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Dynamic Modeling and Simulation of a Flexible Wind Turbine for a Multi-objectives Control

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Abstract

In This paper we provide a model of flexible Wind turbine for multi-objectives control objectives, such load mitigation, speed regulation, power maximization and vibration control, with minimum number of states, needed to design control system. We use Lagrange method to develop the dynamics model; it includes the flexibility of the blades and tower, torsion and rotational dynamic of the shaft. This model describes the dynamic behavior and vibrations due to deformations of the different parts of wind turbine and generator speed. It subdivide to several sub-models such aerodynamic model, structural model and actuator pitch angle model witch are interconnected between.

Keywords: Wind turbine, Flexibility, multi-objectives control, Lagrange, Aerodynamics

1. Introduction

In recent years, the wind energy has experienced unprecedented growth, due to the rising price of energy and oil energy centerpieces, as well as the huge development of technology used in wind turbines, this which made it more competitive. Wind turbines are becoming more reliant on advanced control systems to both maximize the energy captured from the wind and also minimize the loads of these machines, the development and use of control systems to improve performance requires accurate models of the wind turbine environment and also turbine response to environmental forcing during operation.

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Most works done in this field, aim to improve and develop optimal structures [8][9], more efficient and profitable as well as introducing more intelligent algorithms than conventional methods [1][2][5][8].The need to develop an effective method of control requires the development of a complete mathematical model that describes the behavior of all of the studied wind turbine [5][6], introducing all the phenomena that affect the results, such as the flexibility of the different elements of a whole.

Wind turbines are highly flexible machines operating in stochastic environments and modeling these systems requires knowledge from across a range of typical engineering and atmospheric science disciplines, most work in this topic describes the dynamic model of wind turbines such as shaft transmission model, by ignoring flexibility turbine modes [2][3]. In our model, we introduce flexible blades, tower and drive shaft transmission. This flexibility induces resonance and non-resonance flexible modes that may cause the system oscillations. These last may affect the stability of system and cause damage to the blades and other components by stress.

The wind turbine model is built from several sub models or components models, this model describe the combined interaction by the wind and pitch angle with the aerodynamics of the rotor to produce the torque on the main shaft and the forces on the tower and blade. This torque is converted to electrical power through the gearbox and the induction generator, measured power is feedback through the pitch controller to the pitch system that changes this actual pitch angle, these models are interconnected to form the total model, the follow figure present the interaction between its sub-models.

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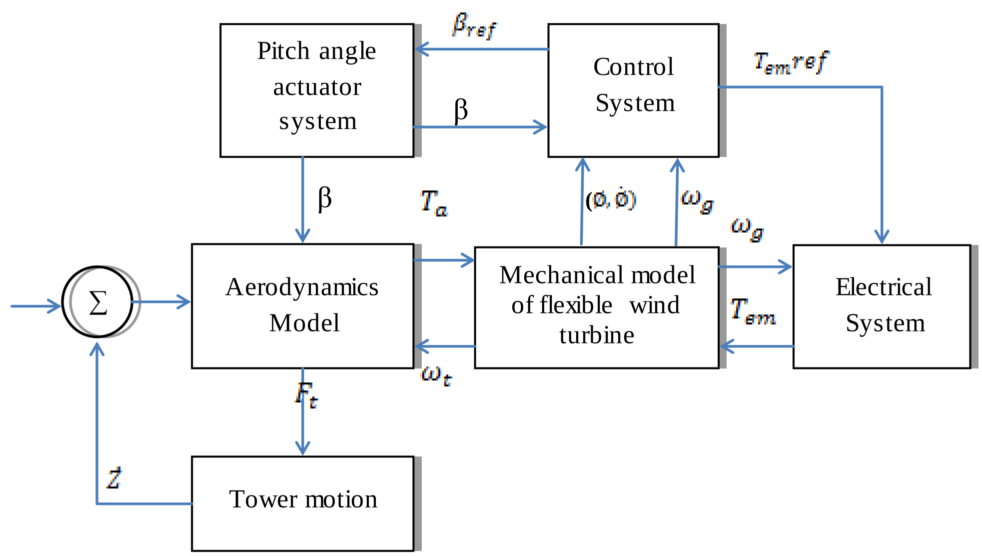

Figure 1: horizontal wind turbine sub-models structure

Modeling of flexible wind turbine

1.1. Aerodynamics Model

The model of interaction wind turbine permits the description of the incidental wind on the blades of the wind turbine, in order to do the conversion of the kinetic energy of the wind into mechanical speed energy. This process generate aerodynamic torque and traction force function of blade pitch angle and wind velocity and flexibility of blade, as it shown in the following schema. Aerodynamic power is done with the following expression [ ]:

$$P_a = \frac{1}{2}\rho R^2 C_p(\lambda, \beta) V^3 \tag{1}$$

$$T_a = \frac{1}{2}\rho R^2 C_p(\lambda, \beta) V^2 \tag{2}$$

Where:

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$$C_p = \frac{P_a}{P_v} \qquad (3)$$

Is the so-called power coefficient, β is the blade pitch angle, and λ is the tip speed ratio. The power coefficient can be calculated by an analytical approximation, the approach is defined as follow:

$$c_p(\lambda,\beta) = (\frac{c1}{\tilde{\lambda}} - c_2\beta - c_3)e^{-\frac{c_4}{\tilde{\lambda}}} + c_5\lambda \qquad (4)$$

With

$$\frac{1}{\tilde{\lambda}} = \frac{1}{\lambda + c_6} + \frac{c_7}{\beta_3 + c_8} \qquad (6)$$

$$\lambda = \frac{R\omega}{v} \qquad (7)$$

Thus any change in the rotor speed or the wind speed induces change in the tip speed ratio leading to power coefficient variation. In this way, the generated power is affected.

