DMC versus Gain Scheduled PI Controller for Pitch Regulation of 100 KW Wind Turbine

Nima Vaezi, Parisa Tavakkoli, and Seyyed Kamal Hosseini-Sani

Abstract— In recent years, wind energy becomes one of the most important sources for electricity production. For instance it is predicted that the installed wind capacity in China will be about 40 GW till 2020. The permanent magnet synchronous generators (PMSG) which contains of a permanent magnet that causes DC excitation current in the windings, are widely used in wind turbines. The advantage of this type of generators in comparison to the others, are higher efficiency, controllable terminal voltage and reactive power. It is also noticeable that the PMSG speed can be controlled by the converter which leads to MPPT implementation. The MPPT is always implemented to control the generator speed and output power between the cut-in and nominal wind speed. It is necessary to control the generator speed by pitch or stall control for upper rated wind speeds. In this paper after explaining the structure and components of a typical wind turbine with permanent magnet synchronous generator, designing of an offline DMC (Dynamic Matrix Control) and a gain scheduled PI pitch controller are presented. Both of these controllers have been tested on the practical simulator of 100 KW wind turbine with PMSG generator and the results are presented and compared.

Index Terms—Adaptive Control, DMC, PMSG, Pitch Control.

I. INTRODUCTION

A WIND turbine is a device that converts mechanical energy captured from the wind into the electrical power. Nowadays the wind turbines are manufactured in a wide range of vertical and horizontal axis type. Arrays of wind turbines, known as wind farms, are becoming an important source of renewable energy and are used as part of a strategy to reduce their reliance on fossil fuels [1].

Windmills were used in Iran as early as 200 B.C. and the first practical windmills were built in Sistan. Nowadays a lot of companies around the world are dealing with wind power generation. Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation and uses little land. The effects on the environment are generally less problematic than those from other power sources. As of 2011, Denmark is generating more than a quarter of its electricity from wind and 83 countries around the world are using wind power to supply the electricity grid. In 2010 wind energy production was over 2.5% of total worldwide electricity usage, and growing rapidly at more than 25% per annum [2].

Wind power is very consistent from year to year but has significant variation over shorter time scales. As the proportion of wind power in a region increases, a need to upgrade the grid, and a lowered ability to supplant conventional production can occur. Power management techniques such as having excess capacity storage, geographically distributed turbines, dispatchable backing sources, storage such as pumped-storage hydroelectricity, exporting and importing power to neighboring areas or reducing demand when wind production is low, can greatly mitigate these problems. In addition, weather forecasting permits the electricity network to be readied for the predictable variations in production that occurs [3].

At the end of 2013, worldwide nominal capacity of wind-powered generators was 318 GW, growing by 35 GW over the preceding year. According to the World Wind Energy Association, an industry organization, in 2010 wind power generated 430 TWh or about 2.5% of worldwide electricity usage, up from 1.5% in 2008 and 0.1% in 1997. Between 2005 and 2010 the average annual growth in new installations was 27.6%. Wind power market penetration is expected to reach 3.35% by 2013 and 8% by 2018 [2-3].

In this years, wind energy becomes one of the most important sources for electricity production. In 2006 he installed wind capacity in China was about 2600 MW and has grown nearly 105% in comparison to the previous year. It is also predicted that the installed wind capacity in China will be about 40 GW till 2020[4].

In this paper after explaining the structure and components of a typical wind turbine, the PI tuning method and DMC basis are discussed and applied to pitch control design of a 100 KW wind turbine. The designed controllers are utilized and compared to regulation of the pitch angle in both simulation and practical application.

II. WIND TURBINE COMPONENTS

As it is shown in figure 1, there are four main parts in a wind turbine: the base, tower, nacelle and blades. Because of the blade's special shape, the wind creates a package of pressure as it passes behind the blade and causing the turbine to rotate. The blades capture the mechanical power from the wind and transmit it to an electrical generator located in the nacelle. The tower contains the electrical conduits, supports the nacelle, and provides access to the nacelle for maintenance. The base which is made of concrete reinforced with steel bars, supports the whole structure [1].

There are a generator and a gearbox in the nacelle. The blades are attached to the generator through a series of gears. The gears increase the rotational speed of the blades to the

generator speed range. A wind turbine gearbox must be robust enough to handle the frequent changes in torque caused by changes in the wind speed. Generators can be either variable or fixed speed. Variable speed generators produce electricity at a varying frequency, which must be corrected to 50 or 60Hz before it is fed onto the grid.
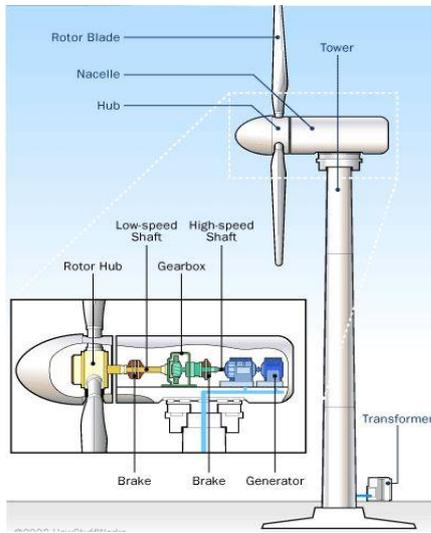

Fig.1. The wind turbine components.

The blades can be rotated around their axis to reduce the amount of lift when wind speed increases over the rated. This rotation is called pitch angle [2].

All wind turbines have a yaw drive system to face the rotor into the wind and to unwind the cables that travel down to the base of the tower. The yaw drive system consists of a hydraulic or electric motor mounted on the nacelle. It contains a brake in order to stop the turbine from turning and stabilizing it during normal operation [5].

The wind turbine consists of a number of sensors to read the speed and direction of the wind, levels of electrical power generation, the rotor speed, the blades' pitch angle and other variables. A computer process the inputs to carry out the normal operation of the wind turbine with a safety system which can override the controller in an emergency. The safety system protects the turbine from operating in dangerous conditions and ensures that the power generated has the proper frequency, voltage and current levels to be supplied to the grid [6].

The wind turbines often produce AC current with erratic voltage and frequency. Therefore an inverter is used to convert the erratic AC to DC, then back to a smoother AC which can be synchronized with the grid [5].

