Simulation of Doubly-fed Machine with Improved Wind Turbine

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Abstract : -Most of wind turbines use induction generators that are very reliable with low costs [2], but when it is straightly connected to the grid, maximum power is not accessible [1] and only a few change of speed between maximum speed and synchronous speed is possible [1].
In this report, a doubly-fed induction generator with winding-rotor configuration, external rotor resistance and external rotor source that has a variable phase and amplitude is used. This doubly-fed induction generator has larger range of change of speed than induction generator and its application in wind systems is very common. Also in doubly-fed machine, both active and reactive power control is possible [3].
In this report, a doubly-fed induction machine with an improved wind turbine has been simulated, then with selecting suitable control parameters by open loop controlling, maximum turbine active power at an adapted speed is exerted to the grid and the results is presented.

Key words: -Doubly-fed machine, Wind Turbine, Gearbox ratio, Low speed shaft, High speed shaft.

1 Introduction

Wind energy is one of the inexhaustible, plentiful, non-polluting and renewable energy sources [8] that were applied from ancient. The elementary systems were used in China and Asia. For example the first wind mill was made by Iranians [4].
Recently environment problems and atmosphere temperature changes via fossil energy sources, have risen and bolded necessity of using renewable and clean sources.
Also with minimizing cost of wind energy by using modern wind turbines and increasing their reliability and performance, process of the installation of wind turbines has rapidly grown in the world [4],[7]. Moreover wind turbines require little maintenance and no fuel. Their technology is simple and robust. Their lifetime is over 15 years and their towers can be manufactured locally [8].
Most of wind turbines use induction generators that are very reliable and have low cost [2]; however maximum power is not accessible when it is straightly connected to the grid [1].
In this report, an improved horizontal wind turbine, a doubly-fed induction generator with winding-rotor configuration, external rotor resistance and external rotor source that has a variable phase and amplitude has been used and this system has a larger range of change of speed and is more applied in wind systems.

2 Wind Turbines

Wind turbines are categorized to two types considering direction of turbine axis that are horizontal axis turbines and vertical axis turbines. Nowadays turbines with vertical axis are less applied for grid applications because of structure and other fundamental design parameters.

Most of horizontal axis wind turbines for grid applications are with upwind configuration and 2 or 3 blades [3].

In this report a horizontal axis wind turbine with upwind configuration has been used.

3 Doubly-fed Induction Machine

Most of wind turbine generators are induction generators that are very reliable and costs of them are low [2].

Induction generators are not complicated. These generators can give active power to grid however they take reactive power from it.

In these generators at 50HZ frequency, the angular frequency is usually among 1200rpm to 1800rpm (relative to number of poles) and gear ratio is among 30 to 50 [4].

Recently using doubly-fed induction generators in wind turbines are more common; however they are more complicated than ordinary induction machines.

For example in this report for a doubly-fed induction generator with external resistance at 4 poles and 60Hz, the angular frequency is around 1000rpm and gear ratio is around 13 and 15 (relative to control parameters that are amplitude and phase of external rotor source and external rotor resistance).

Equations of induction generators in ABC system are [6]:

$$V_{S,r} = R_{S,r} \times i_{S,r} + \frac{d}{dt}\left(L \times i_{S,r}\right) \quad (1)$$

And n, the ratio of equivalent stator turns to equivalent rotor turns is unit [6]:

$$n = 1$$

$$L_{ms} = \frac{2}{3} L_m$$

$$L_{ms} = L_{mr} \quad (2)$$

And electromagnetic torque is according to equation (3)[6]:

$$T_e = \left(i_{abcS}\right)^T \frac{d}{d\theta_m}\left(L'_{sr}\right) \bullet i'_{abcr} \quad (3)$$

And rotor mechanical speed can be obtained from equation (4)[6]:

$$T_e - T_m = J\frac{d\omega_m}{dt} + D\omega_m \quad (4)$$

In induction machine with rotor configuration that is referred to as a winding rotor, rotor external resistance is used to increase slip and its amount is usually low and is nearly one over ten percent of rotor resistance per phase.

