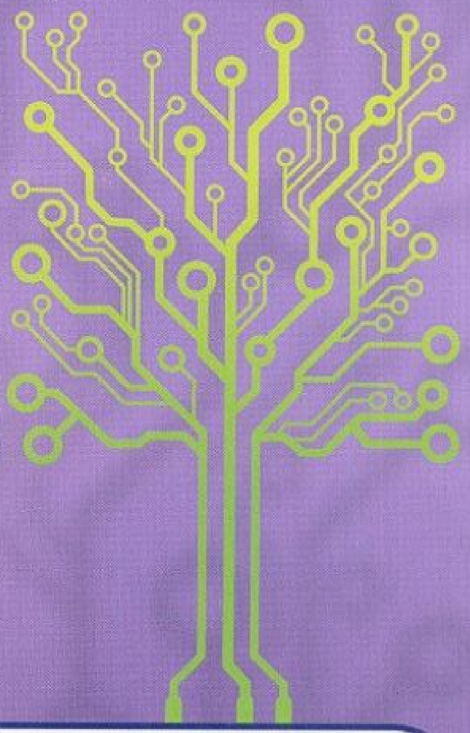

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باسمه تعالی

بدین وسیله گواهی می شود که مقاله زیر در بیست و یکمین کنفرانس مهندسی برق ایران ارائه شده است.

“Wind Turbine Power Tracking Using Multiple Model Predictive Control ”

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میر مجتبی میرصالحی
دبیر کمیته علمی کنفرانس

Wind Turbine Power Tracking Using Multiple Model Predictive Control

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Abstract: *Due to the development of technology and a great demand of energy, researchers try to discover energy sources with lower pollution, so the use of wind power for generating electricity has been increasing over last few decades. Nowadays, controller design for a variable speed variable pitch wind turbine is one of the most challenges for engineers.*

In this paper, a multivariable control strategy based on multiple model predictive control techniques for the control of variable speed pitch regulated wind turbines in the above-rated wind speed (full region) is proposed. Pitch angle and generator torque are controlled to reduce loads by producing a rated generator power and turbine speed.

The advantages of this control structure are to consider the multivariable nature of the system and using a multiple model structure to deal with the nonlinearity in the system.

A 2MW wind turbine is considered to show the good performances brought by the proposed approach by presenting and discussing the simulation results.

Keywords: Variable Speed Pitch Regulated Wind Turbines, Power Control, Multiple Model Predictive Control

1. Introduction

The use of wind power for generating electricity has been constant and rapidly increasing over last few decades. Nowadays, Control design for a variable speed variable pitch wind turbine is one of most challenges to engineers. Control systems play an important role in wind energy conversion systems. A well designed controller for a wind turbine enables more efficient energy generation, good power quality and reducing aerodynamic and mechanical loads resulting in increased life of the installation. Consequently, such a control system will have a direct impact on the cost of energy produced by the system [1].

Usually control systems designed for variable speed pitch regulated wind turbine consists of two loops to perform both increasing power output and keep wind turbine safety over the whole operation region. At below rated wind speed, the optimal tip speed ratio is traced with capturing more wind energy to maximize power output by adjusting the turbine rotational speed (partial load region). At above rated wind speed, in the full load region, the wind turbine is controlled to reduce loads by producing a rated power output at a constant turbine speed, which is obtained by controlling the pitch angle of the turbine's blades and the generator torque. These days there exists an increasing interest in the control of variable speed variable pitch wind turbine in the full load regime and in this paper only operation in this region is considered [2].

Design of wind turbine controller is not a straightforward task. The main reasons for this is that the system is nonlinear and a multiple input multiple output (MIMO) with strongly coupled variable and the wind speed is variable.

The usual implemented controllers are calculated from a linearization of the model around an operating point. PID, robust (H_∞) and LQG controllers are used in [3], [4] and [5] respectively. These controllers are designed for a single operating point and hence, performance degradation can result when the system is not working at this operating point. To cope with the system nonlinearity, local controllers are designed at different operating points, and gain scheduling techniques are used. This approach is used in [6] to adjust the PID controller parameter. In addition, nonlinear control design methods are used in [7], [8]. Most of the work reported ignores the multivariable nature of the problem.

In this paper, a new control strategy based on multiple model predictive control (MMPC) techniques is proposed for controlling variable speed pitch regulated wind turbines in the full load region. The main advantages of the proposed strategy are to consider the multivariable nature of the system and using a multiple model structure to cope with nonlinearity in the system.

