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Modeling and PI Control of Spar Offshore Floating Wind Turbine

Manikandan R. * **Nilanjan Saha** **

* Department of Ocean Engineering,IIT Madras Chennai, India
(e-mail: mkaucbe@gmail.com).
** Department of Ocean Engineering,IIT Madras Chennai, India
(e-mail:nilanjan@iitm.ac.in).

Abstract: Reliable control strategies are necessary for long term operation of offshore wind turbines because they are sited in severe environment. Offshore wind turbines experience environmental loads like wind, wave and current. This paper proposes a stratagem of applying the proportional integral (PI) control algorithm in the blade pitch mechanism of a 5 MW benchmark NREL offshore wind turbine (Jonkman et al., 2009) in a LABVIEW environment. Owing to the irregular wind and waves, the platform will be unstable which in turn affects the overall stability of the turbine. The turbine is assumed to be installed in water depth of 320 m on a spar platform. The spar when subjected to the wave loads, exhibit irregular and chaotic responses. The primary objective is to control the pitch so as to obtain optimum generated power. The control algorithm has to be effective in two regions of operation *viz.*, in controlling power in operational wind speeds and also to keep the wind turbine safe in extreme severe wind conditions. In this process, the control techniques vary the blade pitch angle for generating optimum power production as well as stable closed loop operation. Numerical results and simulations are shown to validate the proposed methodology and to demonstrate its effectiveness.

Keywords: NREL 5 MW reference wind turbine, Spar, pitch control, proportional integral

1. INTRODUCTION

Energy is a very important resource and it is a major requirement for overall socio-economic development. Worldwide energy demand is rapidly increasing. Western countries such as the US, Canada, and the UK, consume the largest amount of energy, mostly from the fossil fuel sources. Use of fossil fuels is expected to fuel the economic development process of a majority of the world population during the next two decades (Spera, 2009). However, at some time during the period $2020 - 2050$, fossil fuels are likely to reach their maximum potential, and their price will become higher than other renewable energy options on account of increasingly constrained production and availability. Therefore, renewables (wind, solar, geothermal, hydroelectric, tidal) are expected to play a key role in accelerating development and sustainable growth in the second half of the next century, accounting then to 50% to 60% of the total global energy supply. Wind energy is a fast-growing interdisciplinary field. The global installed capacity of wind turbines is growing at an average rate of 27% per year. Most state of the art horizontal axis wind turbines extract power from wind by converting the air flow through a three bladed rotor to mechanical energy, which is converted into electric power by a generator. They can be placed either on land or offshore (Jonkman, 2010). The wind energy resource is a random process and the stochastically controlled energy extraction from wind is being actively pursued. The wind power output for a 5 MW wind turbine increases approximately till mean wind speeds of 12 m/s and then remains constant till speeds of 25 m/s. After 25 m/s, the situation is case for an idling turbine when no power is extracted. The mean wind speeds in range of $12 - 16$ m/s *i.e.*, around the rated wind speeds, is recommendable for generation of electricity. Since the wind speed is a random process therefore, the wind power demands changes and the power is also fluctuating. In other words, the wind speed can be very high resulting in power generation that exceeds the demand of the load. This might lead to the turbine exceeding its rotational speed rating and subsequent damage to the turbine. On the other hand, the wind speed can be too low for any power production. The fact that one has no control over the energy source input, the unpredictability of wind and the varying power demands are enough concerns to justify the need for a controller, which will regulate all the parameters that need to be controlled for a matched operation of the wind turbine.

