Model Predictive Individual Pitch Control using Laguerre Filter for Load Mitigation in Wind Turbine

Ahmed A. Lasheen and Mahmoud M. Elnaggar

***Abstract*—This paper focuses on variable speed variable pitch wind- turbine control when operating in region 3. Designing a pitch controller is important while operating in region 3 to regulate the rated generator power and to reduce the flap-wise moment on the turbine blades. The regulation of the generator power and speed is achievable by using the collective pitch control (CPC); while reduction of the flap-wise moment is the objective of individual pitch control (IPC). The main challenge of designing this pitch controller is the pitch-angle constraints. Model predictive control (MPC) using Laguerre network is designed to produce the optimal individual pitch control action that satisfies the system constraints. A typical 5-MW benchmark wind turbine simulator is used to test the performance of the proposed controller. Comparisons between the proposed controller and the standard PI controller, which has been employed generously for wind-turbine control in industry, are performed. The results show the superiority of the proposed pitch controller over the standard controller.**

***Index Terms*—Individual pitch control, model predictive control, pitch control and wind energy conversion systems.**

I. Introduction

Wind energy is now the fast growing renewable energy resource around the world. The total worldwide wind capacity reached 597 GW before the end of 2018. A 50.1 GW were additionally added during 2018 [1]. Nowadays, Wind turbines mounted worldwide before the end of 2018 produce about 6% of electricity demand from the worldwide demand [1].

The generated power from the wind turbine depends on wind speeds. The relation between this output power and wind speed is described by the wind turbine power curve supplied by turbine manufacturers as shown in Fig. 1. It can be divided into three regions of operation according to the wind speed. Cut-in speed is the upper limit of region 1 which starts from zero wind speed. In this region, there is no sufficient torque to rotate the turbine as the losses in the turbine are greater than the wind power so the turbine does not operate. The cut-in and rated wind speed are the lower and upper operating limits of region 2 where the wind power increases rapidly with wind speed. The main objective of the control system in this region is to extract maximum power of the wind flow. Region 3 begins from the rated wind speed and ends at the cut-out speed at where the turbine shuts down. In this region, the wind turbine is controlled to generate constant output power (rated output power) by regulating the generator speed to its rated value, and reduce the flap-wise moment on the turbine blades to avoid the damage of drivetrain. If the wind speed becomes higher exceeding the cut-out threshold, the turbine stops [2]. Pitch control is used to achieve the controller objectives in region 3 through two pitch control techniques which are individual pitch control (IPC) and collective pitch control (CPC). IPC plays role in wind turbine systems by reducing blades moment. The major target of CPC is to regulate the generator power and speed. While the major target of the IPC is to reduce the flap-wise moment on the turbine blades.

In literature, several papers are introduced to control the pitch angle. Most of these papers are interested in controlling the CPC. In [3], a continuous – time L_1 adaptive controller is introduced to control the collective pitch angle. The introduced controller achieves significant enhancement in the regulation of the generator power. The adaptation is used to compensate for the system nonlinearities and uncertainties. The collective pitch angle is controlled using fractional fuzzy PID controller in [4]. The controller is tuned using chaotic optimization algorithms. In [5], model uncertainties are taken into consideration while designing a robust MPC to control the collective pitch angle. The upper boundary of the system uncertainty is calculated based on the tube analysis. The MPC optimization problem is solved offline in order to reduce the on-line computational time using explicit MPC. In [6], a linear quadratic gaussian regulator with integral action is designed to control the IPC. In [7], a multivariable IPC is introduced to reject the periodic disturbances. The controller is designed based on linear matrix inequalities to achieve better performance on reducing the blade moments.

The main focus of this work is to design a discrete-time model predictive control (MPC) using Laguerre filter for IPC. Two main advantages can be achieved by the proposed controller. First, the ability to produce the optimal control action that satisfies the pitch angle constraints. Second, the ability to reduce the periodic disturbances that affect the turbine blades and hence, reduces the damage equivalent load on the turbine tower and blades. Further, the proposed individual pitch controller is coupled with the CPC which is designed based on a set of LMIs to satisfy a certain performance as introduced in [8].

