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 filter for load mitigation 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 capacity reached 597 GW before the end of 2018. A 50.1 GW was 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 L1 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.

Manuscript received March 12, 2020; revised June 16, 2020. Ahmed A. Lasheen and Mahmoud M. Elnaggar are with Electrical Power Engineering, Cairo University, Egypt (e-mail: ahmed_lasheen88@yahoo.com, mhmudmhmd_elnagar@yahoo.com).

doi: 10.18178/ijesd.2020.11.8.1281
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],

\[
M(q,u,t)\ddot{q} + f(q,\dot{q},u,u_d,t) = 0
\]  
(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,

\[
\begin{align*}
\dot{x}_{ipc} &= A_{ipc}(\psi)x_{ipc} + B_{ipc}(\psi)u_{ipc} \\
y &= C_{ipc}x_{ipc}
\end{align*}
\]  
(2)

where \(\psi\) 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 state system 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].

\[
T(\psi) = \begin{bmatrix}
\cos(\psi) & \cos(\psi + \frac{2\pi}{3}) & \cos(\psi + \frac{4\pi}{3}) \\
\sin(\psi) & \sin(\psi + \frac{2\pi}{3}) & \sin(\psi + \frac{4\pi}{3})
\end{bmatrix}
\]  
(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

\[
y_{d-q} = \begin{bmatrix} M_{tilt} \\ M_{yaw} \end{bmatrix} = T(\psi) \begin{bmatrix} M_{y,1} \\ M_{y,2} \\ M_{y,3} \end{bmatrix}
\]  
(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:

\[
\begin{align*}
\dot{x}_{d-q} &= A_{d-q}x_{d-q} + B_{d-q}u_{d-q} \\
y_{d-q} &= C_{d-q}x_{d-q}
\end{align*}
\]  
(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].

\[
\begin{bmatrix}
u_{ipc,1} \\ u_{ipc,2} \\ u_{ipc,3}
\end{bmatrix} = \begin{bmatrix}
\cos(\psi) & \sin(\psi) \\
\cos(\psi + \frac{2\pi}{3}) & \sin(\psi + \frac{2\pi}{3}) \\
\cos(\psi + \frac{4\pi}{3}) & \sin(\psi + \frac{4\pi}{3})
\end{bmatrix} \begin{bmatrix}
u_{d-q}
\end{bmatrix}
\]  
(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

\[
\sum_{k=0}^{m} l_i(k)l_j(k) = 0 \quad i \neq j,
\]  
(7)

The z- domain transfer function of the \(m^{th}\) Laguerre
The linear state space continuous-time system given in (5) can be written in the discrete – time form as follows,

\[ \begin{align*}
    x(k + 1) &= A x(k) + B u(k) \\
    y(k) &= C x(k) \\
    u_{\text{ipc}}(k) &\leq u(k) \leq u_{\text{max}}(k) \\
    \Delta u_{\text{ipc}}(k) &\leq \Delta u(k) \leq \Delta u_{\text{max}}(k)
\end{align*} \]  

(10)

where \( u_{\text{ipc}} \), \( u_{\text{max}} \), \( \Delta u_{\text{ipc}} \), and \( \Delta u_{\text{max}} \) 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

\[ u(k + m) = \sum_{i=1}^{N} l_i(m) c_i = L^T(m) \eta \]  

(11)

where \( \eta = [c_1 \ c_2 \ \ldots \ c_N] \). The prediction equation can be written in terms of Laguerre coefficient as follows,

\[ \begin{align*}
    x(k + 1) &= A^m x(k) + S_c(m) \eta \\
    y(k + m) &= C A^m x(k) + \sum_{i=0}^{m-1} C A^{m-i-1} B L^T(i) \eta
\end{align*} \]  

(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].

\[ AS_c(m) - S_c(m) \omega^T = A^m B L^T(0) - B L^T(m) \]  

(13)

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

\[ y(k + m) = C A^m x(k) + \sum_{i=0}^{m-1} C A^{m-i-1} B L^T(i) \eta \]  

(14)

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

\[ J = Y^T Y + U^T R U \]  

(15)

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

\[ J = \sum_{m=1}^{N_{\text{mpc}}} y(k + m)^T y(k + m) + \eta^T R_i \eta \]  

(16)

where \( R_i \) is constant diagonal matrix. The cost function given in (16) can be reformulated to be in terms of the state variables as follows:

\[ J = \sum_{m=1}^{N_{\text{mpc}}} x(k + m)^T Q x(k + m) + \eta^T R_i \eta \]  

(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,

\[ u_{\text{min}}^{\text{ipc}} \leq u_{\text{ipc}}(k) \leq u_{\text{max}}(k) \]  

(18)

\[ \Delta u_{\text{ipc}}(k) \leq (L(m+i) - L(m)) \eta \leq \Delta u_{\text{max}} \]  

(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 \( u_{\text{cpc}} \) 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 \( u_{\text{ipc}} \), 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 \( u_{\text{cpc}} \), 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
The 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 shown in Fig. 2 and it can be written as,

$$U = u_0 + u_{ipc} + u_{CPC}$$  \hspace{1cm} (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 ($\Delta u_{\min}$) and 0.139 rad/sec ($\Delta u_{\max}$), respectively [2]. The input constraints on the IPC action are rewritten using (20) as:

$$(u_{CPC} - u_0 + u_{\min}) = u_{ipc}(\min) \leq u_{ipc}$$  \hspace{1cm} (21)

$$(u_{CPC} - u_0 + u_{\max}) = u_{ipc}(\max) \geq u_{ipc}$$  \hspace{1cm} (22)

$$(-\Delta u_{CPC} - u_0 + u_{\min}) = \Delta u_{ipc}(\min) \leq \Delta u_{ipc}$$  \hspace{1cm} (23)

$$(-\Delta u_{CPC} - u_0 + u_{\max}) = \Delta u_{ipc}(\max) \geq \Delta u_{ipc}$$  \hspace{1cm} (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).