Figure.2 Shows a group of typical $C_p(\lambda,\beta)$ curves where optimum values of tip speed ratio, λ_{opt} correspond to the maximum power coefficient, $C_{p\max}$

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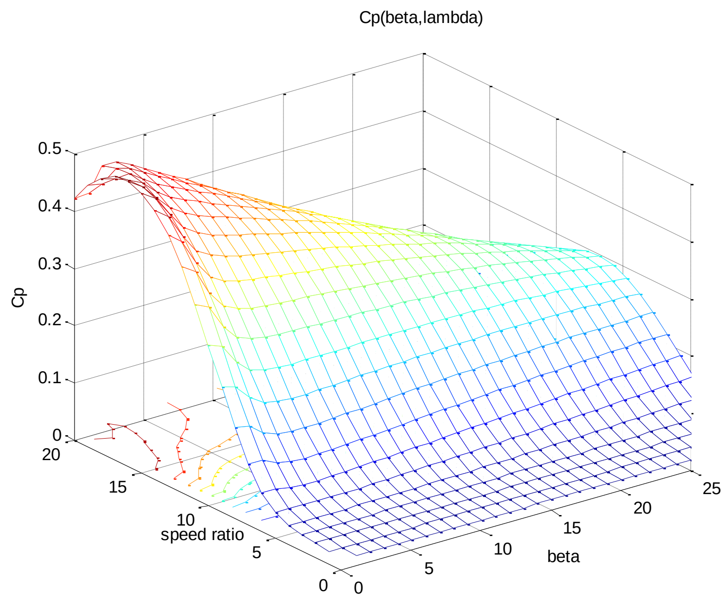

Figure 2 : Power coefficient curves

1.2. Structural Model

In this section a mechanical model of flexible wind turbine is developed including deformations due to the flexibility of the blades, the tower and the main shaft. The drive-train, is modeled as two rigid bodies linked by a flexible shaft.

Tow references systems have been defined, one attached to the base of the tower $S_1(o_1, x_1, y_1, z_1)$ and another attached to the blade and shaft joint $S_2(o_2, x_2, y_2, z_2)$. The set of generalized coordinates of the model of the wind turbine is defined as $q = \left[\theta, \varphi, \theta_r, \theta_g\right]^T$, where θ is the angular position of the tower, φ is the angular position of

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the blade out of the plane of rotation, θ_r is the angular position of the rotor, and θ_g is the angular position of the generator. Figure3 shows the reduced dynamic structure of flexible wind turbine.

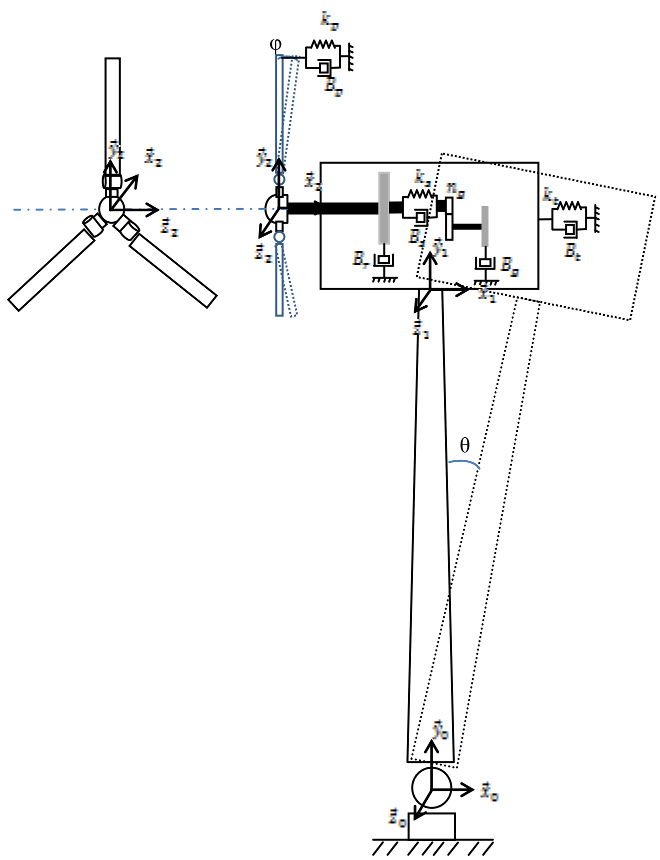

Figure 3 : Structural model of flexible wind turbine

This dynamical equation of flexible wind turbine is given by the flowing Lagrange method.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} + \frac{\partial E_d}{\partial \dot{q}} = Gu \tag{8}$$

$$L = E_k - E_p \tag{9}$$

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Where E_k, E_d and E_p is the kinetic, dissipative, and potential energies, respectively, and G the input control matrix with the control input defined as $u=\left[F_t,T_r,T_g\right]^T \in \mathbb{R}^3$ with T_g and T_r being the generator and aerodynamic torques, respectively, and the thrust forces distributed along each blade were replaced by a lumped F_T applied at a distance r_b from the axis of rotation.

The kinetic E_k and dissipative E_d energies are given, respectively, by

$$E_k=\frac{3}{2}m_p\left[(h^2+a^2+Ra\sin\phi+\frac{R^2}{6}(1+\sin^2\phi))\dot{\theta}^2+RH\cos\phi\dot{\phi}\theta+\frac{R^2}{3}\cos^2\phi\dot{\theta}_r^2+\frac{R^2}{3}\dot{\phi}^2\right]+\frac{I_t}{3}\dot{\theta}^2+\frac{J_r}{2}\dot{\theta}_r^2+\frac{J_g}{2}\dot{\theta}_g^2 \tag{10}$$

$$E_d=\frac{1}{2}(B_t\dot{\theta}^2+3B_p\dot{\phi}^2+B_s(\dot{\theta}_r-\frac{\dot{\theta}_g}{n_g})^2+B^r\dot{\theta}_r^2+B_g\theta_g^2) \tag{11}$$

