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Research Article

Power Regulation for Variable Speed Variable Pitch HAWT Pitch and Torque Control Strategy

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Abstract: This study demonstrates variable speed variable pitch horizontal axis wind turbine operating ranges, concerned on increasing the output power generated by the turbine. To achieve these approaches two control techniques summarized. The resultant technique was applied on a model for commercial wind turbine 'Aeolos 50 kw' was built on simulink. The simulation results show that the developed strategy is better than the classical strategies.

Keywords: Non-linear controllers, permanent magnet synchronous generator, pitch angle, torque control, wind turbine aerodynamics characteristics, wind turbine control strategy, wind turbine model

INTRODUCTION

Nowadays there is great consideration to decrease global warming effect by minimize dependence on fossil fuel and increase clean pure green energies portion in global energy system, renewable energies like wind solar and geothermal are alternative types so many nationals rely on renewable energy forms to gain their energy requirements, wind industry it is not new, wind energy had been used for many centuries for propelling boats along rivers as early as 5,000 B.C., (T. I. of Electrical and E. E. Inc, 2007) and helped pumping water and grinding grain between 500 and 900 B.C., According to Global Wind Energy Council (GWEC) the annual market of wind industry grows by 44%,wind farms produce more than 50 GW in 2014 (Global wind energy council (GWEC Report, 2014) wind energy provide 20.15 MW from India energy demand, 22 MW for Spain, 3.5 MW for brazil. Moreover there is daily increase in energy demands, the global energy demand will almost triple by 2050. Generating electricity become very important and critical in some cases.

Wind turbines can be classified into two types according to axis of rotation, horizontal where blades are parallel to wind direction and vertical if the blades are perpendicular to wind direction (Ofualagba and Ubeku, 2008). Also wind turbine can be classified into off shore turbines can capture more wind resources over oceans and on shore. in the past wind turbine was working at fixed speed which limited the output power transferred to grid (Munteanu *et al*., 2008), by the time turbine become variable speed, the working range had been increased this due to science revolution, electronics science offer multi AC converters which transfer any generated electricity to the grid. Variable speed turbine has more advantages compared to fixed speed turbine like need less maintenance, controller, simple structure, relatively cheap, small payback time (Ofualagba and Ubeku, 2008).

There are two types of generators induction and synchronous. The most common in wind turbines is synchronous type; which is relatively cheap generator, has high efficiency, need less maintenance (Slootweg *et al*., 2003).

Wind industry had been introduced a new branch, wind turbine control. This control purposed for reduce stresses and improve the turbine performance by means of passive technique without external energy expenditure (Thomsen, 2006) or active technique requires external energy, or auxiliary power.

There are two working ranges for the variable speed wind turbine the first when wind speed is less than rated speed, turbine control deal with achieving the maximum available power by rotating the turbine blade around it is axis. The second when wind speed is greater than or equal rated speed at this case control objective is maintained the output power equals rated output power.

Different strategies had been applied in many researches to keep the wind turbine output power constant, equal to rated power. For doing this pitch control as classical PI, PID was applied which treat with the turbine as a linear system (Ma, 1997; Hand, 1999). Some detailed studies deal with turbine linearization, another apply algorithms like LQR, LQG (Leithead *et al*., 1991; Novak *et al*. 1991) the common factor for the previous mentioned work is that they do not consider generator torque as effective item in power regulation. On the other hand there is some steps on solving wind turbine as non-linear system by means

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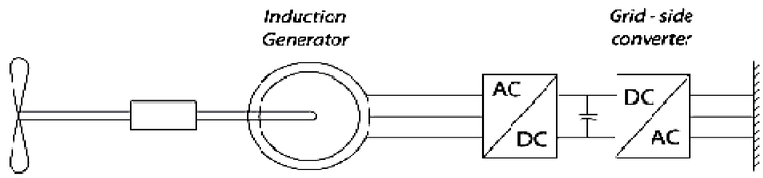

Fig. 1: Wind turbine structure

building nonlinear torque generator using H infinity, lyapunov function these principles make long computations in long time which limits control efficiency.

This study aims to introduce a anew control strategy depend on building two cooperative controllers one non linear deal with torque generator and the other linear deal with the blade pitch angles. For doing this purpose a model for real wind turbine Aeolos 50 KW was built by using simulating program Matlab. The purposed strategy applied on Simulink model and the results were analyzed as following.

