

Control of Grid Voltage and Power of Doubly Fed Induction Generator wind turbines during grid faults

Mohamed Amer Hassn Abomahdi , Manish Kumar Srivastava

SSET,Sam Higginbottom instiute Of Agri.Tech& sciences_Deemed University.Allahabad india.corresponding

Abstract: *This paper presents the design of a voltage control strategy for DFIG wind turbines, which enhances the fault ride-through capability of DFIG wind turbines and their contribution to support the grid, i.e. to the voltage control in the power system, during grid faults. The performance of the presented DFIG protection and voltage control strategy during grid faults is assessed and discussed by means of simulations of a large DFIG wind farm connected to a power transmission system generic model. The simulation results show how a DFIG wind farm equipped with the presented voltage control can help a nearby active stall wind farm to ride-through a grid fault.*

Index Terms: *Doubly Fed Wind Turbine, Power System Control, Grid Faults, Voltage control, Pitch Angle.*

I. Introduction

The increased penetration of wind energy into the power system over the last years has resulted in the power system operators revising the grid connection requirements in several countries, such as in Denmark and Germany [1,2]. A special focus in these requirements is drawn to both the wind turbine fault ride-through capability and the wind turbine grid support capability. Fault ride-through capability addresses primarily the design of the wind turbine controller in such a way that the wind turbine is able to remain connected to the network during grid faults (e.g. short circuit faults). The wind turbine grid support capability represents the wind turbine capability to assist the power system by supplying ancillary services, i.e. such as voltage control, in order to secure a safe and reliable grid operation.

Nowadays, DFIG wind turbines constitute the mainstream configuration for large wind turbines, and therefore their capability to support the grid during faults is a matter of high priority in the research activity over the world. As the DFIG wind turbine modeling and control regarding normal operation have been plenty discussed and published during the years [3,4,5], this paper is focusing on issues important for the modeling and control of DFIG wind turbine regarding grid faults. In contrast to its very good performance in normal operation, the DFIG wind turbine concept is quite sensitive to grid faults and requires special power converter protection. The objective of this paper is to enable and enhance the DFIG wind turbines capability for uninterrupted operation and to support the grid, i.e. to provide voltage recovery assistance, during grid faults.

This paper addresses the design of the DFIG wind turbine voltage control and protection strategy, which is based on the idea that the both converters of the DFIG (i.e. rotor-side converter and grid-side converter) participate to the grid voltage control in a coordinated manner. By default the grid voltage is controlled by the rotor-side converter (RSC) as long as it is not blocked by the protection system, otherwise the grid-side converter (GSC) is taking over the voltage control.

II. DFIG wind turbine modeling

As a mainstream configuration for large wind turbines [5], DFIG wind turbines are required to remain grid connected during grid faults so that they can contribute to the stability of the power transmission system. This raises problems in terms of generator/converter protection and control. In the case of grid faults, the controllability of the DFIG variable speed wind turbine embraces both the wind turbine control for preventing over speeding of the wind turbine and the control and protection of the power converter during and after grid faults [6]. Figure 1 shows the main components of the DFIG wind turbine system configuration [6], [7]:

- Wind turbine - drive train, aerodynamics and pitch angle control system
- DFIG system - control and protection.

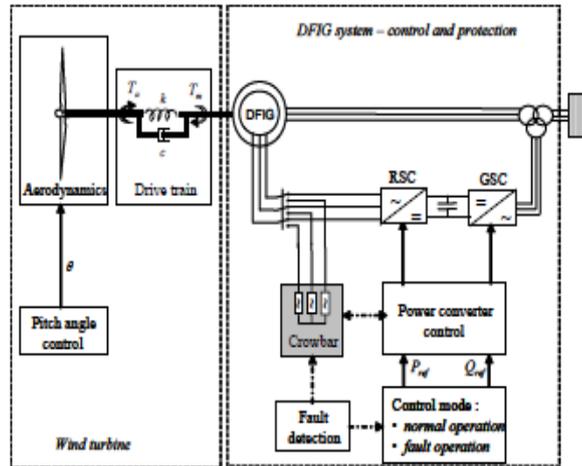


Figure 1: DFIG wind turbine - system configuration and control

III. Drive train, aerodynamics and pitch angle control system

In stability analysis, when the system response to heavy disturbances is analyzed, the drive train system must be approximated by at least a two-mass model [8].

