



OPTIMAL CONTROLLER DESIGN FOR WIND TURBINE SYSTEM USING DYNAMIC PROGRAMMING

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Date: October, 2019

A Thesis Submitted to The School of Electrical and Computer Engineering of Addis Ababa Institute of Technology, School of Graduate Study, Addis Ababa University, In Partial Fulfillment of The Requirement for the Degree of Master of Science in Control Engineering

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Declaration

I, herewith declare that this thesis (optimal controller design for wind turbine system using dynamic programming) is a presentation of my original research work. Wherever contributions are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgment of the collaborative research and discussion.

The work was done under the guidance of Dr. Dereje S. at Addis Ababa university institute of Technology (AAiT), Addis Ababa.

By

Abibual Abate

Signature -----

In my capacity as supervisor of this candidate's thesis, I certify that the above statements are true to the best of my knowledge.

Advisor: D.r Dereje S. (Ph.D.)

Signature -----

Oct / 2019

Abstract

Now a days, many researchers are focusing on renewable energy sources due to the fact that the cost of fuel is growing up in day to day activity and to decrease or limit environmental effects. Wind energy is one of the fastest growing up energy source due to its cost effectiveness and availability.

In this thesis, optimal controller is proposed to extract maximum wind energy from the available wind speed. To extract wind energy, the very volatile nature of wind speed has made it difficult the energy extraction process. Deterministic dynamic programming algorithm is chosen to design optimal controller. This type of numerical programming algorithm is highly applicable for the non-linear model of wind turbine system and its constraints.

The contribution of this thesis is that instead of standard torque control, optimal controller is employed to globally optimize wind energy capture under variable wind condition in region two (from cut-in to rated wind speed) operation of wind turbine system. The performance of this control method is tested via MATLAB software. The outcomes of the system have 7 up to 8.5 tip speed ratio optimal value and the aerodynamic efficiency has 0.411 conversion value. And also the optimal controller captured 13.841% more energy than STC for the piecewise step input wind speed. For the randomly generated wind speed pattern, the optimal controller captured 1.15% more energy than the STC. The lower percentage improvement in this case is due to the limited range of the wind speed value given for the simulation.

Key words:

Optimal control, dynamic programming, optimization.

Acknowledgment

First of all, my hearty gratitude goes to the almighty God. Then I am highly grateful to my advisor Dr. Dereje Shiferaw as without his encouragement, insight and guidance the completion of this work would not have been possible. Next my honorable gratitude goes to my best friends for their unlimited supports and advices for working this thesis.

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Acronym's (Abbreviation)

Abbreviation	Description
HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
TSR(λ)	Tip speed ratio
DP	Dynamic programming
WT	Wind turbine
WECS	Wind energy conversion system
MPPT	Maximum power point tracking
RPM	Revolution per minute
STC	Standard torque control
OTR	Optimal tracking rotor
DSC	Direct speed controller
PD	Proportional derivative
Pcap	Capture energy
TPBVP	Two-point boundary value problem
PI(J)	Performance index cost function)

List of symbols

List of symbol	description
N_g	Number of gear ratio
C_p	Aero dynamic power coefficient
β	Pitch angle
J_r	Aerodynamic inertia
R	Radius of blades
D_r	Diameter of blades
τ_g	Generator torque
ω_r	Wind turbine rotor speed
V_w	Wind speed
T_s	Step time, discrete time system
E	Wind turbine capture energy
K	Number of discrete times
X	State of the system, this equal to rotor turbine speed
U	Control input for the system
τ_{aero}	Aerodynamic torque
N	Number of discretization step
τ_c	Reactive torque
P_w	Wind power
KW	Kilo watt
MW	Mega watt
V_a/V_b	wind speed after/before passing the turbine
N_x	Number of state grid
N_u	Number of control input grade
KE	Kinetic energy
A	Area of wind turbine

CHAPTER ONE

Introduction

1.1 Background

Recently, the clean energy sources such as solar, tidal, and wind energy sources are gaining importance due to their less damaging environmental influences. The wind energy technology is one of the most emerging renewable energy technologies. Over the past few decades, the capacities of wind turbine (WT) units have increased from a few tens of KW power capacity to today's multi-MW level [1]. In view to the steady growth in the power level of the WTs and its increased penetration into the power grid; more advanced generator, power converter system and control solutions have to be developed so as to make the WT units more suitable to be integrated into the power grid [2].