WIND ENERGY CONVERSION SYSTEM DESCRIPTION

A general look at variable speed Horizontal Axis Wind Turbine structure (HAWT), the turbine consists of number of blades, hydraulic pitch mechanism, bearing, gear box, generator, baking system. This structure connected to diode rectifier and internal DC-link as AC/DC converter then connected to DC/AC converter to grid Fig. 1.

This section shown WECS characteristics as following:

- Aerodynamics wind turbine characteristics
- Dynamics wind turbine characteristics
- Permanent magnet synchronous generator characteristics

Aerodynamics wind turbine characteristics: It is known that power produced (T. I. of Electrical and E. E. Inc, 2007) due to wind speed (v) equals:

$$P = \frac{1}{2}\rho A v^3 \quad (1)$$

where, ρ is the air density, A is swept rotor area and the mechanical power extracted HAWT by equals:

$$P = \frac{1}{2}\rho A C_p v^3 \quad (2)$$

Cp power coefficient of the wind turbine, which is a function between pitch angle of blades β and tip-speed ratio γ given by:

$$Cp = 0.517\left(\frac{116}{\gamma_i} - 0.4\beta - 5\right)e^{-21/\gamma_i} + 0.0068\,\gamma_i \quad (3)$$

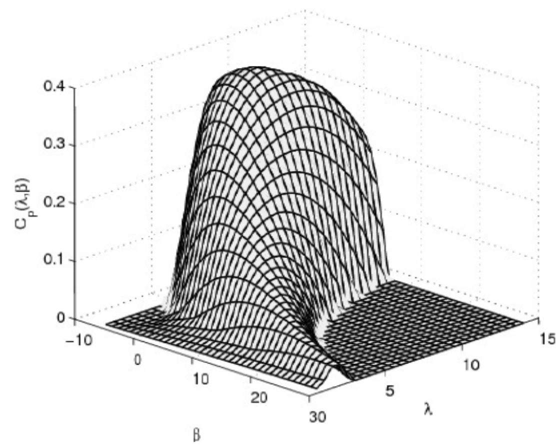

Fig. 2: Power coefficient with tip speed ratio and pitch angle

$$\frac{1}{\gamma_i} = \frac{1}{\gamma + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

$$\gamma = \frac{R\ W_r}{v} \quad (5)$$

where, Wr is rotor speed, R rotor radius. Figure 2 show the relation between power coefficient and tip speed ratio and blade pitch angle.

Also the mechanical power P = T_a, W_r then:

$$T_a = \frac{1}{2}\rho A R C_t V^2 \quad (6)$$

where, is torque coefficient C_t :

$$C_t = \frac{C_p}{\gamma} \quad (7)$$

A commercial wind turbine model was implemented using simulating tool matlab/simulink Fig. 3.

Dynamics wind turbine characteristics: The dynamics of variable speed horizontal axis wind turbine can be represented by two mass-spring model Fig. 4.

