Model Predictive Controller for Performance Enhancement of Extracting Maximum Power for Variable Speed Wind Turbine

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Abstract: *Wind energy gains increasing importance around the world. The efficiency and the energy conversion system are improved due to the advancement of variable speed drive design and control of wind energy systems. For the wind turbine systems, Maximum Power Point Tracking (MPPT) plays an essential role in achieving efficient conversion of energy. The MPPT strategy controls the rotor speed by adjusting electromagnetic torque and maximizing the generator's output power. This paper evaluates applying the Proportional-Integral (PI) Controller and the interested Model Predictive Controller (MPC) on two different control strategies to fulfill MPPT of variable speed wind turbines using the Direct Speed Measurement method and Pitch Angle Control technique. The Matlab Simulink is applied for optimizing and implementing these two control methods. The results are investigated to compare the performance of the controllers employed with the wind turbine under different operating conditions. The obtained results show that our controller (MPC) presents better performance with the direct speed measurement and the pitch angle control system.*

Keywords: *Variable Speed Wind Turbine (VSWT), Maximum Power Point Tracking (MPPT), Proportional-Integral (PI) Controller, Model Predictive Controller (MPC), Genetic Algorithm Optimization Method*

1. Introduction

The wind is considered a huge reserve of green energy [1]. It has dramatically increased in power system networks in many countries in the recent few years. Thus improving the efficiency of wind power systems becomes an important issue, both to reduce the costs of the generation of wind power systems and increase the utilization rate of the renewable energy in the power grids. The wind energy conversion system mainly includes two stages of energy conversion, the first stage is from the kinetic energy of wind to the rotational mechanical energy of the wind turbine, and in the second stage, the mechanical energy is converted to electrical energy using a generator. With the advancement of variable speed drive design and control of wind energy systems, the energy conversion system's efficiency and energy extracted capacity have been improved.The turbine rotor speed is adjusted by using the MPPT controller to extract the maximum power for each wind speed to achieve this goal.

Many different control techniques are dedicated to extracting the MPPT of a variable speed wind turbine, such as the Look-up table method [2]. It’s an array that replaces runtime computation with a simpler array indexing operation. The process is termed "direct addressing ". The primary advantages of the look-up tables are their higher speed to find a solution and their simplicity in implementation. The disadvantage of the look-up tables is their large memory usage.

Also perturb and observe scheme control [3,4,5] is another method applied to the variable speed wind turbine to fulfill the MPPT. The advantages of this scheme are easier implementation with processors, simplicity, low cost, and fast control. The disadvantages of this method are high complexity, randomness, and high oscillations.

Moreover, the hill-climbing method [6,7,8,9] is another technique employed with variable speed wind turbines to search for the MPPT. This algorithm is considered to be one of the simplest procedures for implementing heuristic search, it comes from the idea if you are trying to find the top of the hill and you go up directly from wherever you are. The advantages are: very useful in job shop scheduling, automatic programming, circuit designing, and vehicle routing. It is good for solving the optimization problem while using only limited computation power. The disadvantage of this algorithm does not maintain a search tree, so the current node data structure needs only to record the state and its objective function value. It assumes that local improvement will lead to global improvement.

In addition, the PID controller has been widely used in many industries [10]. It has been applied to the variable speed wind turbine to fulfill the MPPT [11]. However, there are various techniques are employed to tune the PID controller parameters such as the Lambda tuning method [12]. The advantages of this method are it is robustness and workability specifically for systems with a large time delay. One drawback is the slow response, especially for a system with long time delays. Also, the lambda tuning approach is a slow time response and is only suited for PI controllers without derivatives.

Another tuning method of PID controller parameters is the Ziegler-Nicolas method [13]. The advantages of this method are: its ease of implementation, its simplicity, and little information are required, The disadvantages are: very aggressive tuning, some trial and error are involved, used only for the process control system and if any disturbance occurs, no corrective action is taken so, the process can be upset and the results may be misleading.

Also, the Metaheuristic optimization algorithms are applied for tuning the PID controller parameters in many industries [14]. The advantages are: high speed, easy to obtain reasonable results, little process knowledge is required, and it can avoid trapping in local solutions.

The interested MPC is a feedback control system that uses a model to make predictions about future outputs of a process. It has been widely applied in many industrial applications such as speed control and PV Systems [15,16]. It has been also applied to extract maximum power point tracking of variable speed wind turbine.

In [17,18] the authors illustrate how to employ the MPC to follow the trajectory of the maximum power point tracking line. Due to the well behavior of MPC in industrial applications, this paper presents a comparison between the MPC and the PI controller tuned with a genetic algorithm to extract maximum power point tracking of a variable speed wind turbine to validate the performance of MPC.

In this paper, two different control techniques: the Proportional-Integral (PI) controller tuned with a genetic algorithm, and the interested MPC are applied to the VSWT to extract the maximum power point, also controlling the pitch angle to limit the rotational turbine speed at the rated value and maintain the rated turbine power.

The mathematical model of the wind turbine will be discussed in section 2. In Section 3, two major MPPT control strategies for a variable speed wind turbine are discussed in detail. In section 4 the optimization genetic algorithm and the MPC are illustrated in detail. Section 5 discusses applying the two control strategies for variable speed wind turbines to achieve the MPPT and limit the rated turbine power using pitch angle control. A comparison of experimental results and validation of MPPT techniques is presented in section 6. The conclusion of the work is debated in section 7.

2. Wind turbine model

At earlier times, wind turbine operates at the fixed rotor speed configuration and the system is not able to extract optimal power Nowadays, Variable speed generators like Induction generators, Self-Excited Induction generators, and Double Fed Induction generators are preferred because of their ability to operate at variable speed.
The power generated by wind turbines could be identified by the following equation [19,20]

$$P = \frac{1}{2} * C_p\ (\lambda, \beta)\rho\pi R^2 V^3 \tag{1}$$

Where R = turbine rotor radius, ρ= air density, C_p= turbine power coefficient that represents the power conversion efficiency of the wind turbine, V = wind speed, C_p is defined as a ratio of actual power delivered by a wind turbine to the theoretical power available in the wind. It is found that C_p is a function of the tip speed ratio (TSR) λ, and the blade pitch angle β in a pitch control wind turbine where λ is given by $\frac{\omega_t * R}{V}$, and ω_t is the turbine rotational speed of the wind turbine. The max theoretical value of C_{pmax} is 59.26 % [21].