In the variable speed wind turbines with pitch controller which are one of the most popular wind turbines, two types of controller are used to fix and level the output power and rotor speed in different operating regions. The block diagram of this controllers is shown in figure 2. When the wind speed is lower than the rated, the speed controller adjusts the rotor speed so that the maximum power can be obtained from the wind. In another word, the speed controller adjust the tip speed ratio (λ) at its maximum point. When the wind speed is upper than the rated, the pitch controller adjusts the rotor speed at the rated value by increasing the pitch angle of the blades. While the wind speed is lower than the rated value, the pitch angle is controlled so that the maximum power can be obtained from the wind energy [5]. The three main reasons for pitch control system are:

- Optimizing the output power of the system
- Adjusting all system variables at their limits and stability
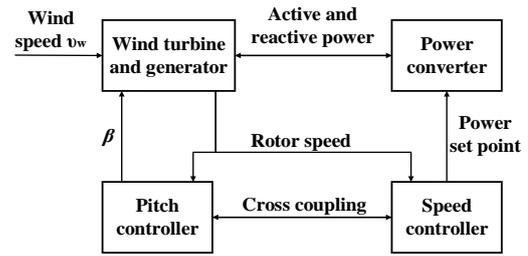- Minimizing the load effect on the mechanical components

Fig. 2. Two types of controller are used in variable speed wind turbines.

Pitch control limits the output power when the wind speed is over the rated value. The PI controller is a widespread method for adjusting the pitch angle. The actuators used in the pitch system are often hydraulic servo motors. This actuators provides a pitch transition rate about 5 to 10 degree/second.

The electrical power produced in the wind turbines are related to the cube of the wind speed. The power coefficient or C_p shows the extractable part of the wind power and is a function of tip speed ratio and pitch angle. In figure 3 the mechanical power characteristics of a wind turbine is shown as a function of rotor and wind speed [7].

The operating regions of the wind turbine system is shown in figure 4. When the wind speed becomes more than the cut in wind speed, the blades start to rotate. When wind speed increases and becomes more than the rated value, the pitch control system adjust the rotor speed at its rated value by increasing the pitch angle. If the wind speed becomes more than the cut out value, mechanical brakes forced the turbine to stop [7]. While the wind energy is not constant and depends on the wind speed, the output power of the wind turbines changes with the cube of the wind speed. If the power coefficient of wind turbine is very low, frequency changes according to wind speed changes, are negligible. But if the power coefficient of wind turbine is high, frequency changes according to wind speed changes will increase [5].
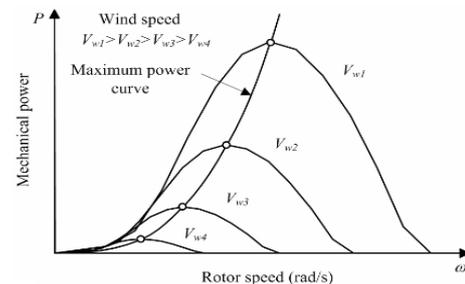

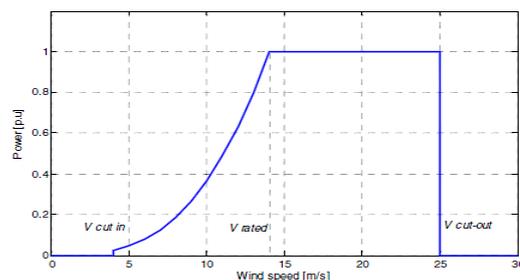Fig. 3. Mechanical power characteristics of a wind turbine [1].

Fig. 4. The operating regions of the wind turbine system [3].

III. Wind Turbine and Permanent Magnet Synchronous Generator

The aerodynamic power produced by the turbine blades P_ω, can be calculated through by (1). In this equation ρ is the air density, r is the rotor radius, v presents the wind speed and β is the pitch angle. The power coefficient is calculated through (2). In this equation ω_m shows the angular rotor speed.

$$P_\omega = \frac{\rho \pi r^2 v^3 C_p(\lambda, \phi)}{2} \tag{1}$$

$$\lambda = \frac{r\omega_m}{v} \tag{2}$$

The aerodynamic torque as shown in (3) is related to P_ω and ω_m.

$$T_\omega = \frac{P_\omega}{\omega_m} = \frac{\rho \pi r^3 v^2 C_p(\lambda, \phi)}{2\lambda} \tag{3}$$

The drive model is shown in (4). In this equation ω_e ($\omega_e = P\omega_g = PN\omega_m$) is the electrical rotor speed and ω_g is the mechanical rotor speed. The number of the poles is shown by P, turbine inertia is shown by J, N is shown the gearbox Conversion ratio and T_e is shown the electrical torque [8].

$$\dot{\omega}_e = \frac{P}{J}\left(\frac{T_\omega}{N} + T_e\right) \tag{4}$$

The permanent magnet synchronous generators (PMSG) which contains of a permanent magnet that causes DC excitation current in the windings, are widely used in wind turbines. The advantage of this type of generators in comparison to other types are higher efficiency, controllable terminal voltage and reactive power. Besides these advantages, having no resistance losses and no need for an extra power supply to excite a generator are some of the distinction of PMSG. Another advantage of PMSG is the ability of bringing out the gearbox while increasing the generator poles. This advantage decreases the mechanical losses and costs [8].

Equation (5) shows the relation between voltage and torque of a PMSG. In this equation u_d and u_q are voltage components of direct and quadrature axis and i_d and i_q are current components of direct and quadrature axis, R_s is the stator resistance, L_d and L_q are inductance components of dq axis and ϕ is the permanent magnetic flux.

$$u_d = R_s i_d + \frac{d}{dt}L_d i_d - \omega_e L_q i_q$$
$$u_q = R_s i_q + \frac{d}{dt}L_q i_q + \omega_e(L_q i_q + \phi) \tag{2}$$
$$T_e = \frac{3}{2}P\left((L_d - L_q)i_d i_q + \phi i_q\right)$$

If $L_d = L_q = L$ then (5) can be written as (6).

$$\frac{di_d}{dt} = -\frac{R_s}{L}i_d + \omega_e i_q + \frac{1}{L}u_d$$
$$\frac{di_q}{dt} = -\frac{R_s}{L}i_q - \omega_e i_d - \frac{\omega_e \phi}{L} + \frac{1}{L}u_d \tag{6}$$
$$T_e = \frac{3}{2}P\phi i_q$$

The 100KW wind turbine parameters are presented in table 1.