$$\dot{W}_r = \frac{1}{J_r}(T_a - T_{dr} - T_{ls}) \quad (8)$$

$$\dot{W}_g = \frac{1}{J_g}(T_g - T_{dg} - T_{hs}) \quad (9)$$

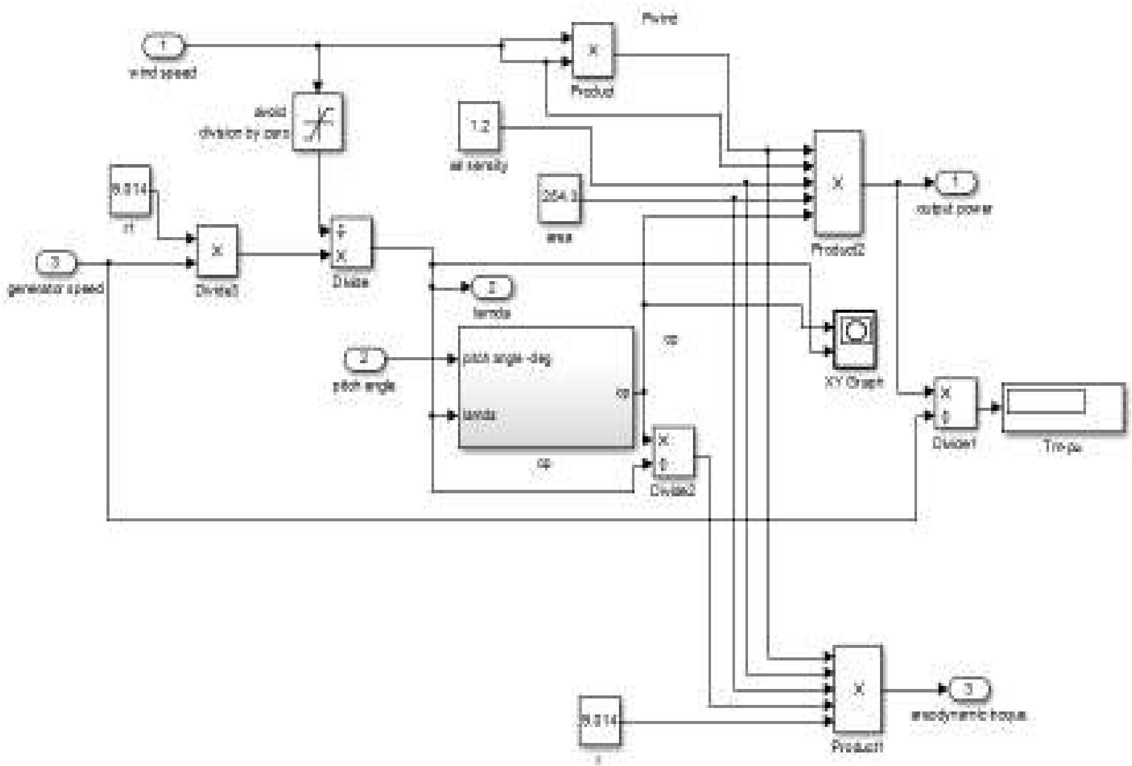

Fig. 3: Wind turbine model on simulink

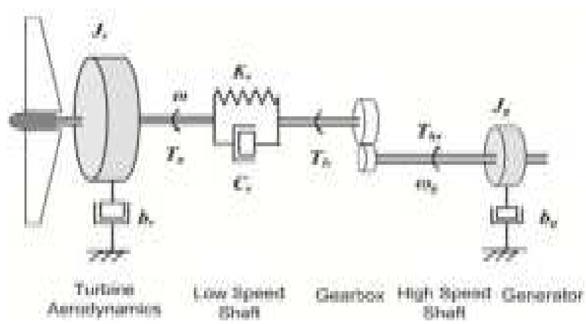

Fig. 4: Two mass drive train model

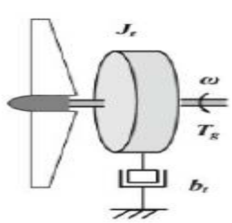

Fig. 5: One mass drive train model

$$\frac{1}{n_g} = \frac{W_r}{W_g} = \frac{T_{hs}}{T_{ls}} \quad (10)$$

where, T_{dr} T_{dg} are resistance torqueses of wind turbine, generator bearing, n_g gear ratio. to simplify the calculations a rigid low speed shaft is considered which convert the system into one mass-spring model Fig. 5.

$$\dot{W}_r = \frac{1}{J_t}(T_a - T_{dt} - T_g) \quad (11)$$

$$J_t = J_r + n_g^2 J_g \quad (12)$$

$$T_{dt} = T_{dr} + n_g^2 T_{dg} \quad (13)$$

And $T_g = n_g T_{em}$ knowing T_{em} is generator electromagnetic torque. One mass drive train mode was implemented on simulink Fig. 6.

Permanent Magnet Synchronous Generator characteristics (PMSG): Generator is a machine converts mechanical power into electric power, so the model will be divided into electrical part model mechanical part model the electric model of PMSG is