The rest of this paper is prepared as follows. Section II introduces the wind turbine nonlinear model and individual pitch model. In Section III, the investigated model predictive control using Laguerre filter is explained. Moreover, the procedure to implement the proposed controller is stated. Simulation results that discuss the proposed controller performance are investigated in Section IV. Conclusions are drawn in Section V.

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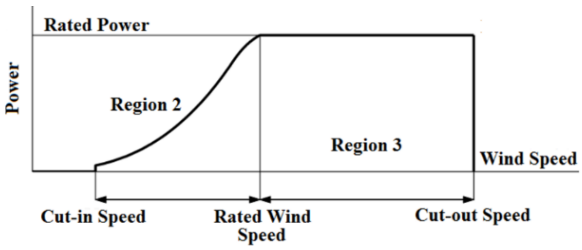


Fig. 1. Characteristic wind output power with steady wind speed.

II. Individual Pitch Model Description

Reduction of asymmetric loads is one of the main objectives of the controller during the operation in region 3. CPC cannot compensate for the asymmetric loads produced by horizontal or vertical wind shear [9] and [2]. This compensation is usually accomplished by designing an individual pitch controller.

The rotating nature of wind turbines provides rise to a periodic system, mainly when concerning the pitch to the bending moments in the blades. The moments produced by wind variation, gravity and relative tower motion are depending on the azimuth angle of each individual blade [10]. In this work, FAST (Fatigue, Aerodynamics, Structure and Turbulence) simulator is used to design and test the performance of the IPC. FAST simulator is one of the benchmark wind turbine models which can be utilized to test the efficiency of different control algorithms [11]. FAST provides up to 24 degrees of freedom (DOF) to simulate almost real-life conditions in the simulation.

The nonlinear equation used in the FAST simulator is expressed as follows [11],

$$M(q,u,t)\ddot{q} + f(q,\dot{q},u,u_d,t) = 0 \tag{1}$$

where M is the mass matrix and f is the forcing vector. q, $\dot{q}$ and $\ddot{q}$ are the DOF vectors of displacement, velocity and acceleration, respectively. u_d and u are the wind and control input vectors, respectively. t is the time index. In this work, FAST models are used to obtain different linearized models at different azimuth angles. The linearized model can be written as follows,

$$\begin{aligned} \dot{x}_{ipc} &= A_{ipc}(\Psi)x_{ipc} + B_{ipc}(\Psi)u_{ipc} \\ y &= C_{ipc}x_{ipc} \end{aligned} \tag{2}$$

where Ψ is the azimuth angle, u_{ipc} is the IPC action, y is the flap-wise moment on the three blades. A_{ipc} and B_{ipc} are time varying matrices depending on the azimuth angle. x_{ipc} is the vector of the system states. In this work, the system states are flap-wise bending displacement and velocity of the three blades. The system given in (2) is a linear time varying (LTV) system as it depends on the azimuth angle. In order to transform the LTV system given in (2) into linear time invariant (LTI) system, Multi-Blade Coordinates 3 (MBC) is used [12] which provides an average model for the system given in (2). The basic idea is to transform the coordinates from the rotating frame to the d-q coordinates using the formula given in (3) [9].

$$T(\psi) = \frac{2}{3}\begin{bmatrix} \cos(\psi) & \cos\left(\psi + \frac{2\pi}{3}\right) & \cos\left(\psi + \frac{4\pi}{3}\right) \\ sin(\psi) & \sin\left(\psi + \frac{2\pi}{3}\right) & \sin\left(\psi + \frac{4\pi}{3}\right) \end{bmatrix} \tag{3}$$

