Simulation of Doubly-Fed Induction Generator in a Wind Turbine

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Abstract

In order to meet power needs, taking into account economical and environmental factors, wind energy conversion is gradually gaining interests as a suitable source of renewable energy. In a country like mine where there is not a single kW installed wind energy, the question is, How to simulate and explore the transients of these variable speed devices? This paper deals with simulation of a Wind Turbine based on a doubly-fed induction machine used in generating mode to produce electrical energy on a power network. A mathematical model of the machine is written in appropriate d-q reference frame is established to investigate simulations.

1. Introduction

Large Wind turbines are often equipped with doubly-fed induction generators. There are several advantages by using adjustable speed generators. Modern wind turbines use complex technologies including power electronic converters and sophisticated control systems. Electromagnetic transients need to be simulated and analyzed in order to study the impact of these generators on the power systems. Methods and tools for simulation of wind turbines in large power systems are therefore needed.

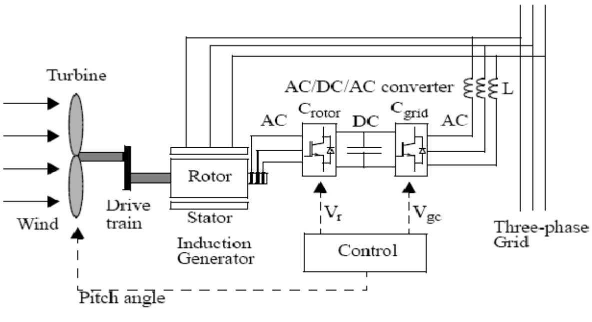

Fig.1. Wind Turbine with Doubly-Fed Induction Generator.

In this paper a average model from Matlab&Simulink v.7.6.0. SymPower systems library is used. The model represents the shaft system, a wound induction machine model, rotor side and grid side converters and a grid model.

1.1 Modeling of the wind turbine doubly-fed induction generator

The wind turbine and the doubly-fed induction generator are shown in Fig. 1. The AC/DC/AC converter is divided into two components: the rotor-side converter C_{rotor} and the grid-side converter C_{grid}. C_{rotor} and C_{grid} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid.

The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine, the DC bus voltage and the voltage at the grid terminals.

An average model of the AC/DC/AC converter is used for real-time simulation. In the average model power electronic devices are replaced by controlled voltage sources. V_r and V_{gc} are the control signals for these sources. The DC bus is simulated by a controlled current source feeding the DC capacitor. The current source is computed on the basis of instantaneous power conservation principle: the power that flows inside the two AC-sides of the converter is equal to the power absorbed by the DC capacitor.

The power flow illustrated in Fig. 2, is used to describe the operating principle.

The mechanical power and the stator electrical power output are:

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

For a lossless generator the mechanical equation is:

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

In steady-state for a lossless generator we have:

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

from where it follows:

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

where $s = \frac{(\omega_s - \omega_r)}{\omega_s}$ is defined as the slip of the generator.

Generally the absolute value of slip is much lower than 1 and consequently P_r is only a fraction of P_s. Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (super-synchronous speed) and it is negative for positive slip (sub-synchronous speed). For super-synchronous speed operation P_r is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}.

The phase-sequence of the AC voltage generated by C_{rotor} is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C_{rotor} and C_{grid} 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.

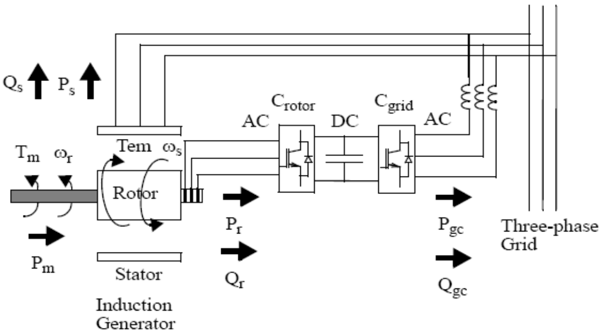

Fig.2. Active and reactive power flows

1.1 Mathematical model of the DFIG

For a doubly-fed induction machine, the Park transformation's application to the traditional a,b,c model allows to write a dynamic model in a d-q reference frame as follows:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \theta_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \theta_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \theta_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \theta_r \psi_{dr} \end{cases}$$