In doubly-fed induction generator, an external source with changeable amplitude and phase is used to control induction generator speed and power [2].

4 Turbine Modeling and Calculations

Turbine torque via wind is inferred from following equations:

$$\lambda = \frac{\omega_M \times R}{V_{wind}} \quad (5)$$

$$P_M = \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M{}^3}{\lambda^3} \quad (6)$$

$$T_M = \frac{P_M}{\omega_M} = \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M{}^2}{\lambda^3} \quad (7)$$

Where, V_{wind} , the wind speed, is measured in m/s, R, the blade radius is measured per m, ρ (1.24kg/m^3[4]), air density is measured in kg/m^3, ω_M, turbine mechanical speed, is measured in rad/sec, λ is tip-speed ratio (TSR) and C_p is power coefficient, i.e. ratio of turbine power (power extracted) to wind power (power available) and it depends on aerodynamics specifications of blades [1],[3].

C_p is function of λ [3]:

$$C_p = 0.22\left[116\left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right) - 0.4\beta - 5\right] e^{-12.5\left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right)} \tag{8}$$

Where β is blade pitch angle.

Simulation of turbine for two typical wind speed, 4 and 5m/s that are in valid range of speed between low-shutdown speed and high stopped speed has been performed for improved turbine parameters according to table1 [1]:

Table1 Turbine parameters.

Nominal power	15kw
Blade radius	5.5m
Blade pitch angle	0°

5 Maximum Turbine Power

In a fixed wind speed, maximum power of turbine can be achieved from C_{Pmax} function considering improved λ. Improved parameters from equation (8) are presented in table2 [1].

Table2 Improved parameters of turbine.

λ_i or Improved TSR	C_{pmax} or Maximum power coefficient
8.636	0.48

Then, by using 5 and 6 equations, maximum turbine power is calculated.

6 Modeling and Parameters of Doubly-fed Induction Generator

According to table 3 and by using induction machine model of MATLAB-SIMULINK the simulation has been performed and fig.1 shows model of improved wind turbine with doubly-fed induction generator.

Table3 Induction machine parameters in side of stator [1].

Nominal power	15 kW
Line to line nominal voltage	460 V
Nominal frequency	60 HZ
Number of poles	4
Stator resistance, R_S	0.2761 Ω
Stator inductance, L_{ls}	2.2 mH
Rotor resistance, R_r	0.1645 Ω
Rotor inductance, L_{lr}	2.2 mH
Magnetizing inductance, L_m	76.14 mH
Inertia, J	0.1 kg.m$_2$
Friction coefficient, F	0.018 N.m.s

7 Simulation Results

Results of simulation are presented in table 3.

Simulation has been performed for 2 seconds, using MATLAB2006a-SIMULINK.

In table3, the polarity of input power to machine is considered negative and that of output from machine is considered positive.

In simulation, the gearbox effect is considered and output torque of gearbox is multiplied by inverse of gear ratio where gear ratio is the ratio of generator shaft speed to low-speed shaft speed.

The curves of simulation are presented in figs. 2 until 9.

Table4 Simulation results of wind turbine and doubly-fed generator

V_{wind}	k	θ	r_{ex}	ω_T	ω_{mr}	Ng	$P_{T3\Phi}$
4	5	-0.02	0.016	6.28	94.5	15	-1.8k
4	5	-0.78	0.016	6.28	94.5	15	-1.8k
4	10	-0.02	0.016	6.28	94.5	15	-1.8k
4	10	-0.78	0.016	6.28	94.5	15	-1.8k
5	15	-0.02	0.016	7.85	95	12	-3.53k
5	15	-0.78	0.016	7.85	95	12	-3.53k
5	20	-0.02	0.016	7.85	95	12	-3.53k
5	20	-0.78	0.016	7.85	95	12	-3.53k