While the potential energy E_d can be decomposed as

$$E_p=E_g+E_f+E_t \tag{12}$$

With

$$E_g=3m_pg(H(1-\cos\theta)-a\sin\theta)+m_tgH(1-\cos) \tag{13}$$

$$E_f=\frac{k_t}{2}\theta^2+3\frac{k_p}{2}\phi^2 \tag{14}$$

$$E_t=\frac{k_s}{2}(\theta_r+\frac{\theta_g}{n_g})^2 \tag{15}$$

Where E_g is due to the gravity action, E_f is due to the flexibility of blades and the tower, and E_t is due to the torsion along the shaft referred to low speed. Let $\theta_s=\theta_r-\theta_g/n_g$ be the torsion angle, thus redefining a new set of generalized coordinates

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as $q = \left[\theta, \phi, \theta_s, \theta_g\right]^T$ and linearizing Lagrange's equation, the equation of motion becomes

$$M\ddot{q} + C\dot{q} + Kq = Gu \tag{16}$$

$$M = \begin{bmatrix} m_1 & m_2 & 0 & 0 \\ m_2 & m_3 & 0 & 0 \\ 0 & 0 & m_4 & m_4 / n_g \\ 0 & 0 & 0 & m_6 \end{bmatrix} \tag{17}$$

With

$$m_1 = H^2 + a^2 + m_p \frac{R^2}{2}(1 + \sin^2 \varphi_{eq}^2) + Ra \sin \varphi_{eq} + I_t$$

$$m_2 = \frac{3}{2} m_p RH \cos \varphi_{eq}$$

$$m_3 = m_p R^2 + I_p$$

$$m_4 = m_p R^2 \cos \varphi_{eq} + J_r$$

$$m_5 = J_g$$

$$C = \begin{bmatrix} B_t & 0 & 0 & 0 \\ 0 & 3B_p & 0 & 0 \\ 0 & 0 & B_r + B_s & \frac{-B_s}{n_g} \\ 0 & 0 & \frac{-B_s}{n_g} & B_g + \frac{B_s}{n_g^2} \end{bmatrix} \tag{18}$$

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$$K=\begin{bmatrix} k_t & 0 & 0 & 0 \\ 0 & 3k_p & 0 & 0 \\ 0 & 0 & k_s & \dfrac{-k_s}{n_g} \\ 0 & 0 & \dfrac{-k_s}{n_g} & \dfrac{k_s}{n_g^2} \end{bmatrix} \tag{19}$$

Finally the matrix control read

$$G=\begin{bmatrix} 3H\cos\theta_{eq} & 0 & 0 \\ 3r_b\cos\phi_{eq} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{20}$$

The dynamic system can be decomposed to three subsystem as shown in (21)(22)(23); the first subsystem given by (21) corresponding to flexibility of the blade and tower, second subsystem given by (22) corresponding to the torsion of the shaft, and subsystem 3 given by (23) corresponding to the rotational dynamics of the generator.

$$\frac{d}{dt}\begin{bmatrix}\theta \\ \varphi \\ \dot{\theta} \\ \dot{\varphi}\end{bmatrix}=\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_5 & a_6 & a_1 & a_2 \\ b_1 & b_2 & b_1 & b_2 \end{bmatrix}\begin{bmatrix}\theta \\ \varphi \\ \dot{\theta} \\ \dot{\varphi}\end{bmatrix}+\begin{bmatrix}0 \\ 0 \\ a_7 \\ b_7\end{bmatrix}F_T+\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & a_3 \\ 0 & b_3 \end{bmatrix}\begin{bmatrix}\theta_s \\ \dot{\theta}_s\end{bmatrix}+\begin{bmatrix}0 \\ 0 \\ a_4 \\ b_4\end{bmatrix}\dot{\theta}_g \tag{21}$$

$$\frac{d}{dt}\begin{bmatrix}\theta_s \\ \theta_s\end{bmatrix}=\begin{bmatrix} 0 & 1 \\ c_5 & c_2 \end{bmatrix}\begin{bmatrix}\theta_s \\ \theta_s\end{bmatrix}+\begin{bmatrix}0 \\ c_7\end{bmatrix}Tg+\begin{bmatrix}0 \\ c_6\end{bmatrix}Tr+\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & c_1 \end{bmatrix}^T\begin{bmatrix}\theta \\ \varphi \\ \dot{\theta} \\ \dot{\varphi}\end{bmatrix}+\begin{bmatrix}0 \\ c_3\end{bmatrix}\dot{\theta}_g \tag{22}$$

$$\frac{d}{dt}\dot{\theta}_g=d_2\theta_g+\begin{bmatrix} d3 & d1 \end{bmatrix}\begin{bmatrix}\theta_s \\ \dot{\theta}_s\end{bmatrix}+d_4T_g \tag{23}$$

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1.3. Pitch Angle actuator system

The pitch angle system allows the blades to adjust the lift forces to keep the power around the nominal value by setting the pitch angle.It acts on the performance of the wind turbine and more precisely on the power coefficient. The pitch angle system generates a blade pitch angle reference that notes β_{reg}. The dynamics of the actuator pitch is generally described by the transfer function following first order:

$$\frac{1}{1+\tau_\beta S} \qquad (24)$$

When modeling the pitch system angle, it is very important to model the rate of change of this angle. Indeed, considering the forces experienced by the blades, the variation of the pitch angle should be limited to 10 ° / s. The saturation value of the pitch angle position is 45°.