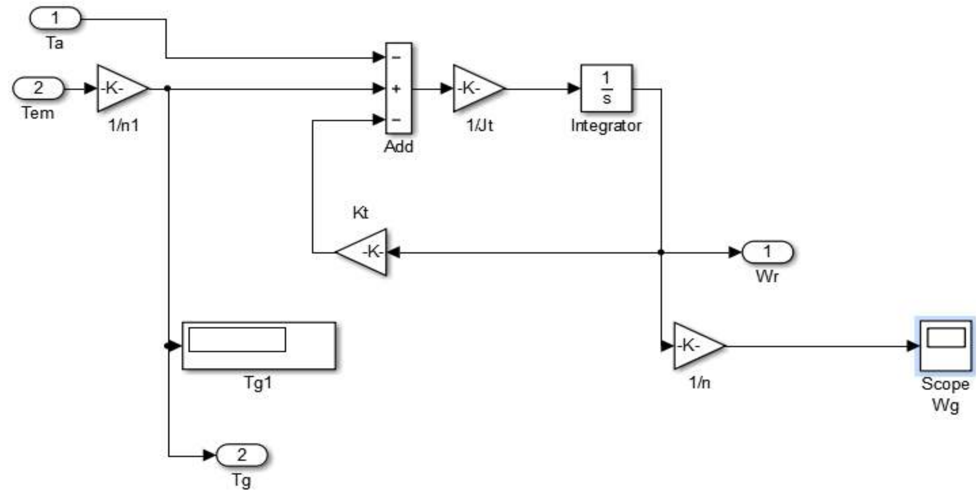

Fig. 6: Drive train model on simulink

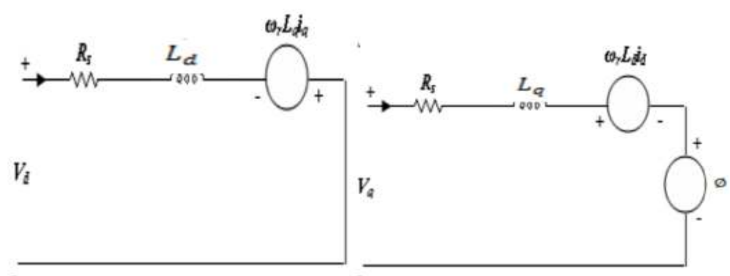

Fig. 7: PMSG model

the same as wound rotor synchronous generator, here generator dynamics will be defined in terms of d-q reference frames

Based on the following assumptions (Krause, 2002) the stator winding are symmetric sinusoidal positioned along air gap and their resistance is constant, however damping factor, capacitance of windings are neglected. Rotor inductances are constant although rotor relative position to stator slots which lead to neglecting induced rotor currents. Magnetic hysteresis, saturation conditions are neglect which mean that the back EMF produced by permanent magnet equal to the back EMF produced by excited coil.

By analysis Fig. 7, the electrical mathematical model of the generator will be:

$$\acute{\overline{i_q}} = \frac{1}{L_q}(V_q - P\, W_g\, Ø - PW_g i_d L_d - R_s i_q) \tag{14}$$

$$\acute{\overline{i_d}} = \frac{1}{L_d}(V_d - P\, W_g i_q L_q - R_s i_d) \tag{15}$$

where, R_s stator resistance, Ø permanent magnet flux, P number of poles, W_g rotational speed of generator $L_q\, L_d$ are generator inductance in d- q axis, $i_q\, i_d$ are currents on d- q axis, $V_d\, V_q$ voltage on d- q axis. On the other hand the mechanical model of the permanent magnet generator will described by the following relation between electromagnetic torque and generator inductances and it is magnetic flux:

$$T_{em} = 1.5\, P\, (L_d\, i_d\, i_q + i_q\, Ø) \tag{16}$$

WIND ENERGY CONVERSION SYSTEM CONTROL MODES

To analysis wind turbine operation, it is preferable to divide wind speed into three categories

The first category: When wind speed is very low which insufficient to rotate wind turbine, overcome turbine rotational inertia in this case wind turbine do not generate electricity.

The second category: When wind speed is less than rated wind speed in this case wind turbine produce electric energy which can be maximized by changing the blade pitch angle.

The third category: When wind speed is larger than or equal rated speed, wind turbine reach it is maximum