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.
- The optimal control action $\eta$ is produced and the optimal IPC action is calculated based on (11).

### 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.

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.

| 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         |
|                      | 1st blade 876 | 1193           |
|                      | 2nd blade 860 | 1210           |
|                      | 3rd blade 876 | 1193           |
|                      | tower 1853   | 2764           |

Table I: Performance Analysis of the Proposed MPC Controller

Fig. 3. Stochastic wind speed profile.

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

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.
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.

REFERENCES

[1] Wind Power Capacity Worldwide Reaches 597 GW. (2019). [Online]. Available: https://www.dea.org/blog/2019/02/25/wind-power-capacity-worldwide-
reaches-600-gw-539-gw-added-in-2018

[2] J. M. Jonkman, S. Butterfield, W. Musial, et al., Definition of a 5-MW Reference Wind Turbine for Offshore System Development, USA, 2007.

[3] M. Elnaggar, M. Saad, H. Abdel Fattah, and A. L. Elshafei, “L1 adaptive fuzzy control of wind energy conversion systems via variable structure adaptation for all wind speed regions,” IET Renewable Power Generation, vol. 12, no. 1, pp. 18-27, 2018.

[4] A. Asgharinia, R. Shahhazi, and A. Jamali, “Performance and robustness of optimal fractional fuzzy PID controllers for pitch control of a wind turbine using chaotic optimization algorithm,” ISA Transactions, vol. 79, pp. 27-44, 2018.

[5] A. Lasheen, M. Saad, H. Emara, and A. L. Elshafei, “Continuous-time tube-based explicit model predictive control for collective pitching of wind turbines,” Energy, vol. 1, pp. 1222-1233, 2017.

[6] S. Rai, S. Y. Yang, and T. C. Tsao, “Wind turbine system identification and individual pitch control,” in Proc. American Control Conference, Seattle, 2017.

[7] M. Vai, J. V. Wingerden, and M. Kuhn, “Optimal multivariable individual pitch control for load reduction of large wind turbines,” in Proc. American Control Conference, Boston, 2016.

[8] H. M. Hassan, A. L. ElShafei, W. A. Farag, and M. S. Saad, “A robust LMI-based pitch controller for large wind turbines,” Renewable Energy, vol. 44, pp. 63-71, 2012.

[9] E. A. Bossanyi, “Wind turbine control for load reduction,” Wind Energy, vol. 6, pp. 229-244, 2003.

[10] K. Selvam, S. Kaney, J. V. Wingerden, T. V. Engelen, and M. Verhaegen, “Feedback-forward individual pitch control for wind turbine load reduction,” International Journal of Robust and Nonlinear Control, vol. 19, no. 1, pp. 72-91, 2009.

[11] J. Jonkman and M. Buhl, “FAST user's guide,” National Renewable Energy Laboratory, Technical Report NREL/EL-500-38230, 2005.

[12] G. S. Bir, “User's guide to MBC3: Multi-blade coordinate transformation utility for 3-bladed wind turbines,” National Renewable Energy Laboratory, Golden, CO, USA, 2008, pp. 1-17.

[13] L. Wang, Model Predictive Control System Design and Implementation Using MATLAB, Melbourne, Australia: Springer, 2009.

[14] N. D. Kelley and B. J. Jonkman, “Overview of the turbosim stochastic inflow turbulence simulator,” National Renewable Energy Laboratory, (NREL), Golden, CO, 2006.

[15] D. J. Leith and E. Leithead, “Appropriate realization of gain-scheduled controllers with application to wind turbine regulation,” International Journal of Control, vol. 65, no. 2, pp. 223-248, 2000.

[16] N. Wang, A. D. Wright, and K. E. Johnson, “Independent blade pitch controller design for a three-bladed turbine using disturbance accommodating control,” National Renewable Energy Laboratory, (NREL), Golden, CO. 80401 USA, 2016.

[17] G. J. Hayman and M. Buhl, MLife User's Guide for Version 1.00, 2012.

Ahmed Lasheen was born in Giza, Egypt. He gained his bachelors, master and Ph.D degree in 2010, 2013 and 2017, respectively from Faculty of Engineering at Cairo University, Egypt. He is an assistant professor at Cairo University. He is interested in wind energy conversion systems, model predictive control, linear matrix inequalities, fuzzy control, adaptive control and neural networks. Dr. Lasheen is an author of 12 scientific articles in academic journal and conferences.

Mahmoud Elnaggar was born in Giza, Egypt. He graduated from Cairo university in 2009. He received his M.Sc and Ph.D degrees in 2013 and 2017, respectively. His research interest is in adaptive control, nonlinear control, predictive control, and control systems applications in renewable energy. Dr. Elnaggar is an author of 9 scientific articles in academic journal and conferences.