs along with motor speed.



It utilizes sequence phase analyzer which outputs the positive, negative, zero or all sequence components (magnitude and phase) of a set of three phasors.

The three sequence components are computed as follows.

$V_1 = 1/3\,(V_a + aV_b + a^2 v_b)$

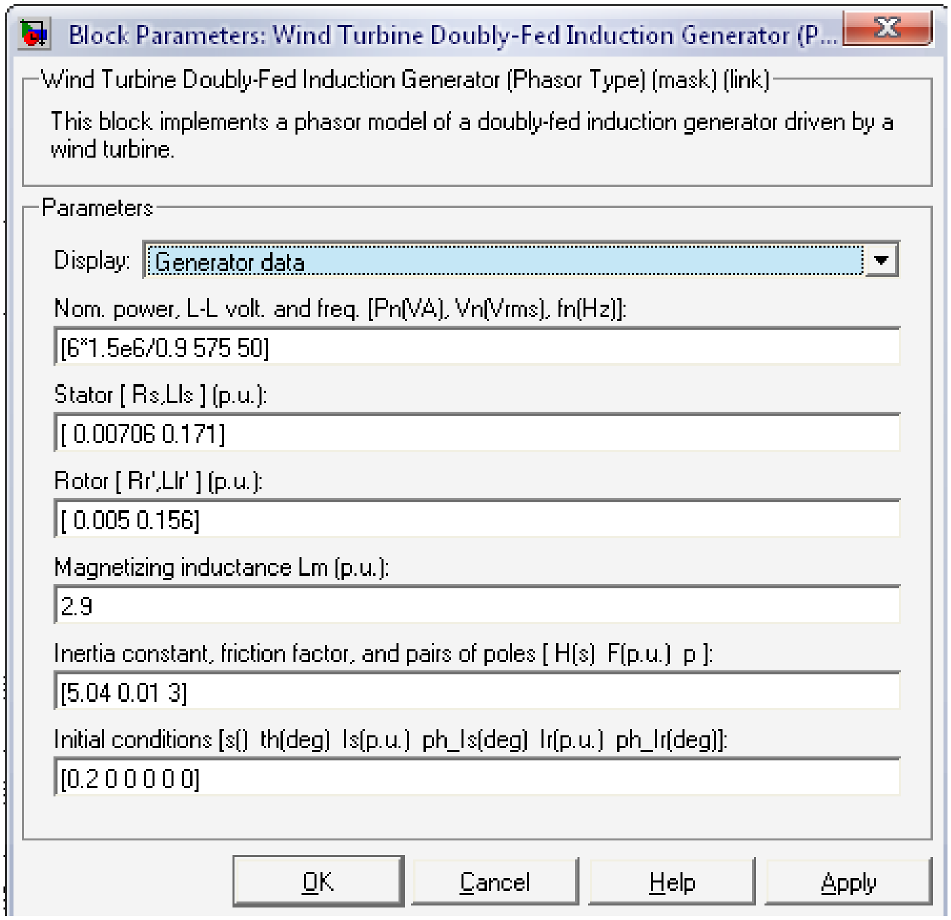
$V_2 = 1/3(V_a + a^2 V_b + aV_c)$

$V_0 = 1/3(V_a + V_b + V_c)$

Va, Vb, Vc are three input phasors and “a” is complex operator with argument less than 120*.

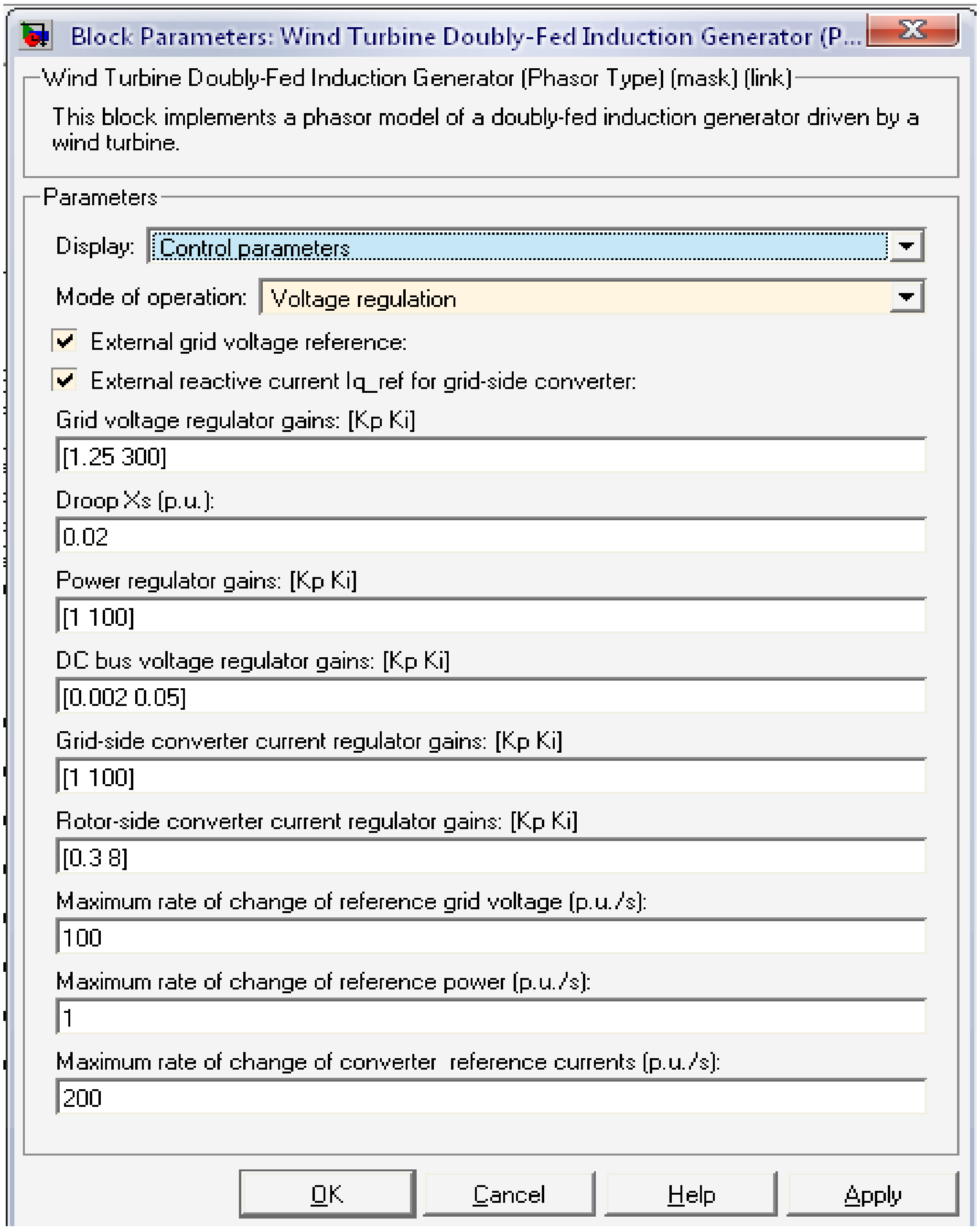
In the wind turbine block menu there are the four sets of parameters specified for the turbine, the generator and the converters (grid-side and rotor-side). The 6-wind-turbine farm is simulated by a single wind-turbine block by multiplying the following three parameters by six, as follows: the nominal wind turbine mechanical output: 6*1.5e6 watts, specified in the Turbine data menu the generator rated power: 6*1.5/0.9 MVA (6*1.5 MW at 0.9 PF), specified in the Generator data menu the nominal DC bus capacitor: 6*10000 microfarads, specified in the Converters data menu Also, notice in the Control parameters menu that the "Mode of operation" is set to " Voltage regulation". The terminal voltage will be controlled to a value imposed by the reference voltage (Vref = 1 PU) and the voltage droop (Xs = 0.02 PU).