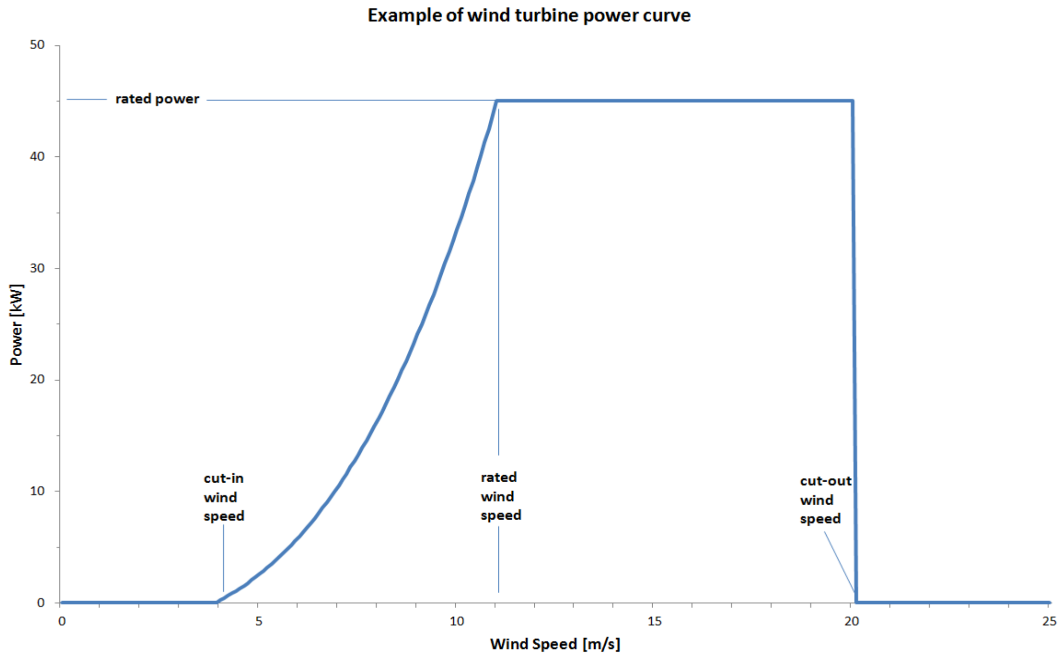

Fig. 8: Wind speed with output power

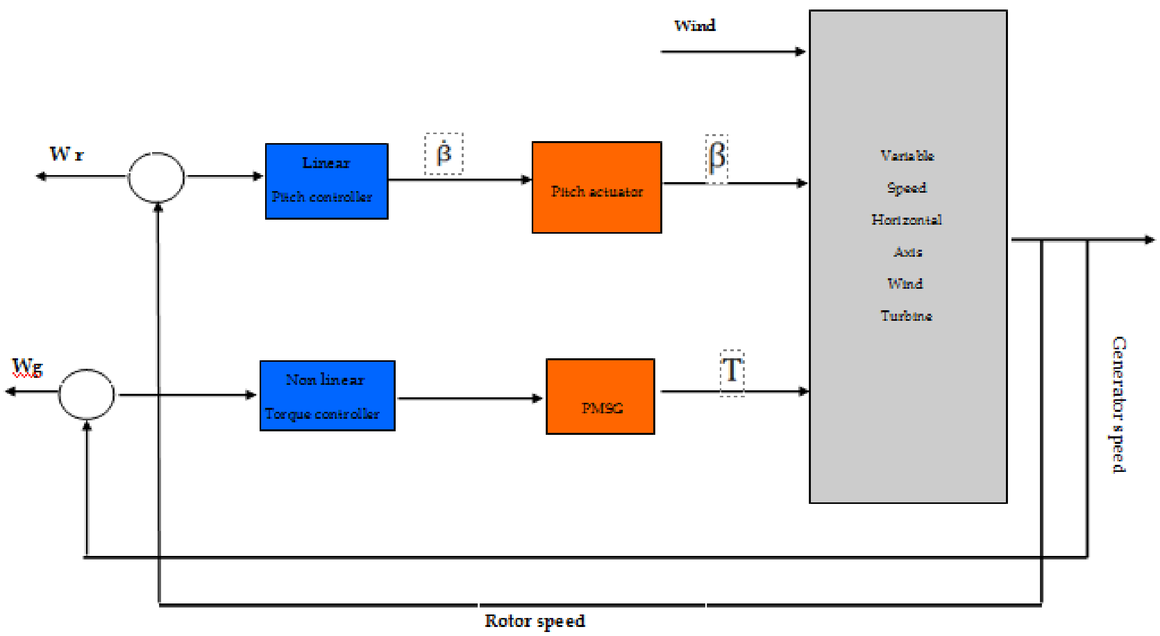

Fig. 9: The developed control system block diagram

efficiency, electric energy generated by the turbine is the maximum energy can be generated so it is desirable to maintain the output power constant in this case. By increasing wind speed the dynamic loads, stresses on the turbine structure increased, which may be cause turbine damage. In the case the aim is reserved turbine structure (Fig. 8 to 10).