IV. MPPT and Converter Control

Maximum power point tracking (MPPT) is a technique that wind turbines solar battery chargers and similar devices use

TABLE 1.
THE 100KW WIND TURBINE PARAMETERS.

Name	Symbol	Value
Inertia	J	70 (For practical simulator) 1000 (For wind turbine)
Friction Constant	B	4.2
Gear Box Ratio	N	5.91
Air Density	ρ	1.05
Nominal Gird Power	P_{Grid}	100 KW
Generator Inductance	L	1 mH
Generator Resistance	R_s	0.147 Ω
Permanent Magnetic flux	ϕ	2.1
Number of Pair Poles	P	11
Rotor Radius	R	13 m
Pitch Rate	---	10 dg/sec
Proportional Gain of Convertor Speed Controller	K_{pp}	1.24
Integral Gain of Convertor Speed Controller	K_{pi}	4.95
Proportional Gain of Convertor Current Controller	K_p	3.675
Integral Gain of Convertor Current Controller	K_i	183.75

to obtain the maximum possible power from the power source. In the wind turbine system, the MPPT procedure is implemented by the convertor. MPPT procedure means tracking a predefined curve which is obtained from C_p and power coefficient characteristics of the wind turbine [9].

In the operational region 2 the MPPT curve should be implemented and if the wind speed increases from rated, the pitch mechanism acts to control the generator speed and output power. The MPPT curve of the 100 KW wind turbine produced in Sun and Air Research Institute is shown in figure5.

There are some limitations on the designed 100 KW wind turbine which are mentioned below.

- Maximum available generator speed in the MPPT curve is 325 rpm.
- Maximum sustainable generator speed for the convertor is 350 rpm and the generator speed more than 350 rpm is sustainable for about 3 or 4 seconds.
- In the operating point the generator torque is 2800 N.m.
- Maximum grid power selected on the MPPT curve is equal to 84 KW. When the generator speed reached to the 325 rpm, the grid power will be within the sustainable power for the convertor which is about 101 KW.

Because of this limitations pitch control of this wind turbine is not feasible with a simple PI controller. Therefore it is necessary to apply a new method.
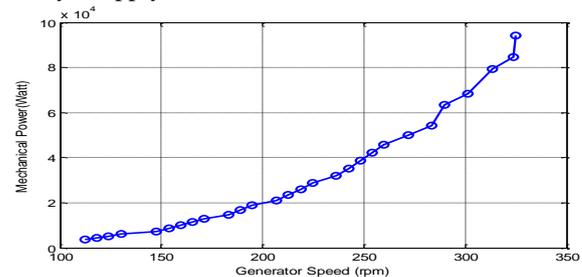

Fig. 5. The MPPT curve of the 100 KW wind turbine produced in Sun and Air Research Institute.

In figure 6 the pitch control system based on the generator speed error is shown. The generator speed measured by sensors is compared with the rated generator speed and the difference is applied to the PI controller. The controller output is the reference value of the pitch angle. The pitch angle reference value is compared with the measured pitch angle and the pitch command is applied to the pitch actuator. Hydraulic actuators or servo motors can be used as the pitch actuator in wind turbines.

The proportional and integral gains of the PI controller is extracted by using the first order Ziegler Nichols method. For the first step the generator speed is fixed on 350 rpm in wind 9.175 m/s by applying pitch angle about 0.5 degree of the pitch angle. The pitch angle changed from 0.5 to 1 degree suddenly and according to the step response of the generator speed, the proportional and integral gain of the PI controller will be designed. The generator speed step response is plotted in figure 7 for the Simulink file.
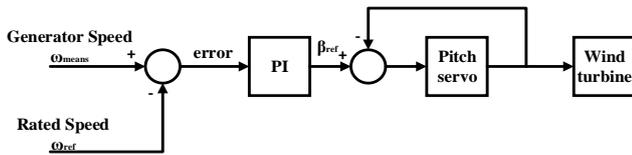

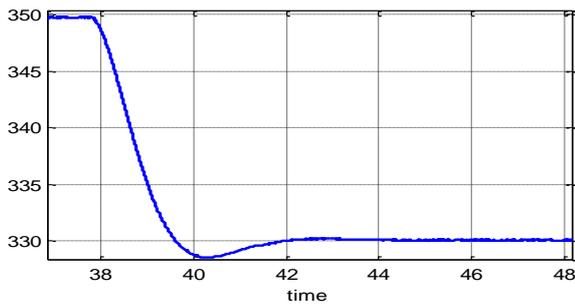Fig. 6. Pitch angle control based on the generator speed error.

Fig. 7. The generator speed step response.

According to the first order Ziegler Nichols method, at this wind speed, the gain K and the time constant τ and the delay τ_d in (7) are calculated as $K = 0.3527$, $\tau = 0.69041$ and $\tau_d = 0.2$.

$$G_{first\ order} = \frac{K}{\tau s + 1} e^{-\tau_d s} \qquad (7)$$

Therefore the controller gain is equal to $K_P = 8.808$ and the integrator time constant is equal to $T_i = 0.66$. The transfer function of the controller is as shown in (8).

$$G_{control} = K_P \left(1 + \frac{1}{\tau_i s} \right) \qquad (8)$$

This test is repeated at different wind speeds and the controller gains and the integrator time constants are calculated for different wind regions. The table 2 which is extracted from this collection of tests, contains K, τ, τ_d, K_P, T_i, pitch angle to control the generator speed at 350 rpm and pitch angle to control the generator speed at 325 rpm for different wind speeds.

The wind region is recognized based on the current pitch signal. In different wind region the pitch controller increases the pitch angle to stabilize the generator speed at 325 rpm. Therefore the current pitch angle specifies the wind region. Because of simplicity T_i is supposed to be fixed in 0.5 second and the controller gain will be determined according to the current pitch angle based on the data represented by table 2.

