Comparison of Output Power Control Performance of Wind Turbine using PI, Fuzzy Logic and Model Predictive Controllers

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Abstract- In the variable speed wind energy conversion system, one of the operational problems is to handle the speed uncertainty and discontinuity of wind, that influence the power generation from a wind energy conversion systems (WECS). In order achieve a stable power output from a WECS despite variations in the wind speed, a number of control algorithms were devised in the literature over the past few years. Pitch angle control is widely used for regulation of output power fluctuations in a WECS. The control objective is to maintain stable power generation against wind speed variation, which can be achieved by regulating the pitch angle and/or generator torque. In view of handling the uncertainties owing to wind speed variations, this paper pursued a comparative assessment of three controllers, namely Proportional-Integral control, Fuzzy logic control (FLC) and Model predictive control (MPC) schemes. To evaluate their performance a simulation setup for implementing these three controllers applied to a WECS is prepared in MATLAB/Simulink. From the obtained results, it is envisaged that the proposed MPC exhibits excellent response and robustness of the WECS in face of uncertainties owing to intermittency and discontinuity of the wind speed.

Keywords Wind Energy Conversion System; Fuzzy Logic Controller; power quality; Fuzzy Inference System; Model Predictive Control (MPC), Step Wind Speed.

1. Introduction

Because of rising environmental concern and fast depletion of fossil fuels, interest towards supplementing generation of renewable power increases. Amongst, several renewable energy options wind energy is considered to be most promising one. Its annual growth rate is around 30% [1].The wind energy available in the wind speed is extracted through the wind conversion process. As the energy extracted from the wind is proportional to the third power of wind speed, so the wind energy conversion system is of nonlinear in nature. Therefore in modern wind energy conversion systems design of an effective control system is a challenging task. According to wind speed measurement, a variable speed variable pitch wind turbine operation regions are shown in Fig.1 [2] .The first region of operation is related to low wind speeds and known as partial load regime or variable speed region (between cut-in wind sped and rated wind speed). As wind speed is low in this regime, the speed controller will adjust the speed of the rotor (variable speed) to maintain the tip speed ratio constant. So that power coefficient will be the maximum and the turbine efficiency will be increased. The next regime is known as full load regime or variable pitch region and is related to medium and high wind speeds (between rated wind speed and cut-out wind speed. Here the control objective is to regulate both output power and speed to their rated values by regulating the generator torque and pitch angle of wind turbine. In this regime torsional torque also plays a leading role because of high wind speed. The torsional torque is also controlled through pitch angle.

Variable speed variable pitch wind turbine is of multiple inputs multiple outputs in nature. So its control design is a difficult task. Different types of control schemes are proposed for addressing the aforesaid control problem. One of the conventional control techniques is the Proportional-Integral [3-10] control. In Proportional- Integral (PI) controller it is to be interface with the process/system and adjust the controller parameter by trial and error method.

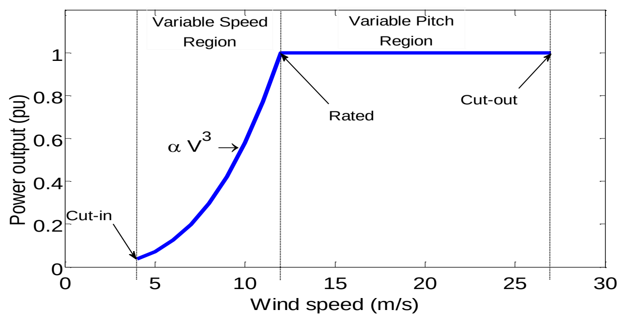

Fig. 1. Wind turbine power curve characteristics [2]

It is known that a complex or an ill-defined system cannot handled properly by using conventional automatic control methods. The control aspect issues of these complex systems can be resolved by using intelligent systems which combine knowledgebase, techniques & inferencing mechanism. The intelligent techniques such fuzzy inference system uses an approximate reasoning, which does not necessitate exact analytical model of a plant. Therefore, control strategies in the fuzzy logic controller are based on expert experience and the determination of fuzzy membership function of control variables. The control rules used in it are pre-constructed by experts to accomplice inference [11].

These fuzzy rules are the key component of fuzzy inference system (FIS) which can effectively model human expertise in a specific application. Therefore Fuzzy control is a suitable choice for pitch angle control of wind energy conversion technology problems [12-17].

However, it is reported in literature that these two controllers encounter a number of drawbacks as follows.

- Rigorous tuning is required for both the cases.
- Computational time goes on increasing for fuzzy logic controllers when membership functions are increased.
- Numbers of controllers are increased, if input variables are increased.

As wind energy conversion system is of multivariable problem, we have to use many number of controllers to control this system. In particular for a double input system, two separate controllers are to be used forming two separate control loops. In this paper in PI and Fuzzy case we used two separate controllers to control the generator speed and generator power independently for each controller case. But designing of these two controllers are difficult owing to the presence of interaction between these two control loops. Also by using this type of control design, a large electric power fluctuation and torsional torque variations will occur.