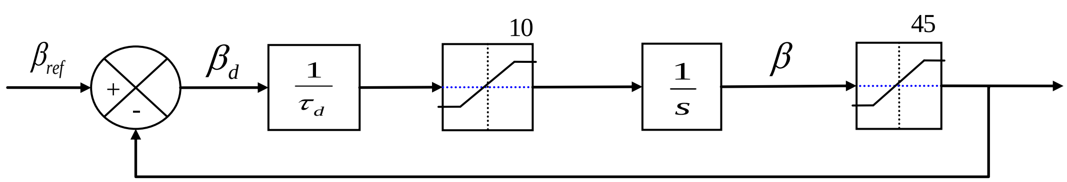

Figure 4: Actuator pitch system model

2. Results and discussion

In this section, we present the results obtained with the computational tools based on the developed model. Simulation where carried out for a standard three blades HAWT with 35 m blades and 80 m tower.

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In the presented work, the cases of study focus on the response of flexible wind turbine for different wind conditions, while keeping the pitch angle fixed. To attain this aim we consider three responses. Firstly, an impulse signal is applied on the system, we extract its behavior's responses. Secondly, we applied a constant wind speed of 18 m/s. A variable wind sped around 12 m/s has been applied on the system finally.

In these results we compare and discuss the behaviors of system with and without blade and tower flexibility and its influence on output of system. The table 1 presents the mechanical parameters simulation of HAWT wind turbine.

Table 1:Wind turbine simulation parameters

Symbol	description	Value
m_t	Mass of the tower	1.6547e10^{6}Kg
m_p	Mass of the blade	5250Kg
I_t	Inertia of the tower	8.10^{9}Kg.m²
I_p	Inertia of the blade	7.5.10^{7}Kg.m^{2}
J_r	Rotor Inertia	55.10^{6}K.m²
J_g	Generator Inertia	390Kg.m²
K_t	Stiffness of the tower	2.55.10^{10} N.m^{-1}
K_p	Stiffness of the blade	1.2738.10^{9}N.m^{-1}
K_s	Stiffness of the transmission	2.710^{9}N.m^{-1}
R	Length of blade	35m
H	Height of blade	82.39m
a	Length of the nacelle	3.3m
B_t	Damping of the tower	66.710^{5}Nmsrad^{-1}
B_p	Damping of the blade	25.69.10^{5} Nmsrad^{-1}
B_s	Damping of the transmission	945.10^{3} Nmsrad^{-1}
B_r	Rotor external damping	34600 Nmsrad^{-1}
B_g	Generator external damping	3.034 Nmsrad^{-1}
n_g	Gearbox ratio	85

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2.1. Impulse Response

In this part, the dynamic behavior of system for impulsion Input with a time series is presented.

The figure 5 shows the response of blade and tower bending and vibration speed. It can be observed that the blade reaches the equilibrium before the tower and its deformation is important.

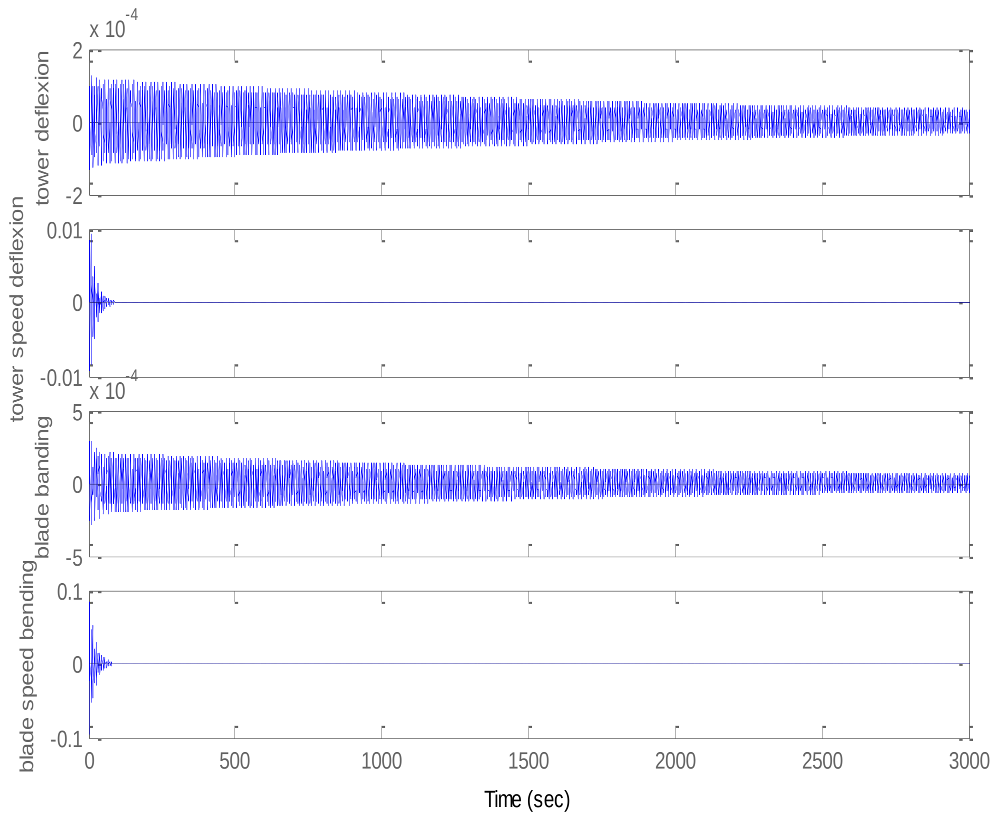

Figure 5 : blade and tower response for step response

The figure 6 shows the torsion angle and torsion speed for transmission shaft for impulse response, as we can see the interval of torsion, speed of torsion and time of equilibrium.