The wind power coefficient C_p is identified by the following equation [22]:

$$C_p(\lambda\,, \beta\,) = C_1(C_2\left(\frac{1}{\lambda + 0.8\beta} - \frac{0.035}{\beta^3 + 1}\right) - C_3\beta - C_4).\,e^{-C_5}\left(\frac{1}{\lambda + 0.8\beta} - \frac{0.035}{\beta^3 + 1}\right) + C_6\lambda \tag{2}$$

where $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$

The mechanical torque obtained at the shaft of the wind turbine could be mathematically identified as follows:

$$T_{turb} = \frac{P_{turb}}{\omega_t} \tag{3}$$

from equation (1)

$$T_{turb} = \frac{0.5\rho}{\omega_t} C_p\ (\lambda, \beta)\pi R^2 V^3 \tag{4}$$

Where P_{turb} is the turbine output power and T_{turb} is the turbine output torque. From Eq. (4), it is found that the turbine shaft torque depends on ω_r, V, and C_p. By regulating the rotor speed, maximum power can be extracted. The generator torque and rotor speed are changed by using a gearbox ratio G. The value of T_g and ω_g are given by Eq. (5) and (6) respectively.

$$Tg = \frac{T_{turb}}{G} \quad (5)$$

$$\omega_g = G.\omega_t \quad (6)$$

The generator shaft is modeled using the following differential equation:

$$\mathcal{J}\frac{\partial \omega_g}{\partial t} = T_g - T_{em} - f.\omega_g \quad (7)$$

Where $\mathcal{J}$ is the total inertia of the generator shaft, f is a viscous friction coefficient, T_g is generated torque, T_{em} is an electromagnetic torque of the generator and ω_g is a rotor speed of the generator. By using the above equations, the wind turbine model for a variable wind speed could be depicted in Figure 1. Parameters of the wind turbine model are listed in Table-1[22].

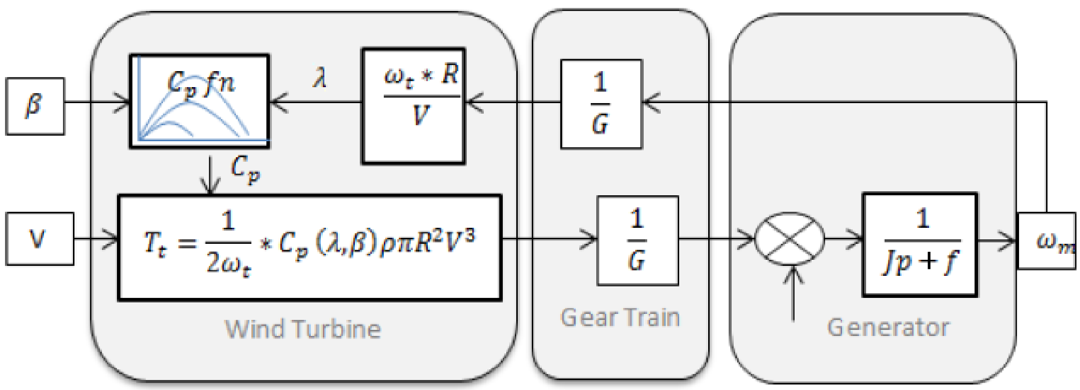


Figure 1. The Block Diagram of the Wind Turbine Model

Table 1. Parameters of wind turbine

P(rated)	**5.7 KW**
V(rated)	14 m/s
ρ	1.226 Kg/m2
G	3
R	1.5 m
$\mathcal{J}$	0.9067 Kg.m2
F	0.005

3. Power control strategy and maximum power point tracking

A power curve shows how the power of a wind turbine varies with the wind speed. A typical power curve is depicted in Figure 2. Wind turbines cannot generate electricity for very low wind speeds due to insufficient torque that can not overcome friction or extremely high velocities that can cause damage to turbine rotor blades. Therefore, a cut-in speed around (2 m/s) and a cut-out speed around (25 m/s) are indicated on the power curve in Figure 2. As the wind exceeds the cut-in speed, the power output increases rapidly. However, around certain speeds, known as rated wind speed (14 m/s), the power output reaches a limit that is called the rated turbine power output. This is the maximum level that the electrical generator can still work and can not be exceeded. When wind speed is higher than the rated output wind speed, the power is kept almost constant by controlling the rotor blade pitch angle. This can be illustrated in the figure.2 [22].

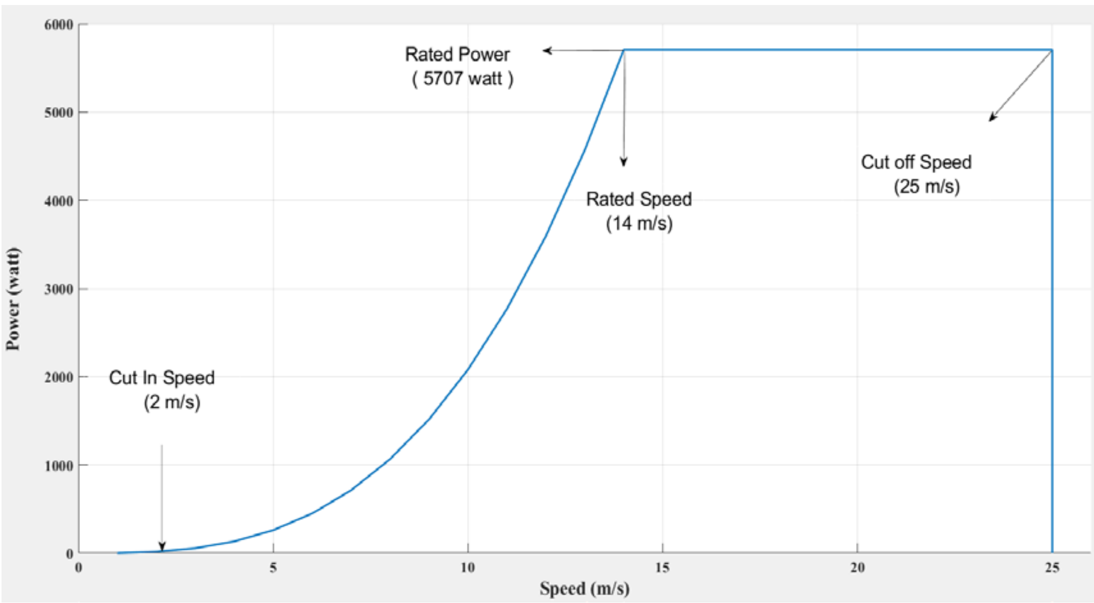
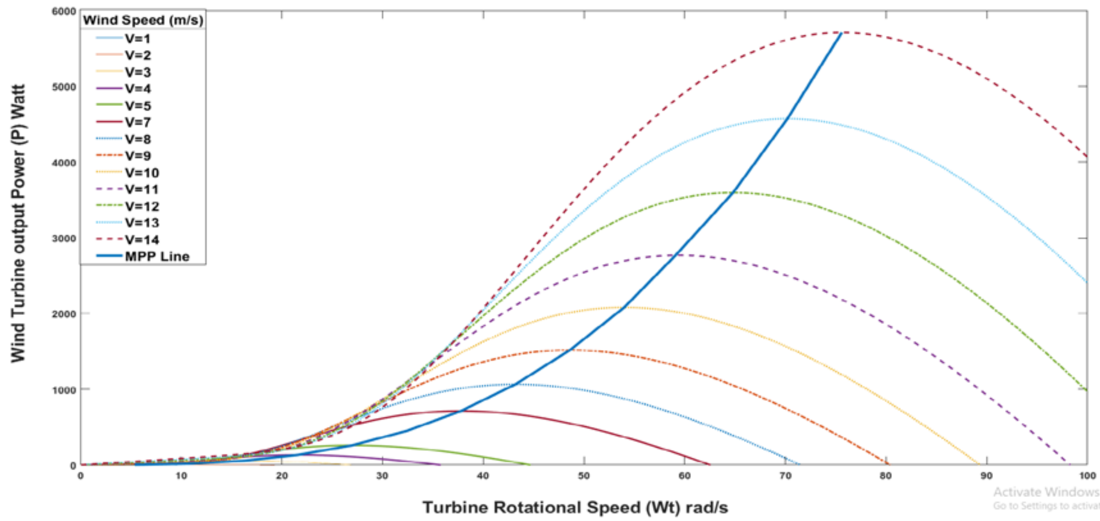