In Laks et al. (2009), they studied the control challenges of both onshore and offshore wind turbine. Even though several studies related to offshore wind turbines but it has been limited to concentrate on the role and importance of controls, because the energy capture of wind turbines are not only on the wind conditions, it also depend on the control mechanism used in the wind turbine operation. Hinrichsen (1984) studied the control requirement of wind turbine generators connected to electric power systems and examined the operation of 2.5 MW wind turbine with induction generators and concluded that designed PI controller allows wind turbines to respond to changes in

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electrical load. Hand (1999) developed a variable speed wind turbine controller in systematic manner and illustrated the robust nature of PI controller and concludes that PI controller is very robust in variable speed wind turbine application. Malinga et al. (2003) has examined the performance estimation, modeling, linearization and control of wind turbine and designed the PI controller using conventional Ziegler-Nichols methods and shows visually the effect of performance of the controller and conclude that an alternative approach must be needed for obtaining the gain values of the PI controller. Wright (2004) applied modern statespace control design methods to a two bladed teetering hub upwind machine and compared the results of modern control techniques with classical controls. Bati and Leabi (2006)has presented a adaptive neural networks self-tuning controls system to a wind turbine in different operating conditions. Wright and Fingersh (2008) studied information about designing, implementing and testing advanced control systems for wind turbines and illustrated the use of available control design tools as well as the steps involved with designing and implementing advanced controllers. Pao and Johnson (2011) proposed different approaches, challenges involved in both offshore and onshore wind turbines. The linear parameter varying schemes and robust controller are investigated and applied to 4.8 MW wind turbine Østergaard et al. (2009). In Namik and Stol (2011), an individual blade pitch state space and disturbance accommodating control were proposed to load reductions of 5 MW wind turbine mounted on barge and TLP. Schlipf et al. (2013) using a model predictive control techniques to reduce wind turbine extreme and fatigue loads on tower and blades as well as to limit the pitch rates. The results addressed that load reduction up to 50% for extreme gusts and 30% for lifetime fatigue loads without negative impact on overall energy production. In Manikandan and Saha (2011), the authors have tried soft computing methods like particle swarm optimization and bacteria foraging optimization algorithm in controlling wind turbine.

In the present study, a PI based controller is implemented using LABVIEW tool to limit the pitch angle for NREL 5 MW benchmark offshore wind turbine. This would help the users to add-on additional control algorithms of their choice in the requisite block. The following section §2 describes the numerical modeling of the system. Then, the brief description of problem formulation and controller design are explained in §3. The results were presented in the section §4. The paper ends with the salient conclusions drawn in section §5.

2. NUMERICAL MODELING OF OFFSHORE WIND TURBINES

2.1 The Model

The kinetic energy, $\mathcal{U}$, of a parcel of air of mass m flowing at upstream speed u_{up} in the axial direction (x-direction) of the wind turbine is given by

$$\mathcal{U} = \frac{1}{2} m u_{up}^2 = \frac{1}{2} (\rho \mathcal{A} x) u_{up}^2 \,. \tag{1}$$

Here, $\mathcal{A}$ is the cross-sectional (swept) area of the wind turbine, ρ is the air density, and x is the thickness of the wind parcel. The power in the wind P_w is the time derivative of the kinetic energy and is given in (2), which represents the total power available for extraction, i.e.,

$$P_w = \frac{dU}{dT} = \frac{1}{2} \rho \mathcal{A} u_{up}^2 \frac{dX}{dT} = \frac{1}{2} \rho \mathcal{A} u_{up}^3 \,. \tag{2}$$

The extracted power is usually expressed in terms of the wind turbine swept area $\mathcal{A}$, because the upstream cross–sectional area is not physically measurable as the cross–sectional area of the wind turbine. The fraction of actual power extracted to the theoretical available power in the wind by practical turbines is expressed by the coefficient of performance C_p. The actual mechanical power (P_m) extracted can be written as:

$$P_m = C_p P_w = C_p \left(\frac{1}{2} \rho \mathcal{A} u_{up}^3 \right) \tag{3}$$