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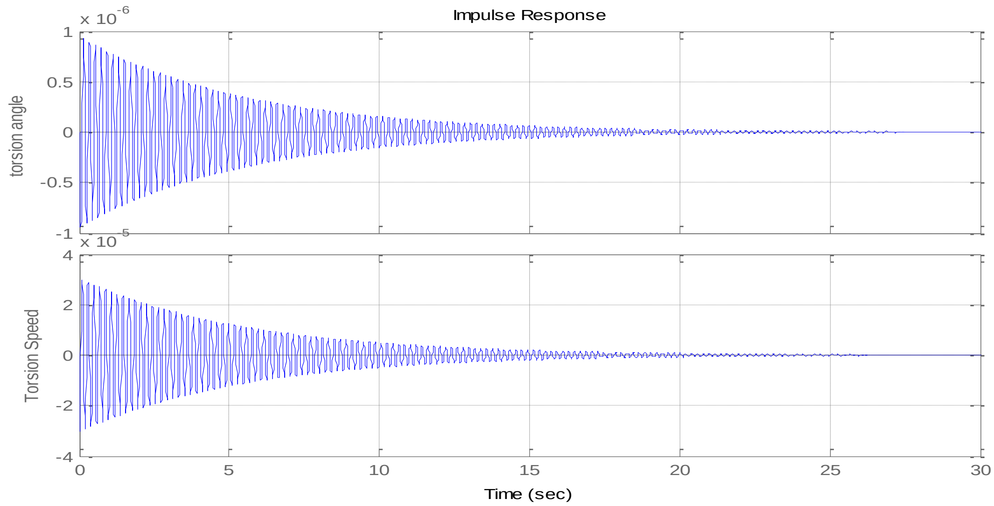

Figure 6 : Impulse Response for shift transmission Torsion

2.2. Response with constant wind speed

In this part, the result obtained for wind turbine behaviors for constant wind speed is presented; a steady wind speed of 18 m / s is applied on system. Figures 7 and 8 show, respectively, the deformation of blade and tower flexibility in time series, and the figure 9 presents a comparison between speed of tower bending and blade flapwise.

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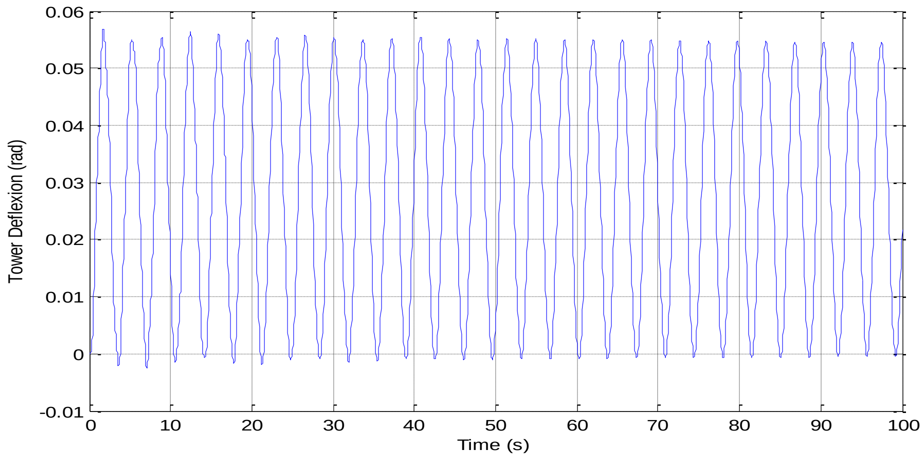

Figure 7 : Tower Defluxion for Step Response

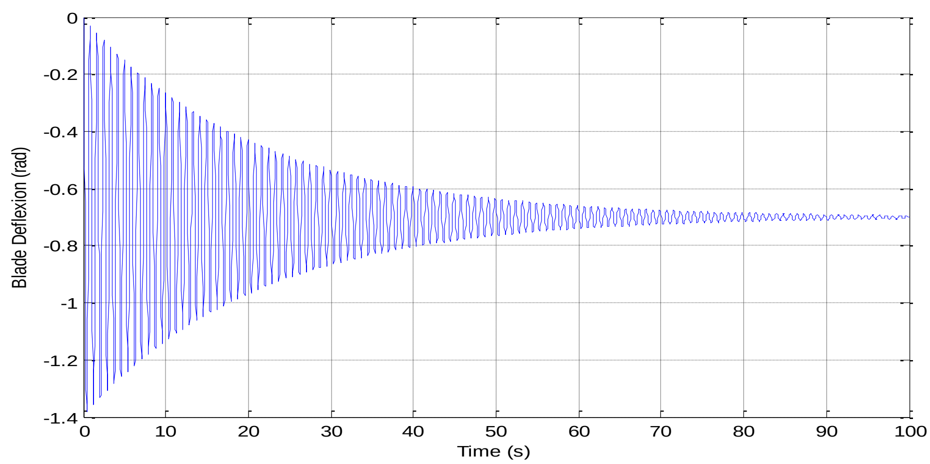

Figure 8 : Blade Flapwise for Step Response

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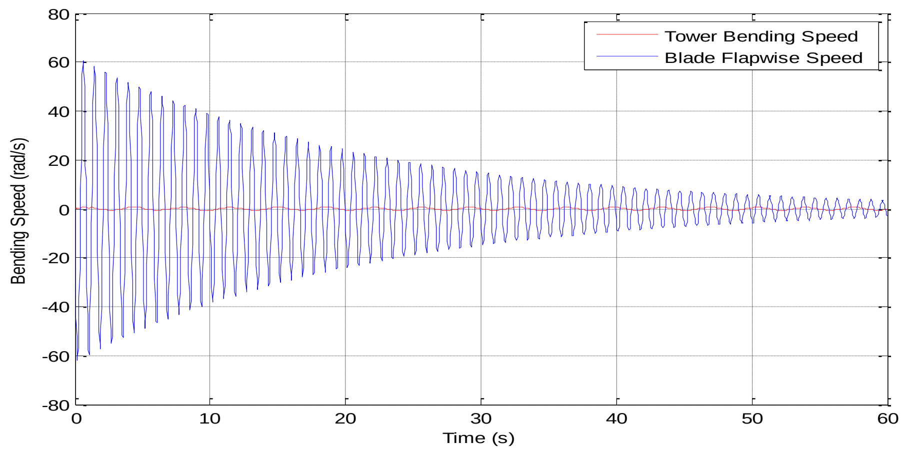

Figure 9 : Blade and Tower Bending Speed for Step Response

The figures from 10 to 12 show the effects of blade and tower flexibility for shaft transmission torsion and generator speed. We note that small fluctuation added to the transmission shaft vibration, increase the amplitude of deformation and its speed.