Figure 2. Operating Range of Wind Turbine

3.1 Maximum power point tracing control zone

A variable speed wind turbine (VSWT) allows for extracting optimal power and at the same time, it helps to reduce the stress on WT shafts and gears. As shown in Figure 3, with a change in wind speed, the maximum power points should be varied and follow MPP Line (solid blue line). The turbine rotor speed should be changed and shifted toward optimal rotor speeds to extract the maximum power at each wind speed. A MATLAB File is designed to obtain the relation between the wind turbine output power (w) and the turbine rotational speed (rad/sec) for each wind speed using Eq. (1),(2)



which are represented in figure (3). It is obvious from this figure that the maximum power line (solid blue line) passes through the maximum power point at each wind speed. It is shown that λ, C_p are constant for wind speed varying from (0-14) m/s and equal to 8.1 and 0.48 respectively.

Figure 3. The Plot of Wind Turbine Output Power For Variable Wind Speed

3.2 Pitch control zone

Figure 4 illustrates the curve of $Cp\ (\lambda)$ for different values of β. The maximum value of $Cp_{\max}$ is found when β=0°. With the increase in β value, C_{pmax} decrease continuously. When wind speed exceeds the nominal wind speed value (14 m/s), the wind turbine's control system adjusts the blade pitch angle to keep the rotor speed at the nominal rotational speed. This can be obvious from Eq. (2) where Cp could be varied by manipulating the pitch angle (β).
So, the optimal value of λ, β for maximum power coefficient (C_{pmax}=0.48) is λ_{opt} = 8.1, $\beta = 0°$

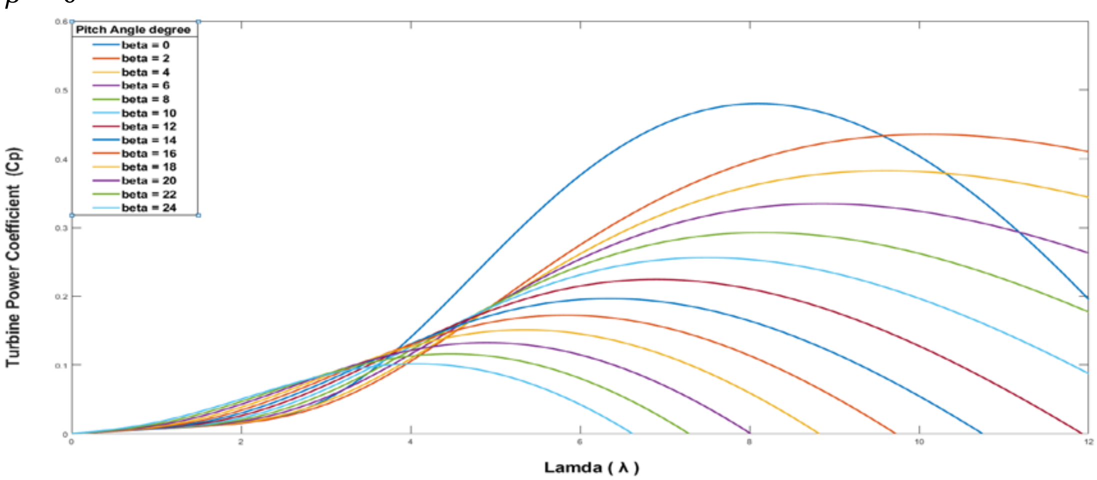


Figure 4. The curve of power coefficient for different pitch angle characteristics

Two proposed techniques are presented in this paper to follow the MPPT of VSWT for below and over nominal wind speed (14 m/s) which are PI controller and MPC approaches

4. Optimization techniques for extracting maximum power point tracking of variable speed wind turbine

4.1 PI controller tuned by genetic algorithm

A genetic algorithm (GA) is an optimization technique interested by Goldbert [23], which imitates Darwin's theory of natural evolution. It is applied to tune the PI controller in industrial applications [24]. It is commonly used to generate high-quality solutions, for optimization and research problems.

It is employed to solve several problems related to electrical power and machines. Effective results have been obtained by GA in optimization problems. It can solve numerous problems that are concerned with its complexity. nonlinearity.GA starts with a randomly generated population and then selects the optimum solution according to the Darwinian theorem, where the fittest solution is survived. The fitness of these solutions is determined based on phenotype, while the process of encoding these solutions depends on the genotype.

According to the evolutionary algorithms, different methods have been scheduled to map phenotype to genotype. Binary strings are considered one of the representative methods that have been applied to GA. Every chromosome identifies a solution in GA.

Depending on the fitness of these chromosomes. the best one is chosen. The most effective criteria for solving an optimization problem by GA are determined by the fitness function. and chromosome achieves the best result of this function. The procedures that GA follows to find the fittest solution can be summarized as follows:

A. Selection: In this process. The better individuals are selected from the population. The fitter individuals guarantee higher fitness offspring generated in the subsequent generation. Various techniques can be utilized to select the fitter individuals which include:

a. Roulette wheel

b. Tournament selection

c. Steady-state selection

d. Boltzmann selection

e. Rank selection

To avoid local optimal occurrence in GA. other parameters should also be defined which include crossover and mutation.