The above problems can substantially be reduced by using an advanced method of control technique known as model predictive control [18]. Model predictive control is proposed for control of a wind energy conversion system in [19-22]. In [19], authors compared the model predictive control with a linear quadratic regulator (LQR) and linear quadratic Gaussian (LQG) control. Also they presented that MPC can handle constraints effectively as compared to LQR and LQG. Unwanted close-up of wind turbines leads to failure of grid because of speed restrictions. In view of resolving the above problem, system constraints can be considered in the MPC controllers in [20]. In [21-22], authors propose optimal power tracking and load mitigation scheme which is superior to PI controller. In view of bringing out a clear picture on performance of MPC compared to a fuzzy and PI controller, we purpose a detailed comparison of performances of the model predictive controller with that of PI and fuzzy logic controller by using simulated as well as step test signal of wind speed.

This paper is organized as follows. Mathematical modeling of wind energy conversion system is discussed in section 2. A detail of MPC control algorithm applied to wind turbine pitch angle control is presented in section 3. Simulation results of different control mechanism are discussed in section 4, followed by the conclusions in Section 5.

2. Modeling of Wind Energy Conversion System

Due to more efficiency and lesser cost to power ratio, three blade upwind horizontal axis wind turbines (HAWT) are widely used today. Horizontal axis wind turbines are of two types i.e. fixed speed and variable speed. The structure of a variable speed, pitch regulated wind energy conversion system can be represented as combination of different subsystem models, which is shown in Fig. 2. [22].

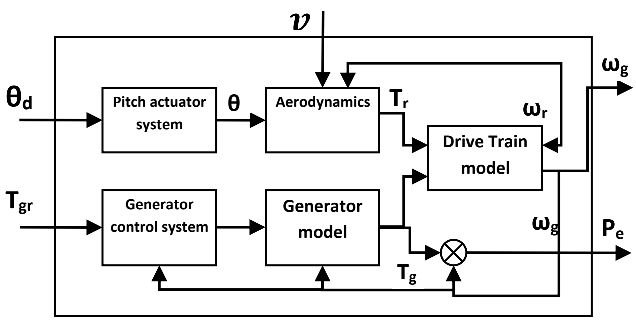

Fig. 2. Control block diagram of WECS [22]

Wind energy conversion systems are mainly subdivided in to four different components i.e. Aerodynamics system, Generator model, Actuator dynamic and Drive train model. Apart from four parts, the design of wind speed model is also considered here. First of all the mathematical equations of above mentioned components were given, then SIMULINK models were derived from it.

The aerodynamic power available at the rotor disc has the following non-linear expression, is given by [23]

$$P_a = 0.5\rho\pi R^2 v^3 \quad (1)$$

where ρ is the air density, R is the blade radius and v is the effective wind speed. Only a fraction of the available power P_a can be converted to the rotor power P_r. This fraction is given by coefficient $Cp(\lambda,\theta)$ [22, 24].

$$P_r = P_a C_p(\lambda,\theta) \quad (2)$$

where $Cp(\lambda,\theta)$ is known as power coefficient and have a theoretical upper limit of 0.593 known as Betz limit. Turbine torque T_r is given by

$$T_r = P_r/\omega_r \quad (3)$$

where ω_r is the rotational speed of wind turbine. The power coefficient $Cp(\lambda,\theta)$ is a function of tip speed ratio λ and blade pitch angle θ.

$$C_p(\lambda,\theta) = 0.5176(116/\lambda_i - 0.4\theta - 5)e^{-21/\lambda_i} + 0.0068\lambda \quad (4)$$

$$1/\lambda_i = 1/(\lambda + 0.08\theta) - 0.035/(\theta^3 + 1) \quad (5)$$

The ratio between effective wind velocity and blade tip speed is known as tip speed ratio (TSR) λ.