The value of C_p is highly non-linear and varies with the wind speed, the rotational speed of the turbine, and the turbine blade parameters such as pitch angle. The control sequence maintains a constant angular speed and constant power P_m. Only the angular speed is given a feedback to accommodate the wind speed fluctuations because controlling the angular speed would control the aerodynamic torque (τ_A). The tip speed ratio λ is defined as the ratio between the rectilinear speed of the turbine tip, $\vartheta_0 R$, and the wind speed u_{up} as

$$\lambda = \frac{\vartheta_0 R}{u_{up}} \,. \tag{4}$$

Another variable used to evaluate the wind turbine performance is the coefficient of torque C_t. The torque coefficient C_t, is related to the power coefficient C_p through the parameter λ. The aerodynamic actual torque τ_A developed by the rotor that turns the rotor shaft is related to the torque coefficient C_t by

$$\tau_A = \frac{1}{2} \rho \mathcal{A} R C_t u_{up}^2 \,. \tag{5}$$

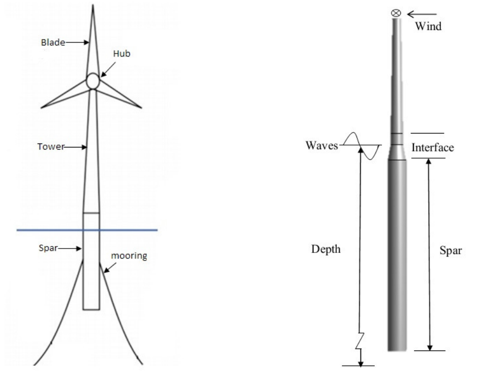
If the torque coefficient is tuned, then the power produced by the turbine would also be tuned. The wind turbine mechanical power P_m is equal to the product of the aerodynamic torque τ_A and rated low-speed shaft rotational speed the rotational speed ϑ_0, which is

$$P_m = \tau_A \times \vartheta_0 \,. \tag{6}$$

Using the above (4), (5) and (6), one can model the wind turbine machine.

2.2 System description

The present study considers an offshore 5 MW wind turbine (Jonkman et al., 2009), which is variable speed with full span blade pitch control and generator torque regulation. Its numerical model obtained from FAST code(Jonkman and Bull Jr, 2005), which is explained in subsequent sections and schematic view is shown in the Fig.1. The structure of a three–bladed wind turbine is modelled by an optional 24 degrees of freedom (DOF), which represents *e.g.*, the flexibilities of the blades, the tower, and the drive-train. However, the translational and rotational displacements of the structure are also presented. The modal representation can present both 1−st and 2−nd mode flexibilities of the structures. The physical properties of the plant model are reproduced in Table 1. The Spar-buoy platform is modeled for the support structure and the details are briefly reported in Aggarwal et al. (2014).



(a) Schematic view (b) Hydrodynamic model of spar

Fig. 1. Catenary moored spar based floating offshore wind turbine

Table 1. FOWT specifications

Power output	5 MW
Blades	3
Rotor orientation	upwind
Hub height	90 m
Rotor diameter	126 m
Hub diameter	3 m
Rated Wind Speed	11.4 m/s
Rated Rotor Speed	12.1 rpm
Rated Tip Speed	80 m/s
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower mass	347,460 kg

2.3 Modeling and analysis tools

Herein,the modeling of the systems carried out through executable numerical code FAST (Jonkman and Bull Jr, 2005) which is capable to simulate the fatigue, aerodynamics, structures and turbulence, freely available and developed by the National Renewable Energy Laboratory (NREL). One can model the both two- and three-bladed horizontal axis wind turbines for upwind or down-wind rotors using this code. The code offers flexibility to add subroutines to model the offshore platforms such as sea–based, *e.g.*, a fixed jacket or a spar-buoy foundation, which includes the hydrodynamics and incident wave loads on the structure. The aerodynamics is modelled in AeroDyn (Moriarty and Hansen, 2005) subroutine of the FAST code and it models using blade element momentum theory (Jonkman, 2007). It is of moderate complexity developed to analyze the structural dynamics of horizontal axis wind turbines. FAST models the tower, blades and the drive-train as flexible elements and uses bending mode shapes for the analysis. Each blade has two flapwise and one edgewise bending modes. The tower has two fore-aft and two side-side bending modes. The drive train flexibility is modelled through a linear spring and a damper for the low speed shaft. The nacelle and hub are modelled as rigid bodies. The fidelity of the model can be set by selecting which degrees of freedom are to be enabled in the non linear model. In addition to simulating a wind turbine, FAST allows for a control algorithm to the simulation environment. The wind turbine actuators can be controlled via a user specified control algorithm through a dynamic link library file or through interfacing with SIMULINK or LABVIEW. LABVIEW interface option is selected for custom and complex controllers to be developed quickly. In FAST code solvers provides a fully nonlinear differential equation model with up to maximum degrees of freedom. The model has the following form,