A two-mass mechanical model is used to get a more accurate response from the wind turbine during grid faults and to have a more accurate prediction of the impact on the power system. One mass represents the turbine inertia J_{rot} , while the other mass is equivalent to the generator inertia J_{gen} . These two masses are connected by a flexible low speed shaft characterised by a stiffness k and a damping c , as described in [3]. It is also assumed a stiff high speed shaft and an ideal gear with the exchange ratio $1:n_{gear}$.

The aerodynamic torque T_a from the rotor acts on one end of the drive train while the mechanical torque T_m from the generator side acts on the other end of the drive train. The result of this is the torsion of the shaft. During grid faults, the electrical torque is significantly reduced, and therefore the drive train system acts like a torsion spring that gets untwisted. Due to the torsion spring characteristic of the drive train, the mechanical torque, the aero dynamical torque and thus the generator speed start to oscillate with the so-called free-free frequency:

$$f_{osc} = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{J_{eq}}} \quad (1)$$

where J_{eq} is the equivalent inertia of the drive train model, determined by:

$$J_{eq} = \frac{J_{rot} \cdot n_{gear}^2 \cdot J_{gen}}{J_{rot} + n_{gear}^2 \cdot J_{gen}} \quad (2)$$

As these torsion oscillations may influence the converter operation both during grid faults and a short while after the grid faults have been removed, their modeling by using at least a two-mass model for the drive train system is essential. Furthermore, these torsion oscillations can even be excited and become undamped at a fast converter control [8].

A simplified aerodynamic model is sufficient to illustrate the effect of the speed and pitch angle changes on the aerodynamic power, during grid faults. This simplified aerodynamic model is typically based on a two dimensional aerodynamic torque coefficient C_q table [3], provided by a standard aerodynamic program.

The pitch angle control, in Figure 1, is realized by a PI controller with anti wind up, using a servomechanism model with limitation of both the pitch angle and its rate-of-change [6]. In the present work, the pitch angle control is implemented in such a way that the pitch angle controls the generator speed, i.e. the input in the controller is the error signal between the measured generator speed and the reference generator speed. In the case of over-speeding, the speed is controlled to its rated value, while the aerodynamic power is automatically reduced by increasing the pitch angle. This control is able to prevent over-speeding both in

normal operations and during grid faults. The rate-of-change limitation for the pitch angle is very important during grid faults, because it decides how fast the aerodynamic power can be reduced in order to prevent over-speeding during faults. The dynamic stability of the generator is increased by the pitch angle control.

A. DFIG control in normal operation

The DFIG control structure, illustrated in Figure 2, contains the electrical control of the power converters, which is essential for the DFIG wind turbine behaviour both in normal operation and during fault conditions. Power converters are usually controlled utilizing vector control techniques [9], which allow decoupled control of both active and reactive power. The aim of the RSC is to control independently the active and reactive power on the grid, while the GSC has to keep the dc-link capacitor voltage at a set value regardless of the magnitude and the direction of the rotor power and to guarantee a converter operation with unity power factor (zero reactive power). As illustrated in Figure 2, both RSC and GSC are controlled by a two stage controller. The first stage consists of very fast current controllers regulating the rotor currents to reference values that are specified by a slower power controller (second stage). The control performance of the DFIG is very good in normal grid conditions. DFIG control can, within limits, hold the electrical power constant in spite of fluctuating wind, storing thus temporarily the rapid fluctuations in power as kinetic energy.

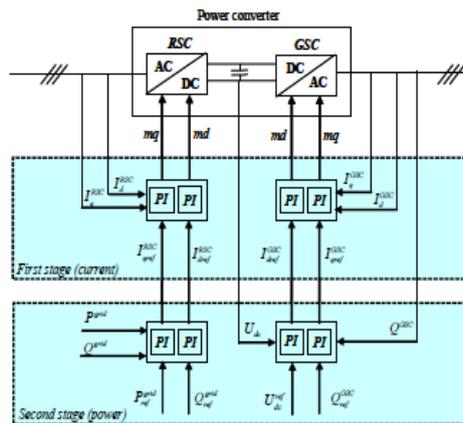


Figure 2: DFIG control structure – normal operation.