By using the transformation given in (3), the flap-wise moment of the turbine blades given in (2) is transformed to the d-q frame as follows

$$y_{d-q} = \begin{bmatrix} M_{tilt} \\ M_{yaw} \end{bmatrix} = T(\psi)\begin{bmatrix} M_{y,1} \\ M_{y,2} \\ M_{y,3} \end{bmatrix} \tag{4}$$

where $M_{y,1}, M_{y,2}$ and $M_{y,3}$ are the flap-wise moment on the three blades, respectively. M_{tilt} and M_{yaw} are the moments (system output) in the d-q frame. Hence, the system given in (2), can be written in d-q frame as follows:

$$\begin{aligned} \dot{x}_{d-q} &= A_{d-q}x_{d-q} + B_{d-q}u_{d-q} \\ y_{d-q} &= C_{d-q}x_{d-q} \end{aligned} \tag{5}$$

where $A_{d-q}, B_{d-q}, C_{d-q}$ are constant matrices for the IPC in the fixed frame. y_{d-q} is the tilt and yaw moment. u_{d-q} is the IPC action in the fixed frame. In order to obtain the individual pitch control signal in the rotating frame (u_{ipc}) the following transformation is used [9].

$$\begin{bmatrix} u_{ipc\_1} \\ u_{ipc\_2} \\ u_{ipc\_3} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & sin(\psi) \\ \cos\left(\psi + \frac{2\pi}{3}\right) & \sin\left(\psi + \frac{2\pi}{3}\right) \\ \cos\left(\psi + \frac{4\pi}{3}\right) & \sin\left(\psi + \frac{4\pi}{3}\right) \end{bmatrix} u_{d-q} \tag{6}$$

III. Individual Pitch Control Design

This Section explains three main parts. The first part is the IPC design, the second part is the pitch control loop, and the third part is the procedure to implement the proposed controller.

A. Proposed IPC Design

In this Subsection, MPC using Laguerre filter is designed to control the individual pitch angle. First, Laguerre network is introduced [13]. Second, discrete-time MPC is designed for IPC using Laguerre network.

1) Laguerre network

The set of real functions $l_i(k), i = 1,2, \ldots.,$ is orthogonal and complete if (7) holds

$$\sum_{k=0}^{\infty} l_i(k)^2=1,\ \sum_{k=0}^{\infty} l_i(k)l_j(k) = 0 \ \ i \neq j, \tag{7}$$

The z- domain transfer function of the m^{th} Laguerre function can be written as follows [13].

$$T_m(z) = \frac{\sqrt{(1-a^2)}}{z-a}\left[\frac{1-az}{z-a}\right]^{m-1} \tag{8}$$

where a is a positive scaling factor less than unity and m is the number of Laguerre function.

The set of discrete Laguerre functions given in (8) satisfies the difference equation given in (9) as discussed in [13].

$$L(k+1) = \omega\, L(k) \tag{9}$$

where $L(k) = [l_1(k) \quad l_2(k) \quad \ldots\ldots \quad l_N(k)]$, $\alpha = 1 - a^2$

$$\omega = \begin{bmatrix} \alpha & 0 & 0 & \ldots & 0 \\ \alpha & a & 0 & \ldots & 0 \\ -a\alpha & \alpha & a & \ldots & 0 \\ a^2\alpha & -a\alpha & \alpha & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -1^{N-2}a^{N-2}\alpha & \ldots & \ldots & \alpha & a \end{bmatrix}$$

$$L(0)^T = \sqrt{(1-a^2)}[1 \quad -a \quad a^2 \quad \ldots \quad -1^{N-1}a^{N-1}]$$