$$M(q,u,t)\ddot{q} + f(\dot{q},q,u,u_d,t) = 0 \tag{7}$$

where M is the turbine mass matrix, f is the non linear function vector, q is the vector of degrees of freedom (DOF-s) displacement, u is the vector of control inputs, u_d is the vector of disturbances and t is the time.

3. PROBLEM FORMULATION AND CONTROLLER DESIGN

The control of blade pitch angle is to improve the overall performance of offshore wind turbines to obtain desired power output. Note that this can also be done by controlling the platform pitch motion, or yaw control of the nacelle. The concept behind is to limit the blade pitch angle to maintain the rotor speed in above rated region, so that the electrical power output is limited. The work develops a control algorithm which will continuously decide/alter the pitch response of the blade of the wind turbine based on the dynamic input of wind-speed, other necessary inputs of turbine structural properties such as dimensions, masses and moment of inertia. The control algorithm is intended to control the pitch such that the power output beyond rated wind-speeds is controlled and in case of extremely high wind-speeds, the wind turbine's blades are stalled so that the turbine is stopped and impending disasters are averted. A controller has to be implemented, tested and if necessary modified so that the desired output response of the wind turbine parameters are achieved during the simulation. Every controller needs to be tuned according to the specific system that it is getting used for, which in our case is the wind turbine. The present PI controller is meant to be implemented for the 5 MW NREL wind turbine. While the interest of the present work is solely on pitch control, the algorithm will rely on other resources developed for simulating the working of a wind turbine. For instance the controller needs the generator reference speed as an input at every time step. This is done using the FAST code. The various parameters required for tuning the controller are planned to be derived in terms of the turbine properties. Hence this can be implemented on any variable speed variable pitch wind-turbine as long as the turbine properties are known, with suitable modifications.

3.1 Controller design methodology

A baseline controller methodology was used to asses the performance the machine. It having two coupled control loops for below and above rated wind speed working environment. In below rated wind speed, the control objective is to use generator torque to maintain optimum tip speed ratio, thus maintaining peak Cp and maximizing power. In region 2, it is necessary to hold pitch constant. In above rated wind speed, generator torque is held constant at rated torque, and blade-pitch control is used to limit aerodynamic power to maintain constant turbine speed. A Gain Scheduled proportional-integral controller is used to limit the blade pitch angle. One can note that wind turbines allow the rotational speed of the machine to vary with wind speed(Saravanakumar and Jena (2015)). This allows the turbine to operate at near optimum C_p and maximize power over a range of wind speeds. The theory behind the method used and the derivation of appropriate coefficients are explained as follows.

The wind turbine is operated in region 3, where the wind speed is sufficient to cause the generator speed to exceed the rated value, the aim of pitch control to regulate rotor speed to a certain set point to reduce the rated value, thus the difference between the working(ω_G) and the rated generator speed (ω_R) is fed in to the control loop as error value.