B. DFIG control under grid faults

In normal operation the active power set-point for the RSC control is defined by the maximum power tracking point (MPT) look-up table, as function of the optimal generator speed (Figure 3) This means that for each wind speed there is only one generator speed resulting in maximum aerodynamic coefficient C_p . However, in case of grid faults, the generator speed variation is not due to the wind speed change but due to electrical torque reduction. This means that, in the case of grid faults the active power set-point has to be differently defined, i.e. as the output of a damping controller. Such a controller has as task to damp the torsion excitations which are excited in the drive train owing to the grid fault.

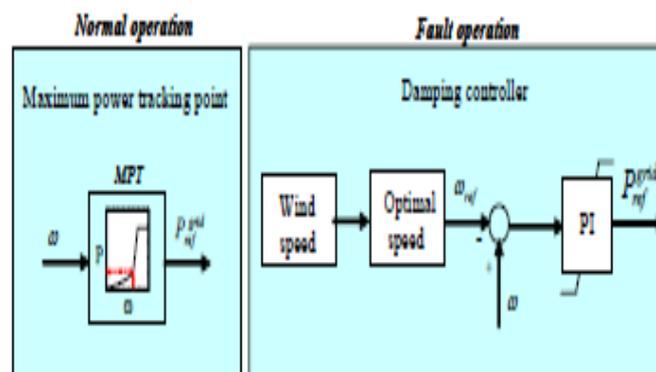


Figure 3: Definition of active power set-point for normal and fault operation, using MPT and damping controller respectively. Different control schemes can be applied to damp these torsion oscillations. In this work, the damping controller suggested by [8] is adopted. As illustrated in Figure 3, the PI damping controller

produces the active power reference signal based on the deviation between the actual generator speed and its reference. The speed reference is defined by the optimal speed curve at the incoming wind. The damping controller is tuned to actively damp the torsion oscillations excited at a grid fault in the drive train system. [11] shows that absence or insufficient tuning of this PI controller may lead to self-excitation of the drive train system and to a risk of grid power tripping as protection against vibrations in the mechanical construction. The pitch control system is not able to damp the torsion oscillations, because of several delay mechanisms in the pitch [12]. The pitch control damps the slow frequency variations in the generator speed.

IV. Single-Line Diagram of the Wind Farm Connected to a Distribution System

The wind farm consists of six 1.5 MW wind turbines connected to a 25 kV distribution system exporting 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. A 500 kW load is also connected on the 575 V bus of the wind farm. The single-line diagram of this system is illustrated in fig

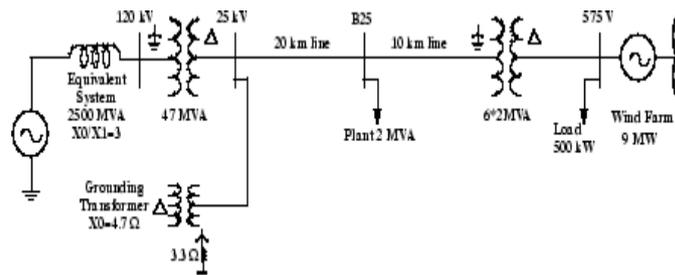


Fig.4 Single line diagram of the wind form

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 60 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 generators.

C. Diagram of the Wind Farm Connected to the Distribution System

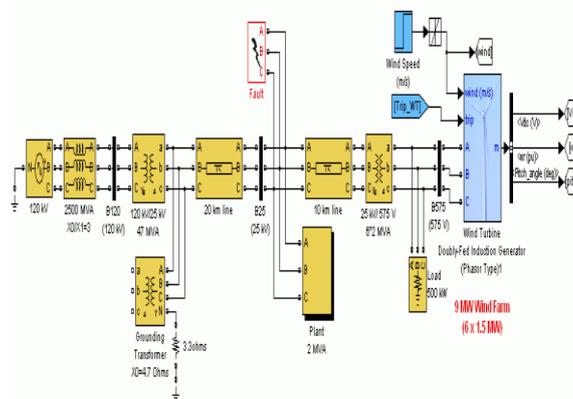


Fig.5 MATLAB model of the wind form connected to distribution system

Initially, wind speed is set at 8 m/s, and then at $t=5s$, wind speed increases suddenly at 14 m/s. This wave form illustrates the waveforms associated with this simulation. At $t=5 s$, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9MW in approximately 15s. Over that time frame the turbine speed increases 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 to limit the mechanical power. Observe also 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 you change the mode of operation to