In that case the controller gain will be changed in different region based on the pitch angle. With normalization the gain

TABLE 2.
THE GAIN SCHEDULING TABLE FOR J=70.

Wind (m/s)	Pitch (350rpm) in degree	Pitch (325rpm) in degree	K	τ	τ_d	K_P	T_i (Sec)
9.175	0.5	0.3	0.352	0.6904	0.2	8.808	0.66
10	4.37	2.5	0.440	0.5774	0.2	5.9039	0.66
11	6.675	7.34	0.446	0.3718	0.15	4.999	0.495
12	8.52	9.16	0.441	0.3480	0.15	4.735	0.495
13	10.21	10.98	0.448	0.2428	0.1	4.789	0.33
14	11.56	12.44	0.433	0.26167	0.12	4.526	0.396
15	12.98	13.9	0.371	0.21009	0.1129	4.509	0.3728
16	14.42	15.41	0.413	0.19261	0.095	4.414	0.3135
17	15.6	16.65	0.409	0.16918	0.085	4.38	0.2805
18	16.68	17.9	0.352	0.1402	0.085	4.212	0.2805
19	17.85	19.19	0.306	0.12197	0.085	4.217	0.2805
20	19.1	20.3	0.319	0.13171	0.088	4.212	0.2904
21	20.24	21.42	0.320	0.12509	0.088	3.996	0.2904
22	21.32	22.58	0.321	0.1182	0.088	3.763	0.2904

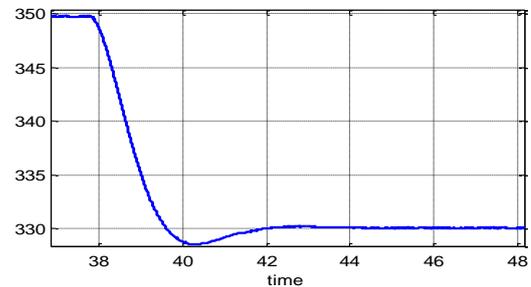
Fig. 8. The controller gain attenuation coefficient for J=70.

presented in table 2, the controller gain attenuation coefficient according to the current pitch angle will be as presented in figure 8.

In this condition there is no delay between the grid power and the reference for generator speed in MPPT and the generator speed which is injected to the pitch controller is averaged by 0.03 second with a moving average block. The grid power is calculated through grid current and voltage directly and without involving in any delay or filters.

For decreasing the effect of torque oscillation on the pitch angle control signal, a generator speed window is defined. If the absolute error of generator speed with considering 325 rpm as a reference, is less than 0.8 rpm then the generator speed injected to the pitch control system is averaged by 1 second and if not the generator speed directly injected to the pitch control system. The PI controller with the gain scheduling table is applied to the Simulink file of the 100 KW wind turbine and the results are plotted in figures 9, 10 and 11 for $J = 70$.

For the wind turbine with $J = 1000$ the convertor speed controller proportional gain is equal to $K_{pp} = 6.1875$ and it's integral gain in equal to $K_{ip} = 24.75$ and according to the Ziegler Nichols method for the first order systems, the gain scheduling table will be as presented in table 3.

Similar to table 2, the wind region is recognized based on the current pitch signal. In different wind region the pitch controller increases the pitch angle to stabilize the generator speed at 325 rpm. Therefore the current pitch angle specifies the wind region. Because of simplicity T_i is supposed to be fixed in 1.98 second and the controller gain will be determined according to the current pitch angle based on the data represented by table 3.

TABLE 3.
THE GAIN SCHEDULING TABLE FOR J=1000.

Wind (m/s)	Pitch (350rpm) in degree	Pitch (325rpm) in degree	K	τ	τ_d	K_P	T_i (Sec)
9	0.5	0.8	0.3455	10.8	0.7	46.85	2.3
10	4.37	1	0.2623	8.3	0.67	42.514	2.21
11	7	7.501	0.3202	7.1	0.562	35.49	1.85
12	8.52	9	0.4392	4.44	0.534	25.2673	1.76
13	10.21	11.06	0.2497	3.2	0.534	21.597	1.76
14	11.56	12.44	0.2448	3.1	0.53	21.5	1.74
15	12.95	14.44	0.2107	2.63	0.53	21.2	1.74
16	14.4	14.96	0.2436	2.41	0.502	17.74	1.65
17	15.6	15.5	0.4058	2.2	0.48	16.2598	1.58
18	16.68	16.25	0.3526	1.88	0.468	15.9929	1.54
19	17.85	17.94	0.303	1.63	0.468	16.1429	1.54
20	19.1	19.3	0.3189	1.68	0.468	15.8018	1.28
21	20.25	22.7	0.3189	1.6	0.388	15.0517	1.28
22	21.3	23.2	0.3207	1.51	0.38	14.1236	1.25

In that case the controller gain will be changed in different region based on the pitch angle. With normalization the gain presented in table 3, the controller gain attenuation coefficient according to the current pitch angle will be as presented in figure 12.

In this condition there is no delay between the grid power and the reference for generator speed in MPPT and the generator speed which is injected to the pitch controller is averaged by 0.03 second with a moving average block. The grid power is calculated through grid current and voltage directly and without involving in any delay or filters. For decreasing the effect of torque oscillation on the pitch angle control signal, a generator speed window is defined. If the absolute error of generator speed with considering 325 rpm as a reference, is less than 0.5 rpm then the generator speed injected to the pitch control system is averaged by 0.5 second and if not the generator speed directly injected to the pitch control system. The PI controller with the gain scheduling table is applied to the Simulink file of the 100 KW wind turbine and the results are plotted in figures 13, 14 and 15 for $J = 1000$.

V. PI TUNING AND GAIN SCHEDULING FOR PITCH CONTROL SYSTEM

Model Predictive Control (MPC) developed considerably over the last two decades, is the most modern and general way of posing the process control problem in the time domain. Model Predictive Control formulation integrates optimal control, stochastic control, control of processes with dead time, multivariable control and future references when available. Because of the finite control and predictive horizon, industrial processes can be handled by MPC. This is one of the advantage of MPC but this advantage makes the robustness and stability proofs more difficult than other methods. Implementation requirements and mathematical complexities intensify the general and industrial usage of MPC, however technology progress will solve this problem in the near future [12].