The stator and rotor fluxes can be expressed:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + L_m I_{dr} \\ \psi_{qs} = L_s I_{qs} + L_m I_{qr} \\ \psi_{dr} = L_r I_{dr} + L_m I_{ds} \\ \psi_{qr} = L_r I_{qr} + L_m I_{qs} \end{cases}$$

The mechanical and electromagnetic torque are expressed with the following equations:

$$T_m = T_e + j\frac{d\omega}{dt} + f\omega$$

$$T_e = -P\frac{L_m}{L_s}(\psi_{qs} I_{dr} - \psi_{ds} I_{qr})$$

The active and reactive powers at the stator are defined as:

$$P_s = v_{ds} I_{ds} + v_{qs} I_{qs}$$
$$Q_s = v_{qs} I_{ds} - v_{ds} I_{qs}$$

Also the active and reactive powers at the rotor :

$$\boldsymbol{P_r = v_{dr} I_{dr} + v_{qr} I_{qr}}$$
$$Q_r = v_{qr} I_{dr} - v_{dr} I_{qr}$$

1.2. C_{rotor} control system

The rotor side converter is used to control the wind turbine output power and voltage or the output power and reactive power measured at the grid terminals.

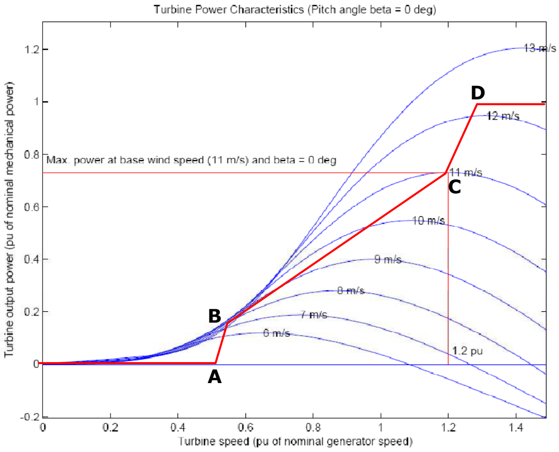

Fig.3. Turbine characteristic and tracking characteristic

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 in Fig. 3 imposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ω_r 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 (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.). The generic power control loop is illustrated in Fig. 5. 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 C_{rotor}. This is the current component that produces the electromagnetic torque T_{em}. 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 C_{rotor}. 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 C_{rotor}. The reactive power is exchanged between C_{rotor} 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 C_{rotor}. The generic control loop is illustrated in Fig. 5.

1.3 C_{grid} 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:

1.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. The output of the DC voltage regulator is the reference current *Idgc_ref* for the current regulator (*Idgc* = current in phase with grid voltage which controls active power flow).

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 C_{grid} *(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 C_{grid} output voltage.