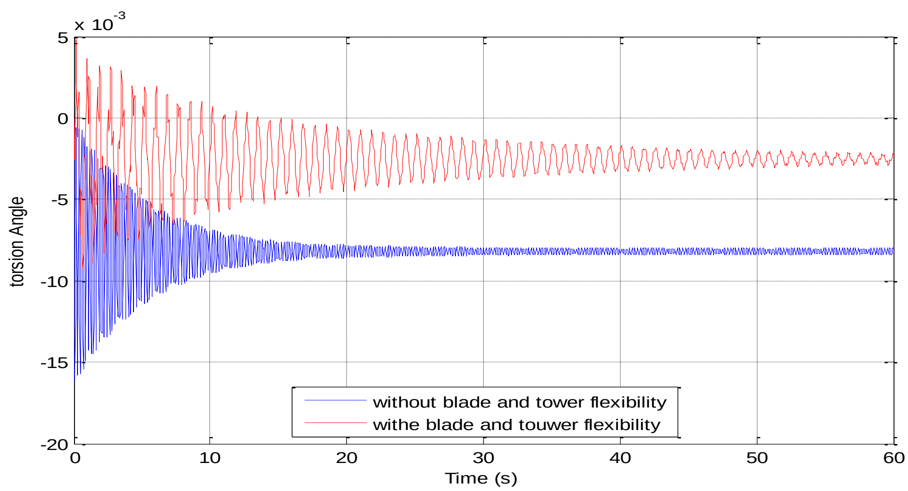

Figure 10 : Tower and blade flexibility influence of shaft transmission torsion angle.

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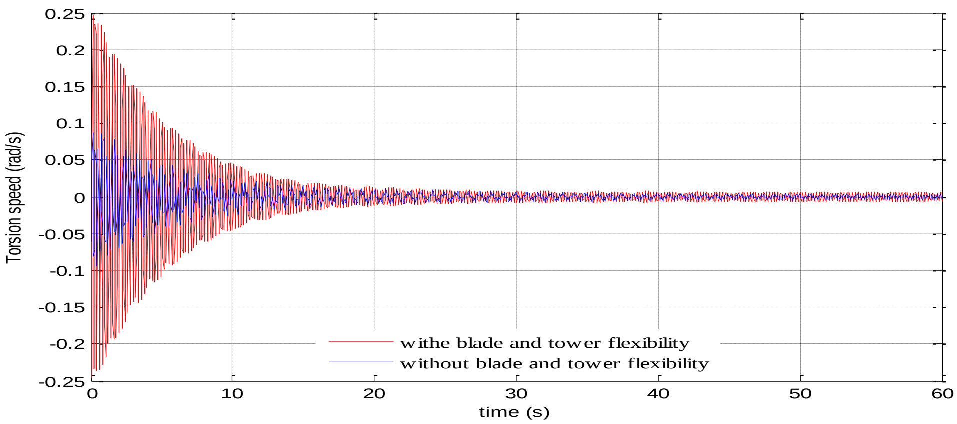

Figure 11 : Tower and blade flexibility influence of shaft transmission speed torsion.

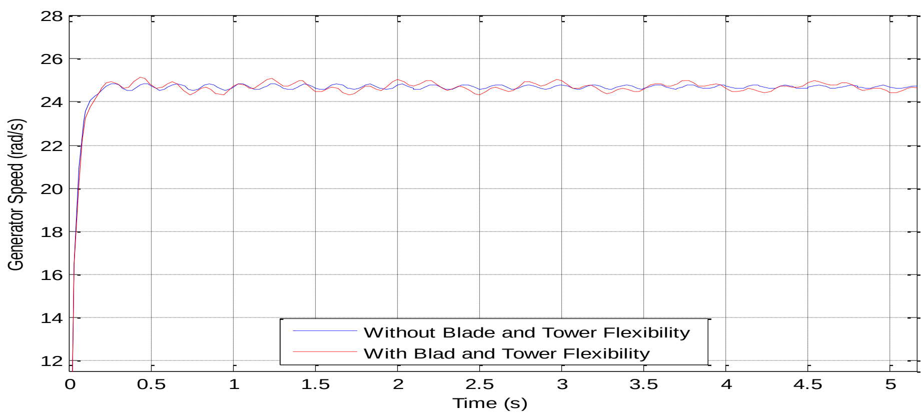

Figure 12 : Generator Speed with and without Tower and blade flexibility

2.3. Response with variable wind speed

To examine the model in real conditions, we applied a variable stochastic wind speed on system.

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Wind modeling

The modeling of wind turbine requires the knowledge of wind speed variation over time; however, this source is unpredictable and difficult to reproduce. The wind can be schematized by stochastic process with two components (stationary and turbulent):

The stationary $V_m(t)$ slowly varies and the turbulent $g(t)$ has high frequency variation.

$$V = v_m(t) + g(t) \tag{25}$$

Where

V is the wind speed

The statistical characteristic of the random part can be defined by a spectral power density of turbulence as that associated with Vonkarman model.

The turbulence spectral density, $S_v(\omega)$ as that associated with Vonkarman model is :

$$S_v(\omega) = \frac{0.475\sigma^2 \frac{L}{u_m}}{(1+(\frac{\omega L}{u_m})^2)^{\frac{5}{6}}} \tag{26}$$

Where L is the length of wind turbine, U_m is the Average velocity of wind and σ_v is the standard deviation of the wind speed.