6.5 Generator Data



6.6 Control Parameters

This is the block diagram for control parameters showing different modes of operation in which we can select the voltage regulation mode and Var regulation mode. Also we can set the external reactive current Iq_ref for grid side to zero which gives flexibility to simulate various fault conditions. Here we input the required values of voltage regulator gains (both proportional and integral), power regulator gains, current regulator gains and their respective rate of change.



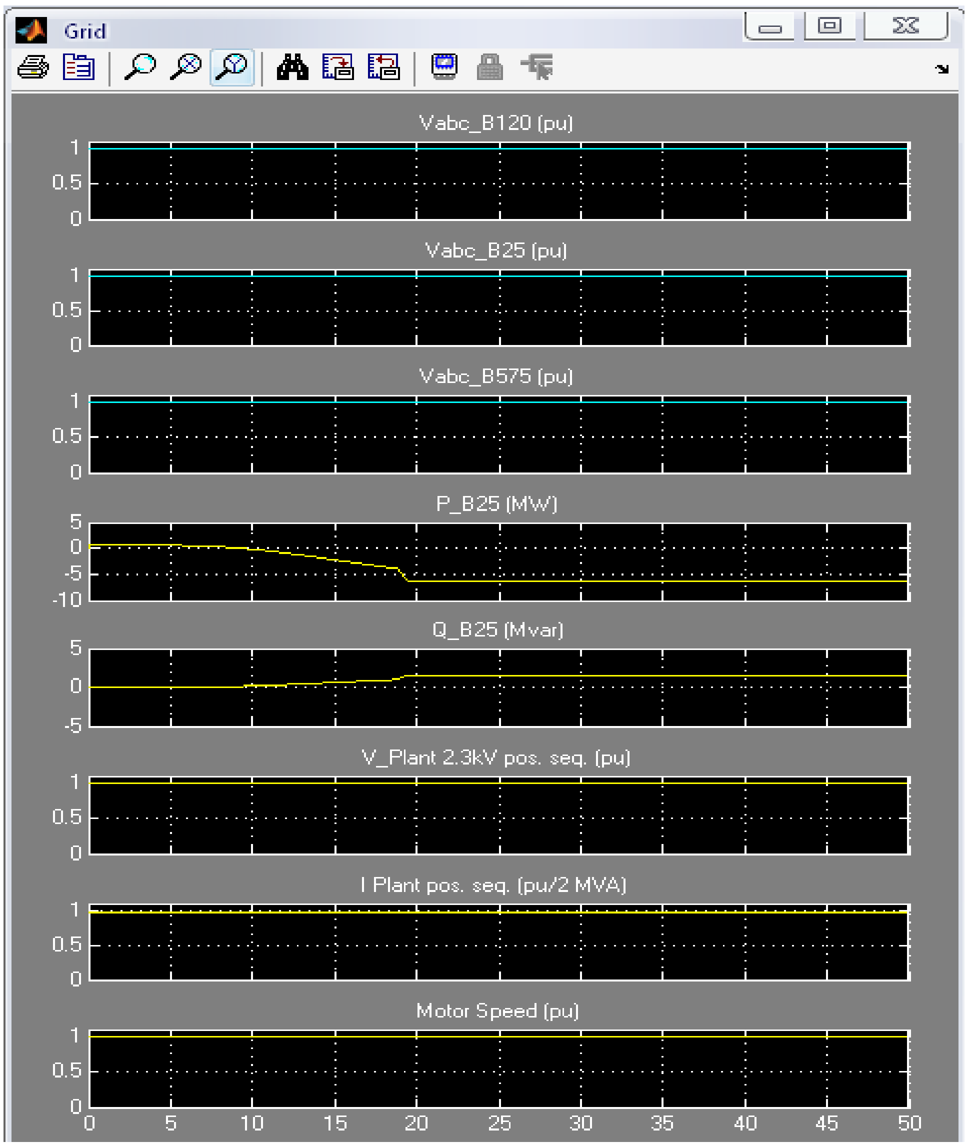
Chapter 7

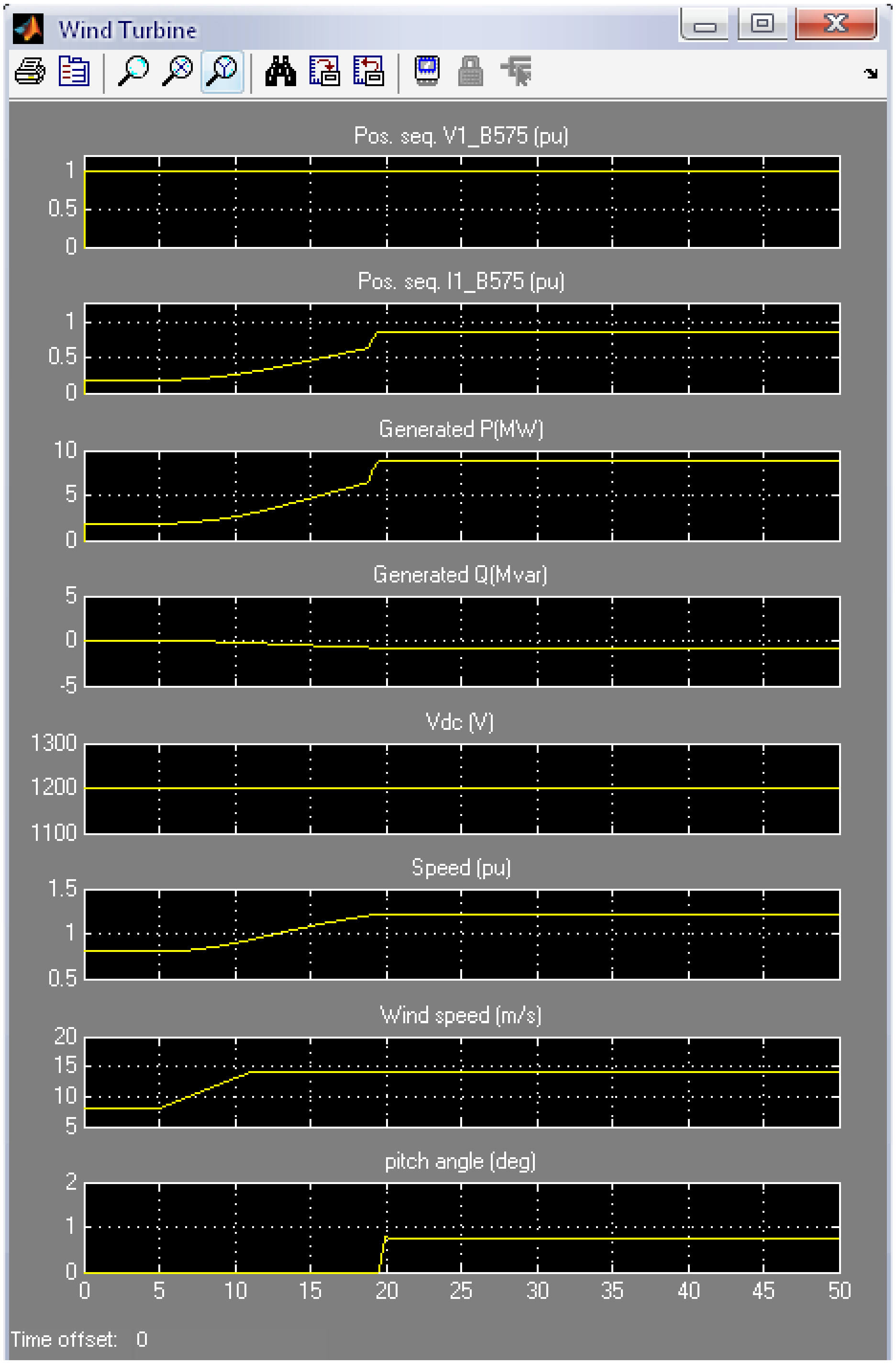
SIMULATION RESULTS

SIMULATION RESULTS

7.1 Turbine response to a change in wind speed

In the "Wind Speed" step block specifying the wind speed. Initially, wind speed is set at 8 m/s, then at t = 5s, wind speed increases suddenly at 14 m/s. Start simulation and observe the signals on the "Wind Turbine" scope monitoring the wind turbine voltage, current, generated active and Reactive powers, DC bus voltage and turbine speed.