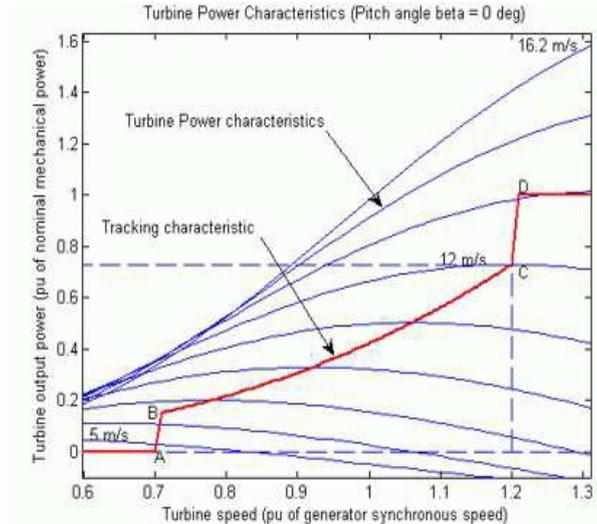


Fig. 6 Turbine speed power characteristics

The DFIG is controlled to follow the ABCD curve in Turbine Power Characteristics. Turbine speed optimization is obtained between point B and point C on this curve. The wind turbine model is a phasor model that allows transient stability type studies with long simulation times. In this case study, the system is observed during 50 s. 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 power: $6 \times 1.5 \times 10^6$ watts, specified in the Turbine data menu The generator rated power: $6 \times 1.5 / 0.9$ 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 The mode of operation is set to Voltage regulation in the Control Parameters dialog box. The terminal voltage will be controlled to a value imposed by the reference voltage ($V_{ref}=1$ pu) and the voltage droop ($X_s=0.02$ pu).

Var regulation with the Generated reactive power Q_{ref} set to zero, you will observe that the voltage increases to 1.021 pu when the wind turbine generates its nominal power at unity power factor.

D. Waveforms for a Gust of Wind (Wind Farm in Voltage Regulation Mode)

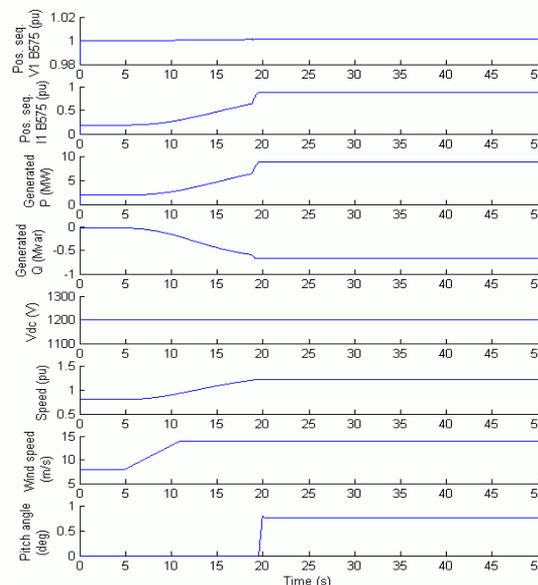


Fig. 7 Waveform of Wing Form in voltage regulation mode

E. Generator Data

Parameters

Generator data

Nom. Power : $6 \times 1.5 \times 10^6 / 0.9$ VA

Line –Line Voltage: 575 V_{RMS}

Frequency : 50 hz

Stator Resistance : 0.00706 P.U.

Stator Inductance: 0.171 P.U.

Rotor Resistance : 0.005 PU

Rotor Inductance : .156 PU

Magnetizing Inductance : 2.9 PU

Inertia constant : 5.04

Friction factor : 0.01

Pair of poles : 03

F. 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 I_{q_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.

Grid voltage regulator gains (K_p, K_i)= (1.25, 300)

Droop X_s(pu)= 0.02

Power regulator gains(K_p, K_i)= (1, 100)

DC bus voltage regulator gains(K_p, K_i)= (0.002, 0.05)

Grid side convertor current regulator gains(K_p, K_i)= (1, 100)

Rotor side convertor current regulator gains (K_p, K_i) = (0.3, 8)