The turbulence intensity is defined as:

$$\mathrm{I} = \frac{\sigma_v}{u_m} \tag{27}$$

The time series of the wind can be generated using the Shinozaki formula [2].

$$u_\infty = u_m + \sqrt{2}\sum_{J=1}^{N} S_V(\omega_j)\Delta\omega.\cos(\omega_j t + \psi_j) \tag{28}$$

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With ω_f is the frequency of order j, $\Delta\omega$ is frequency increment and ψ_j is the random phase. Figures 13 and 14 represent the variable wind speed profile with medium speed equal 12m/s in 60s, and the aerodynamic torque.

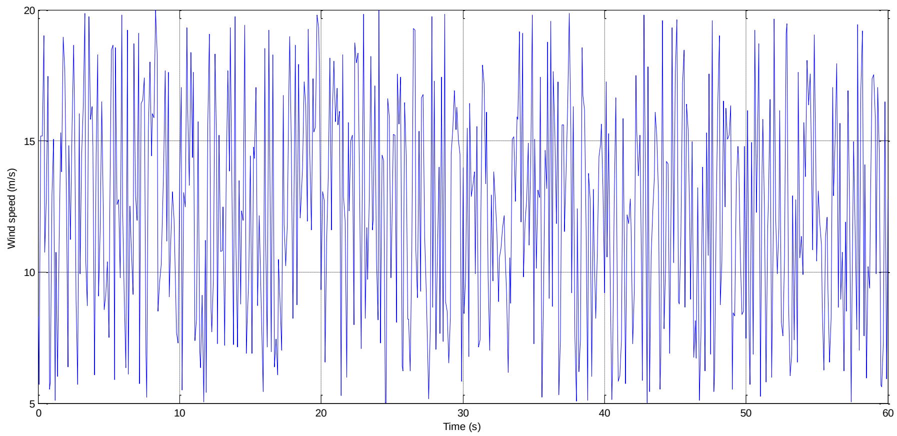

Figure 13 : Variable Wind Profile

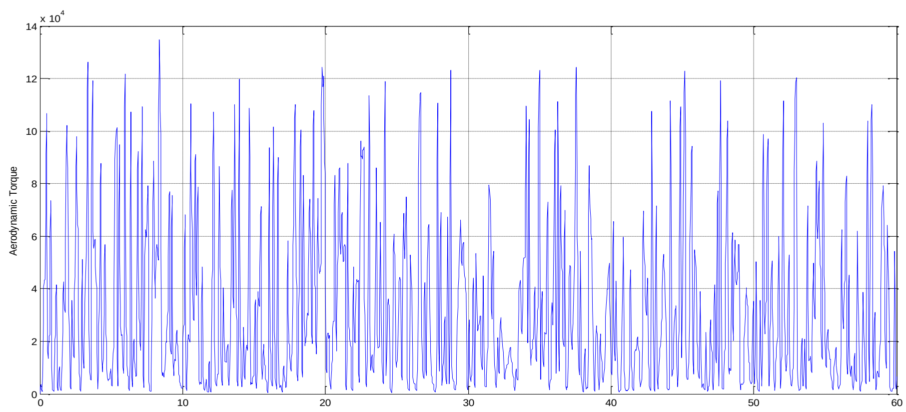

Figure 14 : aerodynamic Torque

The figure 15 shows the blade and tower bending, it can be observed that the blade has high deformation than tower.

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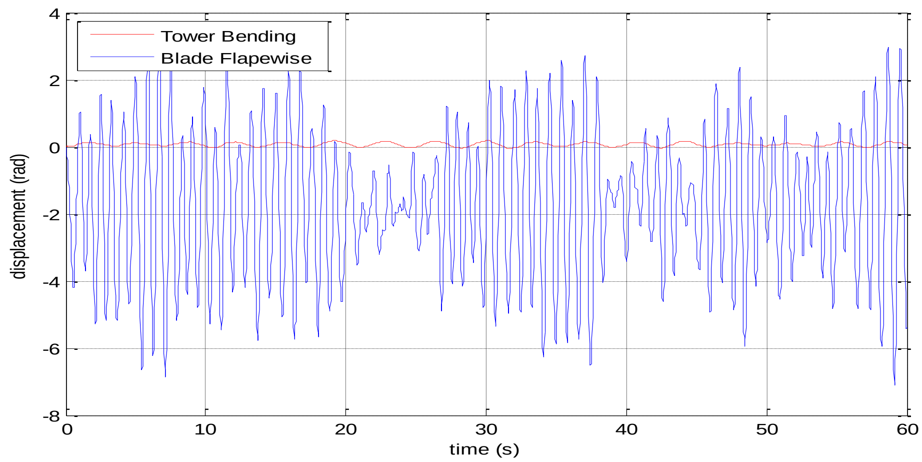

Figure 15 : Tower Bending and Blade Flapwise for variable wind speed input

The influence of flexibility of blade and tower on transmission shift torsion and speed are shown in figure 16.

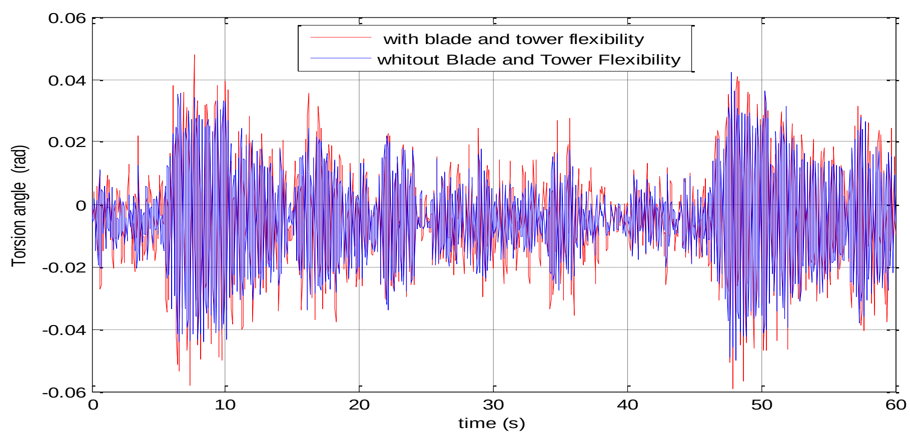

Figure 16 : Shaft Transmission Torsion Angle with and without flexible of blade and tower