Dynamic Matrix Control (DMC) is one of the most popular methods of model predictive control. It is specially powerful for multiple input multiple output (MIMO) control systems. A way to have students explore the nature of DMC control is to use it on a simulated process [12].
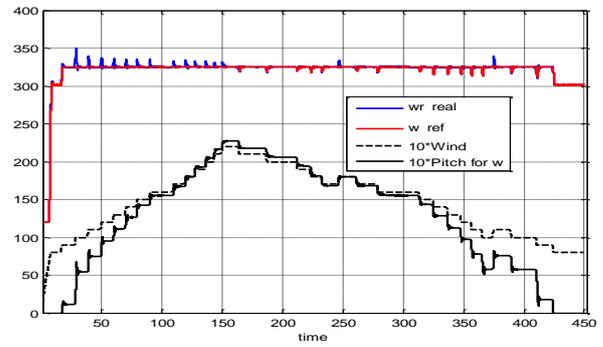

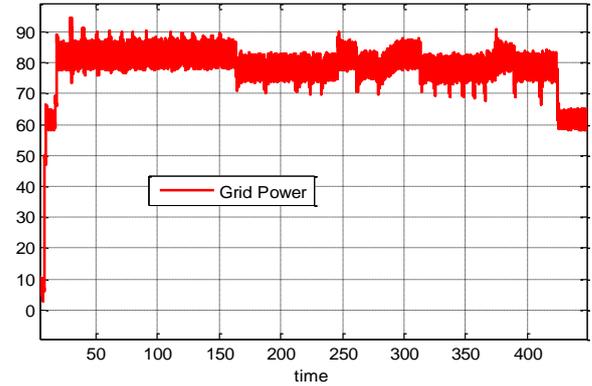Fig. 9. Generator speed, pitch angle and wind speed with gain scheduled PI pitch controller (J=70).

Fig. 10. The grid power with gain scheduled PI pitch controller (J=70).
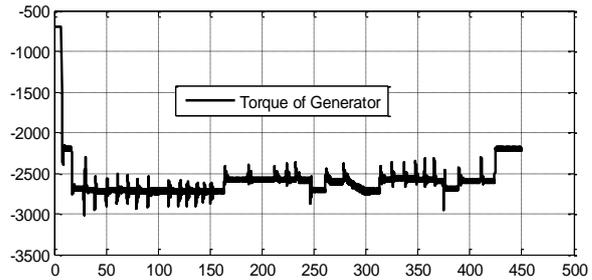

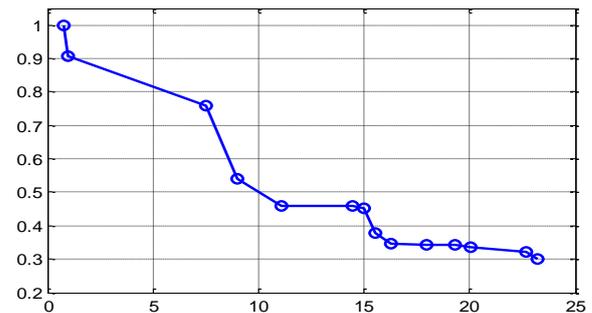Fig. 11. Generator Torque with gain scheduled PI pitch controller (J=70).
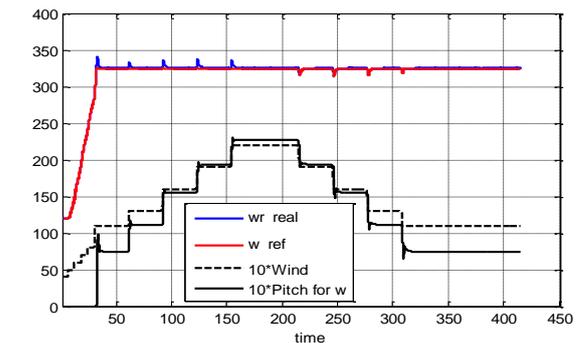

Fig. 12. The controller gain attenuation coefficient.

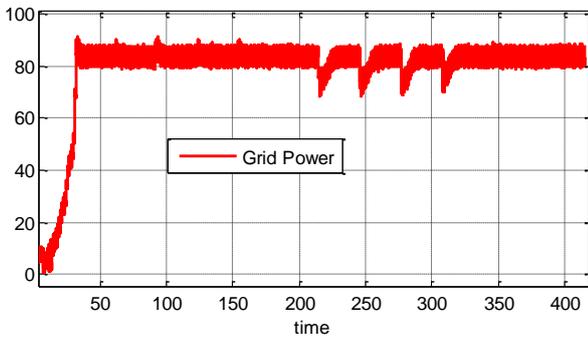Fig. 13. Generator speed, pitch angle and wind speed with gain scheduled PI pitch controller (J=1000).

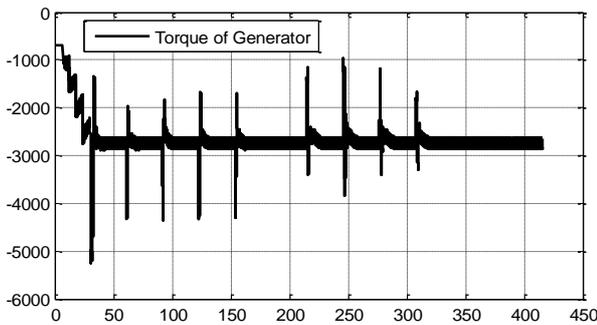Fig. 14. The grid power with gain scheduled PI pitch controller (J=1000).

Fig. 15. Generator Torque with gain scheduled PI pitch controller (J=1000).

Dynamic Matrix Control (DMC) was the first Model Predictive Control (MPC) algorithm introduced in early 1980s. These are proven methods that give good performance and are able to operate for long periods without almost any significant intervention. Model predictive control is also the only technique that is able to consider model restrictions. Today, DMC is available in almost all commercial industrial distributed control systems and process simulation software packages [13].

DMC is a form of control algorithm in which the current control action is obtained by solving a finite horizon of open loop optimal control problem using the current state of the plant as the initial state. This process is repeatedly done for each sampling point. The optimization yields an optimal control sequence and the first control in this sequence is applied to the plant [12].