$$\lambda = R\omega_r/v \quad (6)$$

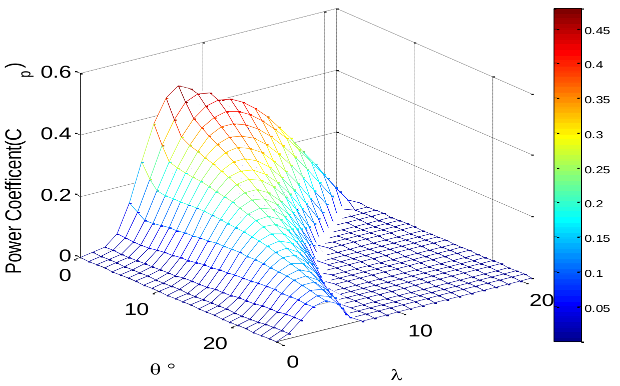

Fig. 3. The power coefficient C_p as a function of λ and θ

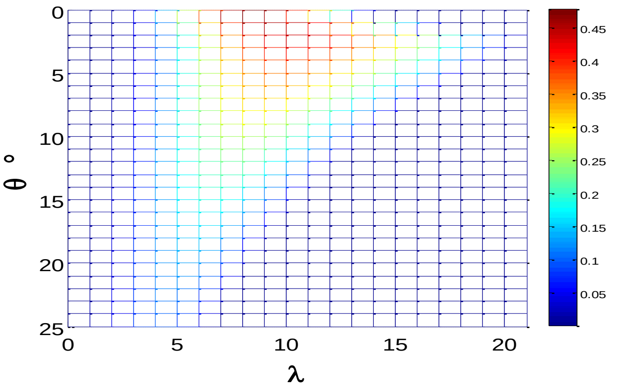

Fig. 4. Top view of figure 3

A three dimensional plot of power coefficient $Cp(\lambda,\theta)$ and its top view are shown on Fig.3 and Fig.4. Power curves for different rotor speed are shown in Fig. 5. From Fig. 3 it is found that Power coefficient changes with variation in tip speed ratio and these are reaches to their peak or maximum, for a single value of λ with a specific value of pitch angle.

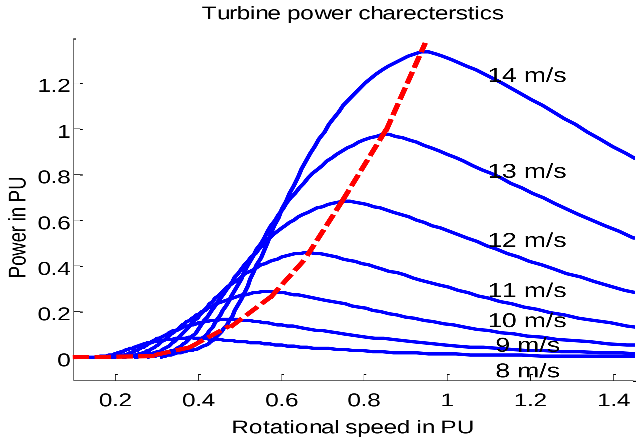

Fig. 5. Turbine Power Characteristics with variable speed

Mechanical response is slower than electric response because electric time constant is negligible compared to the mechanic time constant [25]. So to make a balance between them, wind turbine controllers are designed with simple models. The induction generator torque can be manipulated and is approximated by a first order system with time constant τ_t.

$$\frac{dT_g}{dt} = -\frac{1}{\tau_t}T_g + \frac{1}{\tau_t}T_{gr} \quad (7)$$

where T_{gr} is the output of the actuator and used as the reference for the generator system.

The power generated P_e by the generator is given by [22]:

$$P_e = T_g\omega_g \quad (8)$$

where ω_g is rotational speed of the generator.

The actuator model describes the dynamic behaviour between the pitch demand from the pitch controller to the actuation of this demand. The actuator can be modelled as first order dynamics with time constant τ_θ.

$$\frac{d\theta}{dt} = -\frac{1}{\tau_\theta}\theta + \frac{1}{\tau_\theta}\theta_d \quad (9)$$

where θ_d is the blade pitch angle reference value.

A drive train model can be represented by a two mass system with a flexible shaft connected to it. Where dynamics is given by [26],

$$\dot{\omega_r} = -\frac{N}{J_r}T_{tw} + \frac{1}{J_r}T_r \quad (10)$$

$$\dot{\omega_g} = \frac{1}{J_g}T_{tw} - \frac{1}{J_g}T_g \quad (11)$$

$$\dot{T_{tw}} = k_d N\omega_r - k_d\omega_g - \left(\frac{N^2B_d}{J_r} + \frac{B_d}{J_g}\right)T_{tw} + \frac{NB_d}{J_r}T_r + \frac{B_d}{J_g}T_g \quad (12)$$

$$T_{tw} = k_d\beta_{tw} + B_d\left(N\omega_r - \omega_g\right) \quad (13)$$

Here, turbine and the generator inertia constants are J_r and J_g respectively; β_{tw} is the shaft twist angle; N is the gear ratio; k_d, B_d are the shaft stiffness and damping coefficients respectively.

By superposing two frequency components, wind speed $v(t)$ model can be designed based on [27]. The two components are, a low-frequency component $v_l(t)$ and a turbulence component $v_t(t)$. Wind shear, rotational sampling effects and tower shadow are included in the wind speed model.

$$v(t) = v_l(t) + v_t(t) \tag{14}$$

The non linear model of the wind turbine is formulated by adding equations (1) to (14). The main nonlinearity is due to presence of turbine torque expression in equation (3). After linearizing the turbine torque expression we will get

$$\delta T_r = L_\omega \delta\omega_r + L_v \delta v + L_\theta \delta\theta \tag{15}$$

$$L_\omega = \frac{\partial T_r}{\partial \omega_r},\ L_v = \frac{\partial T_r}{\partial v},\ L_\theta = \frac{\partial T_r}{\partial \theta} \tag{16}$$

The deviation of a variable from its operating point is represented by the character δ. The operating point of WECS can be completely defined by $\bar{v}$. The linearized state space representation of the wind energy conversion system with state vector, control input and measured output [22] can be written in following manner

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} \delta\omega_r \\ \delta\omega_g \\ \delta T_{tw} \\ \delta T_g \\ \delta\theta \end{bmatrix} \text{ is the state vector}$$