A wind turbine is a revolving device that converts wind's kinetic energy into electrical power that can be fed into the grid. It can be configured to rotate about either a vertical or a horizontal axis. Therefore, wind turbines can be categorized into two major types, horizontal-axis wind turbine (HAWT) and vertical-axis wind turbines (VAWT). The maximum aerodynamic efficiency of any vertical-axis wind turbine is 15-25% lower than available horizontal-axis wind turbine designs. A VAWT may enjoy due to lower drivetrain and maintenance costs. Therefore, the HAWT configuration is more common and preferred for modern wind turbines [3].

Also, Wind turbines are categorized into two groups that are based on either *fixed* or *variable-speed* operation. The former is the traditional approach that is most widely used and has the lowest cost. Additionally, fixed-speed wind turbines utilize induction generators, which are highly reliable and facilitate a direct connection to the grid [4]. The drawback to these configurations is a lack of efficiency during partial-load operation, also known in Region two.

In order to increase efficiency in Region two, variable speed operation was introduced to allow the rotor speed to adapt to changes in wind speed, thus increasing aerodynamic efficiency in this region. This technique also reduces drive train fatigue and is the latest trend in wind energy conversion [5].

In the near future, wind energy will be the most cost-effective source of electrical power. In fact, a good case can be made for saying that it already has achieved this status. The major technology developments enabling wind power commercialization have already been made. There will be infinite refinements and improvements, of course. International, standardized applications for renewable energies, regardless of national regulations or climate conditions, are more and more likely to be put into place. The wind energy industry's future looks optimistic.

As an important device that converts the kinetic energy from the wind into mechanical energy, maximizing the efficiency of wind turbine plays an important role in the development of the wind power. Especially in wind farms where hundreds of wind turbines are installed, the efficiency improvement of an individual wind turbine could result in a significant energy gain for the entire wind farm and this will make the wind energy more economically viable [6]. Therefore, the main goal of thesis is to improve wind turbine's operation efficiency.

Although the optimal torque or power can be calculated easily, however, due to the inertia of the mechanical system, it is not possible to achieve instantaneous tracking as the wind velocity is changing rapidly. This situation becomes even worse when the wind speed is in the low speed region where the acceleration or deceleration torque is rather small if an existing MPPT controller is adopted. As a result, the extracted energy in fact is significantly less than the maximum energy available [7]- [8].

For region two wind turbine system operation, the main objective is to extract maximum wind energy capture by tracking the maximum aero dynamic power coefficient. In order to track such power coefficient, a number of control algorithm have been applied. Standard torque control (STC) is one of control algorithms. It maximizes wind energy capture based on global maximum assumption of aerodynamic power coefficient. Despite their good performance and simple implementation, these controllers assume the knowledge of the global maximum power coefficient is always available. Unfortunately, this assumption does not apply to all wind turbine systems, especially because requirements for long service lives and inexpensive electronic components impose limits on generator speeds [4] , [9].

In order to avoid resonance effect on wind turbine structure fatigue, several control algorithms have been developed recently to limit the turbine operation speed [10].The constraint, in addition

to the inherent variability of wind speed, can lead to situations where the global maximum of the power coefficient and the ideal turbine speed are not achievable. Such situations pose serious challenges for the aforementioned control algorithms.

There are a few algorithms that have been developed to avoid relying upon the global maximum power coefficient, such as adaptive torque control [11] and Hill-Climb Search methods [12]. These methods greatly enhance wind turbine efficiency in the partial load region, but generally take a long time to converge and are more suitable for applications where the wind speed input is steady or slowly changing. When the wind speed is more variable, the energy capture capability is not fully realized with these methods. With increased demands on wind power generation, more turbines will be installed at sites with more volatile wind conditions.

Accordingly, it is necessary to develop the optimal controller that maximizes the wind power generation under these conditions. This control algorithms can be used to control wind turbine future behavior based on a nonlinear turbine model. This control methods, generally, convert the optimal control problem into a discretize optimization problem. It can be suitable to apply deterministic dynamic programming algorithm. In this thesis, the select control method is compare with standard torque control to show the effectiveness of maximum energy capture from available wind speed and volatile wind condition in MATLAB simulation.

1.2 Statement of problem

Even though a number of researches have been done about extraction of maximum power from wind, but still the wind energy conversion system (WECS) needs additional improvement so as to get the most optimal output due to the reason that a unique limitation of WECS is their inability to track peak power production efficiently at varying wind speeds.