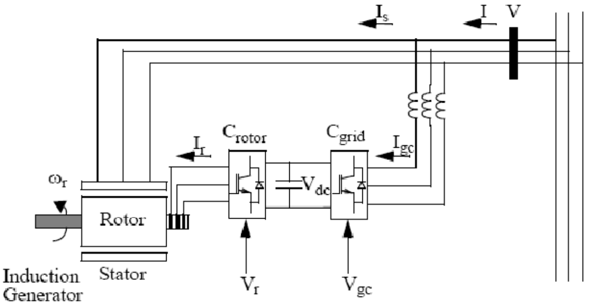

Fig.4. rotor-side and grid-side converters

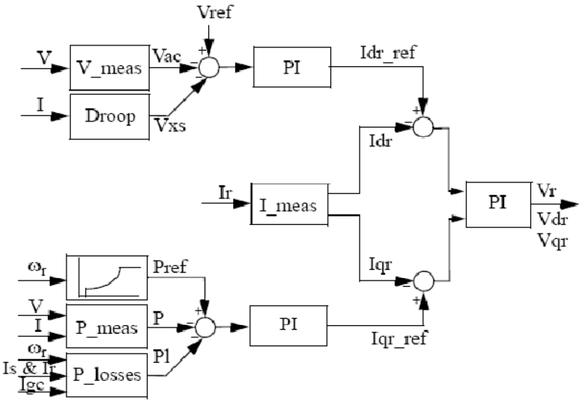

Fig.5. rotor-side controller

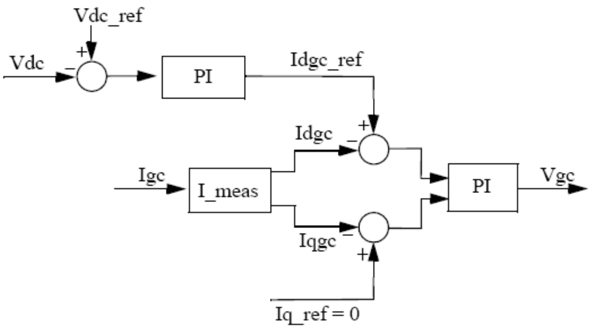

Fig.6. grid-side controller

1.4 Torsional resonance

The rotating shaft system in a wind turbine is devided into sections. The turbine itself is quite heavy and the machine rotor is light. The shaft connecting the generator and the turbine cannot be assumed to be of infinnite stiffness. The gearbox reducess the stiffness. Therefore the shaft will twist as it transits torque from one end to other. A simple method for modeling the shaft system in matlab is shown in Fig.7.

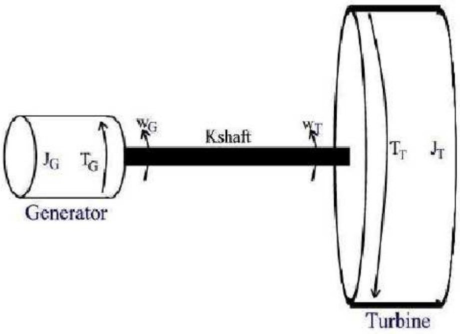

Fig.7. Generator and turbine torque interaction.

Because the mass of the shaft itself is very small, seen from the geneerator, it is reduced to zero.

The inertia at the turbine gives a negative contribution to the torque when the generator is in generatong mode.

The torque T_{shaft} available to be transmitted by the shaft is:

$$T_{shaft} = T_T + J_T \frac{d\omega_T}{dt};$$

The torque at the generator end seen from the shaft is:

$$T_{shaft} = T_G - J_G \frac{d\omega_G}{dt};$$

The twisting of the shaft depends from the shaft torsional or the compliance coefficient K_{shaft} :

$$(\theta_G - \theta_T) = \frac{T_{shaft}}{K_{shaft}};\ \theta - pitch\ angle;$$

The inertia constant H, is defined as:

$$H = \frac{\frac{1}{2} J \omega_0^2}{S_N};$$

$$\omega_0 - rated\ speed; J - moment\ of\ inertia;$$

1.5 Pitch angle control system

The pitch angle is 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 then point D speed.

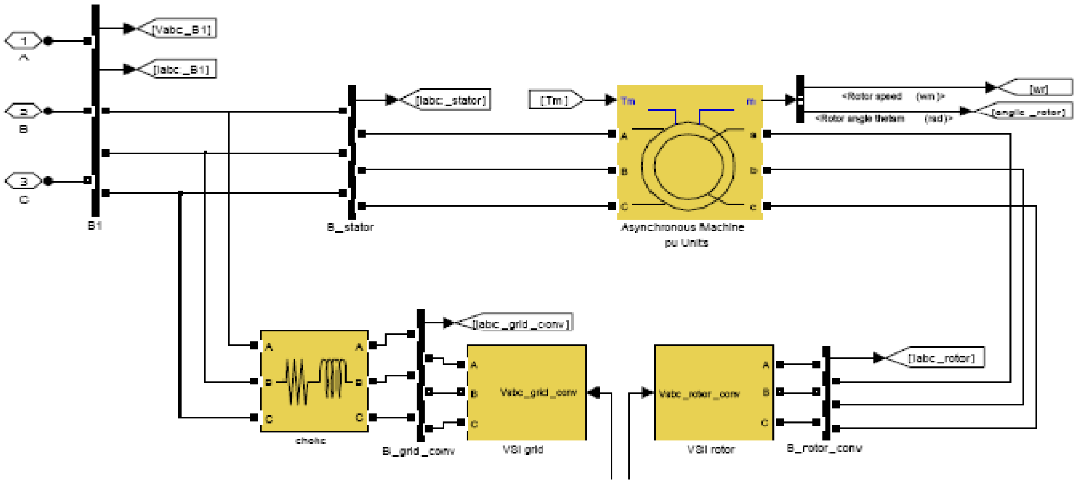

Fig.8. Doubly-Fed Induction generator diagram.