$$\mathrm{e(t)} = \omega_{\mathrm{G}} - \omega_{\mathrm{R}} \tag{8}$$

The error term above determines how the pitch control takes place. It is known that in Region 3 generator torque is held constant at rated value, and the blade-pitch control is used to limit the aerodynamic power to maintain a constant turbine speed. A transition region is included between the Regions 2 and 3 to allow the machine to reach the rated torque at a rotational speed. As for the turbine rotor, its dynamics equation is represented by:

$$\tau_A - \tau_E = (\mathcal{J}_R + \eta_G^2 \mathcal{J}_G)\frac{d}{dt}(\mathcal{V}_0 + \Delta\mathcal{V}) \tag{9}$$

where, J_Rotor is the moment of inertia of the turbine rotor including generator, gears, etc. ϑ_0 is the rated low-speed shaft rotational speed, τ_E is the mechanical generator torque, which is also expressed as a product of τ_G and η_G. Herein, the generator torque in Region 3 is inversely proportional to the generator speed,

$$\tau_G = \frac{P_m}{\eta_G \mathcal{V}} \tag{10}$$

Similarly, the aerodynamic torque in Region 3 is

$$\tau_A = \frac{P_m}{\mathcal{V}} \tag{11}$$

where, $\mathcal{V}$ is rotor speed, using a first-order Taylor series expansion of Eqs.10, 11, it shown as

$$\tau_G \approx \frac{P_m}{\eta_G \mathcal{V}_0} - \frac{P_m}{\eta_G \mathcal{V}_0^2}\Delta\mathcal{V} \tag{12}$$

$$\tau_A \approx \frac{P_m}{\mathcal{V}_0} + \frac{1}{\mathcal{V}_0}(-\frac{\partial P}{\partial \phi})\Delta\phi \tag{13}$$

One can note that, to derive the equation of motion for the rotor-speed error, to substitute expansion of Eqs.10, 11 to the Eqn.9(cite). The equation becomes

$$\frac{P_m}{\mathcal{V}_0^2}\Delta\mathcal{V} + \frac{1}{\mathcal{V}_0}(-\frac{\partial P}{\partial \phi})\Delta\phi = \mathcal{J}_D \Delta\dot{\mathcal{V}} \tag{14}$$

where,$\Delta\phi$ is a small perturbation of the blade-pitch angles about their operating point. $\mathcal{V}_0$ is rated low-speed shaft speed, $\Delta\mathcal{V}$ is the small perturbation of low-speed shaft rotational speed about the rated speed, $\Delta\dot{\mathcal{V}}$ is the low-speed shaft rotational acceleration. The aim here is to use the Proportional Integral Derivative(PID) pitch control to regulate the turbine speed. The standard PID expression is related to the rotor-speed perturbations by as follows:

$$\Delta\phi\,(t) = K_P \eta \Delta\mathcal{V}\,(t) + K_I \int \eta \Delta\mathcal{V}\,(t)\, dt + K_D \eta \Delta\dot{\mathcal{V}}(t) \tag{15}$$

Assuming $\dot{\chi} = \Delta\mathcal{V}$, solving the equations.14 and 15, the equation of motion for the rotor-speed error becomes

$$[\mathcal{J}_D + \gamma K_D]\ddot{\chi} + [\gamma K_P - \frac{P_m}{\mathcal{V}_0^2}]\dot{\chi} + [\gamma K_I]\chi = 0 \tag{16}$$

where, $\gamma = \frac{1}{\mathcal{V}_0}(-\frac{\partial P}{\partial \phi})\eta_G$, K_P, K_I and K_D are the blade pitch controller gains, $\mathcal{J}_D$ is a drive train inertia, P is mechanical power and ϕ is a full-span rotor-collective blade-pitch angle. $(\frac{\partial P}{\partial \phi})$ stands for a sensitivity of aerodynamic power to rotor-collective blade pitch. The LABVIEW software tool is used to implement the above algorithm. The algorithm meant for executing the mechanism, which is stated above. The time step of the program is $0.0025s$, it has been kept sufficiently low so as to improve accuracy of calculations. This loop of code takes in the rated generator speed as input from the FAST code, calculates the blade pitch and torque. The time steps of FAST is the same as that of the control loop and the two code loops are synced suitably for successful execution. Herein, the recommended the optimal gain values of proportional($K_P = 0.01882681$) and integral($K_I = 0.008068634$) gains at minimum blade-pitch setting for the baseline wind turbines. For further information, the reader is referred to [Jonkman (2007), Manikandan and Saha (2011)].