Control algorithms have been developed to improve turbine's efficiency for both low and high wind speed wind turbine system. For low wind speed the control objective is to maximize the wind energy capture and this can be realized by tracking the maximum aerodynamic power coefficient. Algorithms like the traditional feedback control, the adaptive torque control and the maximum-power-point-tracking (MPPT) are all able to make the turbine track its maximum power coefficient. All of the aforementioned control algorithms provide good performance for the wind turbine system under a specific operation mode. And also standard torque control assume the knowledge of the global maximum power coefficient is always available, based on this assumption turbine acceleration is controlled by feedback control law but it doesn't consider constraints, and Non linear model of WTS.

However, This assumption dose not apply to all types of wind speeds and the variation of wind speed is involved in turbine's operation, applying the corresponding control algorithms to this variation of wind speed may not provide the overall optimal turbine system performance. Therefore, it is necessary to develop an optimal controller that is able to provide the overall optimal turbine system performance.

For this thesis, optimal control method is applied to capture maximum wind energy capture. The numerical algorithm, deterministic dynamic programing is applied to evaluate this control method. This numerical algorithm is wide applicable for complex nonlinear and constraint system. It is also used for global maximization.

1.3 Objective of thesis

1.3.1 General objective

- To maximize energy capture for Region two operation of WTS using dynamic programming.

1.3.2 Specific objective

- To study mathematical model of wind turbine system for dynamic programming.
- To design optimal controller for region two operation of wind turbine system.
- To simulate, analyse and compare of overall wind energy conversion system by using dynamic programming algorithm method and STC.

1.4 Methodology

The engineering approaches followed here is discussed as follows. First, reading and analysis different literatures related to this thesis. Hereafter, taking the most important ones and use them as standing base so as to save both time and energy and formulate the problems and specify the main and specific objective of the proposed work. Next to this move forward to proceed the mathematical model of wind turbine. This is followed by study the basic control algorithm of standard torque control and optimal control to maximize wind energy capture. And change continues optimal control problem to discrete optimal control. This is suitable to use the proposed optimization method to improve the controlling mechanism. The way of optimization of wind energy capture numerical by using numerical algorithm, such as selecting type of numerical algorithm to help me for finding global optimization point. Then I focus on Dynamic programming algorithm for region two (the wind speed between cut-in to rated wind speed) wind turbine system. Finally compare the performance of standard torque control and numerical optimal control.

1.5 Scope of the thesis

According to the structure of wind energy conversion system, it classified in to vertical and horizontal axis structure. Since, the later wind energy conversion system structure is more efficient than the former, on this thesis, horizontal axis WECS is selected. It has three main parts that help to extract energy from the wind. This are aerodynamic, mechanical, and electrical part. For this work, only focus from aerodynamic to mechanical part. On the other hand, according to the availability of wind speed, wind energy conversion system can have four operation regions. Region one, which have small wind speed and cannot have more energy to rotate the turbine. Region two, this is a region between cut-in wind speed and rated wind speed and wind turbine start extract or capture energy from the available wind speed. This is the selected region to study on the thesis. Region three, at this region the wind speed is greater than the rated wind speed. It needs good controller to regulate turbine speed in order to avoid mechanical damage. The final region is cut-off or shutdown region.

Based speed control criteria, WECS classified into fixed and variable speed wind turbines. Fixed speed wind turbines are the pioneer of wind turbine industry, simple, reliable and use low-cost electrical parts. But like variable-speed operation they are not allows the rotational speed of the wind turbine to be continuously accelerated or decelerated, that helps the wind turbine operates constantly at its highest level of aerodynamic efficiency. Due to variable speed WECS are more preferable.

To capture energy among one or all of this region of operation, it needs optimal control to extract energy from the available wind speed. Deterministic dynamic programing algorithm is selected to optimize the wind energy capture numerically, for such variable speed of WECS. Finally, this thesis compares standard torque controller with numerical optimal controller via MATLAB simulation.

1.6 Organization of the thesis

In chapter one, background about wind energy conversion system, the over view of related works, the main idea of the proposed control system, and little bit introduction about wind turbine system, statement of the problem, objective, specific objective, the methodology and scope of the thesis are discussed.

More detail about wind turbine system, includes components of wind turbine system, types of wind turbine based on structure of wind energy conversion system, general derivation of optimal aerodynamic efficiency, classification based on length of diameter of the blades and other are discuss in chapter two.