The remainder of this paper is organized as follows. Section 2 and 3 describe the nonlinear model and linearization of wind turbine respectively. Section 4 describes the control problem in the full load region. Section 5 introduces the multiple model predictive controller. Simulation results are shown in Section 6. Finally, Section 7 concludes this paper.

2. Nonlinear model of the wind turbine

A model of the entire wind turbine can be structured as several interconnected subsystems as shown in Fig. 1. Details of the individual blocks are given more [9].

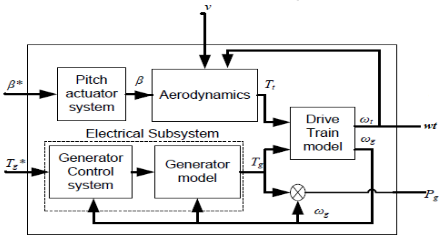

Fig. 1: Wind turbine global scheme [10]

2.1 Aerodynamic system and drive train model

A variable speed, horizontal axis wind turbine can be represented by a two mass model as shown in Fig. 2. In Fig. 2, G_g is the gearbox ratio, ω_t and ω_g are the turbine and the generator rotational speeds, k and d are respectively the mechanical coupling stiffness and damping coefficients, T_g is the generator torque and T_{aero} is the torque caught by the wind turbine, which is given by the following Equation (1):

$$T_{aero} = \frac{c_p(\lambda,\beta)}{\lambda}\frac{1}{2}\rho\pi R^3 v^2 \tag{1}$$

Where ρ is the air density, R is the turbine radius, the power coefficient C_p is a nonlinear function of the blade pitch angle β and the tip speed ratio λ depending of the wind speed value v and given by Equation (2):

$$\lambda = \frac{\omega_t R}{v} \tag{2}$$

Considering a flexible drive train model, the wind turbine can be described by the following differential Equation (3):

$$\begin{aligned} J_t\frac{d\omega_t}{dt} &= T_{aero} - T_{mec} \\ J_{g-Ls}\frac{d\omega_{g-Ls}}{dt} &= T_{mec} - G_g T_g \\ \frac{dT_{mec}}{dt} &= k(\omega_t - \omega_{g-Ls}) + d\left(\frac{d\omega_t}{dt} - \frac{d\omega_{g-Ls}}{dt}\right) \end{aligned} \tag{3}$$

Where T_{mec} is the low-speed shaft torque, J_T and $J_{g\text{-}Ls}$ are respectively the turbine and the generator (reported to the low-speed shaft) inertia and $\omega_{g\text{-}Ls}$ is the generator rotational speed reported to the low speed shaft [9].

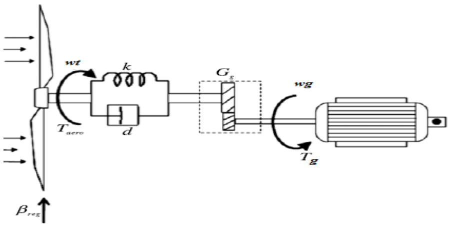

Fig. 2: Wind turbine drive train dynamics [9]

2.2 Pitch actuator system

The pitch actuator is modelled by a firs order equivalent dynamic system with the saturation in the amplitude and derivative of the pitch, as seen in Equation (4):

$$\frac{d\beta}{dt} = \frac{1}{\tau_\beta}\beta^* - \frac{1}{\tau_\beta}\beta \tag{4}$$

Where β^* is the reference signal for the blade pitch angle and τ_β is the time constant of the pitch actuator [9].

2.3 Generator model

For turbine controller design, it is important to use simple models that capture the relevant dynamics of the system. Fortunately, the dynamics of the electrical subsystem are much faster than the turbine dynamics and simple models can be used to represent the electrical dynamics. In this paper, a first order model, given in Equations (5), (6) is used.

$$\frac{dT_g}{dt} = \frac{1}{\tau_g}T_g^* - \frac{1}{\tau_g}T_g \tag{5}$$

$$p_g = \eta T_g \omega_g \tag{6}$$

Here, T_g, τ_g and η are the generator torque, time constant and efficiency, respectively [10].