4. SIMULATION RESULTS

4.1 Results

In this section, the NREL 5 MW wind turbine is tested and simulated with the FAST and LABVIEW under in the with wind speed 18.0 m/s which is important as the PI controller takes major effect in this regime above rated wind speeds 11.4 m/s. The objective was to obtain the desired power which is shown through the simulation results of the proposed controller through the power curve, the generator speed, rotor speed and tower base pitching (fore-aft) moment in Figures (2) to (5). In order to demonstrate that the present implemented controller works on extreme wind speeds (above operational conditions), the power tracking and the generator speed is shown in Figures (6) to (8)

5. CONCLUSION

In this paper, numerical simulation of the benchmark offshore 5 MW NREL (Jonkman et al., 2009) wind turbine is simulated. The offshore wind turbine is installed on a spar platform in the water depth of 320 m. Irregular wave forces are generated using Pierson-Moskowitz spectrum. The time series is obtained for the combined wind and wave loads in irregular sea states. The proportional integral control methodologies for horizontal axis wind

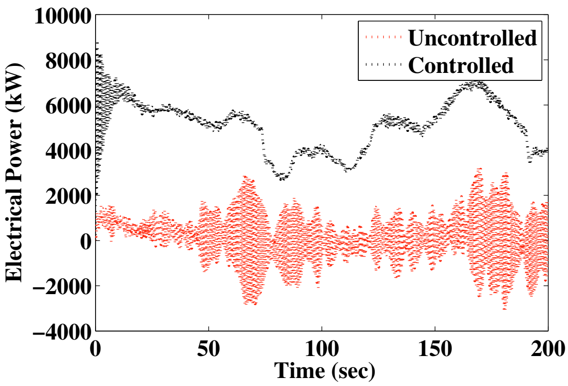


Fig. 2. Comparison of power tracking at wind speed 18.0 m/s

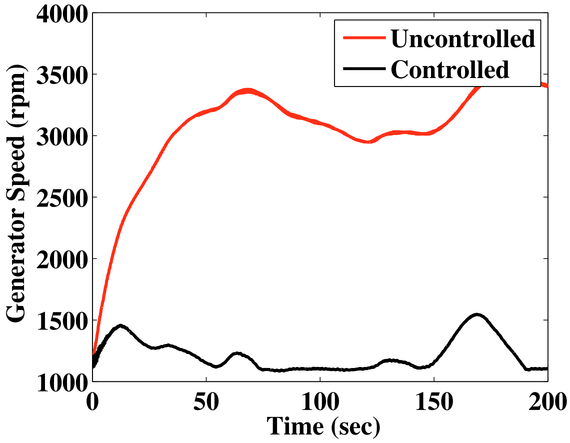


Fig. 3. Comparison of generator speed at wind speed 18.0 m/s

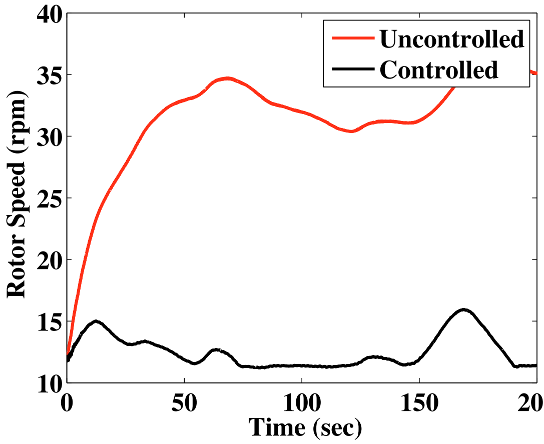


Fig. 4. Comparison of rotor speed at wind speed 18.0 m/s

turbine is used to control the blade pitch mechanism. The controller design is implemented in LABVIEW environment and tested using range of wind speeds. It is shown that the wide range of operation and performance of the controller may be tested by this design simulation tool. From the numerical simulations, it was concluded that the rotor speed is found to be controlled above the rated wind-speed (18.0 m/s). Once it overshoots the rated speed, it is brought back to the desired value by increasing the pitch. Hence this controller has achieved its objective. The method is being implemented with other advanced control algorithms as nonlinear quadratic regulator (Manikandan and Saha, 2015, 2014) are being taken up to be reported elsewhere.