2) MPC using laguerre filter for IPC

The linear state space continuous-time system given in (5) can be written in the discrete – time form as follows,

$$\begin{gathered} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \\ u_{min}^{ipc}(k) \le u(k) \le u_{max}^{ipc}(k) \\ \Delta u_{min}^{ipc}(k) \le \Delta u(k) \le \Delta u_{max}^{ipc}(k) \end{gathered} \tag{10}$$

where $u_{min}^{ipc}, u_{max}^{ipc}, \Delta u_{min}^{ipc}$ and Δu_{max}^{ipc} are the minimum, maximum, minimum change rate and maximum change rate of IPC action, respectively. Let the future control action of the input at the future time m be

$$u(k+m) = \sum_{i=1}^{N} l_i(m)c_i = L^T(m)\,\eta \tag{11}$$

where $\eta^T = [c_1 \quad c_2 \quad \cdots \quad c_N]$. The prediction equation can be written in terms of Laguerre coefficient as follows,

$$x(k+m) = A^m x(k) + S_c(m)\,\eta \tag{12}$$

where the convolution term in equation (12) : $S_c(m) = \sum_{i=0}^{m-1} A^{m-i-1}B\,L^T(i)$ is obtained by solving the linear matrix given in (13) as discussed in [13].

$$AS_c(m) - S_c(m)\omega^T = A^m BL^T(0) - BL^T(m) \tag{13}$$

The output prediction equation can be obtained by multiplying equation (12) by the output vector C,

$$y(k+m) = CA^m x(k) + \sum_{i=0}^{m-1} CA^{m-i-1}B\,L^T(i)\,\eta \tag{14}$$

The cost function of the MPC problem is selected as follows,

$$J = Y^T Y + U^T R U \tag{15}$$

where $Y = [y(k+1) \quad y(k+2) \quad \ldots \quad y(k+N_{mpc})]$, $U = [u(k) \quad u(k+1) \quad \ldots \quad u(k+N_{mpc}-1)]$ and R is a diagonal matrix (one of the tuning parameters of MPC). N_{mpc} is the prediction horizon. From equation (7), (11), and equation (15), the cost function given in (15) can be rewritten as [13],

$$J = \sum_{m=1}^{N_{mpc}} y(k+m)^T y(k+m) + \eta^T R_l \eta \tag{16}$$

where R_l is constant diagonal matrix. The cost function given in (16) can be reformulated to be in terms of the system states as follows:

$$J = \sum_{m=1}^{N_{mpc}} x(k+m)^T Q x(k+m) + \eta^T R_l \eta \tag{17}$$

where $Q = C^T C$.

In order to solve the cost function given in (17) subject to the system model given in (10). The constraints given in (10) should be reformulated to be in terms of Laguerre filter as follows,

$$u_{min}^{ipc} \le L^T(m)\,\eta \le u_{max}^{ipc} \tag{18}$$

$$\Delta u_{min}^{ipc} \le (L(m+i)^T - L(m+i-1)^T)\eta \le \Delta u_{max}^{ipc} \tag{19}$$

The main advantages of using Laguerre filter in the design of MPC are to reduce the online computational time by reducing the number of the tuning parameters, and the produced control action is smoother than the traditional MPC as discussed in [13].

B. Pitch Control Loop

The proposed pitch control signal consists of three main signals. The first signal u_0, is the steady state value of the pitch angle. The objective of this signal is to ensure zero steady state error in the regulation of the generator speed and power. It is calculated based on the average wind speed at the hub height. The second signal u_{ipc}, is the individual pitch control signal. As mentioned previously, the main objective of this signal is to reduce the flap-wise moment and the damage equivalent load on the turbine blades. In this work, the IPC signal is designed using MPC and the solution of the MPC is based on Laguerre network. The main advantage of the proposed controller is the ability to produce the optimal control action that satisfies the pitch angle constraints. The third signal u_{CPC}, is the collective pitch control signal. The objective of this signal is to maintain the generator speed and power to be at their rated values. In this work, the CPC signal is designed using the same technique introduced in [8]. This technique is designed using a linear matrix inequality to satisfy certain objectives. These objectives are the performance specification ($H\infty$ problem), minimum control effort (H2 problem) and pole clustering. Finally, pitch control signal (U) is showed in Fig. 2 and it can be written as,