B. Crossover: In this process, new offspring are generated to reach the optimum solution. This is executed by choosing a pair of parents. where a part of these parents' strings is swapped for each other and new generations are developed. Crossover is not applied to all individuals but a percentage is assigned.

C. Mutation: In this process. a modification is applied to the new offspring. This is performed by applying low mutation probability to several genes. The mutation process enhances diversity and avoids premature convergence.

The process of GA is terminated either the criterion for the optimum solution is defined, or the maximum number of generations is reached. It has many advantages, like searching from a population of points, not a single point, supporting multi-objective optimization, being robust, stochastic, and working well on discrete or continuous problems. The flow chart of GA is depicted in Figure 5.

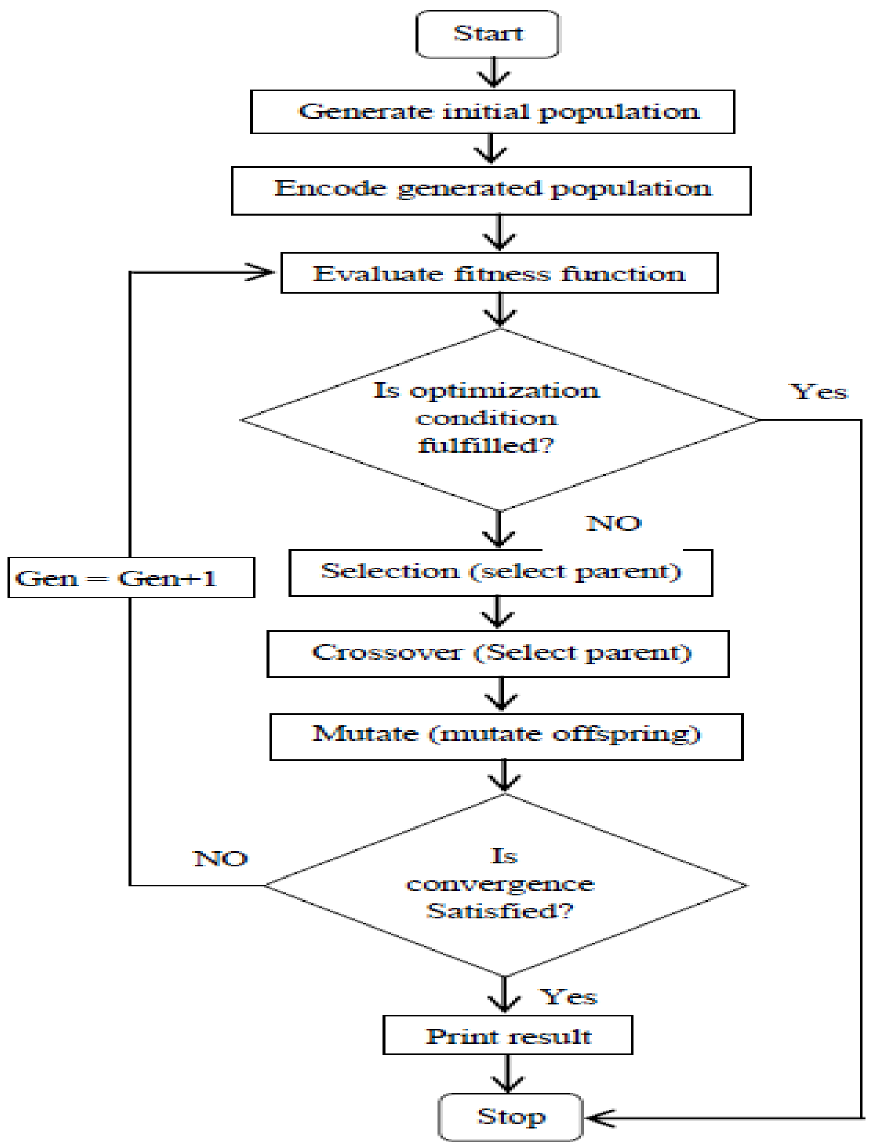


Figure 5. Flow Chart of GA

4.2 Model predictive controller

4.2.1. Basic structure of mpc and advantages

The MPC controller makes predictions of plant output [25], and the optimizer finds the optimal sequence of control inputs that drives the predicted plant output as close to the setpoint as possible as shown in Figure 6.

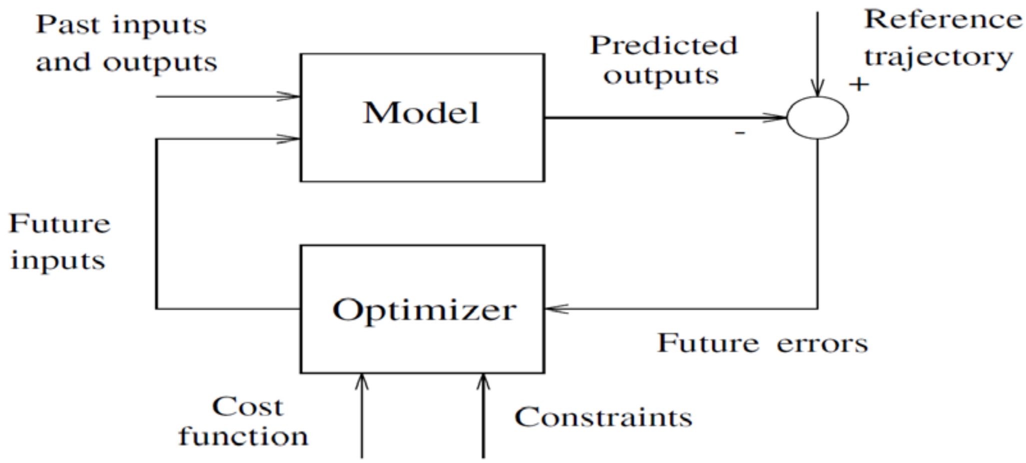


Figure 6. The Basic structure of MPC

To implement this strategy, a model is used to predict the future plant outputs, based on past and current values and the interesting optimal future control actions. These actions are calculated by the optimizer, taking into account the cost function (where the future tracking error is considered) as well as the constraints. The process model plays, in consequence, a decisive role in the controller. The chosen model must be able to capture the process dynamics to precisely predict the future outputs and be simple to implement and understand.

MPC design parameters are sample time, prediction horizon, control horizons, constraints, and weights. Choosing proper values for these parameters is important as they affect the controller performance and the computational complexity of the interested MPC algorithm that solves an online optimization problem at each time step.

Choosing the sample time determines the rate at which the controller executes the control algorithm.

If the sample time is too big, when a disturbance comes in, the controller won't be able to react to the disturbance fast enough.