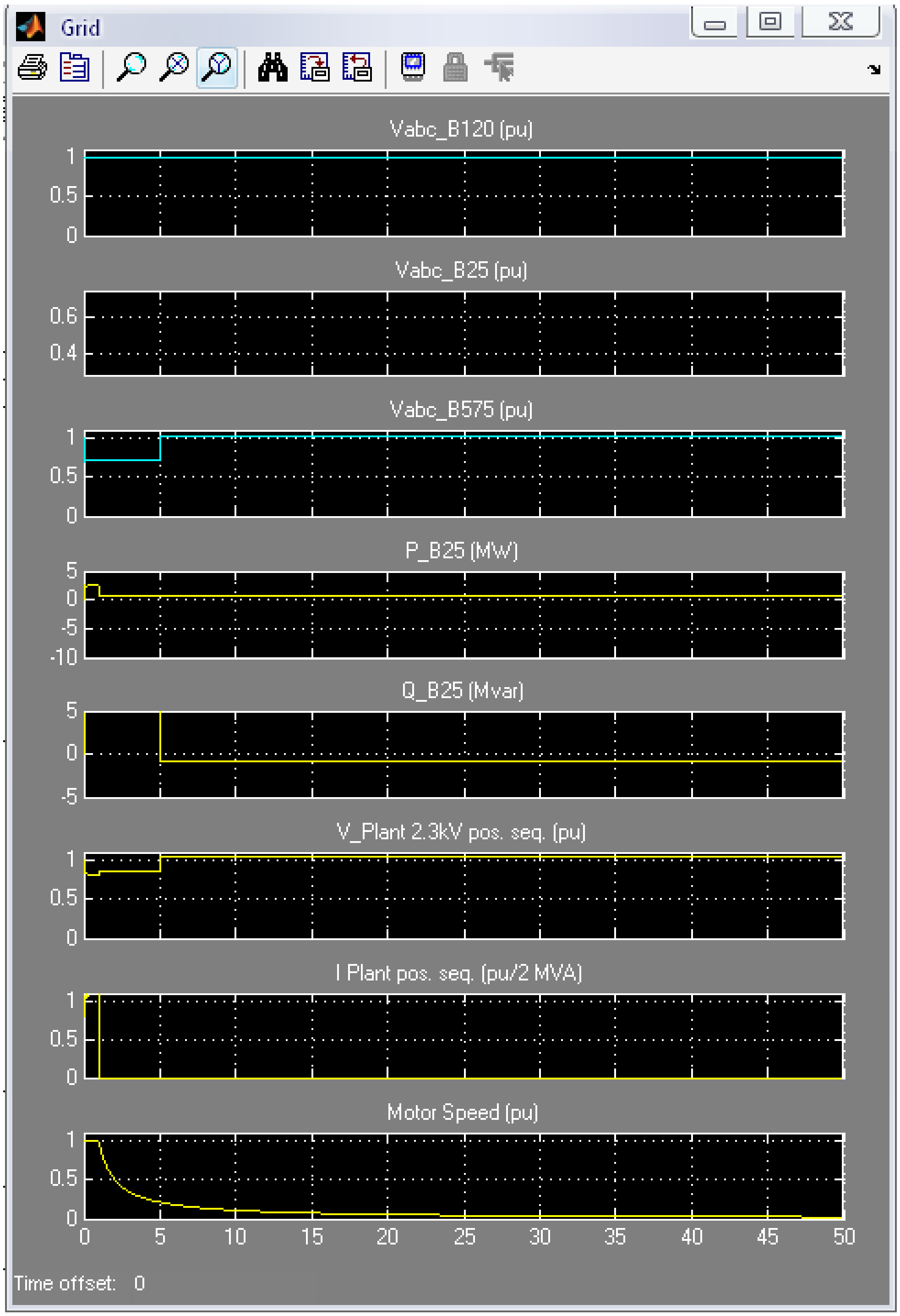


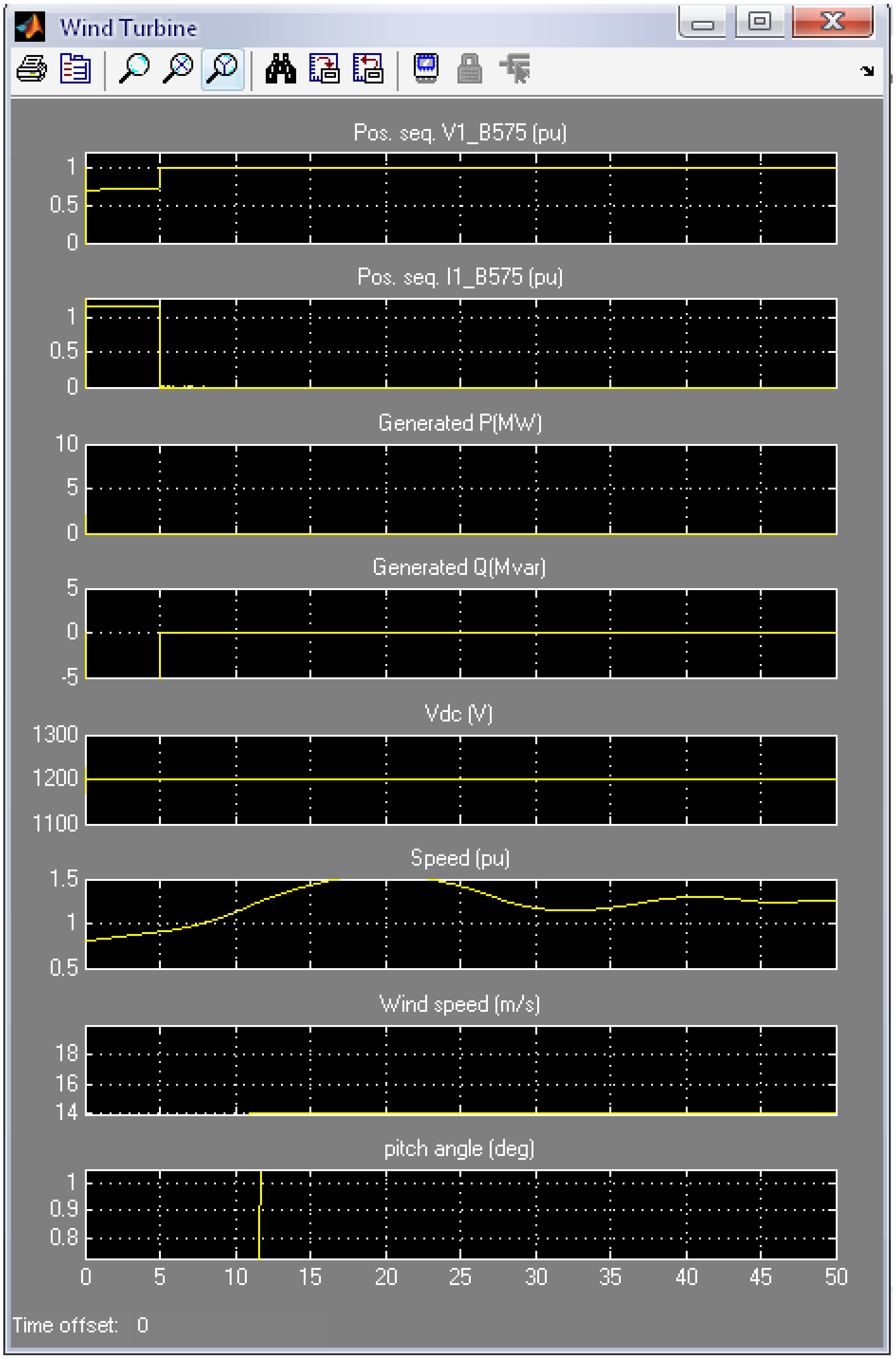


At t = 5 s, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9 MW in approximately 20 s. Over that time frame the turbine speed will have increased from 0.8 PU to 1.21 PU. Initially, the pitch angle of the turbine blades is zero degree and the turbine operating point follows the red curve of the turbine power characteristics up to point D. Then the pitch angle is increased from 0 deg to 0.76 deg in order to limit the mechanical power.

We also observed the voltage and the generated reactive power. The reactive power is controlled to maintain a 1 PU voltage. At nominal power, the wind turbine absorbs 0.68 Mvar (generated Q = -0.68 Mvar) to control voltage at 1PU.

If we change the mode of operation to "Var regulation” with the "Generated reactive power Qref " set to zero, we will observe that voltage increases to 1.021 PU when the wind turbine generates its nominal power at unity power factor.