3. Linearization and state representation

The nonlinearity of the system is due to the C_p characteristic, which is used in the expression of the aerodynamic torque. We need then to linearize the Equation (1) of T_{aero} around an operating point defined by the wind speed value. We can define:

$$\Delta T_{aero} = \frac{\partial T_{aero}}{\partial \omega_t}\Big|_{op}\Delta\omega_t + \frac{\partial T_{aero}}{\partial \beta}\Big|_{op}\Delta\beta = a\Delta\omega_t + b\Delta\beta \tag{7}$$

Where

$$\begin{aligned} a &= \left(\frac{1}{2}\rho\pi R^3\frac{v^3}{\omega_t}\left[\frac{\partial C_p}{\partial\lambda} - \frac{C_p}{\lambda}\right]\right)\Big|_{op} \\ b &= \left(\frac{1}{2}\rho\pi R^2\frac{v^3}{\omega_t}\frac{\partial C_p}{\partial\beta}\right)\Big|_{op} \end{aligned} \tag{8}$$

The symbol Δ is used to represent the deviation of a variable from its operating point.

Thereafter, the linearized state space model of the system can be written as Equations (9), (10):

$$\begin{aligned} \dot{x} &= Ax - Bu \\ y &= Cx + Du \end{aligned} \tag{9}$$

Where x, y and u are respectively the state vector, control input and measured output defined as Equation (10):

$$\begin{aligned} x &= \begin{bmatrix}\omega_t & \omega_{g-Ls} & \beta & T_g & T_{mec}\end{bmatrix}^T \\ u &= \begin{bmatrix}\beta^* & T_g^*\end{bmatrix}^T \\ y &= \begin{bmatrix}\omega_t & p_g\end{bmatrix}^T \end{aligned} \tag{10}$$

And A, B, C and D are respectively the state, input, output and feed through matrices defined as follows:

$$A = \begin{bmatrix} \frac{a}{J_t} & 0 & \frac{b}{J_t} & 0 & \frac{-1}{J_t} \\ 0 & 0 & 0 & \frac{-G_g}{J_{g-Ls}} & \frac{1}{J_{g-Ls}} \\ 0 & 0 & \frac{-1}{\tau_\beta} & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{\tau_g} & 0 \\ k + \frac{d.a}{J_t} & -k & \frac{d.b}{j_t} & \frac{d.G_g}{J_{g-Ls}} & -d(\frac{1}{J_t} + \frac{1}{j_{g-Ls}}) \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{\tau_\beta} & 0 \\ 0 & \frac{1}{\tau_g} \\ 0 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & G_g T_{g-op} & 0 & G_g \omega_{g-Ls-op} & 0 \end{bmatrix}$$

$$D = Zeros(2,2)$$

It can be seen that the system is MIMO and that the system dynamics vary when the average wind speed varies.

4. Control problem description

Wind turbine operation can be divided into four regions:

(1) Region 1: $v < v_{cin}$.
(2) Region 2: (partial load): $v_{cin} < v < v_{rated}$.
(3) Region 3: (full load): $v_{rated} < v < v_{cout}$.
(4) Region 4: $v > v_{cout}$.

Where v_{cin}, v_{rated} and v_{cout} are cut-in, rated and cut-out wind speed respectively.

During full load operation the control objective is defined as, turbine speed regulation at its nominal value and yield of rated power, by controlling the blade pitch angle and generator torque in such a manner. The use of pitch control is limited by the constraints on the amplitude and speed of the pitch actuator. One of the main challenges for designing wind turbine control systems in the full load region is the presence of severe fluctuations in the turbine power, caused by erratic variations in the wind speed. Fluctuations in turbine power can lead to variations in the drive train torsional torque, and in the electric power supplied to the grid. These, in turn, can cause reduction in the life time of the wind turbine components. If a multivariable controller that can use of both pitch angle and generator torque is used, the quality of the electrical power generated by the wind turbine can be improved [2], [10].

5. Proposed control strategy

In this paper, a multivariable control strategy based on multiple model predictive control techniques for the control of variable speed variable pitch wind turbines in the above-rated wind speed zone is proposed.

5.1 Reviews of Model Predictive control

Model-based predictive control (MPC) has been successfully used in many industrial applications in recent decades. There are several reasons for this success. First, predictive control algorithms can take into account in a natural way constraints on both process inputs (control signals) and process output values (controlled variables), which often decide on the quality, effectiveness and safety of production. They generate control signals taking on-line into account these constraints, and owing to a direct use of a model, also internal interactions within the process. Thus, they can naturally be applied to multivariable process control, also when the numbers of the control inputs and the controlled variables differ. Third, the principle of operation of these algorithms is comprehensible and relatively easy to explain to engineering, which is a very important aspect when introducing new techniques into industrial practice [11].