For archiving wind turbine control aims two different control strategies used:

Pitch controller: A classical P controller was used to increase blade area faced wind consequently increase the output power, control rotor speed around nominal rotor speed range. The electric power tracking error was defined by:

$$e = P_r - P_m \quad (17)$$

The error minimized by both proportional and integral gains:

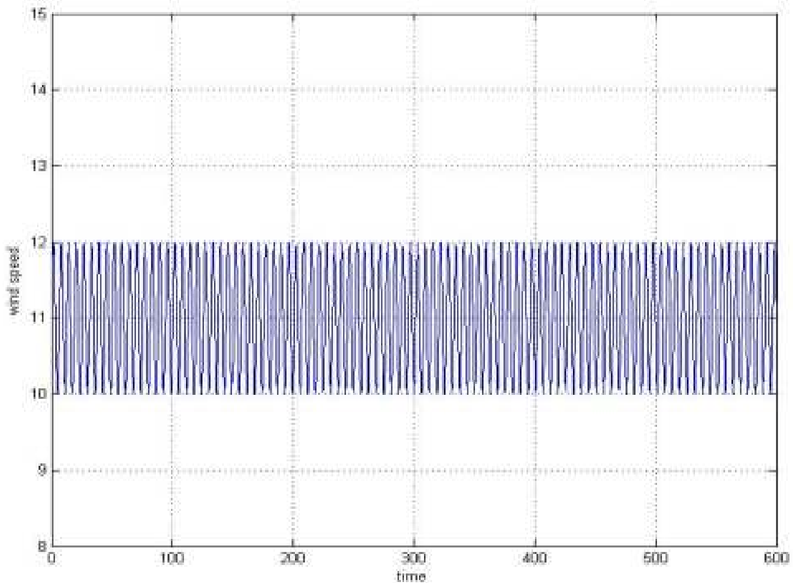

Fig. 10: Realist wind speed profile

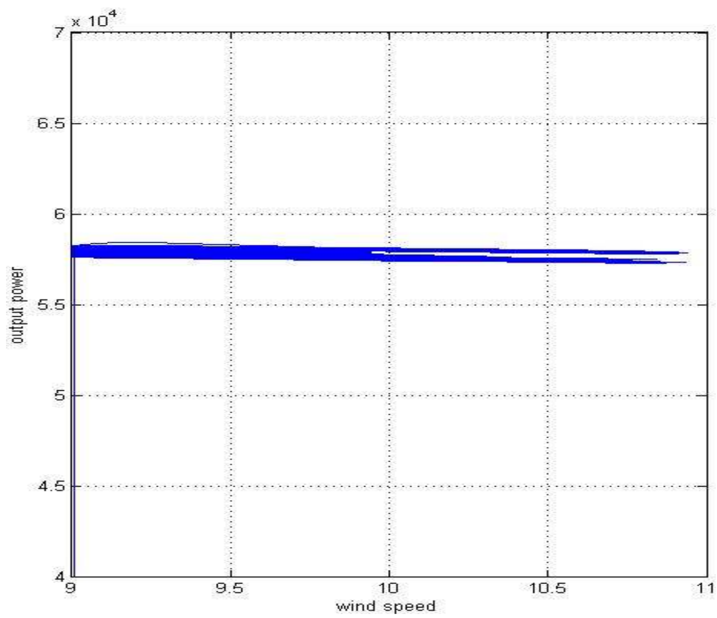

Fig. 11: Output power with wind speed

$$\Delta\beta = k_p e \tag{18}$$

The pitch actuator on the linear P controller represented as integrator only to limit number of steps done by actuator in each case 5 to 10°/S

Torque controller: As previously mentioned when wind speed become greater than the rated value, control objective become maintained turbine output power nearly constant, all classical control strategies do not deal with torque generator, almost considered it constant along the operating period. However the experiment results of applying torque control on wind turbine is very acceptable (Jonkman *el al*., 2009) but the main problem is the used methods need a long time computations, more parameters about the wind turbine which always unknown this decrease controller efficiency and validity. Here a nonlinear torque controller built with dynamic state feedback by substituting the first dynamics equation which simplifies tracking error challenge into stabilization problem of the error. This strategy does not need turbine operating parameters, the controller starts with general information and total turbine inertia only:

$$\dot{e} + \epsilon e = 0 \ , \ \epsilon > 0$$

Knowing that the power tracking error was defined by:

$e = P_r - P_m$ and $P = T_{em}.W_g$

The error equation will be:

$$T_{em} W_g + T_{em} W_g + (P_r - P_m) \varepsilon = 0 \quad (19)$$

The suggested strategy is combining both torque and pitch controller show Fig. 11 to reach the best performance, as pitch control treat slow response which resulted from torque generator dynamics, decrease the rotor speed fluctuations and preserver the normal value.