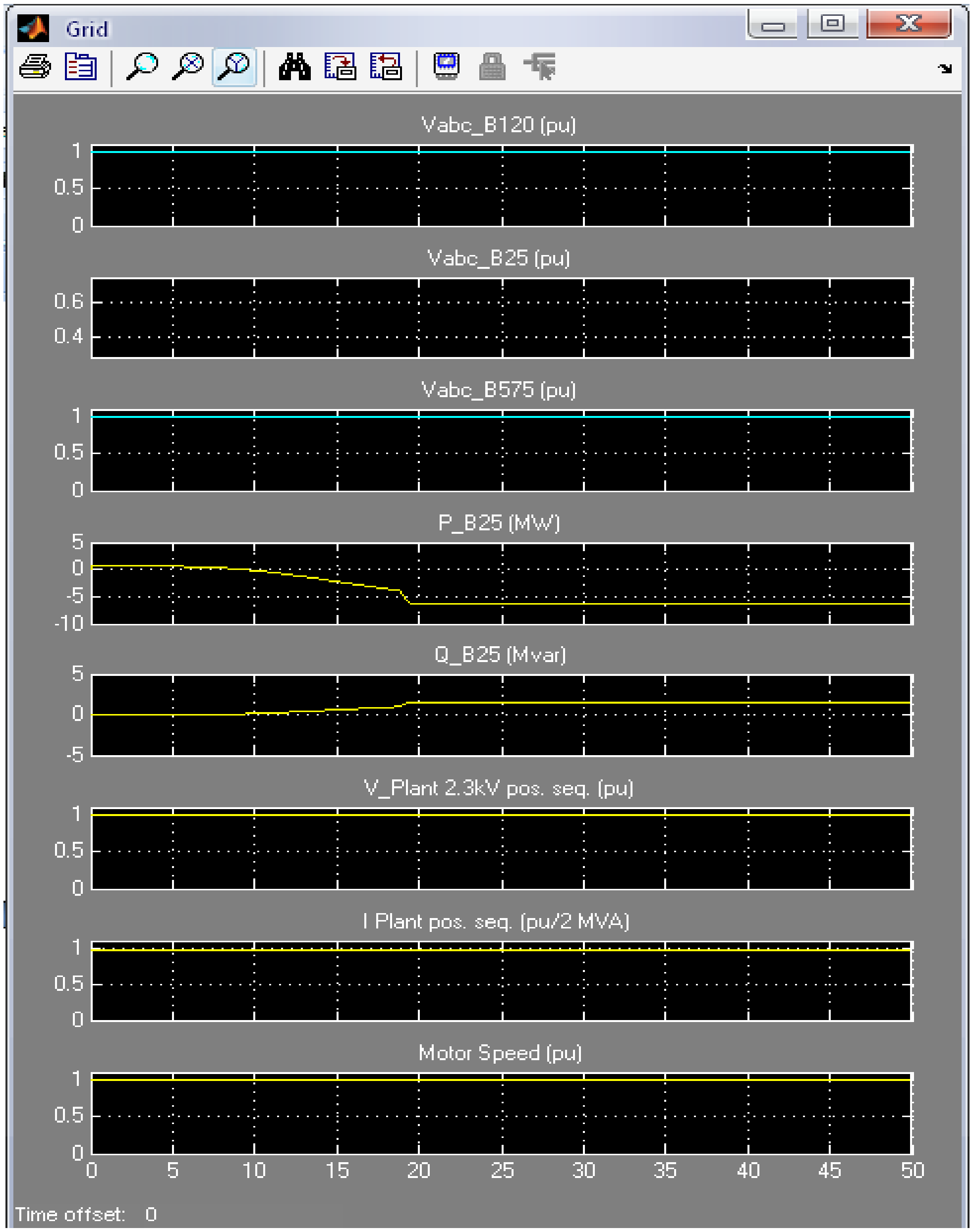




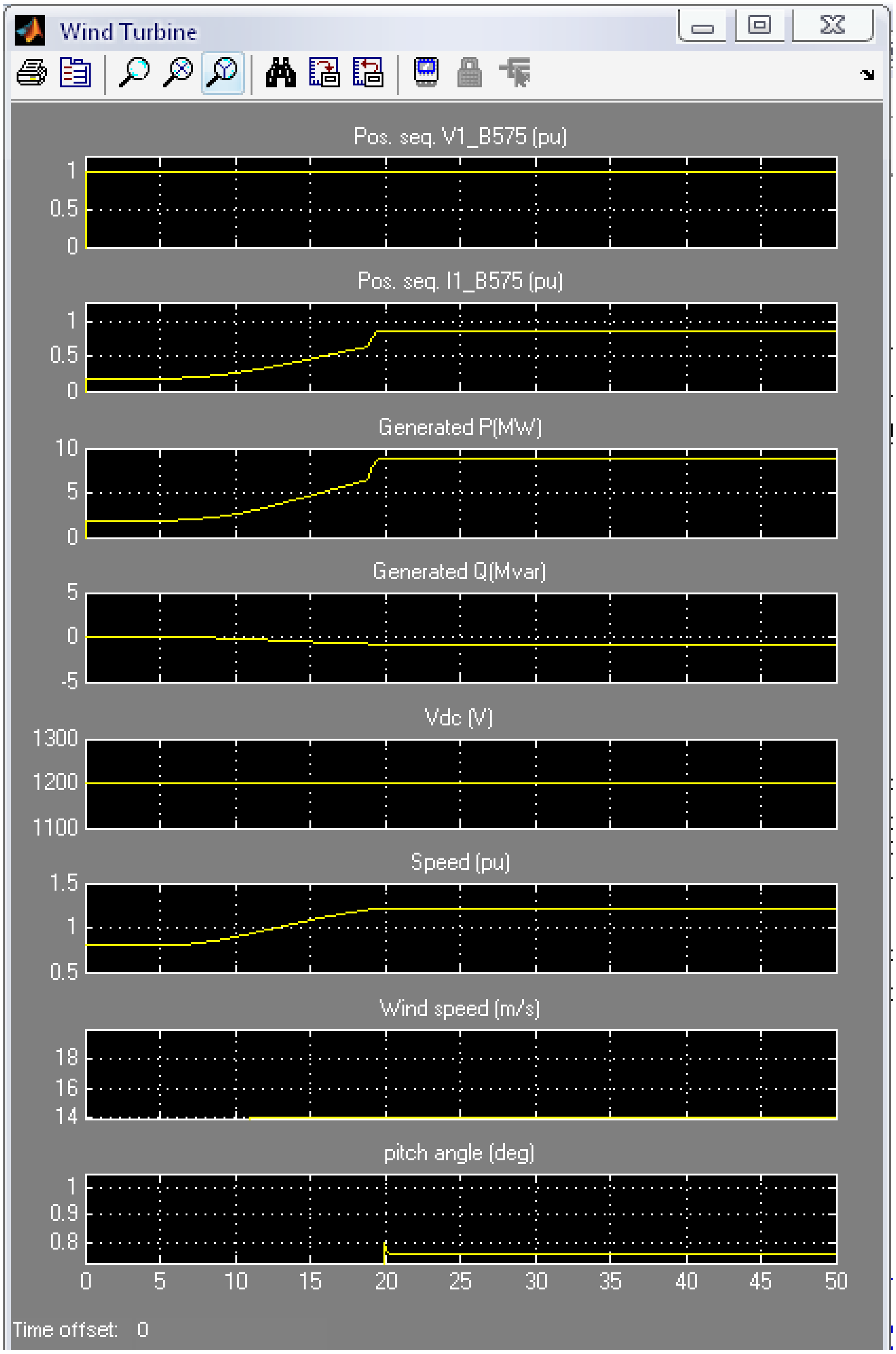
In this mode the wind turbine speed varies very much starting from 0.7 PU to 1.6 PU and then tending to stabilize at 1.0 PU. At about t= 12 s the pitch angle increases abruptly.