Max rate of change of reference grid voltage= 100 pu/s

Max rate of change of reference power = 1 pu/s

Max rate change of convertor reference current = 200 pu/s

V. Simulation Results

G. 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.

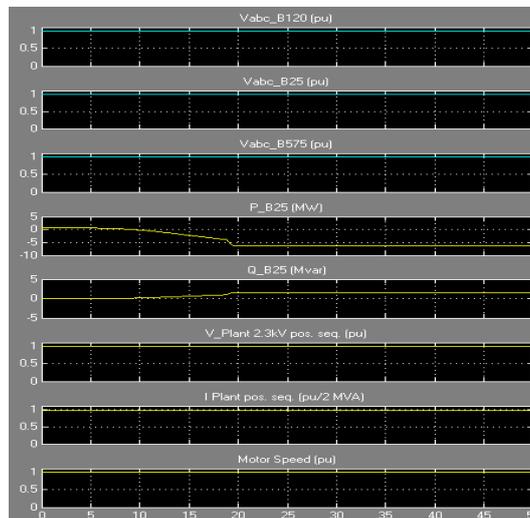


Fig.8 Response of the Wind turbine(without pitch angle control)

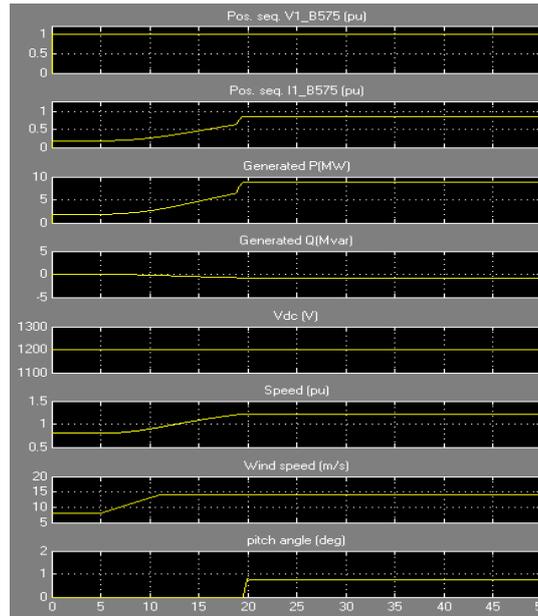


Fig 9. Response of the Wind turbine (with pitch angle control)

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 Q_{ref} " 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.

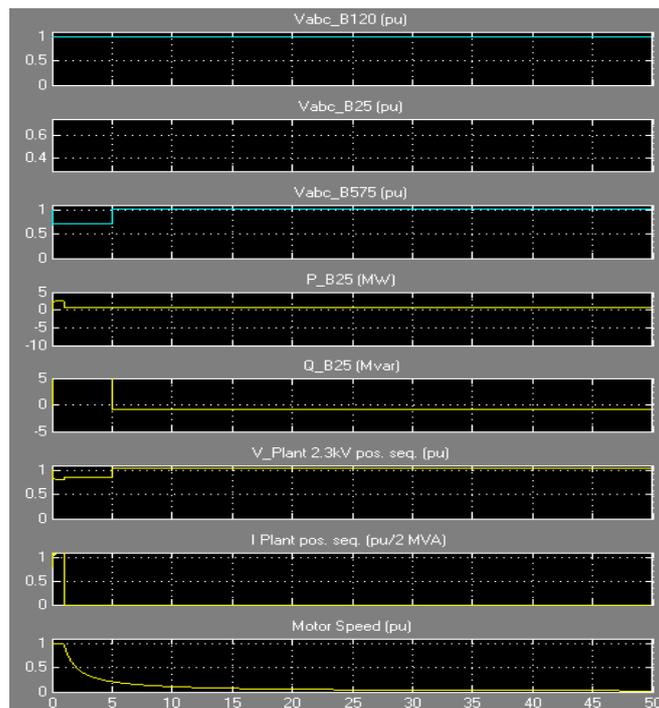


Fig.10 Response of the voltage, Power with change of speed

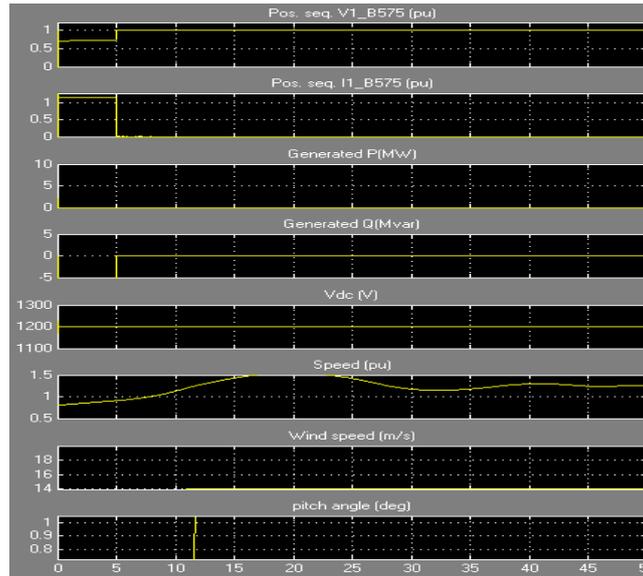


Fig. 11 Response of the voltage, Power with change of speed and pitch angle

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.