On the contrary, if the sample time is too small, the controller can react much faster to disturbances and setpoint changes, but this causes an excessive computational load. To find the right balance between performance and computational effort at each time step, the MPC controller makes predictions of plant output, and the optimizer finds the optimal sequence of control inputs that drives the predicted plant output as close to the setpoint as possible.

The number of predicted future time steps is called the prediction horizon and shows how far the controller predicts into the future.

we should choose a prediction horizon that will cover the significant dynamics of the system.

Another design parameter is the control horizon. If this is the set of future control actions leading to this predicted plant output, the number of control moves to the time step is called the control horizon. The rest of the inputs are held constant.

Each control move in the control horizon can be thought of as a free variable that needs to be computed by the optimizer, the smaller the control horizon, the fewer the computations.

MPC can incorporate constraints on the inputs, the rate of change of inputs, and the outputs.

The advantages of MPC:

- It's a multivariable controller that controls the outputs simultaneously by considering all the interactions between system variables
- It can handle constraints.
- it handles multi-input multi-output systems,

4.2.2 MPC strategy

1. The future outputs for a determined horizon N called the prediction horizon, are predicted at each instant t using the process model. These predicted outputs y(t + k | t) 1 for k = 1. . . N depends on the known values up to instant t (past inputs and outputs) and on the future control signals u (t+k | t), k = 0. . . N−1, which are those to be sent to the system and calculated.

2. The set of future control signals is calculated by optimizing a determined criterion to keep the process as close as possible to the reference trajectory w(t + k) (which can be the setpoint itself or a close approximation of it). This criterion usually takes the form of a quadratic function of the errors between the predicted output signal and the predicted reference trajectory. The control effort is included in the objective function in most cases. An explicit solution can be obtained if the criterion is quadratic, the model is linear, and there are no constraints; otherwise, an iterative optimization method has to be used. Some assumptions about the structure of the future control law are also made in some cases, such as that it will be constant from a given instant.

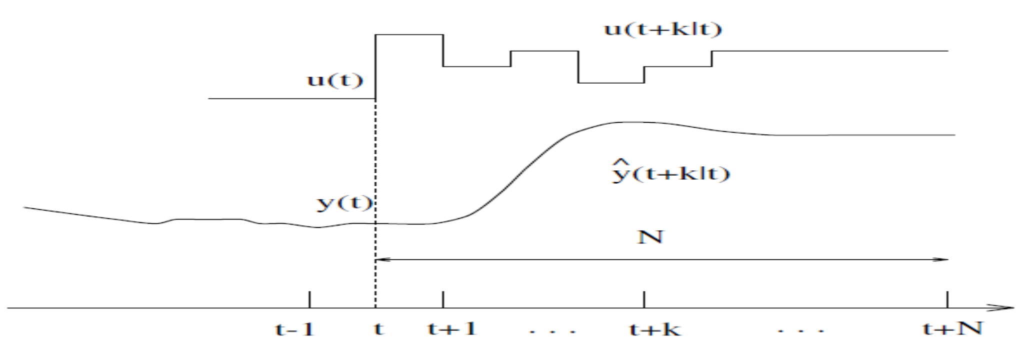


Figure 7. MPC strategy

3. The control signal u (t | t) is sent to the process whilst the next control signals calculated are rejected because at the next sampling instant y(t + 1) is already known, and step 1 is repeated with this new value and all the sequences are brought up to date. Thus u (t + 1 | t + 1) is calculated (which in principle will be different from u(t + 1 | t) because of the new information available) using the preceding horizon concept. This is illustrated in figure (7).

5. Matlab simulink for modeling MPPT using direct speed measurement and pitch angle control

5.1 Applying PI controller tuned by genetic algorithm, and MPC on the model of MPPT using direct speed measurement

In this control strategy, accurate knowledge of wind speed is required. Usually, wind speed fluctuates continuously and it causes a change in the available power level of the wind. So, to extract maximum power from the turbine, the rotor speed should be regulated continuously. Under the maximum power extraction condition, the machine's electromagnetic torque is equal to the reference torque ($T_{em,ref}$) and is given by Eq. (8).

$$T_{em} = T_{em,ref} \tag{8}$$

With a change in wind speed, reference rotor speed changes. Speed control using reference electromagnetic torque is used to track reference rotor speed.

$$T_{em,ref} = PI\ (\omega_{ref} - \omega_{g}) \tag{9}$$

where PI is the proportional-Integral controller to regulate speed and ω_{ref} is the reference rotor speed. Reference rotor speed is calculated on the optimal Lamda value on which Cp is a maximum and it is given by:

$$\omega_{ref} = \frac{1}{G}\,\frac{\lambda_{C_{pmax}} {}^{*}V}{R} \tag{10}$$

The block diagram of the wind turbine control strategy by the PI Controller and the interested MPC Controller for VSWT using direct speed measurements are shown in Figure 8 and Fig .9 respectively.