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \delta T_{gr} \\ \delta\theta_d \end{bmatrix} \text{ is the control input and}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \delta\omega_g \\ \delta P_e \end{bmatrix} \text{ is the measured output.}$$

$$\frac{dx(t)}{dt} = Ax(t) + B_u u(t) + B_v \delta v(t) \tag{17}$$

$$y(t) = Cx(t) \tag{18}$$

$$A = \begin{bmatrix} \frac{L_\omega}{J_r} & 0 & -\frac{N}{J_r} & 0 & \frac{L_\theta}{J_r} \\ 0 & 0 & \frac{1}{J_g} & -\frac{1}{J_g} & 0 \\ k_d N + \frac{NB_d}{J_r} L_\omega & -K_d & -\left(\frac{N^2 B_d}{J_r} + \frac{B_d}{J_g}\right) & \frac{B_d}{J_g} & \frac{NB_d}{J_r} \\ 0 & 0 & 0 & -\frac{1}{\tau_t} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{\tau_\theta} \end{bmatrix} \tag{19}$$

$$B_u = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{\tau_t} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\tau_\theta} \end{bmatrix}^T,\quad B_v = \begin{bmatrix} \frac{L_v}{J_r} & 0 & 0 & \frac{NB_d}{J_r} & 0 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 0 & 0 \\ 1 & \overline{T_g} \\ 0 & 0 \\ 0 & \overline{\omega_g} \\ 0 & 0 \end{bmatrix}^T \tag{20}$$

The different parameters [22] of the wind energy conversion systems used in this work are shown in Table 1.

Table 1. WECS Parameters

Sl. No.	Parameter	Unit	Value
01	Rated turbine power, $P_{r,\,rat}$	[MW]	2
02	Rated rotor speed, $w_{r,\,rat}$	[rad/s]	3.0408
03	Blade radius, R	[m]	33.29
04	Pitch actuator constant, τ_θ	[s]	0.1
05	Max. blade pitch, θ_{max}	[deg]	45°
06	Min. blade pitch, θ_{min}	[deg]	0°
07	Max, blade pitch rate, $\dot{\theta}_{max}$	[deg/s]	10^0
08	Min, blade pitch rate, $\dot{\theta}_{min}$	[deg/s]	-10^0
09	Gear ratio, N	[--]	74.38
10	Generator inertia, J_g	[kg.m^2]	56.29
11	Rotor inertia, J_r	[kg.m^2]	1.86e6
12	Generator time constant, τ_t	[s]	20e-3

3. Model Predictive Controller

Model predictive control or MPC is an advanced control method which is actually developed for process industry. Now this control method is included in various sectors like electrical power systems, control engineering, process engineering and medical diagnosis etc. Model predictive controllers depend on the dynamic model of the process/plant. The dynamic models of the plant are obtained in two ways. One way is from input-output data set obtained from simple plant tests and second one is by applying system identification techniques. An internal model is existed in a model predictive controller, which is used to predict the future behavior of the plant by solving the optimization problem. In this optimization process it allows the present time slot to be optimized, while keeping future time slots in account. It has the capability to anticipate the future events and can take control actions accordingly. The main reasons for success applications of this control are

- It handles multivariable control problems.
- It is based on optimal technique.
- It takes easily different constraints.
- It is also based on state space model.
- It provides online & offline computation of the optimization law.
- The wind-up problem does not arise

The basic idea behind model predictive controller is shown in Fig. 6 [28] and MPC as a controller is shown in Fig. 7 [22]. In Fig. 6 it shows the curves of reference trajectory, set point trajectory, plant output, predicted plant output, past input control action and future input control action with current plant state is sampled at time 't'.

A set point trajectory is that trajectory to which the output will follow it ideally. Reference trajectory is different from the set point trajectory. The reference trajectory approaches to meet the set point exponentially from the current output value. From the figure we find that the control output 'y'and predicted control output '$\hat{y}$' can be controlled by manipulating the control input 'u' in such a manner {at present time ‘k’ and predicted time (k+j)}, so that it will track the set point trajectory in an optimal way after a certain amount of samples known as prediction horizon P. Manipulation of control input is done over a certain number of samples known as control horizon M. Control horizon is less than prediction horizon.

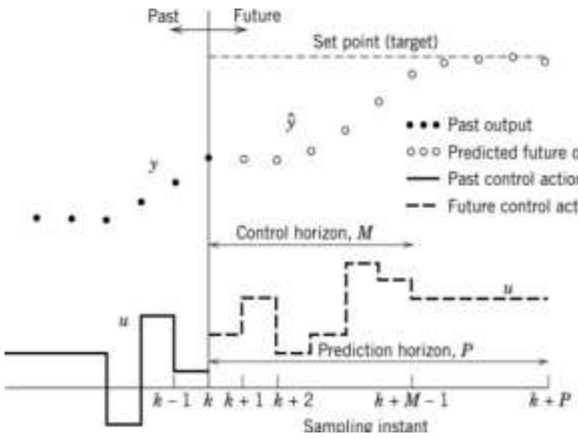

Fig. 6. Basic idea behind Model Predictive Control [28]