7.2 Simulation of wind turbine and grid parameters when the mode of operation is set to Control Parameters

When the mode of operation is set to control parameters then we see that for grid the active power starts decreasing after 5 s and becomes nearly 5 MW while the reactive power becomes positive and starts increasing to nearly 2MW before becoming constant.

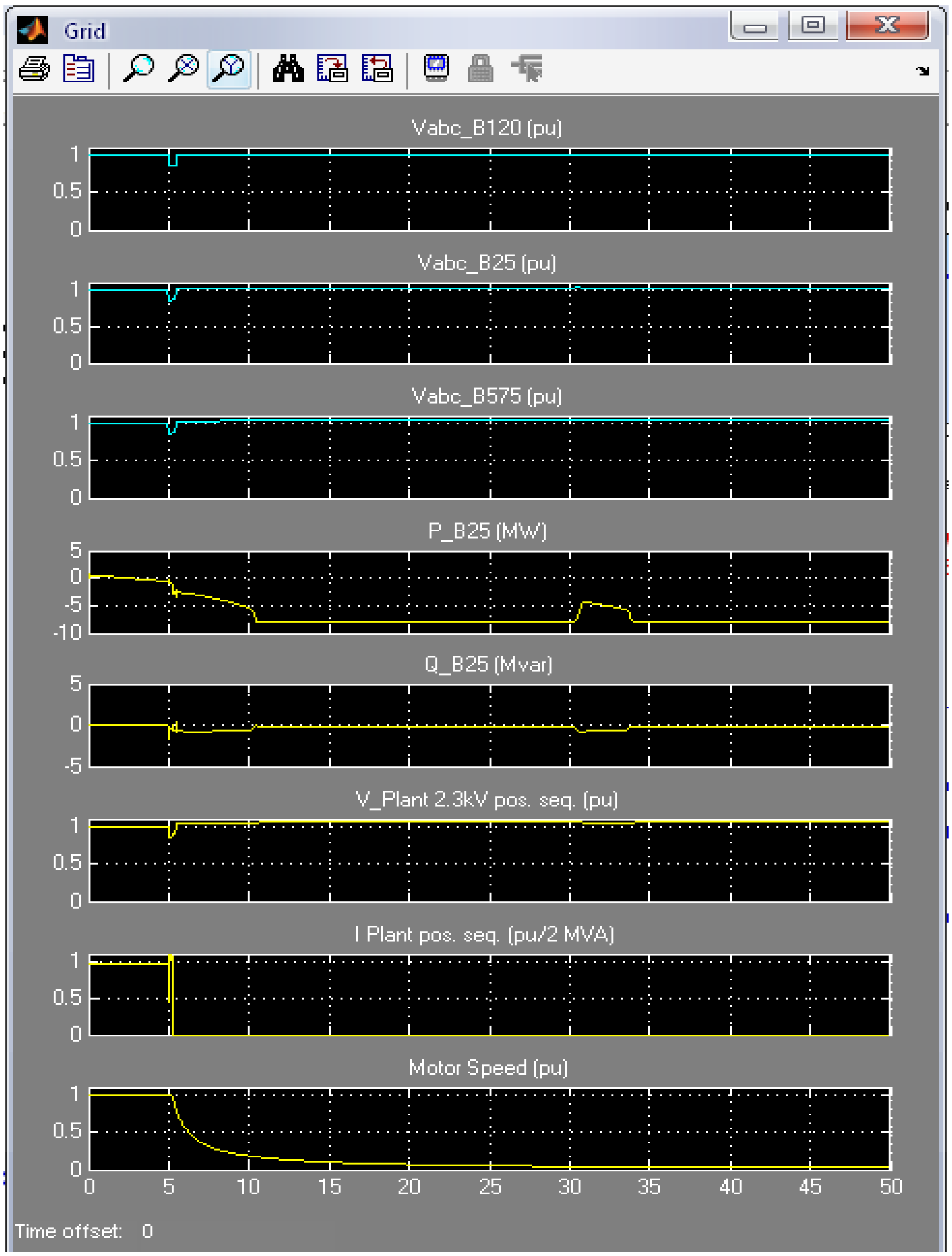


in the grid side simulation the active power generated starts increasing as the voltage increases and reaches to nearly 9 MW as the voltage reaches to 1 Pu. The reactive power requirement is less initially but gradually it increases to few MWs. The wind turbine speed remains constant for 7 s then it increases and again becomes constant at 20 s.


Wind Turbine
Pos. seq. V1_B575 (pu)
Pos. seq. I1_B575 (pu)
Generated P(MW)
Generated Q(Mvar)
Vdc (V)
Speed (pu)
Wind speed (m/s)
pitch angle (deg)
Time offset: 0