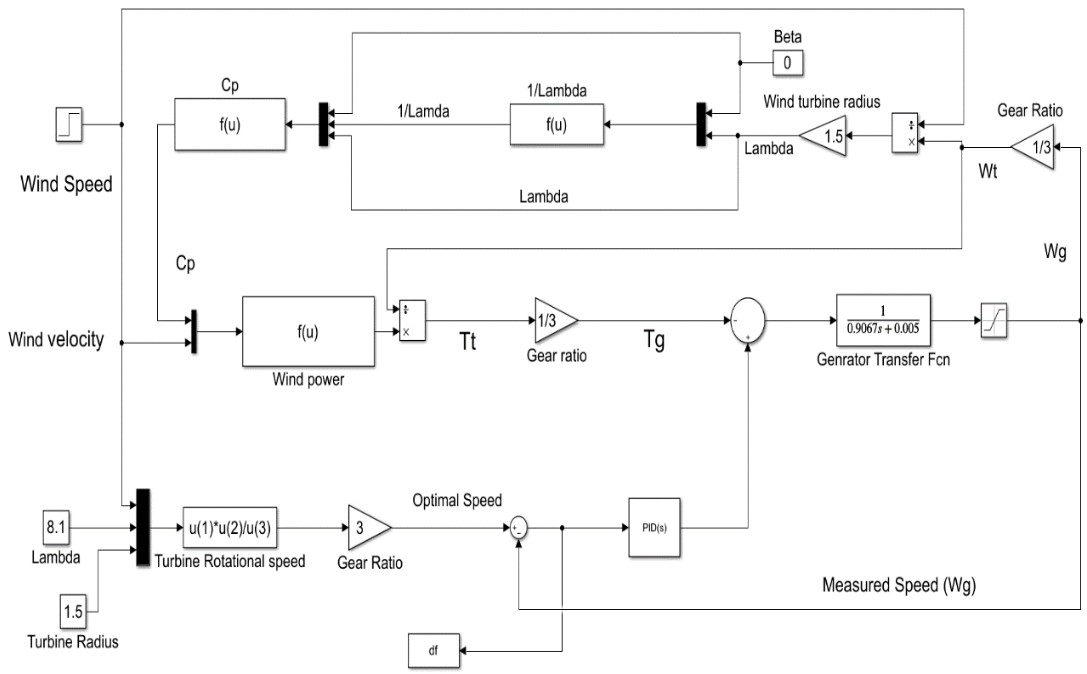


Figure 8. MPPT Scheme Using Direct Wind Speed Measurement with PI Controller

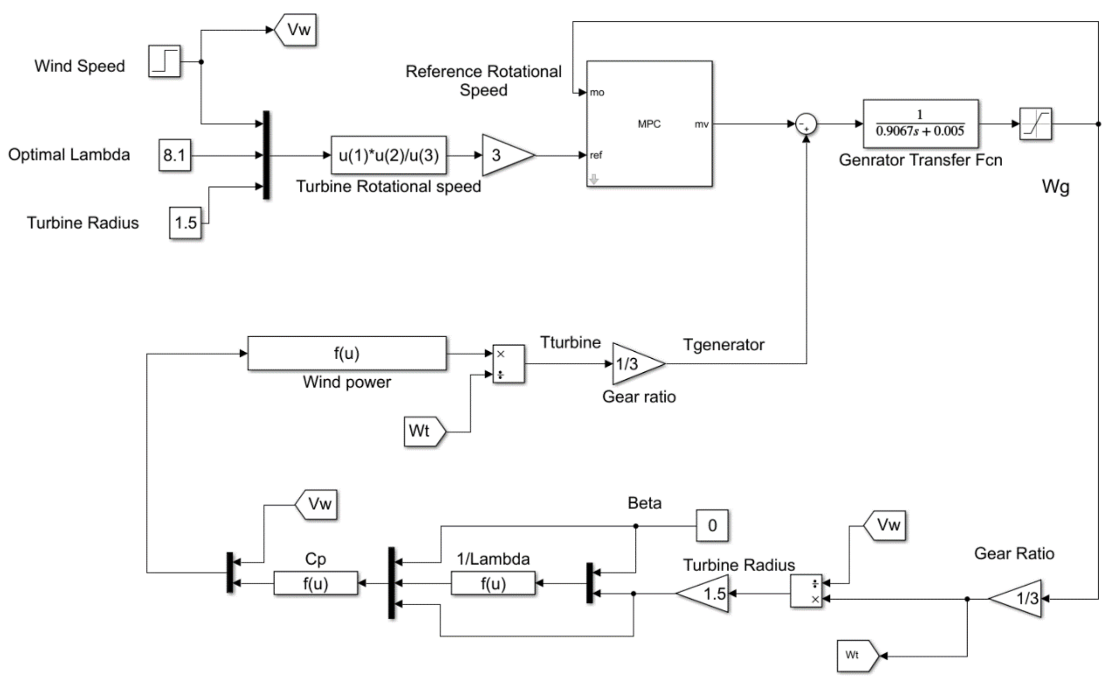


Figure 9. MPPT Scheme Using Direct Wind Speed Measurement with MPC Controller

5.2 Applying PI controller tuned by genetic algorithm and MPC on the model of MPPT using pitch control

Figure 10. MPPT Scheme on Pitch Control Zone with PI Controller

Figure 11. MPPT Scheme on Pitch Control Zone with MPC Controller

6. Simulation results and comparison

The same wind speed profile is used for the simulation of the above MPPT methods. Based on the response of the above methods, the Simulation system is designed in the MATLAB, MPC controller, and other traditional controllers (PI Controller) are compared.

Table 2. Comparison of Control Methods on the MPPT Control Zone at Wind Speed = 14 m/s, the optimum turbine Rotor Speed (Wt) = 75.6 rad/S, turbine power = 5707 Watt, MPC Controller parameters are Sample Time = 0.0001, Prediction horizon = 1000, Control horizon = 20, Closed Loop Performance: aggressive, State estimation: faster

	Turbine Power (Pt)			**Turbine Speed (Wt)**		
Technique	(S.S.E) %	(Tr) ms	Overshoot %	(S.S.E) %	(Tr) ms	Overshoot %
Un-Controlled	5.05	1486	0.486	12.47	1784	0.498
PI	0	79.231	0.466	0	79	4.737
MPC	0.49	0.485	0.502	-0.12	0.884	3.646