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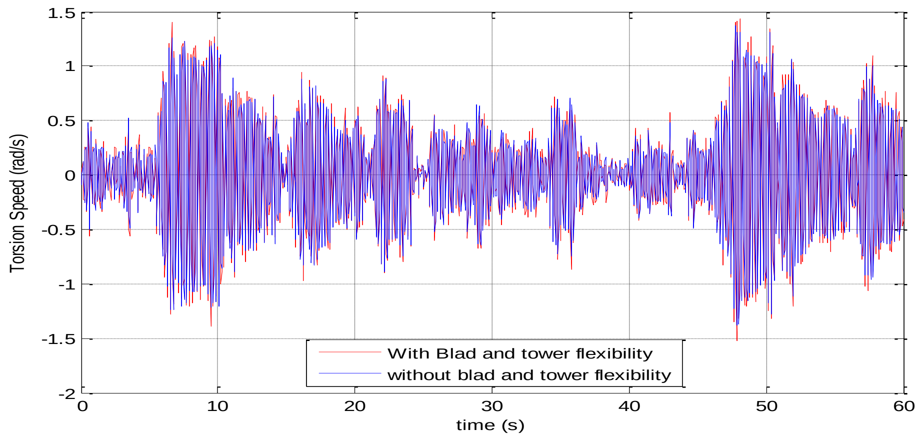

Figure 17 : Shaft Transmission Torsion Speed with and without flexible of blade and tower

The figure 18 shows the effect of flexibility of blade and tower on generator speed, we note as its act is negligible.

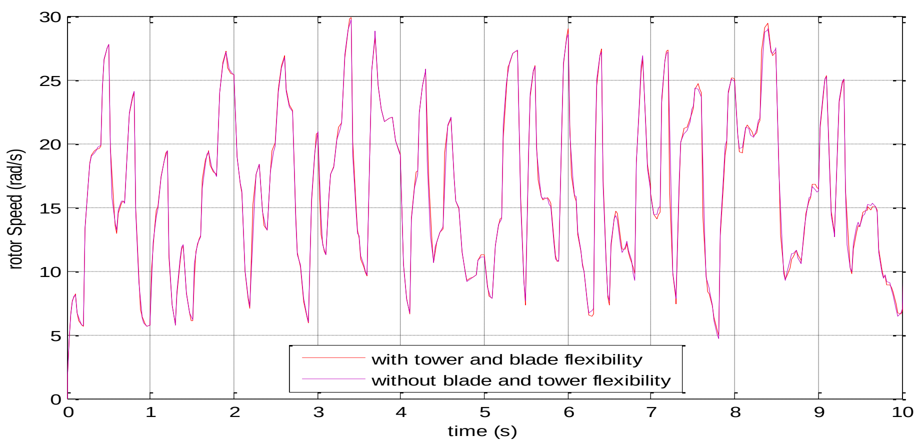

Figure 18 : Generator Speed with and without flexibility of blade and tower

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Conclusion

The model presented in this paper is a reduced flexible wind turbine, is relatively simple and it's included the necessary dynamics. The specific model is suited for control design due to the low of states space; it can be used to develop an algorithm for control power and vibration of flexible bodies of wind turbine, this last one need a good knowledge for the dynamic behavior of system. However, three responses are exanimated for study the behavior of different flexible components of system (blades, tower, shaft transmission and generator speed), and its influence on the developing control of system.

References

[1]. B.Boukhezzara.L.Lupua, H.Siguerdidjane, M.Handb "Multivariable control strategy for variable speed, variable pitch wind turbines" Renewable Energy 32 (2007) 1273–1287

[2]. B.ayyat "Techniques avancées de contrôle des aérogénérateurs à base d'observateurs de la vitesse du vent » Phd thesis, Faculty of sciences- Tétouan 2010

[3]. Martine.O.L.Hansen " Aerodynamics of Wind Turbine" , Second edition published by Earthscan in the UK and USA in 2008

[4]. Furat Abdal Rassul Abbas and ohammed Abdulla Abdulsada "Simulation of Wind-Turbine Speed Control by MATLAB", International Journal of Computer and Electrical Engineering, Vol. 2, No. 5, October, 2010, 1793-8163

[5]. Alan D. Wright "Modern control design for flexible wind turbine" Technical Report National renewable energy laboratory–colorado.USA

[6]. R. Oulad Ben Zarouala,C. Vivas, J. ´ A. Acosta, and L. El Bakkali "On Singular Perturbations of Flexible and Variable-Speed Wind Turbines" International Journal of Aerospace Engineering Volume 2012

[7]. Fangfang Songa, Yihua Ni, Zhiqiang Tan "Optimization Design, Modeling and Dynamic Analysis for Composite Wind Turbine Blade", Procedia Engineering 16 (2011) 369 – 375

[8]. Patrick J. Moriarty and Sandy B. Butterfield "Wind Turbine Modeling Overview for Control Engineers" 2009 American Control Conference Hyatt Regency Riverfront, St. Louis, MO, USA, June 10-12, 2009

[9]. M. Jureczko, M. Pawlak, A. Mezyk "Optimization of wind turbine blades" Journal of Materials Processing Technology 167 (2005) 463–47

[10]. J.G HOLIERHOEK "Aeroelasticity of Large Wind Turbines", PhD thesis, Technische Universiteit Delft, 2008.