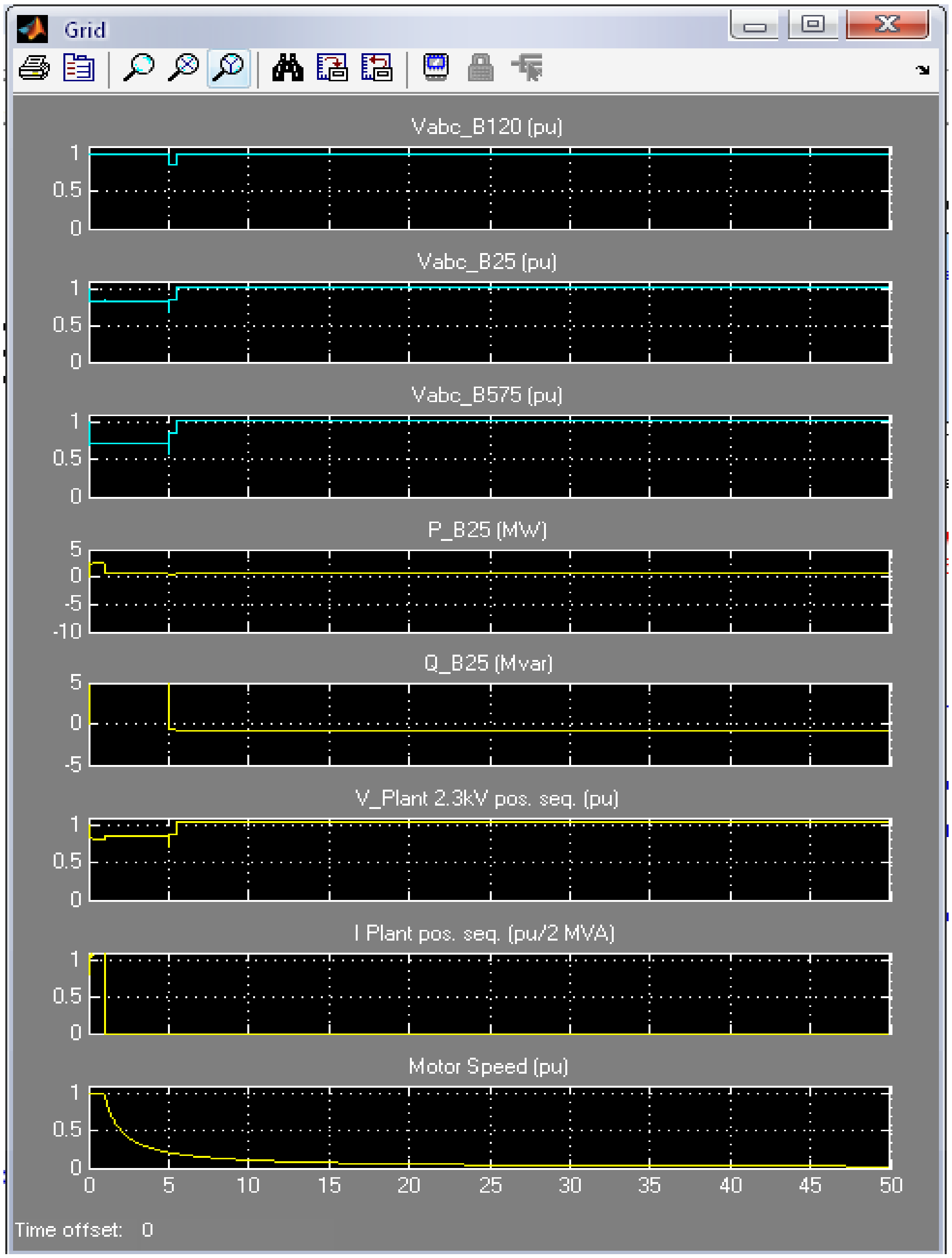
7.3 Simulation of a voltage sag on the 120-kV system

We now observed the impact of voltage sag resulting from a remote fault on the 120-kV system. First, in the wind speed step block, we disabled the wind speed step by changing the Final value from 14 to 8 m/s. Then open the 120-kV voltage source menu. In the parameter "Time variation of", selected "Amplitude" 0.15 PU voltage drop lasting 0.5 s is programmed to occur at t = 5 s.



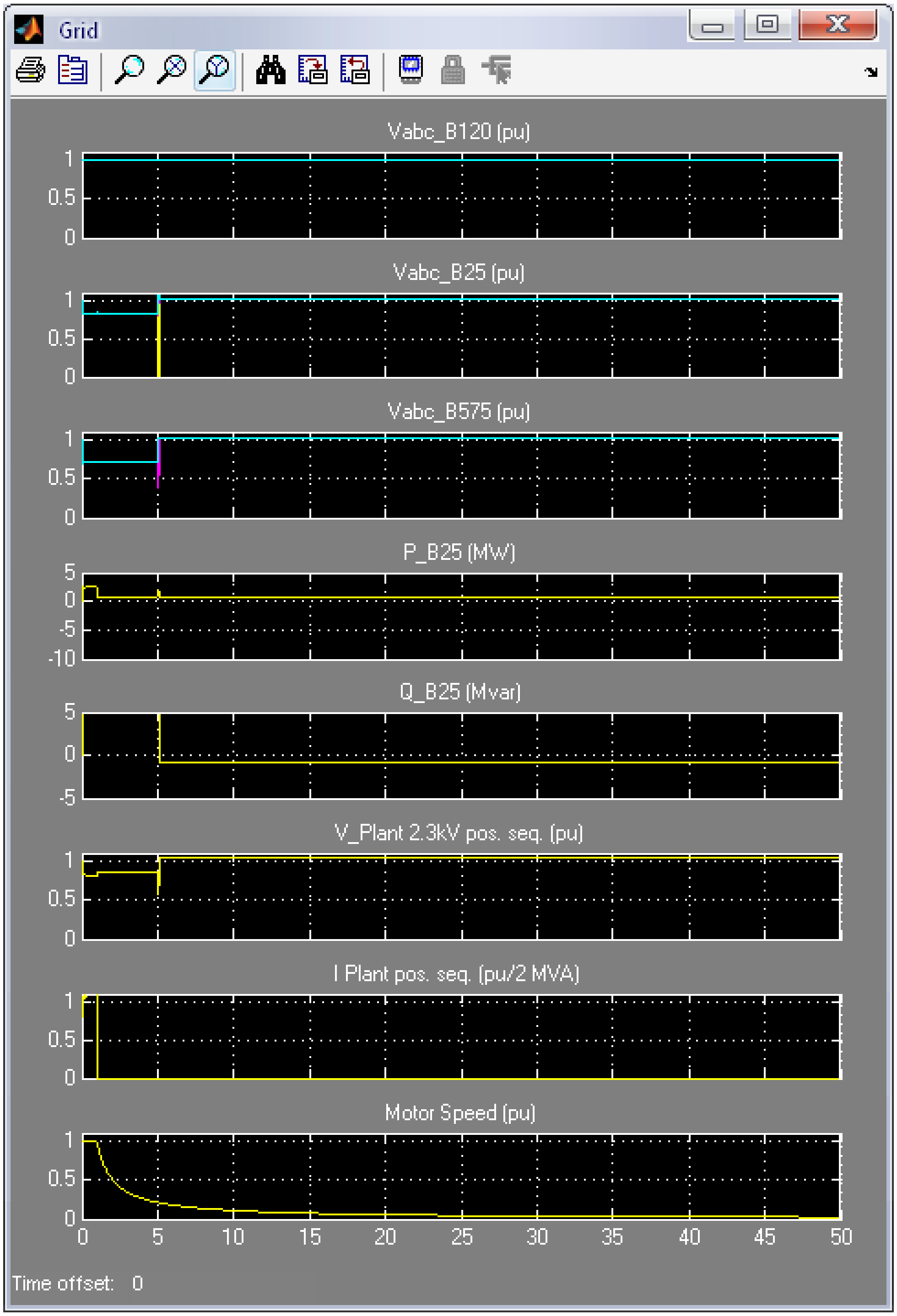
We made sure that the control mode is still in Var regulation with Qref = 0. Then we Started the simulation and opened the "Grid" scope. We observed the plant voltage and current as well as the motor speed. Note that the wind farm produces 1.87 MW. At t = 5 s, the voltage falls below 0.9 pu and at t = 5.22 s, the protection system trips the plant because an under voltage lasting more than 0.2 s has been detected (look at the protection settings and status in the "Plant" subsystem). The plant current falls to zero and motor speed decreases gradually, while the wind farm continues generating at a power level of 1.87 MW. After the plant has tripped, 1.25 MW of power (P_B25 measured at bus B25) is exported to the grid.