WIND ENERGY CONVERSION SYSTEM VALIDITY

The developed strategy was applied on a model for customized wind turbine Aeolos 50 Kw equipped with gearbox connected to permanent magnet synchronous generator which was built on simulink/matlab, turbine parameter was shown in Table 1 and 2 while PMSG parameters was shown in Table 3. A numerical comparison was done to show developed strategy validity range by using realistic wind inflow as Fig. 10. The wind speed is described as a slowly varying average wind speed associated with turbulent wind speed to create realistic wind speed profile was built using multi function step, sinusoidal and noise, with mean value 10 m/s.

The simulation results show that the developed control technique is very effective. The results close to desired values, system fluctuations are very fine which may not consider. Controller had been archived his targets, both power and rotor speed. Figure 11 show the electric power is constant however wind speed is varying with time.

The turbine generator speed and rotor speed follows reference value as Fig. 12 and 13 shown.

The generator torque curve, Figure 14 show that the torque is constant during turbine operation time, which considered good indicator about controller performance. Also pitch angle varies in normal range during operation as Fig. 15.

Table 1: Aeolos wind turbine general parameters

Parameter	Symbol	Value
Rated wind speed	v	10 m/s
Swept area	A	254.3 m^2
Rotor diameter	d	18 m
Air density	ρ	1.205 kg/m'
Number of blades	N	3
Rotor speed	Wr	60 rpm
Rated wind turbine power	P	50 Kw

Table 2: Wind turbine dynamic parameters

Parameter	Symbol	Value
Gearbox ratio	ng	1:25
Turbine weight	W_t	3120 kg
Generator mass	Wg	300 kg

Table 3: Permanent magnet synchronous generator parameters

Parameter	Symbol	Value
Generator inductance in q axis	L_d	2.05 mH
Generator inductance in q axis	L_q	2.05 mH
Voltage on q axis	V_q	360 v
Voltage on d axis	V_d	360 v