H. 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.

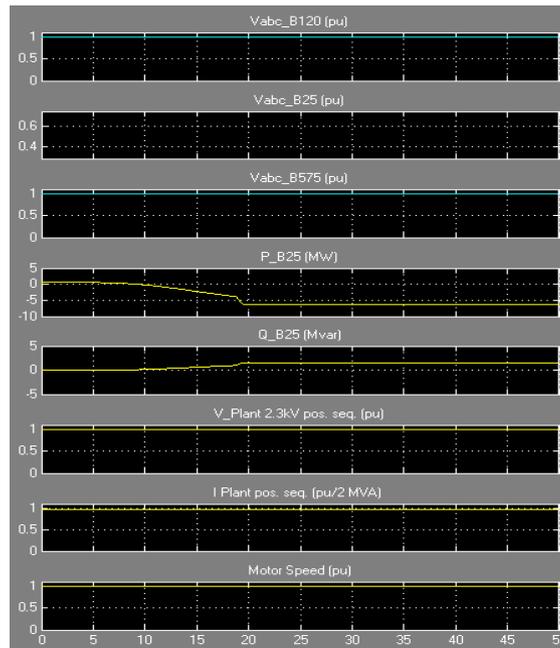


Fig.12 Response of the change of active and rective power(motor speed constant)

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.

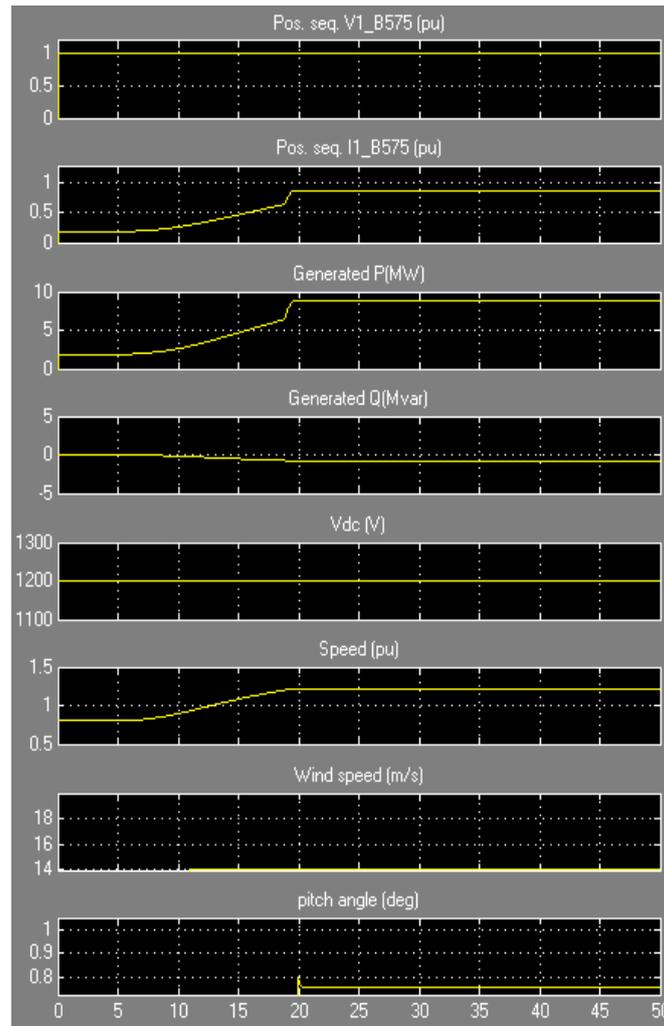


Fig.13 Response increase of active and reactive power with speed and pitch angle.

VI. Conclusion

We have discussed here the basic operation of DFIG and its 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.

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 and proper pitch angle adjustment.

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