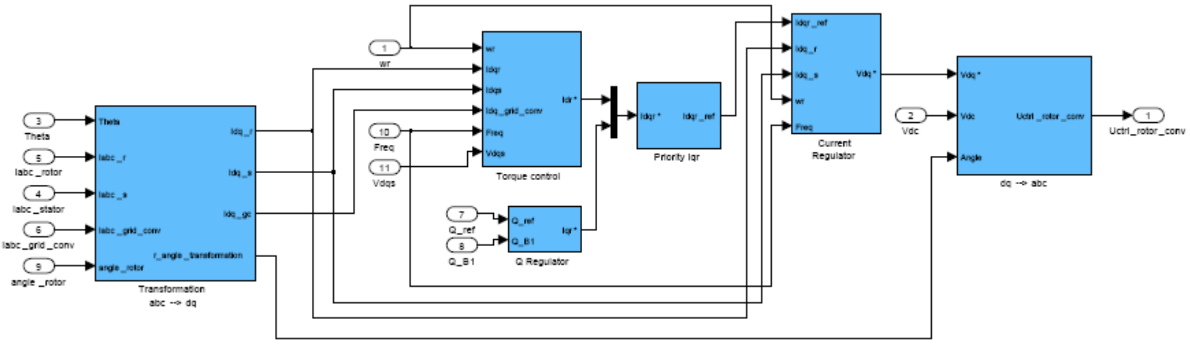

Fig.9. Rotor – side converter control system diagram.

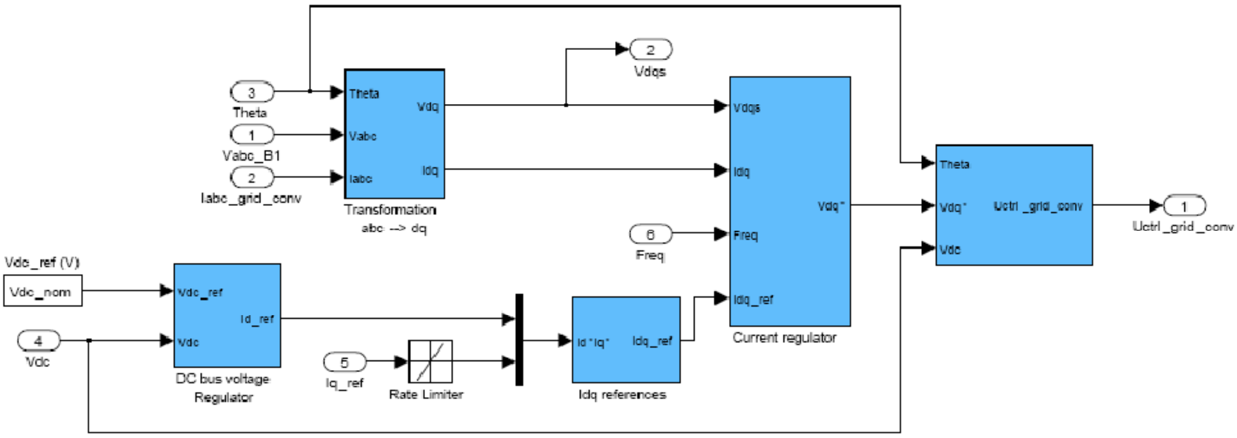

Fig.10. Grid – side converter control system diagram.

2. Simulation & Results

On the figures above are shown the block diagrams of the Doubly-Fed induction generator Fig.8; The rotor-side control system Fig.9 and the grid-side control system diagram Fig.10;

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 500 kW resistive load and a 0.9 Mvar (Q=50) filter are connected at the 400 V generation bus. The turbine parameters specifying ratings of power components of the wind turbine are saved in a companion M file:

```
Pnom=1.5e6/0.9; %Nominal power (VA)
Vnom=400;       %Line-Line voltage
                 (Vrms)
Fnom=50;        %Hz
Rs=0.00706;     %pu
Lls=0.171;      %pu
Rr=0.005;       %pu
Llr=0.156;      %pu
Lm=2.9;         %pu
H=5.04;         %Inertia constant (s)
F=0.01;         %Friction factor (pu)
p=3;            %Number of pairs of
                 poles
```

Initially the DFIG wind farm produces 4.8 MW. This active power, corresponds to the maximum mechanical turbine output for a 10m/s wind speed (0.55*9 MW=4.95 MW) minus electrical losses in generator. The corresponding turbine speed is 1.09 pu of generator synchronous speed. The DC voltage is regulated at 1200 V and reactive power is kept at 0 Mvar. At t=0.03 s the positive-sequence voltage suddenly drops to 0.8 p.u. causing an oscillation on the DC bus voltage and on the DFIG output power.