5.2 Predictive Control Principle

MPC is a digital controller, i.e. a discrete time technique. The general principle MPC can be understood from Fig. 3. Assume we are at certain sampling time k. The past trend for the output (y) up to k and input (u) up to k-1 are known. The objective is then to find the future trend for the input that moves the future trend of the output approaches the desired reference trajectory r(k+1). The control actions are found through iteration. In fact, an optimization problem is solved to compute online and in real-time the open loop sequence of present and future control moves [u(k|k), u(k+1|k) … u(k+N_c-1|k)], such that the predicted outputs [y(k+1|k) y(k+2|k) … y(k+N_p|k)] follow the predefined trajectory. The optimization is solved taking into consideration constraints on the outputs and inputs. The first control action u (k|k) is then implemented on the real plant over the interval [k, k+1]. In the method, N_c is known as the control horizon and N_p as the prediction horizon.

At the next sampling time k+1, the prediction and control horizon are shifted ahead by one step and a new optimization problem is solved using updated measurements from the process. Thus, by repeatedly solve an open-loop optimization problem with every initial conditions updated at each time step, the model predictive control strategy results in a closed-loop constrained optimal control technique [12].

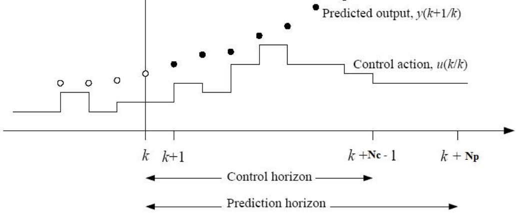

Fig. 3: MPC principle

5.3 Multi-model description

Many researchers advocated the use of the multi-model approach in the modeling, analysis and control of nonlinear complex systems.

In this approach, the whole operating region is divided into M sub-regions with M linearized models that adequately represent the local system dynamics within each sub-region. A linear controller based on each model is designed. Finally, a criterion by which the control system switches one controller to another as operating conditions change is defined [13].

5.4 Multi-model Predictive Control

Controller designs for the proposed action are as follows:

- First, the wind turbine system is approximated with M linear models that built a hybrid state space model:

$$x^i(k+1) = A^i x^i(k) + B_u^i u(k) + B_d^i d^i(k) \quad (12)$$
$$y^i(k) = C^i x^i(k) \qquad ,i = 1,\dots,M$$

In Equation (12), k is the discrete time index, d(k) is used to represent the effect of actual unmeasured disturbance and it is modelled as the output of the system with Gaussian white noise as the input.

- Second, a linear MPC controller based on each model is designed. The optimization problem involving the physical constraints on the variables of the controlled system, such as limits on the pitch angle, pitch angle rate, power and turbine speed. The optimization cost function is given by Equation (13)

$$J(N_p, N_c) = \sum_{j=1}^{N_p} Q[y(k+j\,|\,k) - y^*(k+j)]^2 + \sum_{j=0}^{N_c-1} R[\Delta u(k+j)]^2 \quad (13)$$

Where y^* is reference output, $\Delta u(k)$ is defined as u(k)-u(k-1) and {Q, R} are weighting coefficient matrices.

- Finally, a criterion for switching between different controller is defined. In this paper, switching between different MPCs is based on the value of average wind speed.

This control scheme is presented in Fig. 4. [10], [14].

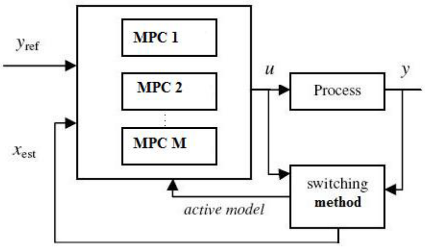

Fig. 4: Multiple model predictive control scheme

6. Simulation Result

The performance of the proposed control strategy is assessed in this section. In all simulations provided in this section, the designed controllers are tested on the nonlinear wind turbine model. The proposed control strategy has been implemented on a simulated 2 MW wind turbine. The parameters of the simulated plant are given in Table I.

TABLE I: Wind turbine parameter value

Parameter	Value
Turbine radius	40m
Nominal power	2 MW
Nominal turbine speed	2.47 rad/s
Rated wind speed	11 m/s
Cut-out wind speed	22 m/s

First, we show a performance comparison between different partitioning of the full load region. We assume 2 and 4 linear models and compare results of each structure. A simulation results are shown in Fig. 5- Fig.9.