Rest of table4

V_{wind}	k	θ	$P_{S3\Phi}$	$P_{r3\Phi}$	P_{loss}	$Q_{S3\Phi}$	$Q_{r3\Phi}$
4	5	-0.02	1.4k	6	394	-7.5k	11.5
4	5	-0.78	1.4k	6	394	-7.5k	11.5
4	10	-0.02	1.4k	10	390	-8.5k	47
4	10	-0.78	1.4k	10	390	-8.5k	47
5	15	-0.02	3k	7	523	-8k	21
5	15	-0.78	3k	7	523	-8k	21
5	20	-0.02	3k	10	480	-8.5k	40
5	20	-0.78	3.53k	10	480	-8.5k	40

Where k and θ are amplitude and phase of external rotor source, r_{ex} is external rotor resistance, $Q_{S3\Phi}$ and $Q_{r3\Phi}$ are 3-phased reactive power of rotor and stator in VAR, $P_{T3\Phi}$ is maximum turbine power, $P_{r3\Phi}$ and $P_{S3\Phi}$ are 3-phased active power of rotor and stator and P_{loss} is power losses of machine that all are in watt, ω_T is turbine speed in rad/sec, V_{wind} is wind speed in m/s, ω_{mr} is mechanical speed of rotor in rad/sec and Ng is ratio of gear ($Ng = \frac{\omega_{mr}}{\omega_T}$).

Table5 shows the results of simulation for two amounts of external rotor resistance.

Table5 Simulation results of wind turbine with doubly-fed generator for two different r_{ex}

V_{wind}	k	θ	r_{ex}	ω_T	ω_{mr}	Ng	$Q_{r3\Phi}$
4	10	-0.78	0.016	6.28	94.5	15	47
4	10	-0.78	3	6.28	96.7	15.4	-1
5	15	-0.78	0.016	7.85	95	12	21
5	15	-0.78	3	7.85	99	12.6	-0.5

Rest of table5

V_{wind}	k	$Q_{S3\Phi}$	$P_{T3\Phi}$	$P_{S3\Phi}$	$P_{r3\Phi}$	P_{loss}
4	10	-8.5k	-1.8k	1.4k	10	390
4	10	-7.2k	-1.8k	1.5k	-0.5	300.5
5	15	-8k	-3.53k	3k	7	523
5	15	-7.3k	-3.53k	3.1k	2	428

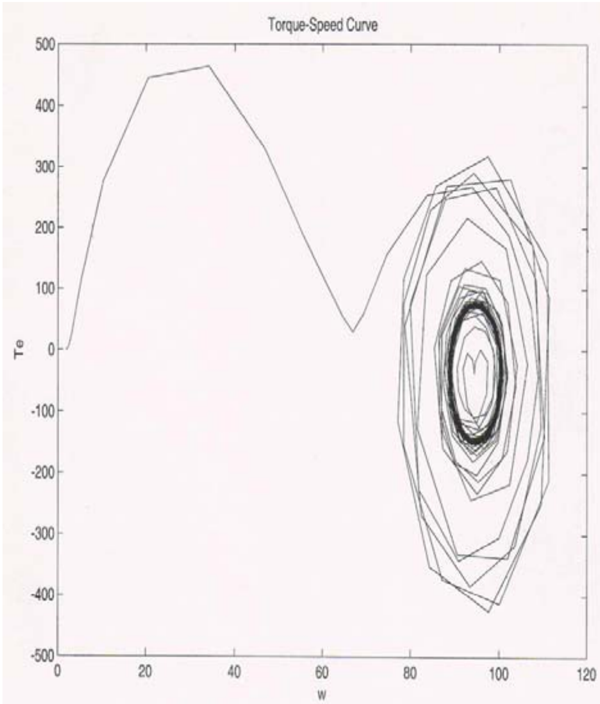

Fig.2 Curve of torque-speed for K=15, r_{ex}=0.016, V_{wind}=5, Θ=-0.78, N_g=12.