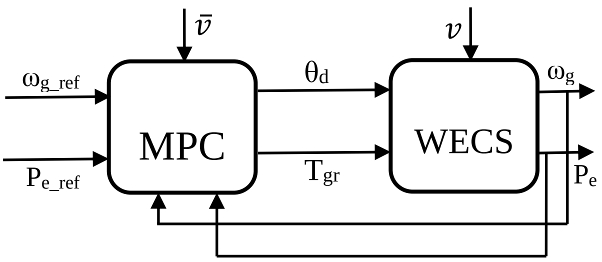

Fig. 7. MPC used as Controller [22]

A model predictive control design approach mainly consists of following components:

- Prediction Model
- Objective Function
- Constraints

Linearized, discrete time, state space dynamic model of the plant model used in model predictive control is given as

$$x(k+1) = Ax(k) + B_u u(k) + B_v d(k) \tag{21}$$

$$y(k) = Cx(k) + D_v d(k) \tag{22}$$

where $x(k)$ is the state vector, $u(k)$ is the input vector and $y(k)$ is the output vector at the sampling instant ‘k’. Fictitious unmeasured disturbance is represented by $d(k)$. The computation of a control law of MPC is based on minimization of the following objective function [29]

$$J = \sum_{j=1}^{P}[\hat{y}(k+j) - r(k+j)]^2 + \rho \sum_{j=1}^{M}[\Delta u(k+j-1)]^2 \tag{23}$$

where $\hat{y}(k+j)$ is the output prediction at time j from present measurement time k. $r(k+j)$ shows that the reference trajectory depends on the conditions at time k. $u(k+j-1)$ is calculated control input based on prediction at time $(j-1)$ and ρ is weighing factor that balances between input and output cost.

With input and output constraints:

$$u_{min} \le u(k+j) \le u_{max}$$

$$\Delta u_{min} \le \Delta u(k) \le \Delta u_{max}$$

$$y_{min} \le y(k+j) \le y_{max}$$

where j=1,2,3,……………

track the set point trajectory in an optimal way after a certain amount of samples known as prediction horizon P.

4. Results and Discussion

Three controllers namely Proportional-Integral, Fuzzy and MPC were implemented on a wind energy conversion system by using MATLAB/SIMULINK software simulation, for a variable speed wind turbine for different test step (up and down) wind speeds with above the speed rated. In PI controllers, the gains of the power and speed controller transfer functions are properly tuned till to get the desired response. In fuzzy controller, inputs to the fuzzy controllers are error (e) {difference between reference power and measured power} and change in error (de) for power control. For speed control, it is error (e) {difference between reference generator speed and measured speed} and change in error (de) is input to the speed fuzzy controller. For model predictive control, MPC model was simulated based on a linearised model of the system with an operating wind speed $\bar{v}$ of 20 m/s. In this simulation sampling time T_s, prediction horizon length P and control horizon length M is taken as 50ms, 20 and 10 respectively.

A wind speed in the form of step variation is shown in Fig.8 and Fig.13. In these figure a step change (up as well as down) will occur at the instant of 30 sec with a magnitude of two. By applying this step wind speed, the generator speed, torsional torque, pitch angle and generator power is compared using PI, Fuzzy and MPC.

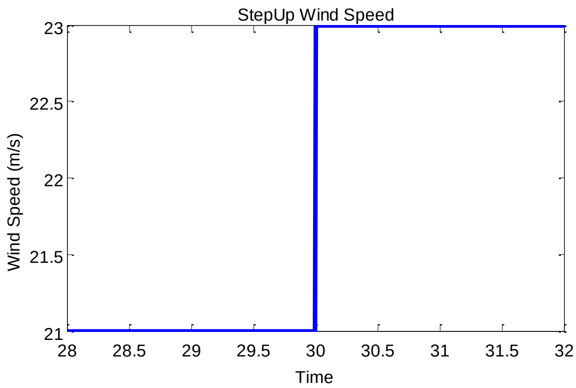

Fig. 8. Step wind Speed (Up)

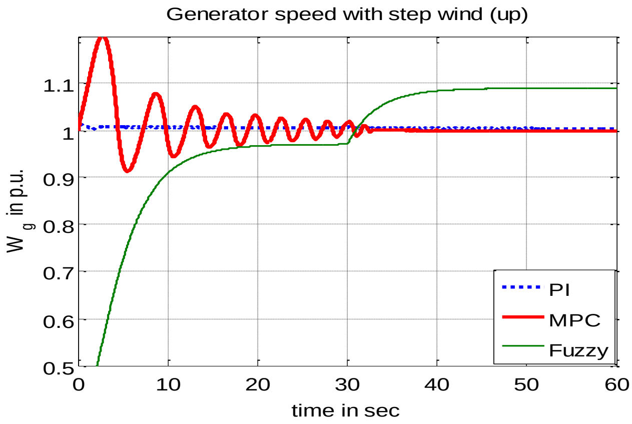

Fig. 9. Generator speed with step wind (Up)