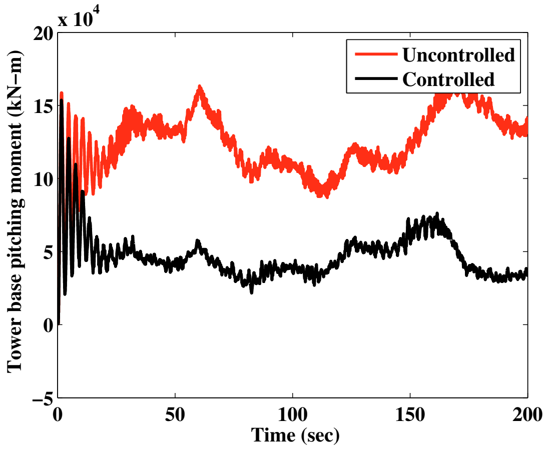


Fig. 5. Comparison of tower base pitching (fore-aft) moment(kN-m) wind speed 18.0 m/s

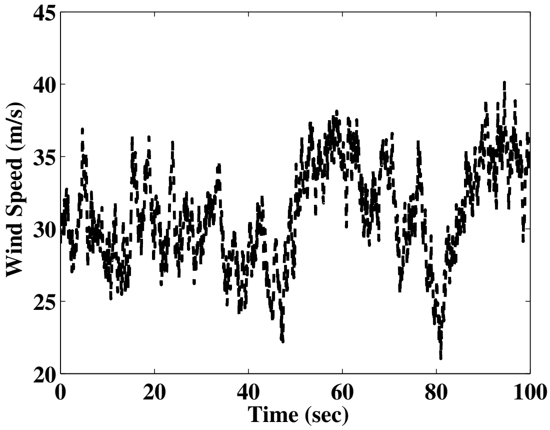


Fig. 6. Input wind time history (Average speed 31.0 m/s)

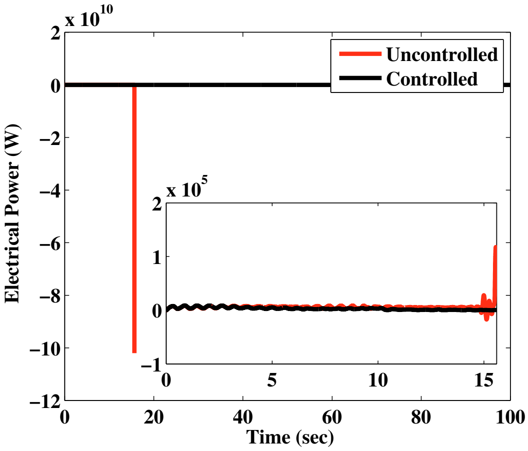


Fig. 7. Comparison of power tracking at wind speed 31.0 m/s

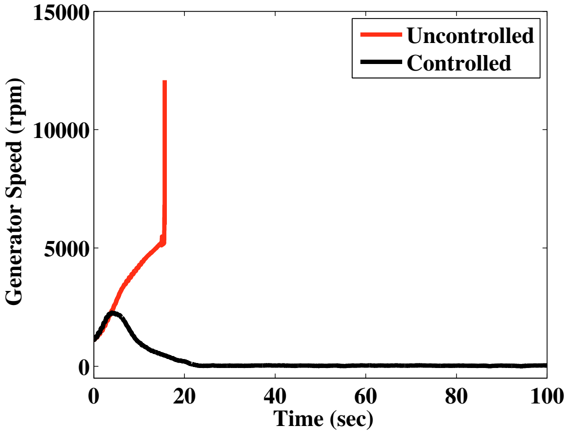


Fig. 8. Comparison of generator speed at wind speed 31.0 m/s

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