$$U = u_0 + u_{ipc} + u_{CPC} \tag{20}$$

The total pitch angle U given in (20) has allowable range of values from 0 rad (u_{min}) to 1.57 rad (u_{max}) with a minimum and maximum rate of change of -0.139 rad/sec ($\Delta \mathrm{u}_{\min}$) and 0.139 rad/sec ($\Delta \mathrm{u}_{\max}$), respectively [2]. The input constraints on the IPC action are rewritten using (20) as:

$$\{(-u_{cpc} - \mathrm{u}_0 + u_{min}) = u_{min}^{ipc}\} \leq u_{ipc} \tag{21}$$

$$\{(-u_{cpc} - \mathrm{u}_0 + u_{max}) = u_{max}^{ipc}\} \geq u_{ipc} \tag{22}$$

$$\{(-\Delta u_{cpc} - \Delta \mathrm{u}_0 + \Delta \mathrm{u}_{\min}) = \Delta u_{min}^{ipc}\} \leq \Delta u_{ipc} \tag{23}$$

$$\{(-\Delta u_{cpc} - \Delta \mathrm{u}_0 + \Delta \mathrm{u}_{\max}) = \Delta u_{max}^{ipc}\} \geq \Delta u_{ipc} \tag{24}$$

C. *Implementation Steps*

The proposed IPC controller consists of offline calculations and online calculations:

1) Offline calculation

- The continuous-time state space model in the form of (2) is obtained using FAST simulator.
- The model given in (2) is transformed from the rotating frame using the transformation given in (3) in to the fixed d-q frame as shown in (5).
- The discrete-time state space model is obtained as given in (10).
- The prediction horizon N_{mpc} and the number of the Laguerre filter are selected.

2) Online calculation

- Flap-wise moment on the three blades , azimuth angle and generator speed are measured
- The tilt and yaw moments (moment on d-q frame) are calculated based on the azimuth angle and the blades moment as shown in (4).
- CPC component u_{cpc} is calculated Based on the generator speed as given in [8].
- The nominal pitch angle u_{o}, is calculated based on the wind speed as shown in Fig. 2.
- IPC constraints are calculated based on equations (21)-(24).
- Transform the IPC constraints to the d-q frame using the transformation matrix given in (3). This is illustrated in the pitch constraints generation block in Fig. 2.
- Transform the IPC constraints to be in terms of Laguerre coefficient (η) as given in (18)-(19).
- Solve the optimization problem given in (17) subject to the model given in (10) and the constraints given in (18)-(19).
- The optimal control action η is produced and the optimal IPC action is calculated based on (11).
- According to the receding horizon policy, the first element on the optimal trajectory is applied to the plant.
- The total control action is calculated and applied to the nonlinear model based on (20).