In DMC, the models which are used, determine the behavior of complex dynamical systems. These models compensate for the effect of nonlinearities present in the variables and the chasm caused by non-coherent process devolution. Hence the models are used to predict the behavior of dependent variables or outputs of the modeled dynamical system with respect to changes in the process independent variables or inputs [12].

In most processes, independent variables are most often set points of regulatory controllers that govern valve movement (e.g. valve positioners with or without flow, temperature or pressure controller cascades), while dependent variables are most often constraints in the process (e.g. product purity, equipment safe operating limits). The model predictive controller make use of the models and current plant measurements to calculate future moves in the independent variables that will result in operation that honors all independent and dependent variable constraints. The model predictive controller then sends this set of independent variable moves to the corresponding regulatory controller set points which get implemented in the process [13].

Despite the fact that most real processes are approximately linear within only a limited operating window, linear MPC

approaches are used in the majority of applications with the feedback mechanism of the MPC compensating for prediction errors due to structural mismatch between the model and the process. In model predictive controllers that consist only of linear models, the superposition principle of linear algebra enables the effect of changes in multiple independent variables to be added together to predict the response of the dependent variables. This simplifies the control problem to a series of direct matrix algebra calculations that are fast and robust. Hence it is called Dynamic Matrix Control. The basic structure of a MPC controlled system is shown in figure 16.
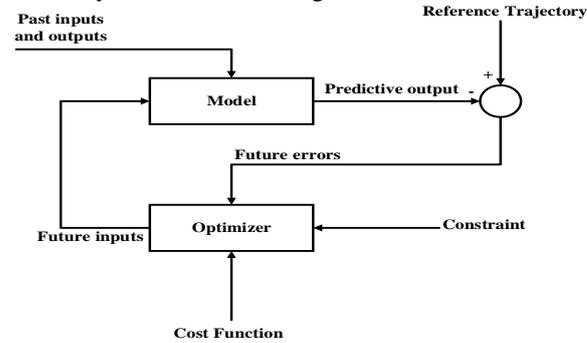

Fig. 16. The basic structure of a MPC [14].

When linear models are not sufficiently accurate because of process nonlinearities, the process can be controlled with nonlinear MPC. Nonlinear MPC utilizes a nonlinear model directly in the control application. The nonlinear model may be in the form of an empirical data or a high fidelity model based on fundamentals such as mass, species, and energy balances. The nonlinear models are linearized to derive a Kalman filter or specify a model for linear MPC. The time derivatives may be set to zero (steady state) for applications of real-time optimization or data reconciliation. Alternatively, the nonlinear model may be used directly in nonlinear model predictive control and nonlinear estimation (e.g. moving horizon estimation). A reliable nonlinear model is a core component of simulation, estimation, and control applications [15]. In the next section the reason for using the DMC method is described.

VI. WHY USING MPC AND DMC FOR PITCH REGULATION

Dynamic Matrix Control (DMC) has been popular for the control of chemical and petroleum processes. These processes commonly include integrating process units, which produce a ramp change in the output for a step change in input. In the wind turbine system, specially in the 3rd operating region, the stochastic variations in the wind speed will lead to sudden changes in the generator speed and the grid power. This changes will be great enough to produce a great error signal and lead to a great change in the pitch control signal. This command signal increases the actuator fatigue and depreciation, besides of this, the mechanical limitation of the pitch actuator and constraint on the pitch rate, will not allow the pitch angle to change rapidly and this may lead to generator over speed while the pitch angle command is sufficient for controlling the speed change. Therefore prediction of the generator speed variations will lead to a better deal with speed ups and downs.

VII. DMC DESIGN

Transfer function models are used to represent the dynamic behavior of a process. The first order models with time delay

are normally used for modeling different kinds of process. Transfer function models need the order to be specified. Here another way is to use a "discrete response model". It has the advantage that the model coefficients can be obtained directly from the state response which can be represented as (9).

$$x(k+1) - Ax(k) + bu(k),$$
$$y(k+1) = Cx(k) \qquad (9)$$

Here $x(k)$ is the input at instant k, $u(k)$ is the unit step function and $x(k+1)$ and $y(k+1)$ are the input and output at the next step. In equation (9) A, B and C are the state space coefficient of the model [12].

With considering the control horizon Nu as the number of the control actions that are taken in a model with predictive horizon of Np, the vector presented in (10), represents the state response coefficient vector.

$$\bar{a} = [a_1 \quad a_2 \quad a_3 \quad ... \quad a_N]^T \qquad (10)$$

If the current time instant is k the control action has to be taken at time instant $k-1$. The predicted output of the process at instant k can be represented by (11).

$$y(k) = \sum_{i-1}^{N} a_i \Delta u(k-1) + a_{ss} u(k-N-1) \qquad (11)$$
$$+ d(k)$$

In equation (11), $d(k)$ is the effect of disturbance and a_{ss} is the state response coefficient for the steady state situation. The above equation can be written as (12).

$$d(k) = y_{measured} - \sum_{i-1}^{N} a_i \Delta u(k-1) \qquad (12)$$
$$+ a_{ss} u(k-N-1)$$

For one step ahead prediction, equation (12) can be written as
$$y(k+1) = a_1 \Delta u(k) + a_2 \Delta u(k-1) + \cdots \qquad (13)$$
$$+ a_{ss} \Delta u(k-N-1) + d(k)$$

With this assuming that disturbance $d(k)$ is constant for all values of prediction variables. Since prediction horizon is greater than one, with generalization the above equation can be written as (14).

$$u(k+N) = y_{past} + A\Delta u(k) + D \qquad (14)$$

To get the perfect output, it can be supposed that $y_{sp} = y(k+1)$. Hence the variation of control signal can be represented as (15).

$$\Delta u = A^{-1}(y_{sp} - y_{past} - D) \qquad (15)$$

The equation (15) is the control law for DMC method. Every controller design has some design parameters, which can be tuned to get the desired response of the controller. These parameters are called the tuning parameters of the controller. The following guidelines are basically used to tune a DMC:

1- The model horizon N should be selected so that $N\Delta t$ will be greater than open loop settling time. Values of N is normally taken between 20 to70. In our design it is selected to 20.
2- The prediction horizon Np determines how far into the future the control objective is reached. Increasing Np makes the control more accurate but increases the computation. The most recommended value of Np is when $Np = N + Nu$.
3- The control horizon Nu determine the number of the control actions calculated into the future. Too large value of Nu causes excessive control action. Small value of Nu makes the controller insensitive of noise [12].