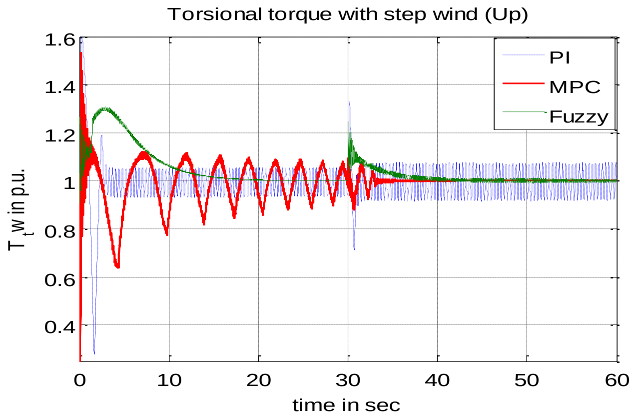

Fig. 10. Torsional torque with step wind (Up)

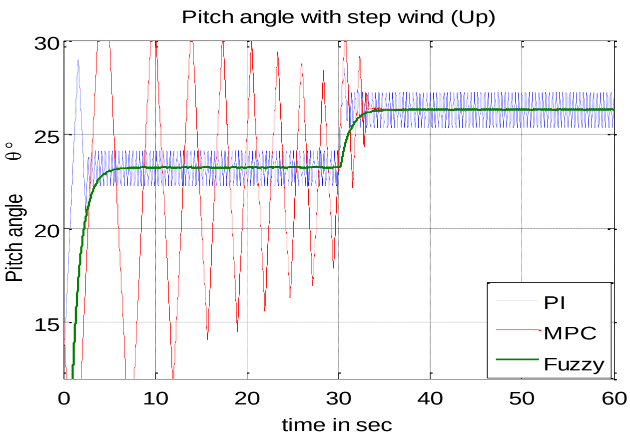

Fig. 11. Pitch angle with step wind (Up)

A simulated wind speed of above the rated is shown in Fig.18, which is comprised of a fast variation wind and a slow variation wind as given in equation (14). In this case the wind speed ranges between 18 m/s to 22m/s, with an average of 20 m/s. By using this simulated wind speed, Generator speed, Drive train torsional torque, Pitch angle and Generator power are calculated by using PI, Fuzzy Logic and MPC controller. The comparision of above parametrs with these three controllers are shown in Fig. 19 to Fig. 22.

From Fig.9 to Fig.17, it is found that, in conventional control method the fluctuation in power output, drive train torsional torque and pitch angle are very high as compared to fuzzy control method. In case of fuzzy control method, the fluctuation in power output is reduced completely. Drive train torsional torque fluctuates in the begining of few seconds and again at 30 sec. There after it stabilizes and fluctuations are reduced. Similarly pitch angle fluctuations and generator speed oscillations are also reduced for the case of fuzzy control.

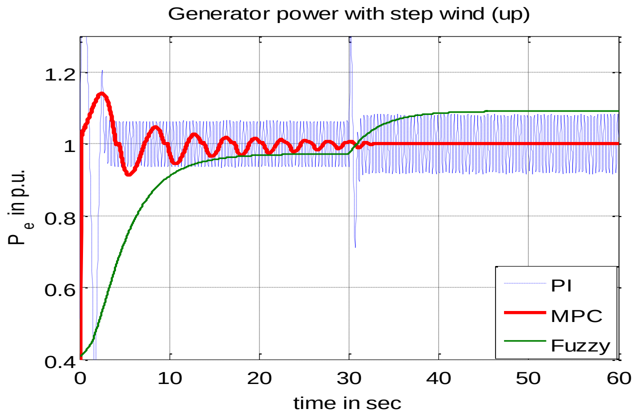

Fig. 12. Pitch angle with step wind (Up)

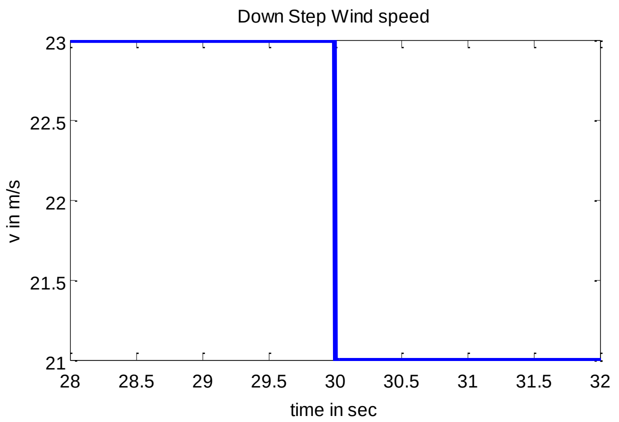

Fig. 13. Step wind Speed (Down)