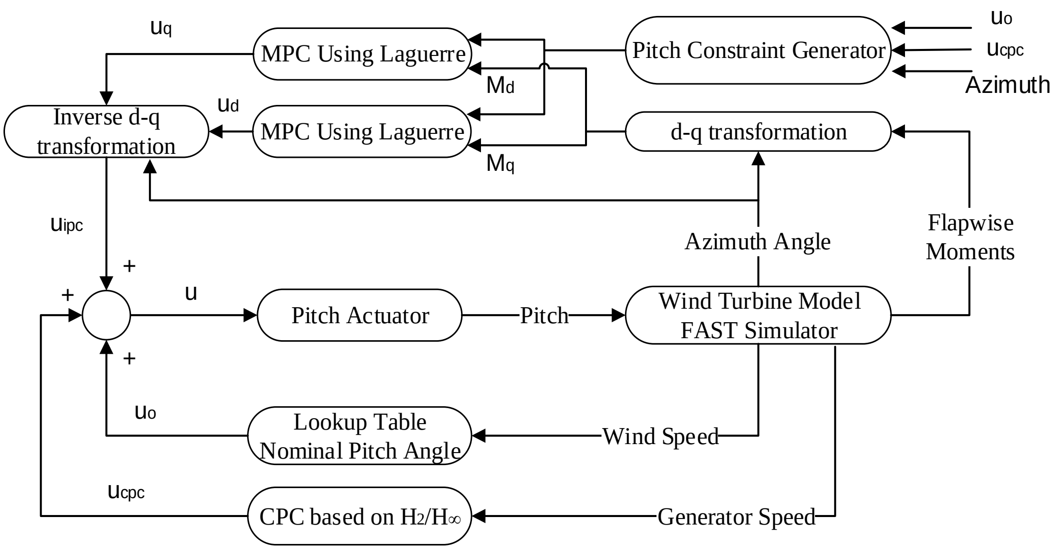


Fig. 2. Pitch control command.

IV. Simulation Results

In this section, a 5 MW wind turbine model provided by FAST is used to test the performance of the proposed pitch controller [2]. In order to obtain realistic results, all the DOFs supported by FAST models are enabled. Further, results comparison is done based on IEC turbulence wind-speed profile obtained using TurbSim software package [14].

A. *CPC and IPC PI Controllers*

The performance of the proposed controller is compared with traditional gain-scheduled PI controller for CPC coupled with PI controller for IPC. The gain-scheduled PI controller is designed based on the frequency response analysis to achieve a 60 degree phase margin as discussed in [2] and [15]. The IPC controller is designed in the fixed coordinates (d-q) frame. The full details of the PI controller for the IPC is discussed in [9] and [16].

B. Overall Performance Comparison

In this section, the performance of the proposed controller is analyzed and compared with the PI controllers discussed in the previous subsection. Fig. 3 shows the wind speed profile used to obtain the results which is generated by TurbSim [14]. Generator speed, generator power and flap-wise moments on the turbine blades are shown in Fig. 4. As shown in Fig. 4, the proposed controller achieves significant enhancement on the regulation of the generator speed and power. The analysis of the results is stated in Table I. As shown in Table I, the regulation of the generator power is improved by 2.7% and the standard division is reduced by 68.25% while using the proposed controller. Moreover, the proposed controller reduces the average flap-wise moment on the turbine blades by 3.12 % and the standard division is reduced by 39.47%.

C. Load Mitigation Analysis

As discussed in Section II, the main motivation of this work is to reduce the cyclic loads by reducing the 1P frequency loads (0.2 Hz in our case). In order to validate that the proposed controller reduces the cyclic loads, power spectral density of the flap-wise moment is plotted in Fig. 5. As shown in Fig. 5, using the individual pitch control significantly reduces the cyclic loads using the PI controller and the proposed MPC. The magnitude of the flap-wise moment at 0.2 Hz when using CPC only is 960 kN.m, and it is 400 kN.m and 220 kN.m when using IPC as a PI and MPC controllers, respectively. This reduction on the cyclic loads significantly reduces the damage equivalent load (DEL) on the turbine blades and tower [17]. As shown in Table I, relative to the traditional PI controller, the proposed controller reduces the DEL by 26.6%, 28.9%, 26.6% and 32.95% on the turbine blades and tower, respectively.