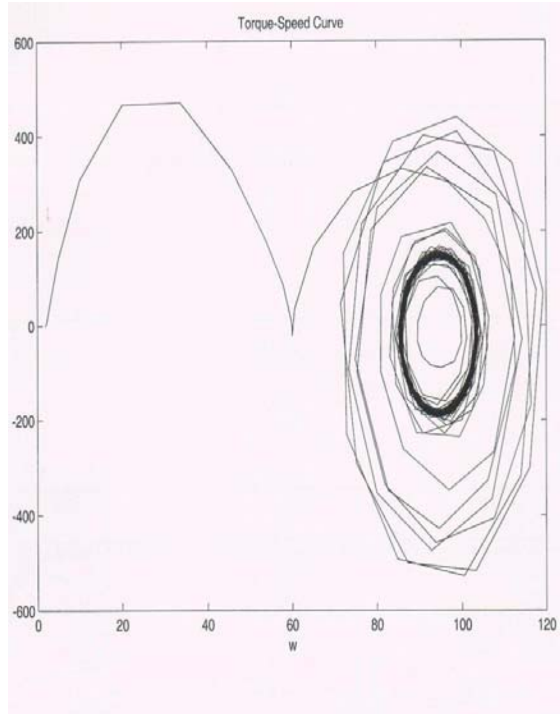

Fig.4 Curve of torque-speed for K=10, r_{ex}=0.016, V_{wind}=4, Θ=-0.78, N_g=15.

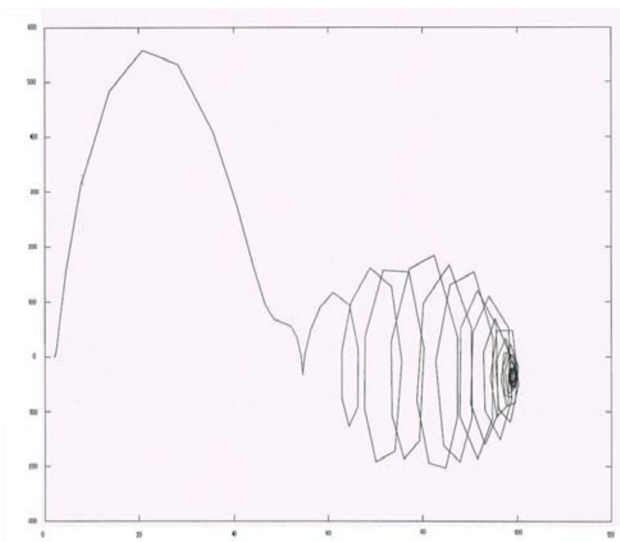

Fig.3 Curve of torque-speed for K=15, r_{ex}=3, V_{wind}=5, Θ=-0.78, N_g=12.

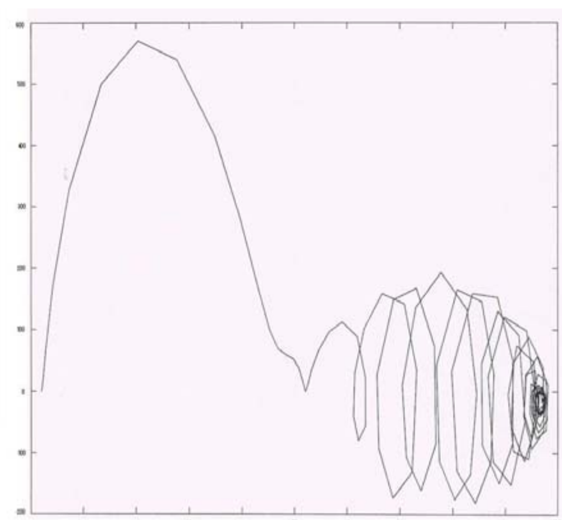

Fig.5 Curve of torque-speed for K=10, r_{ex}=3, V_{wind}=4, Θ=-0.78, N_g=15.