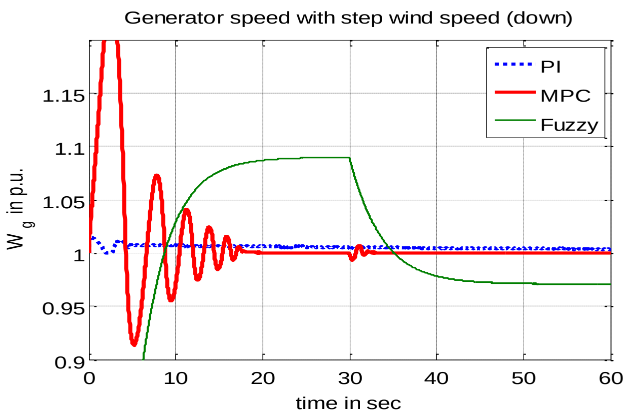

Fig. 14. Generator speed with step wind (Down)

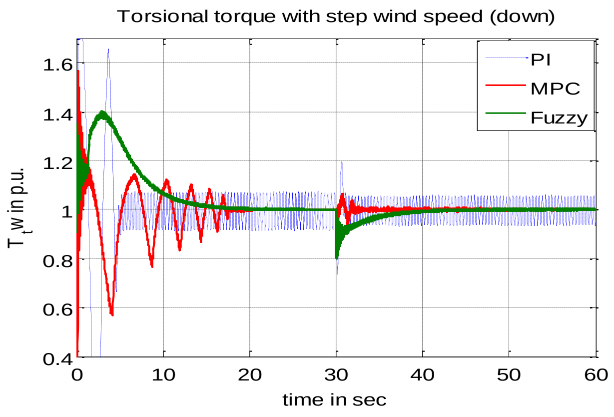

Fig. 15. Torsional torque with step wind (Down)

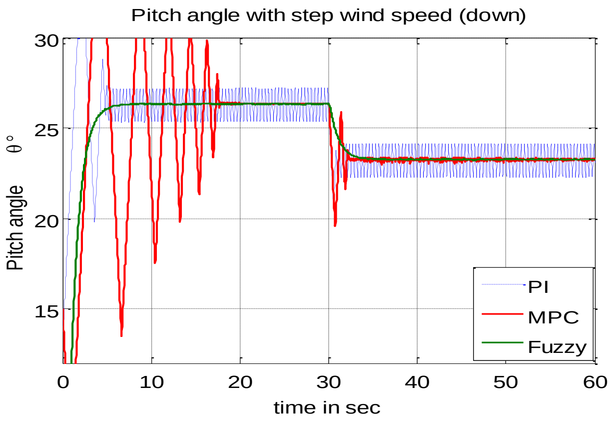

Fig. 16. Pitch angle with step wind (Down)

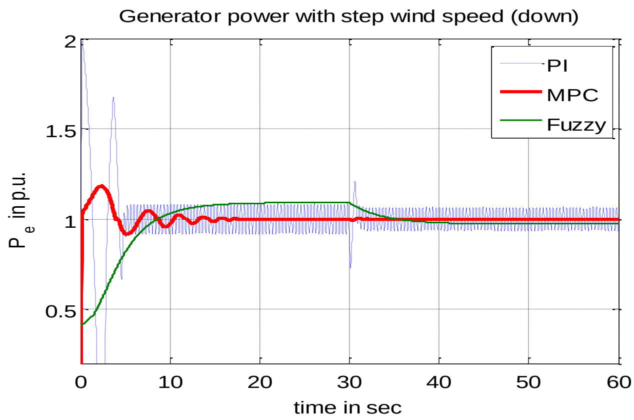

Fig. 17. Pitch angle with step wind (Down)

But in Fig. 9 to Fig. 17, it is observed that the MPC controller works well to control generator power, drive train torsional torque and the generator speed. The controller acts very fast to reach the target value. As the drive train torsional torque oscillation is low, so its effect will be on the generated power of the wind turbine i.e. power quality will be improved and it also increases the life span of mechanical parts of the wind energy conversion system. But in case of pitch angle control, it oscillates more in the initial periods, and then its rate of oscillation is reduced.