VIII. Design, Simulation and Test of the DMC Method

To design the dynamic matrix controller for the pitch control system, the model horizon is selected to 20 and the first order transfer function obtained from the test described in figure 7 for the Ziegler Nichols method, is used. The transfer function is converted to a state space model and the DMC control law is calculated for different initial conditions. These initial conditions are initial speed and the error signal will be produced by the wind speed changes. According to these tests and the results the pitch curve presented in figure 17 is obtained.

According to figure 17, the pitch angle should be changed based on the error value. The error is calculated by subtraction the predicted generator speed and the reference speed which is equal to 325 rpm n region 3. The prediction transfer function is an ARX model represented in (16).

$$(q - 0.959)y(k) = 0.959u(k) + e(k) \qquad (16)$$

In the above equation $y(k)$ is the current generator speed and $u(k)$ is the difference between the current generator speed and the generator speed of the previous step. The equation (16) can be written as (17) to directly calculate one step ahead prediction of the generator speed.

$$y(k+1) = 0.959y(k) + 0.959u(k) + e(k) \qquad (17)$$

The block diagram of the implemented DMC method is shown in figure 18. The DMC curve is implemented by a look up table. For elimination of steady state error one integrator element is embedded in parallel to the DMC curve. The result of applying this method is shown in figures 19, 20, 21.

According to the results appeared in figures 9, 10, 11 and figures 19, 20 and 21, utilization of DMC controller reduces the unwanted oscillations and deviation from the reference value in generator speed and gird power but it causes some tiny fluctuation on the pitch signal. The pitch signal is smooth while using the gain scheduled PI controller but some unwanted swings are appeared on the generator speed and gird power. The pitch signal increases from zero before the generator speed becomes equal to 325 rpm. This is because the prediction mechanism forecasts the generator speed in the next step time.
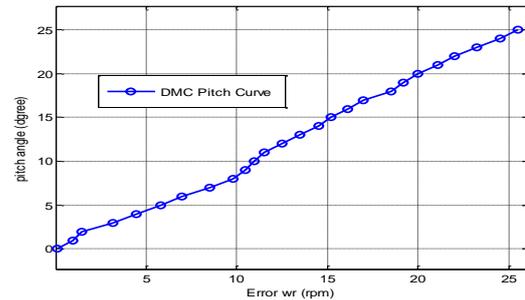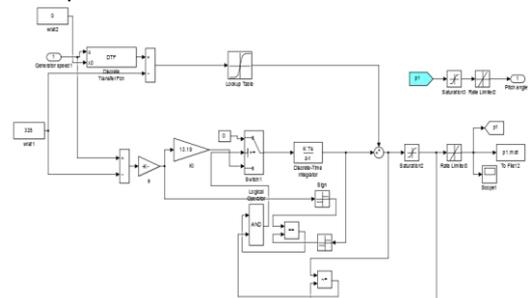

Fig. 17. DMC pitch curve.
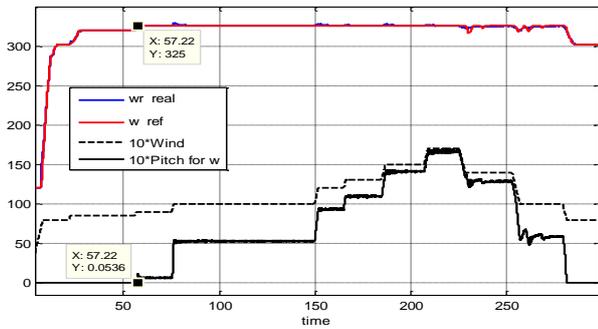

Fig. 18. The implementation of DMC method.

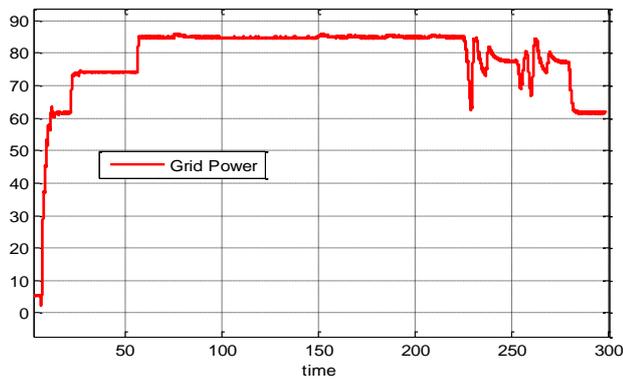Fig. 19. Generator speed, pitch angle and wind speed with DMC (J=70).
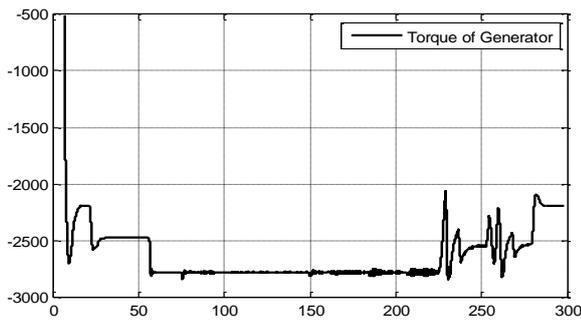

Fig. 20. The grid power with DMC (J=70).

Fig. 21. Generator torque with DMC (J=70).

IX. THE PRACTICAL TEST OF THE DESIGNED CONTROLLERS ON THE 100 KW WIND TURBINE SIMULATOR

Both of the designed controllers are implemented and tested on the practical simulator of 100 KW wind turbine. The simulator is produced in the Sun and Air Research Institute and is utilized as the test bed to perform different designing tests related to production process of 100 KW wind turbine. This equipment is shown in figure 22.

Fig. 22. The practical simulator of 100 KW wind turbine in Sun and Air Research Institute.