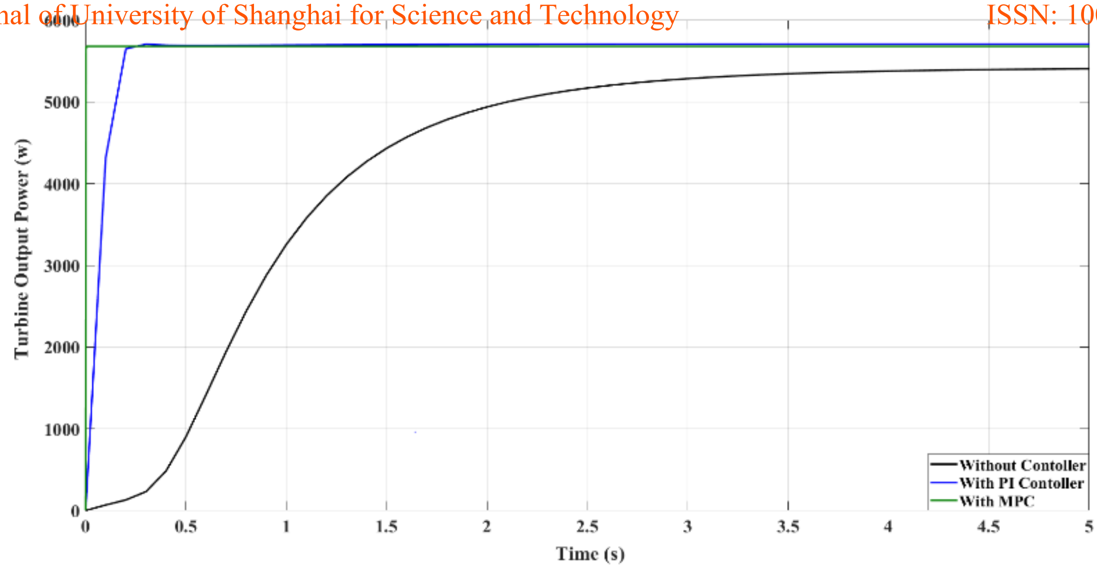


Figure12. Turbine Output Power at Wind Speed = 14 m/s

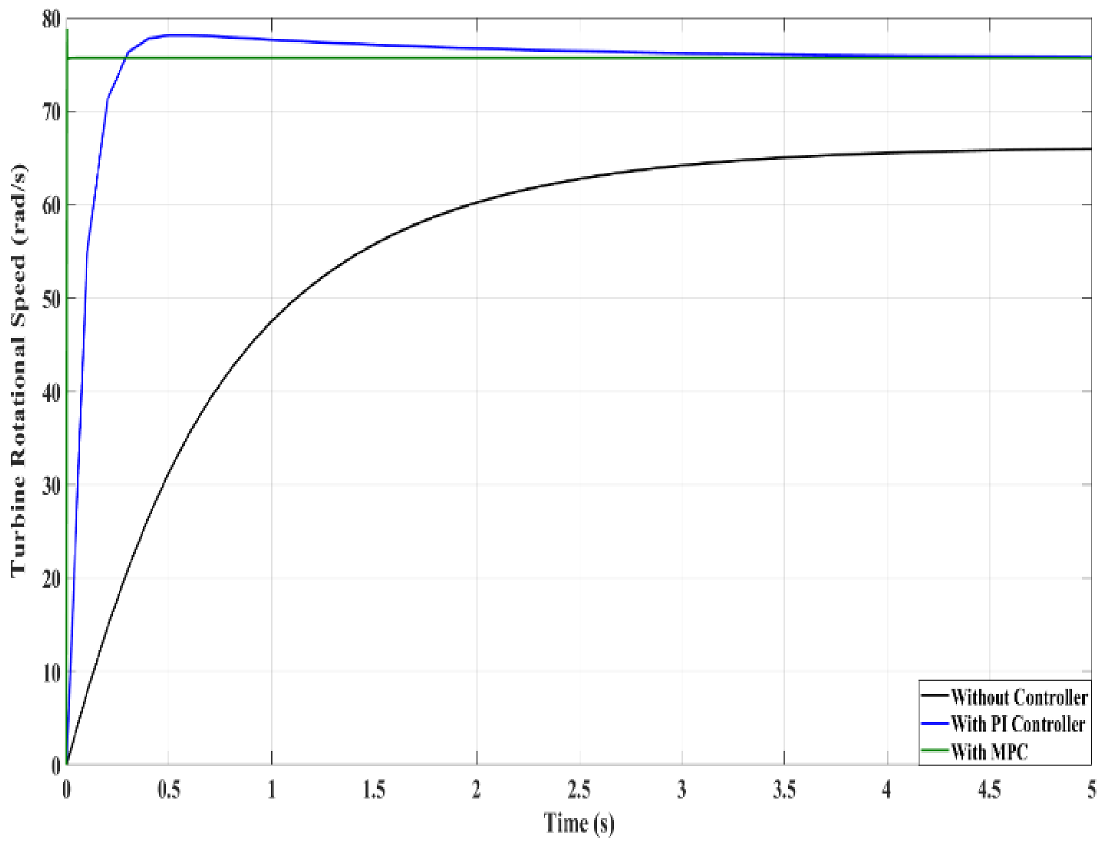


Figure13. Turbine Rotational Speed at Wind Speed = 14 m/s

Table 3. Comparison of Control Methods on the Pitch Control Zone at Wind Speed = 17 m/s, MPC Controller Parameters are Sample Time = 0.005, Prediction horizon = 1000, Control horizon = 20, Closed Loop Performance: aggressive, State estimation: faster

	Turbine Power (Pt)			**Pitch angle (β)**		**Turbine Speed (Wt)**		
Technique	(S.S.E) %	(Tr) ms	Overshoot %	(Tr) ms	Overshoot %	(S.S.E) %	(Tr) ms	Overshoot %
Un-Controlled	-0.05	1028	0.505	2510	0	13.22	1856	0.497
PI	0	8.009	25.949	71.371	1.531	0	20.537	0.494
MPC	-0.28	2.372	17.059	11.813	0.502	0	6.664	1.531