If we calculate the deviation of turbine speed and generator power from its nominal value and standard deviation of the pitch rate, we obtain that with M=2, these are 0.0047 , 0.0055 and 9.82 respectively and for M=4, these are 0.00043, 0.0045 and 5.608. It can be observed that when we use 4 linear models, the turbine speed and generator power fluctuations and pitch actuator activity are reduced.

In general, increasing the number of partitions will enhance the linear approximation and the prediction accuracy. This comes at the cost of increasing the controller complexity and may increase load caused by switching between controller, so we can designed controller to provide the desired trade-off between number of partitioning and reducing the load of switching.

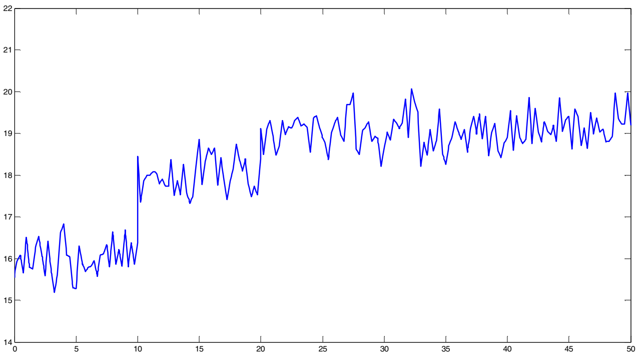

Fig. 5: Wind speed

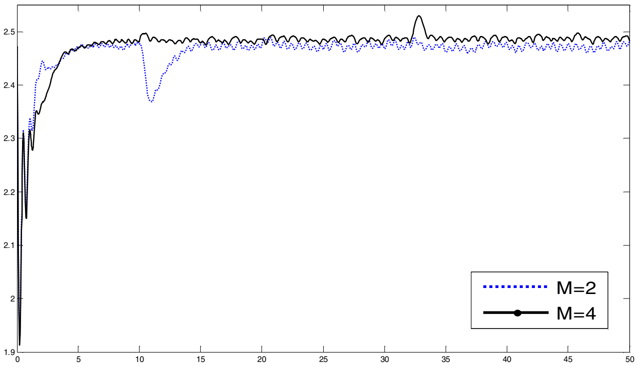

Fig. 6: Turbine rotational speed

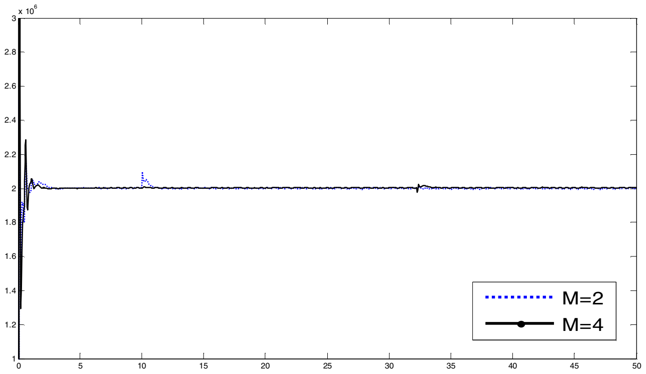

Fig. 7: Generator power

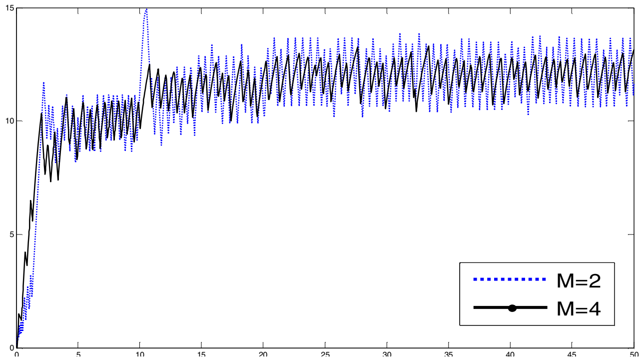

Fig. 8: Pitch angle

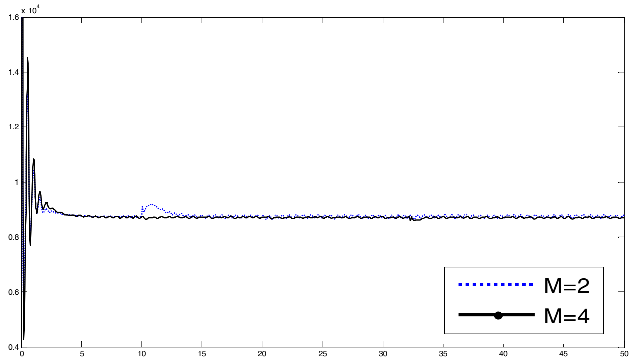

Fig. 9:Generator torque

Second, we compare Performance of the multivariable MPC controller with the classical PI control strategy. In the classical approach, the generator torque set point is fixed at its rated value, while the pitch angle set point is used as a control signal to regulate the turbine speed at its rated value. A simulation results are shown in Fig 10-Fig.14. The deviation of turbine speed and generator power from its nominal value and standard deviation of the pitch rate for MMPC are 0.004 , 0.0026 and 5.31 respectively and for PI are 0.0105, 0.0065 and 3.5626. It can be observed that when using MMPC controller, turbine speed overshoot and generator power fluctuations are reduced. However, this is achieved by increasing the pitch actuator activity.