The result of the simulator tests are shown in figures 23 and 24. Figure 23 shows the generator speed and its average. As it is shown the generator speed is stabilized under the critical speed (350 rpm) on its nominal speed (325 rpm). Figure 24 shows the pitch signal for both DMC and gain scheduled PI controller. As its shown DMC controller pitch signal is smoother in comparison with the gain scheduled PI one. The smooth variations leads to increase the actuator age.
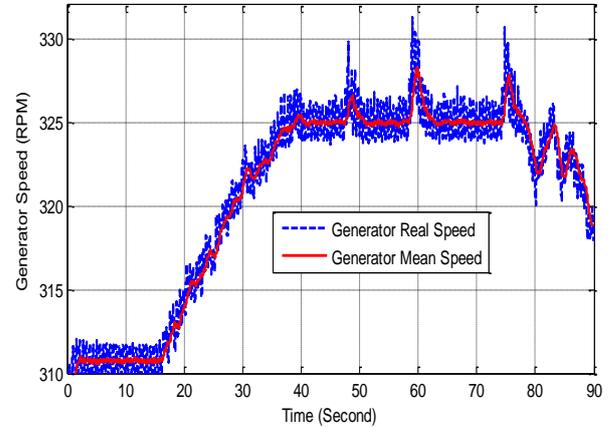

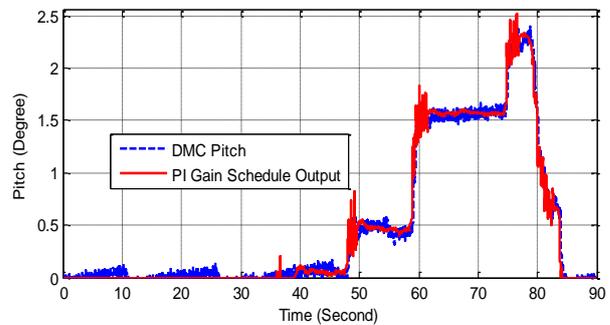Fig. 23. Generator speed with DMC (J=70) practical test on the simulator.

Fig. 24. Pitch angle with DMC (J=70) practical test on the simulator.

X. CONCLUSION

According to the results, utilization of DMC controller reduces the unwanted oscillations in generator speed and gird power but it causes some tiny fluctuation on the pitch signal. The pitch signal is smooth while using the gain scheduled PI controller but some unwanted swings are appeared on the generator speed and gird power. The pitch signal increases from zero before the generator speed becomes equal to 325 rpm. This is because the prediction mechanism forecasts the generator speed in the next step time. In the normal and quasi normal wind conditions it is proposed to use the gain scheduled PI controller and in gust conditions, the DMC controller will be reliable because of the prediction mechanism.

Please use automatic hyphenation and check your spelling. Additionally, be sure your sentences are complete and that there is continuity within your paragraphs. Check the numbering of your graphics and make sure that all appropriate references are included.

XI. ACKNOWLEDGMENT

REFERENCES

[1] B. Hu, G. K. I. Mann, R. G. Gosine, "New Methodology for Analytical and Optimal Design of Fuzzy PID Controllers", IEEE TRANSACTIONS ON FUZZY SYSTEMS, vol. 7, pp. 521-539, October 1999.

[2] L. Y. Pao, K. E. Johnson, "A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms", American Control Conference , June 10-12, 2009.

[3] C. Buenoa, J.A. Carta,"Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands", Renewable and Sustainable Energy Reviews, vol. 10, pp. 312–340, 2006.

[4] X. Changliang, S. Zhanfeng," Wind energy in China: Current scenario and future perspectives", Renewable and Sustainable Energy Reviews , Vol. 13, pp. 1966 – 1974, October 2009.

[5] S. Zhang, N. T., King-Jet Tseng, D. M. Vilathgamuwa, T. D. Nguyen, "Design of a Robust Grid Interface System for PMSG-Based Wind Turbine Generators", IEEE Transactions on Industrial Electronics, vol. 58 , pp. 316-328, Jan. 2011.

[6] H. W. Kim, S. S. Kim, H. S. Ko,"Modeling and control of PMSG-based variable-speed wind turbine", Electric Power Systems Research, vol. 80, pp. 46 – 52, January 2010.

[7] M. A. Lackner, "An investigation of variable power collective pitch control for load mitigation of floating offshore wind turbines", Wind Energy, vol. 16, pp. 519–528, May 2013.

[8] A. Urtasun, P. Sanchis, I. S. Martín, J. López, L. Marroyo, "Modeling of small wind turbines based on PMSG with diode bridge for sensorless maximum power tracking", Renewable Energy, vol. 55, pp. 138 – 149, July 2013.

[9] Y. Xia, K. H. Ahmed, B. W. Williams, "Wind Turbine Power Coefficient Analysis of a New Maximum Power Point Tracking Technique", IEEE Transactions on Industrial Electronics , vol. 60 , Issue. 3 , pp. 1122-1132, July 2012.

[10] N. Ell, D. Turschner, H. P. Beck, "Active Damping of Oscillations on the Drive Train of a Synchronous Generator Wind Turbine using Field Oriented Control and the MILD Controller Concept", Global Virtual Conference, vol. 1, pp. 8-12. April 2013.

[11] K. R. M. Vijaya Chandrakala, S. Balamurugan, K. Sankaranarayanan, "Variable structure fuzzy gain scheduling based load frequency controller for multi source multi area hydro thermal system", International Journal of Electrical Power & Energy Systems, vol. 53, pp. 375 – 381, December 2013.

[12] C. E. García, D. M. Prett, M. Morari, "Model predictive control: Theory and practice—A survey", Automatica, vol. 25, pp. 335 – 348, May 1989.

[13] M. N. Zeilinger, C. N. Jones, M. Morari, "Real-time suboptimal Model Predictive Control using a combination of Explicit MPC and Online Optimization", IEEE Transactions on Automatic Control, vol. 56 , pp. 1524-1534, July 2011.

[14] E. F. Camacho, C. Bordons, "Model Predictive Control in the Process Industry", Springer, 1995.

[15] A. Mirzaee, K. Salahshoor, "Fault diagnosis and accommodation of nonlinear systems based on multiple-model adaptive unscented Kalman filter and switched MPC and H-infinity loop-shaping controller", Journal of Process Control, vol. 22, pp. 626 – 634, March 2012.