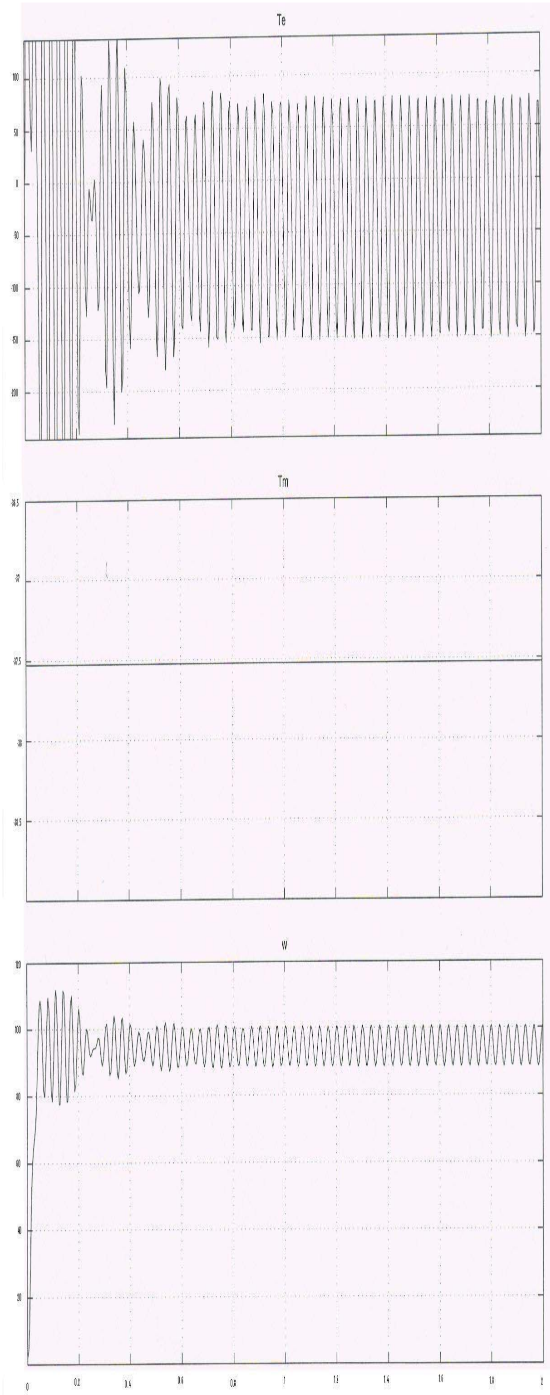

Fig.6 Curve of torques and mechanical rotor speed for K=15, r_{ex}=0.016, V_{wind}=5, Θ=-0.78, N_g=12.