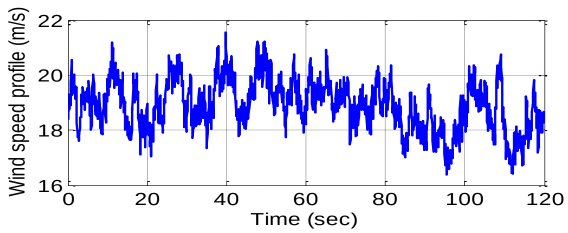
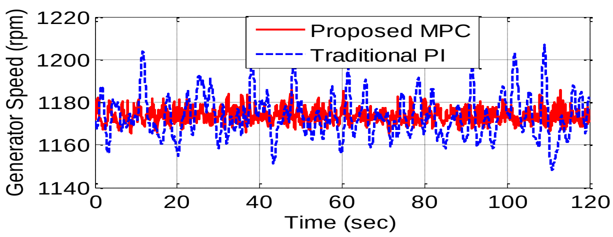
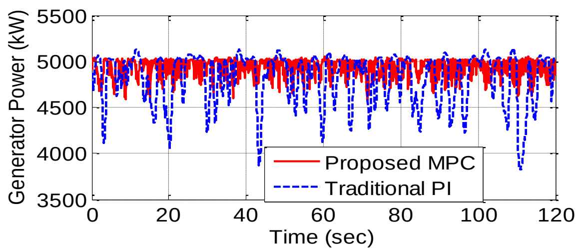


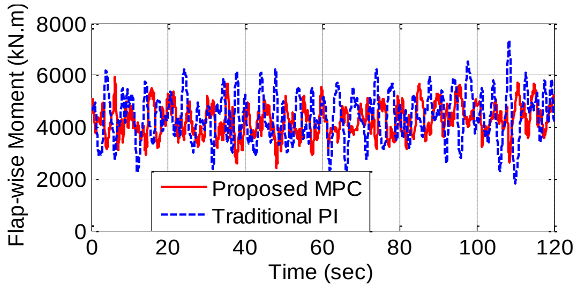
Fig. 3. Stochastic wind speed profile.



(a)

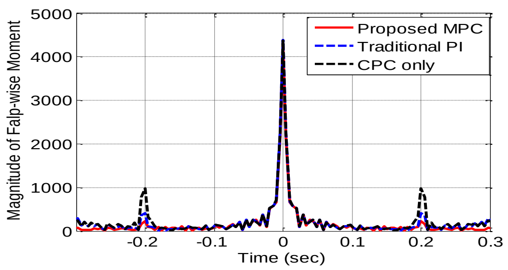


(b)

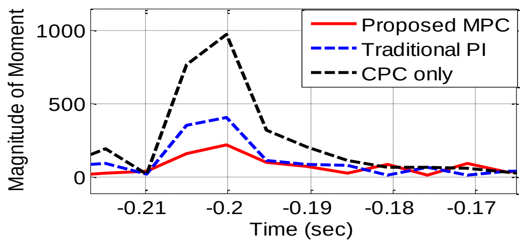


(c)

Fig. 4. Results of the proposed MPC and PI controller (a) generator speed (b) generator power (c) flap-wise moment.



(a)



(b)

Fig. 5. (a) Power spectral density of the proposed MPC versus traditional PI of the flap-wise moment on the 1st blade (b) zoomed view at 0.2 Hz.

V. CONCLUSION

This paper discusses the design of model predictive control using Laguerre network to control the individual pitch angle. Controlling the individual pitch angle reduces the flap-wise moment on the turbine blades and hence reduces the damage equivalent load. The proposed controller has the ability to produce the optimal individual pitch control action that satisfies the pitch constraints. Further, the proposed controller is coupled with a robust collective pitch controller to maintain the generator speed and power. Simulation results illustrates the superiority of the proposed controller on reducing the flap-wise moment and regulating the generator power over the traditional PI controller.

TABLE I: PERFORMANCE ANALYSIS OF THE PROPOSED MPC CONTROLLER

Index		Proposed MPC	Traditional PI
Generator speed (rpm)	Mean	1173.6	1173.4
	Std.	3.26	10.27
Generator power (kW)	Mean	4937	4807
	Std.	93	283.17
Flap-wise moment (kN.m)	Mean	4260	4394
	Std (error)	599.5	990.5
DEL	1st blade	876	1193
	2nd blade	860	1210
	3rd blade	876	1193
	tower	1853	2764

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Lasheen and Elnaggar worked together to simulate the MPC on the FAST model. The paper was written by Lasheen and was revised by Elnaggar.

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