During the voltage sag the control system regulates DC voltage and reactive power at their set points (1200 V, 0 Mvar). The system recovers in approximately 4 cycles.

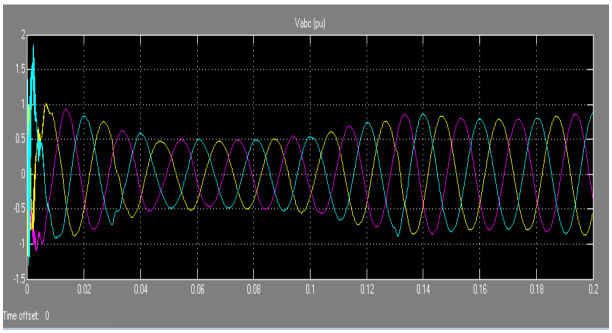

Fig.11. Voltage at the DFIG terminals

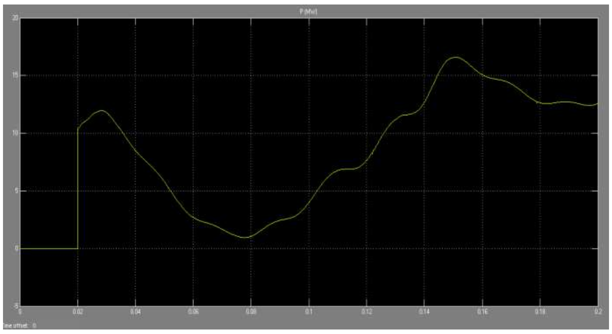

Fig.12. Active power.

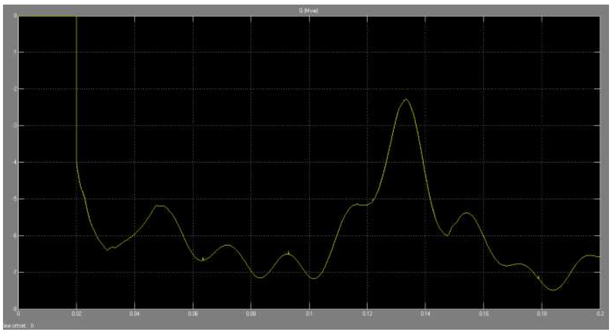

Fig.13. Reactive power

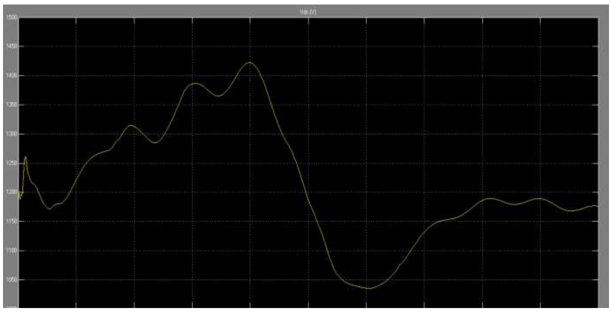

Fig.14. DC link Voltage.

4. Conclusion

The modeling of a Doubly-Fed induction generator driven by a wind turbine has been described. The model is a discrete-time version of the Wind Turbine Doubly-Fed Induction Generator (Phasor type) of Matlab&Simulink Sym-Power systems.

Simulation results shown in Fig. 11-15 illustrate the system response to a line-to-ground fault.

Fig. 14 shows that the DC bus voltage of the wind turbine is strongly affected by the fault.

This suggests that nearby faults should be simulated to study their impacts on the wind farms and on the power systems.

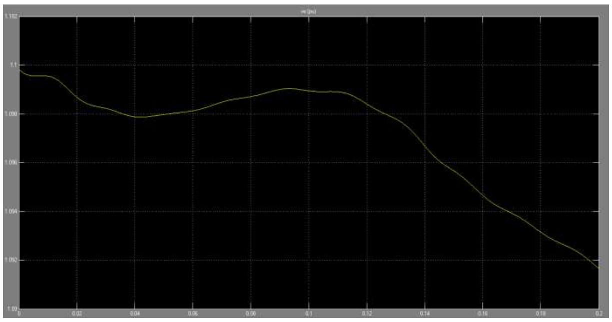

Fig.15. Turbine speed.

3. Bibliography

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[4] Wind Turbine - Wikipedia

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