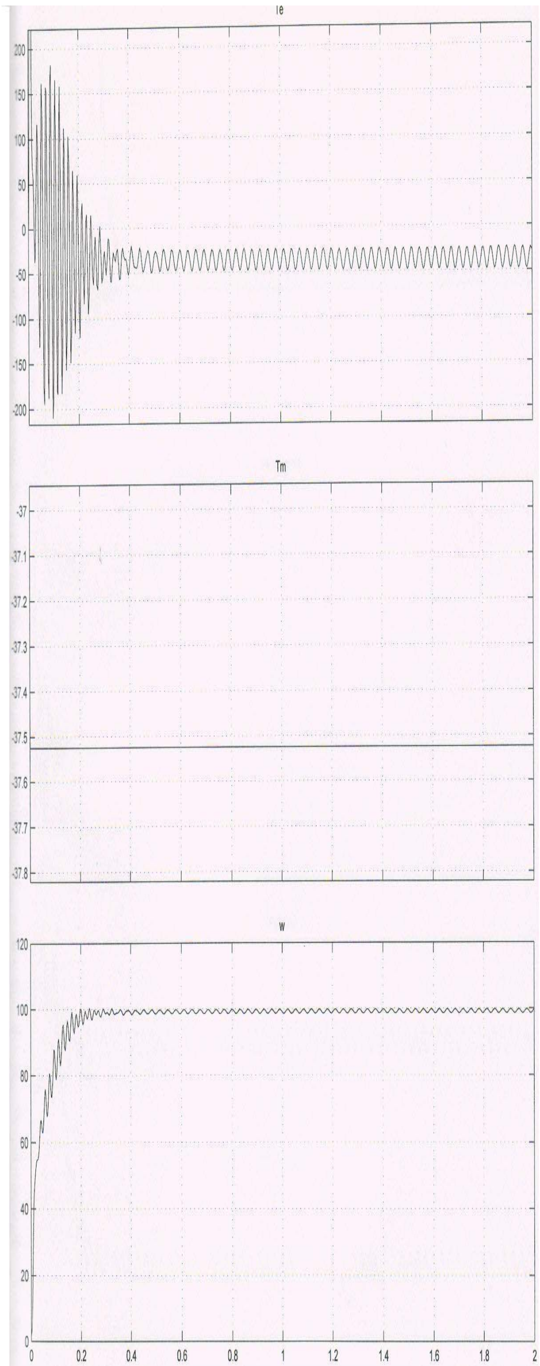

Fig.7 Curve of torques and mechanical rotor speed for K=15, r_{ex}=3, V_{wind}=5, Θ=-0.78, N_g=12.

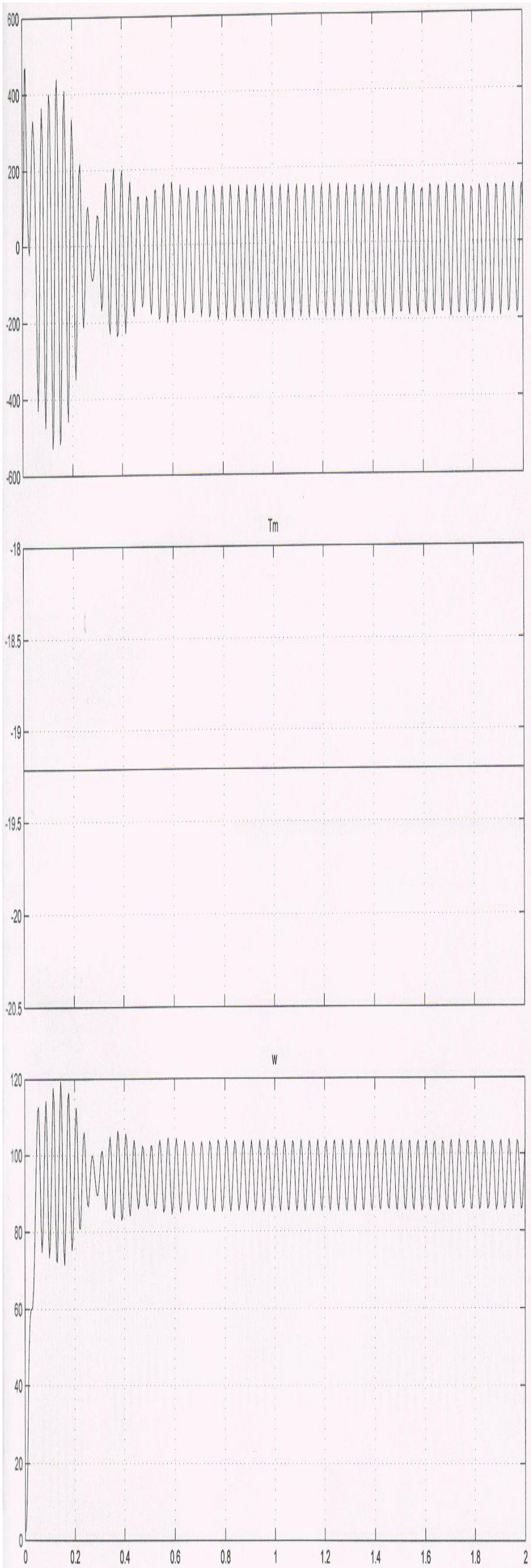

Fig.8 Curve of torques and mechanical rotor speed for K=10, r_{ex}=0.016, V_{wind}=4, ϴ=-0.78, N_g=15.