Now, we changed the wind turbine control mode to "Voltage regulation" and repeat the test. We will notice that the plant does not trip anymore. This is because the voltage support provided by the 5 Mvar reactive power generated by the wind-turbines during the voltage sag keeps the plant voltage above the 0.9 pu protection threshold. The plant voltage during the voltage sag is now 0.93 pu.



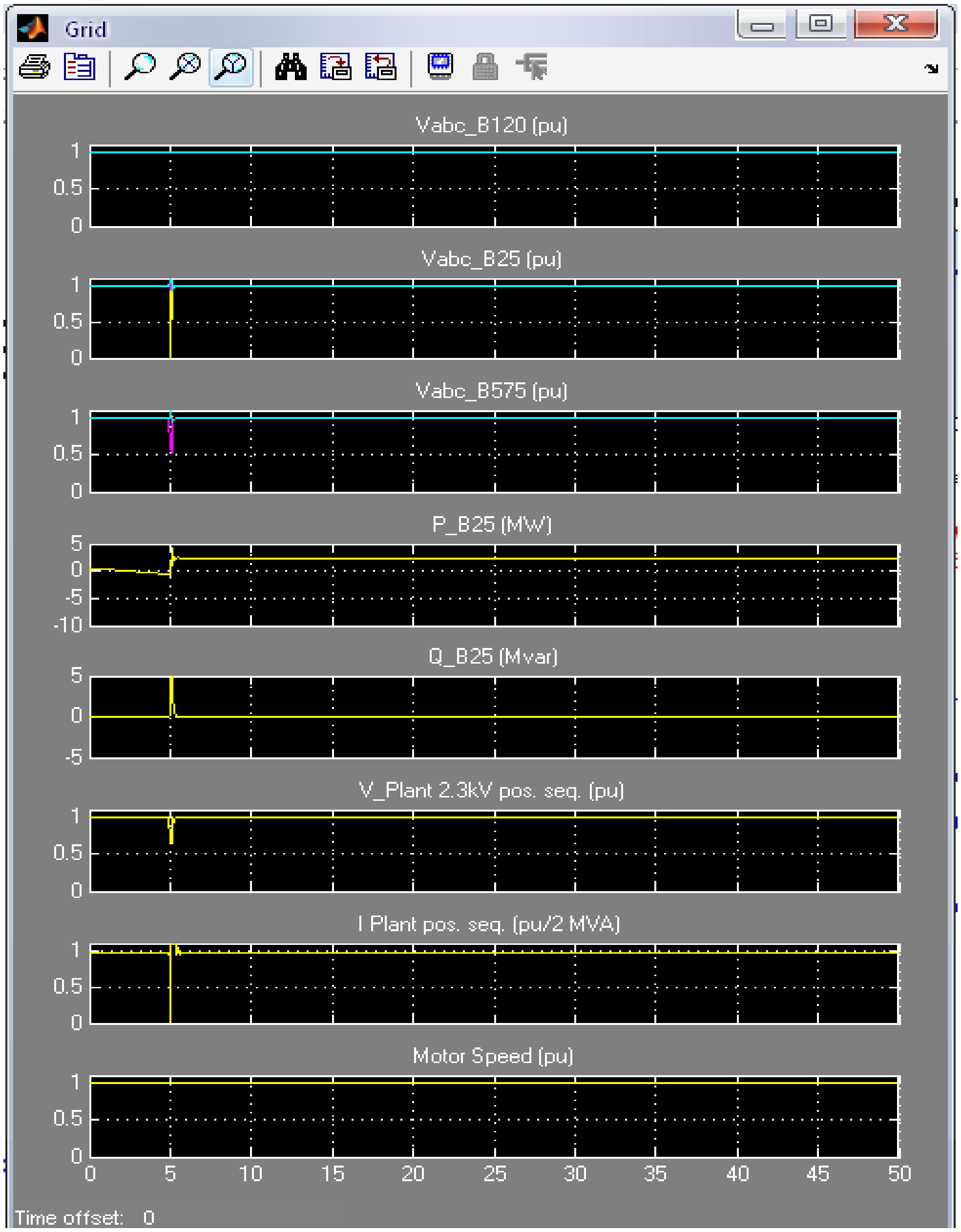
7.4 Simulation of a fault on the 25-kV system

Finally, we will now observe impact of a single phase-to-ground fault occurring on the 25-kV line at B25 bus. First disable the 120-kV voltage step.



Now open the "Fault" block menu and select "Phase A Fault". Check that the fault is programmed to apply a 9-cycle single-phase to ground fault at t = 5 s.

We observed that when the wind turbine is in "Voltage regulation" mode, the positive-sequence voltage at wind-turbine terminals (V1_B575) drops to 0.8 pu during the fault, which is above the under voltage protection threshold (0.75 pu for a t > 0.1 s). The wind farm therefore stays in service.



However, if the "Var regulation" mode is used with Qref = 0, the voltage drops under 0.7 pu and the undervoltage protection trips the wind farm. We can now observe that the turbine speed increases. At t= 40 s the pitch angle starts to increase in order to limit the speed.

Chapter 8

Conclusion

CONCLUSION

We have discussed here the basic operation of DFIG and it's controls using AC/DC/AC converter. First We simulated a wind turbine driven isolated (not connected to grid) induction generator. But for best efficiency the DFIG system is used which is connected to grid side and has better control. The rotor side converter (RSC) usually provides active and reactive power control of the machine while the grid-side converter (GSC) keeps the voltage of the DC-link constant. So finally we simulated grid side and wind turbine side parameters and the corresponding results have been displayed. The model is a discrete-time version of the Wind Turbine Doubly-Fed Induction Generator (Phasor Type) of Matlab/SimPowerSystems. Here we also took the protection system in consideration which gives a trip signal to the system when there is a fault (single phase to ground fault) on the system. The faults can occur when wind speed decreases to a low value or it has persistent fluctuations. The DFIG is able to provide a considerable contribution to grid voltage support during short circuit periods. Considering the results it can be said that doubly fed induction generator proved to be more reliable and stable system when connected to grid side with the proper converter control systems.

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