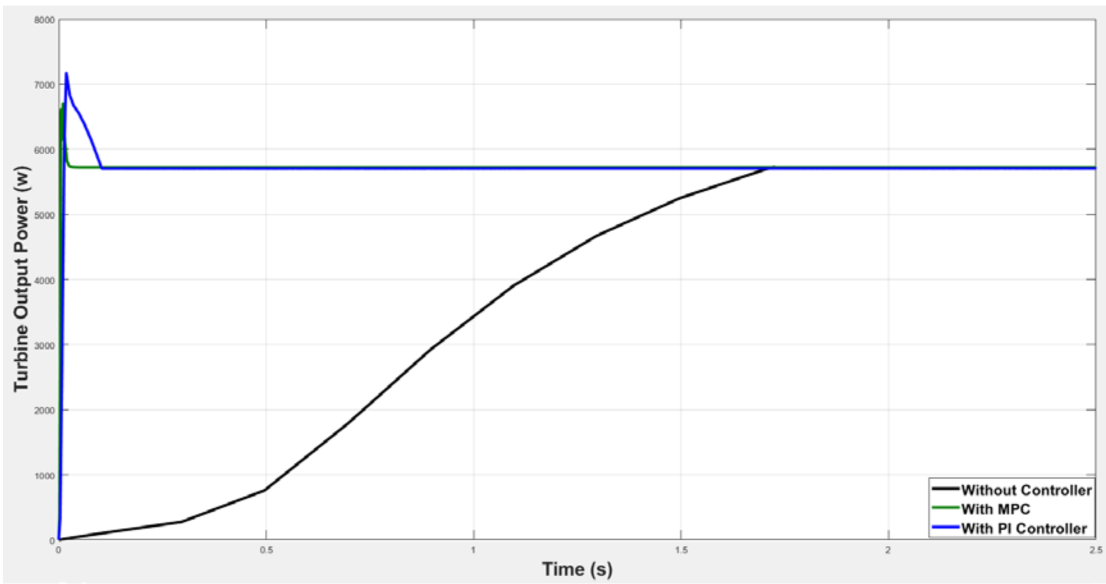


Figure 14. Turbine Output Power at Wind Speed = 17 m/s

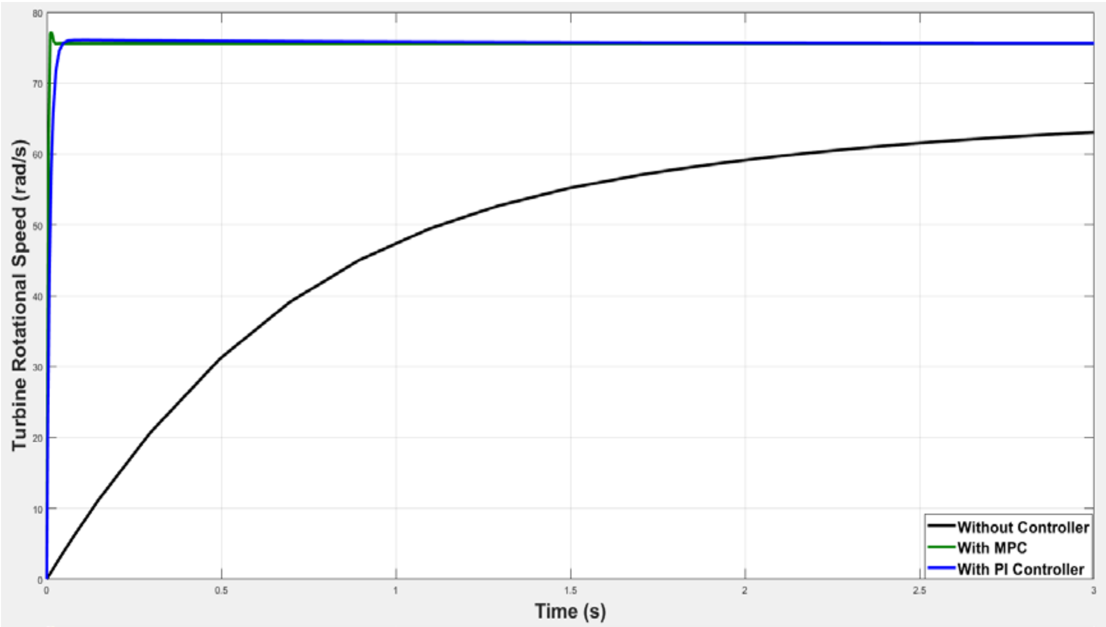


Figure 15. Turbine Rotational Speed at Wind Speed = 17 m/s

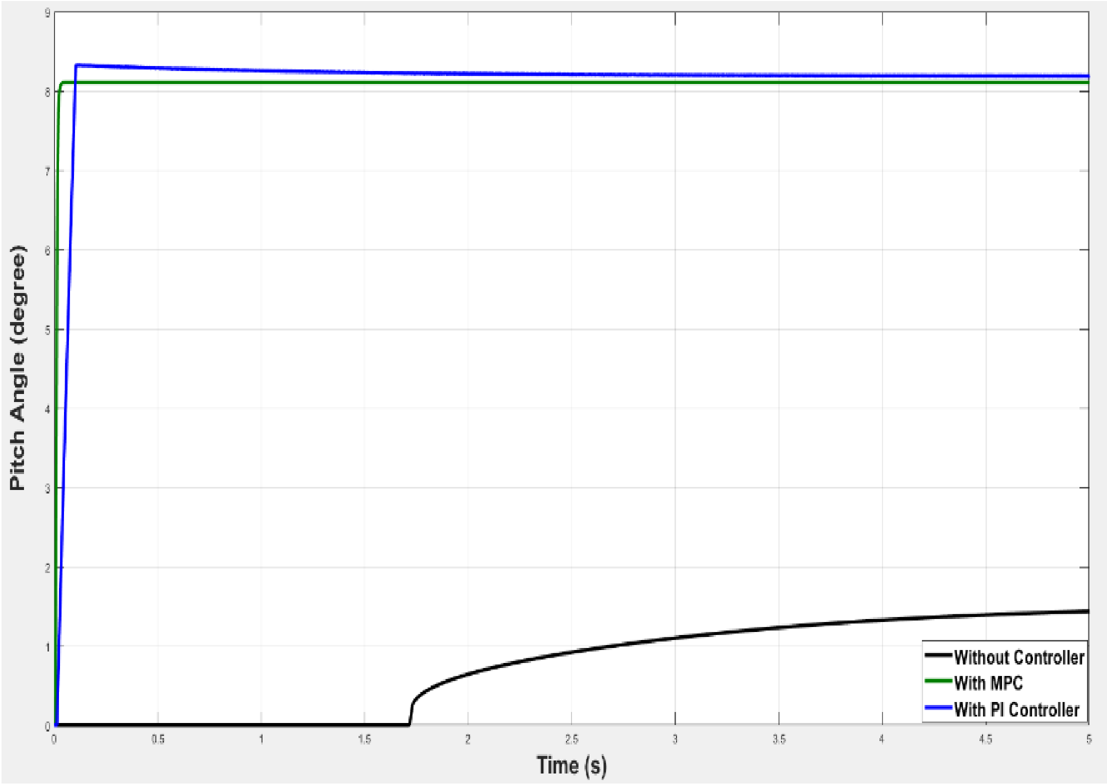


Figure 16. Pitch Angle at Wind Speed = 17 m/s

7. Conclusion

Based upon the aerodynamic structure of the wind turbine model; mathematical equations and characteristics are derived. MPPT is used to extract maximum power, by changing the rotor speed with changes in wind speed. Two methods of power control are investigated in detail. The performance and ability of each method to track the maximum power point have been validated by simulation results. This paper implements the MPC to investigate the MPPTof a variable speed wind turbine. This control method is applied to two region power-speed curve characteristics using direct speed measurement and pitch angle control techniques. The interested MPC studies both the dynamic and steady-state responses of the overall system. The PI controller technique is also applied to the variable speed wind turbine to ensure the validity of the MPC results. The tuning scheme that is applied to the PI controller to enhance the output performance is the genetic algorithm. To investigate the results obtained by the two control techniques, the interested algorithm MPC and the PI controller are applied with various wind speeds. Various wind speeds are investigated in this literature, but in this paper wind speed of 14 m/s is applied to study the beviour of direct speed measurement control. Also the wind speed of 17m/s is excuted with the pitch angle control technique to analyze the performance of this technique.

It is concluded from the results that the interested MPC and the PI show better performance than the uncontrolled scheme applied to MPPT both in the dynamic and steady-state responses of the overall system. Also, it is clear from the result that the rise time and maximum percentage overshoot in the case of direct speed measurement that MPC is superior to the PI controller. However, the result obtained the by PI controller concerning steady-state error is less than the MPC. Also, the interested MPC presents better results with the pitch angle control system in terms of maximum percentage overshoot and rise time. But, the PI controller introduces less steady-state error. The investigated MPC gives better performance with good robustness and high efficiency. The succeeded process employed by MPC in terms of the dynamic response is a result of the behavior of MPC. This is due to the interested MPC scheme, which can predict a system's output response and introduce control signals in advance accordingly. However, the PI controller depends on an error that occurs to take action.

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