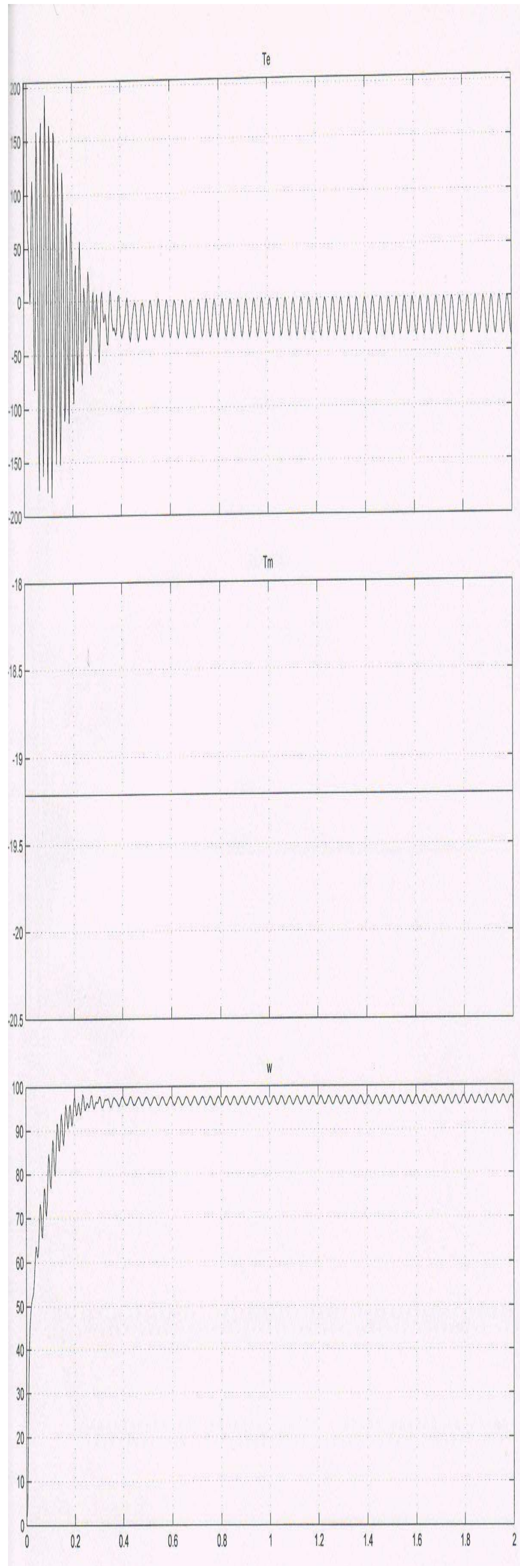

Fig.9 Curve of torques and mechanical rotor speed for K=10, r_{ex}=3, V_{wind}=4, ϴ=-0.78, N_g=15

8 Conclusion

In this report for a doubly-fed induction generator with external resistance at 4 poles and 60Hz, the angular frequency is around 1000rpm and gear ratio is around 13 and 15 (relative to control parameters that are amplitude and phase of external rotor source and external rotor resistance).

According to table4 and 5, the results are:

1- Sensitivity of Q to K is more than sensitivity of P (especially in that of rotor).
2- The simulated doubly-fed induction machine with improved wind turbine, in generator mode, gives active power to the grid and takes reactive power from it.
3- In this system, gear ratio is set proportional to speed and it differs for different speeds and this variation is obvious specially in high speeds because adapting of turbine speed to induction generator speed in high speeds is harder.
4- By increasing r_{ex}, slope of torque-speed curve rises and speed of induction machine increases.
5- Sensitivity of P,Q and ω_{mr} to θ is very low.
6- Sensitivity of ω_{mr} to k is low and increasing of k, raises swing of ω_{mr}.
7- In a set point, with increasing k, machine losses declines.