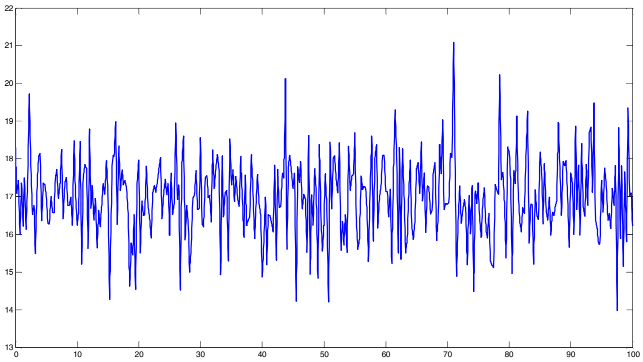

Fig. 10: Wind speed

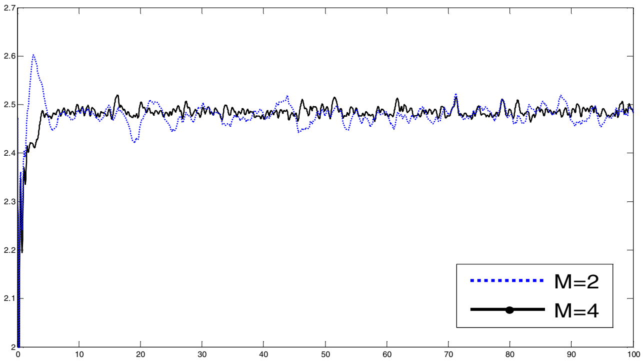

Fig. 11: Turbine rotational speed

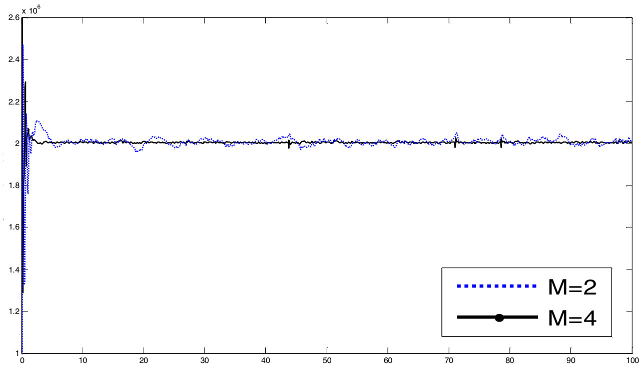

Fig. 12: Generator power

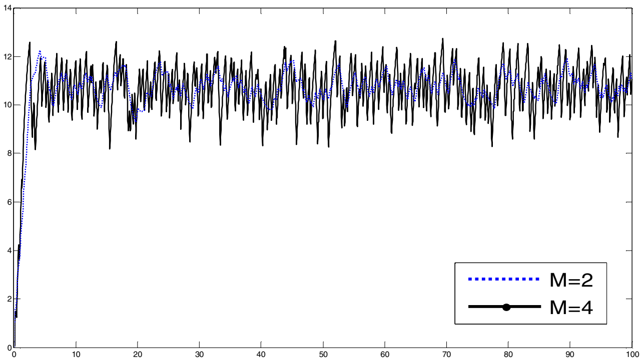

Fig. 13: Pitch angle

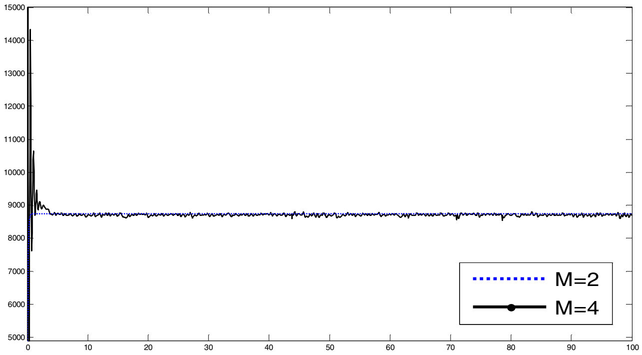

Fig. 14: Generator torque

7. Conclusion

In this paper, multivariable multiple model predictive control is proposed to control wind turbine in the full load region. The advantages of this control structure are to consider the multivariable nature of the system and using a multiple model structure to deal with the nonlinearity in the system. Multiple model strategy causing good performance of the closed-loop system over the whole operating region in the full load regime. The MMPC controller can be designed to provide the desired trade-off between number of partitioning for increase the linear approximation accuracy and reducing load caused by switching. Performance of the MMPC controller is compared with the traditional PI controller. Simulation results show that the MMPC controller provides much better smoothing for the turbine speed and the generator power. This has its effect on improving the power quality of the electrical power generated by the wind turbine.

References

[1] Lucy Y. Pao and Kathryn E. Johnson, “A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms”, *American Control Conference Hyatt Regency Riverfront, St. Louis, MO, USA*. June 10-12, 2009, pp. 2076-2089.

[2] Andres Petersson, “Analysis, Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines”, PhD Thesis, Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, Goteborg, 2005.

[3] N, Horiuchi , T. Kawahito, “Torque and Power Limitations of Variable Speed Wind Turbines Using Pitch Control and Generator Power Control”, *Power Engineering Society Summer Meeting, IEEE*,2001.