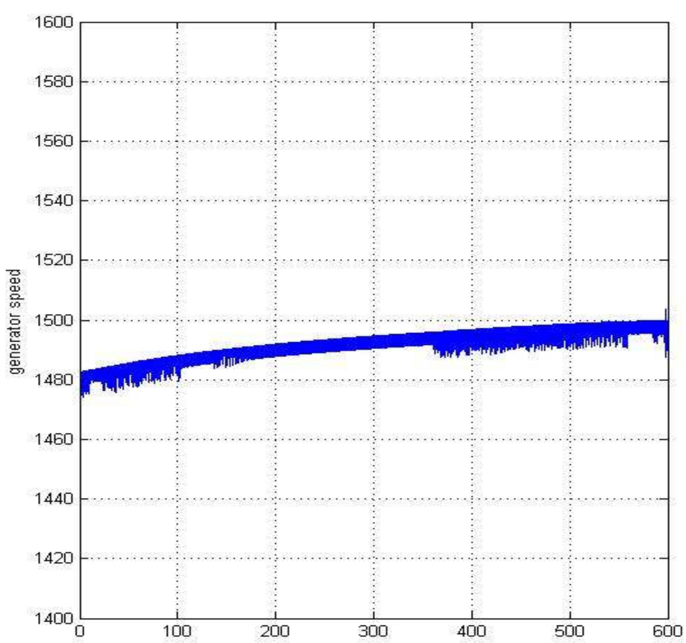

Fig. 12: Generator speed

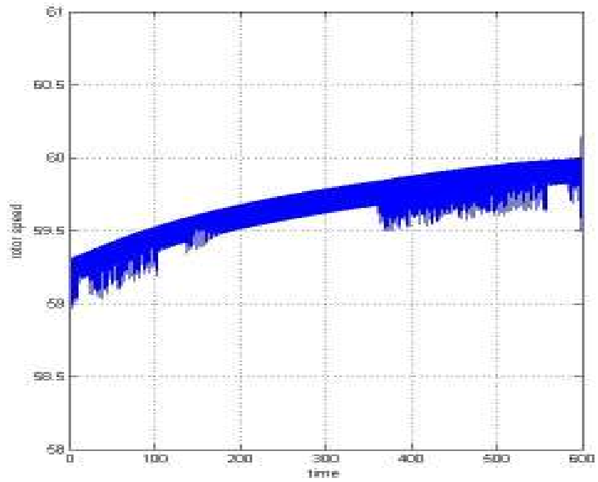

Fig. 13: Wind turbine rotor speed

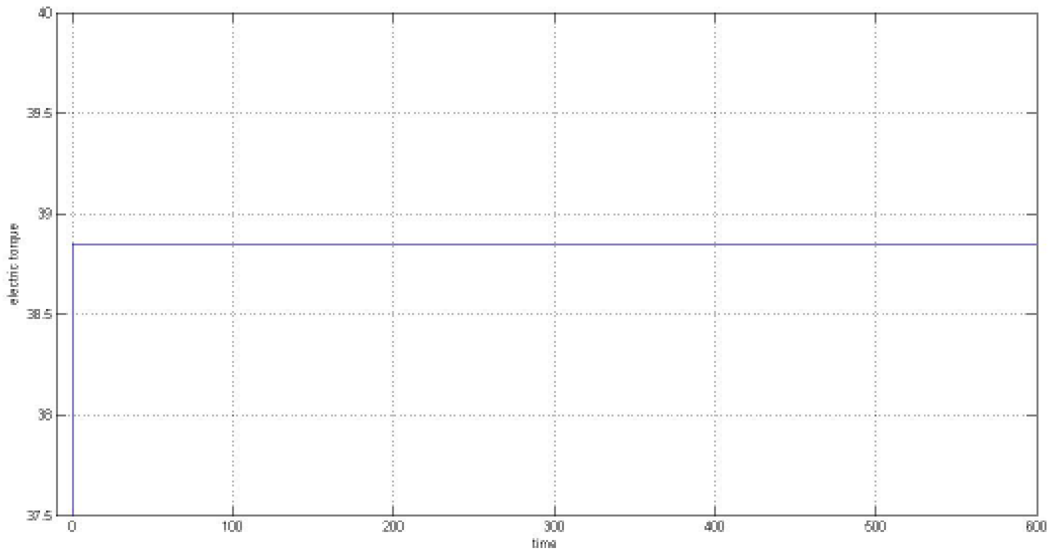

Fig. 14: Torque generator

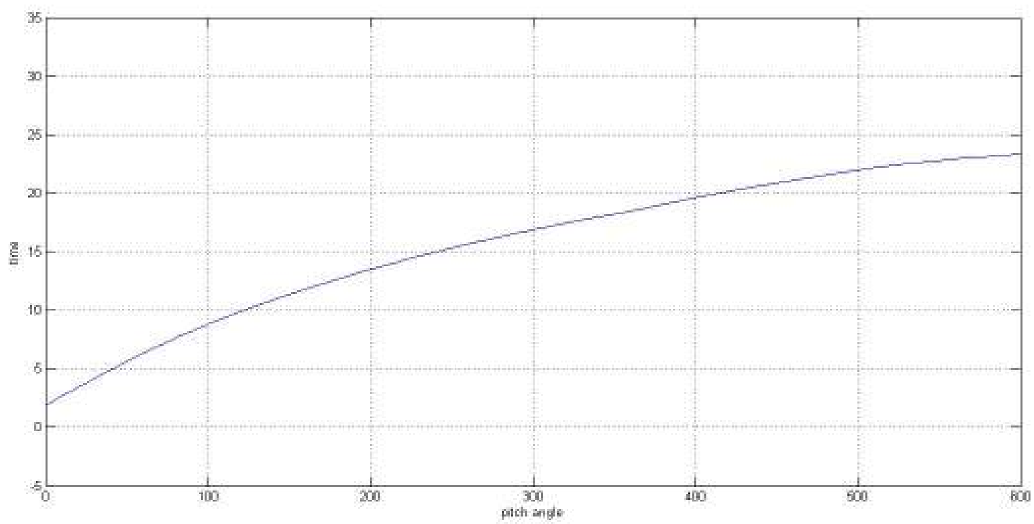

Fig. 15: Blade pitch angle

CONCLUSION

The dynamic behavior of aerodynamic, mechanical and electrical parts of customized variable speed variable pitch wind turbine equipped with an permanent magnet synchronous generator was studied.

A model for Aeolos 50 kw wind turbine, drive train, permanent magnet synchronous generator was implemented using simulating program matlab/simulink. These models provide the relation between output power, torque generator and rotor speed.

Two controllers for blade pitch angle and torquegenerator were investigated to guarantee the output power almost constant, the strategy appears better than classical approaches according to rotor speed, output power.

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