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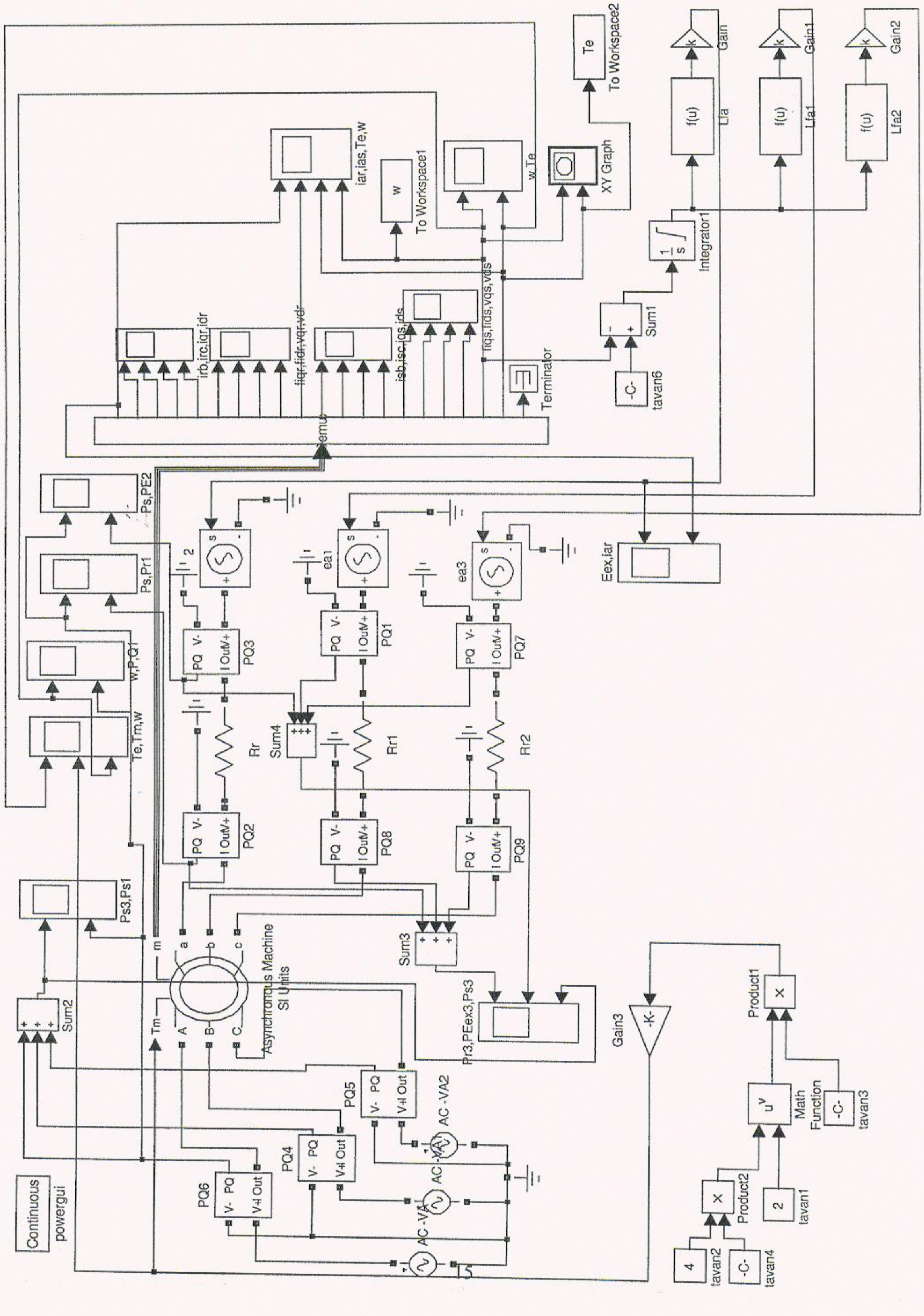

Fig .1 Model of Doubly-fed machine with improved wind turbine.