[4] Ryosei Sakamoto,Tomonobu Senjyu,Toshiaki Kaneko, Naomitsu Urasaki, “Output Power Leveling of Wind Turbine Generator by Pitch Angle Control Using H_∞Control”, *Power Systems Conference and Exposition, IEEE,* 2006.

[5] Xingjia Yao, Changchun Guo and Zuoxia Xing, Yan Li, Shu Liu and Xiaodong Wang, “Pitch Regulated LQG Controller Design for Variable Speed Wind Turbine”, *International Conference on Mechatronics and Automation, IEEE*, 2009.

[6] Zuoxia Xing, Qinwei Li, Xianbin Su, Hengyi Guo, “Application of BP Neural Network for Wind Turbines*”, Intelligent Computation Technology and Automation, IEEE*, 2009.

[7] Lei Zhang, Chunliang E, Haidong Li, Honghua Xu, “A New Pitch Control Strategy for Wind Turbines Base on Quasi-Sliding Mode Control”, *Power Generation and Supply, IEEE*. 2009.

[8] Beijing. “Nonlinear Feed Forward Pitch Controller for Wind Turbine based on Rotor’s Aerodinamic Characteristic”. *Machine Learning and Cybernetics, IEEE,* 2010.

[9] Nadhira Khezami, Naceur Benhadj Braiek Xavier Guillaud, “Wind turbine power tracking using an improved multimodel quadratic approach”. *ISA Transactions* 49, pp. 326-334, 2010.

[10] M.Soliman, O.P.Malik, D.T.Westwick, “Multiple Model Predictive Control for Wind Turbines with Doubly Fed Induction Generators”, *IEEE Transactions on Sustainable Energy, Vol. 2, NO. 3,* 2011.

[11] Eduardo F.Camacho, Carlos Bordons, “Model Predictive Control”, *Springer*, 1999.

[12] A. Bemporad, M. Morari and N.L. Ricker, “Model Predictive Control Toolbox, for Use with MATLAB”. The Mathworks, 2005.

[13] Boštjan Pregelj, and Samo Gerkšic, “Multiple Model Approach to Multi-Parametric Model Predictive Control of a Nonlinear Process – simulation case study, http://as.utia.cas.cz/files/113.pdf, 2006.

[14] Francesco Borrelli, Manfred Morari, "Offset Free Model Predictive Control*", Proceedings of the 46th IEEE Conference on Decision and Control, New Orleans*, LA, USA, Dec. 12-14, 2007.