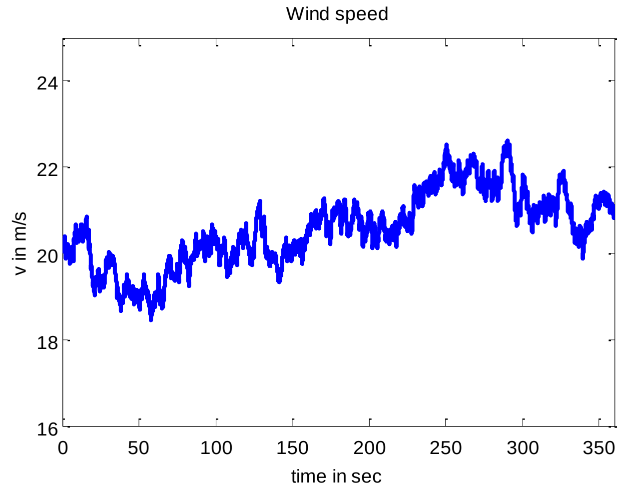

Fig. 18. Simulated Wind speed

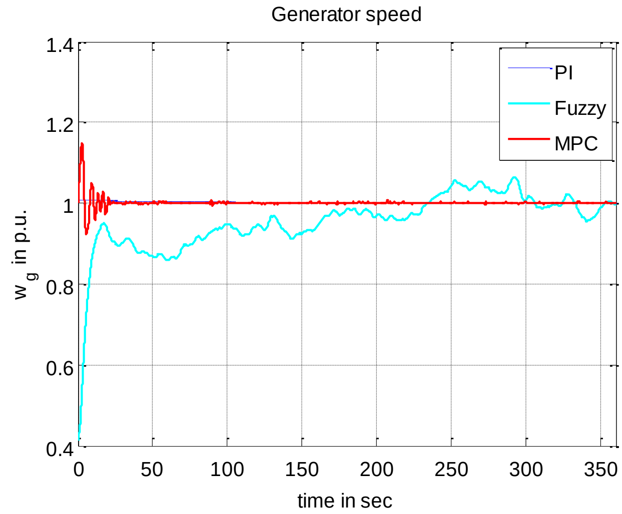

Fig. 19. Comparison of generator speed response for simulated wind Speed

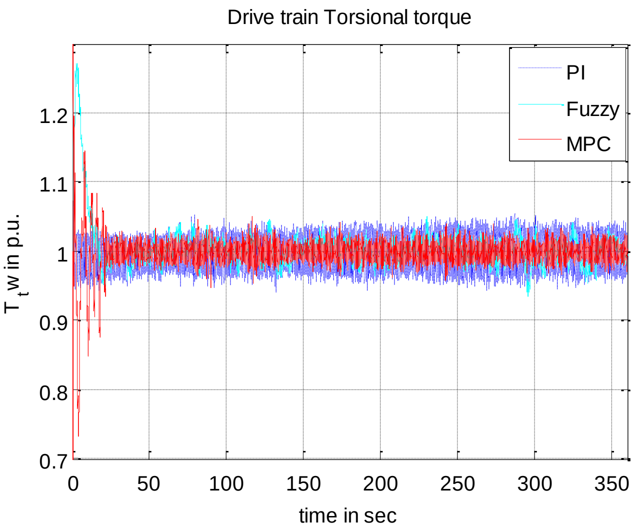

Fig. 20. Comparison of torsional torque response for simulated wind speed

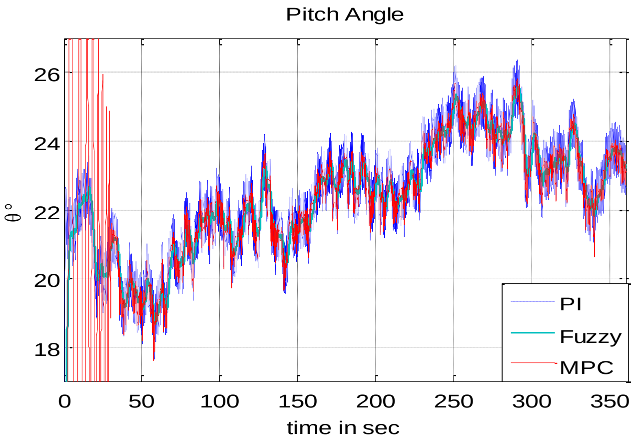

Fig. 21. Comparison of pitch angle response for simulated wind speed

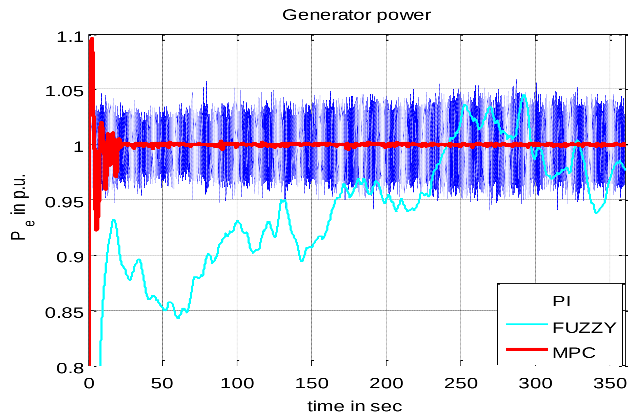

Fig. 22. Comparison of generator output power response for simulated wind speed

Finally in Fig. 19 to 22, Generator speed, Torsional torque, Pitch angle and Generator power output are compared using PI, Fuzzy and MPC controllers with simulated wind speed varying from 18 m/s to 22 m/s and again with an average of 20 m/s. All the figures from Fig. 19 to 22 are clear and self explanetory. From the afore said obtained results it is envisaged that the MPC outperforms over both PI and Fuzzy controllers.

5. Conclusion

In this paper a comparative study on the performances of three controllers such as PI, Fuzzy and MPC is made. In view of evaluating their performance we considered variation of wind speeds in above the rated speed and simulated all the controllers on a wind energy conversion system using MATLAB and Simulink. The WECS parameters like generator speed, torsional torque, pitch angle and output power is considered for comparative analysis in MATLAB and Simulink. From the comparison it is observed that although fuzzy controllers handle the wind speed uncertainties but the MPC is the best controller because it handles afore mentioned uncertainties whilst providing faster response.

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