In chapter three, the thesis focuses wind turbine model, the dynamic of wind turbine, controlling mechanism such as numerical optimal control and standard control torque, optimization, general statement of optimal control problem, the algorithm of dynamic programming use for numerical optimal control design and optimization, and the way of how to evaluate dynamic proگرامing in MATLAB for wind turbine system to extract energy from wind. Are explain in this chapter.

Results of MATLAB simulation of wind turbine rotor speed, tip speed ratio, pitch angle, aerodynamic efficiency (C_p), generator input torque, and total energy capture based on the input of wind speed is discussed. wind speed has step input and random input by assumption via try and error method.

Chapter five contains the conclusion about the general over work of this thesis and recommendation and future works. The remain part is reference and appendices.

CHAPTER TWO

Wind Turbine System Theory and Literature Review

2.1 General Description of WECS

Now a day's wind energy is the most acceptable and efficient energy source. The purpose of the turbine is to capture the kinetic energy from the wind and then converts it to the usable form of electrical energy. Wind is a sustainable energy source since it is renewable, widely distributed, and plentiful. In addition, it contributes to reducing the greenhouse gas emissions since it can be used as an alternative to fossil-fuel-based power generation. The kinetic energy of winds rotates the blades of a wind turbine. The blades are connected to a shaft. The shaft is coupled to an electric generator. The generator converts the mechanical power into electrical power [13]. The general block diagram of wind energy conversion system from turbine to generator is shown in figure. 2.1.

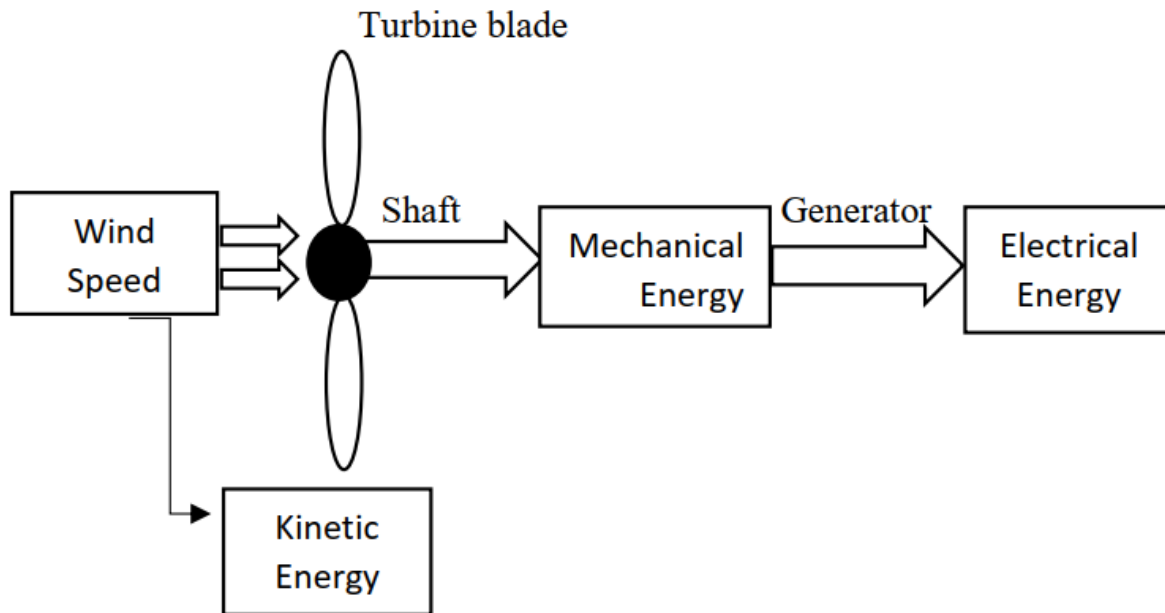


Figure 2.1 General block diagram of WECS

The selection of the number of wind turbine blades is not an easy way. Three blade wind turbine system cost in excess of two blade systems, yet two blade wind generators have to operate on higher rotational speeds than three blade ones [14]. Wind turbines has different classifications.

These are:

- depending on the size of blade radius
- depending on the position of blades
- depending on its pitch type

Depending on size of blade radius, wind turbines can be classified as small, medium and large. It ranges from a few kilo watts for residential to a megawatt for a large wind farm. Small to medium wind turbines range to a few hundred kilo watts and mostly they are installed at home and business to offset the consumption of utility power [15], [13]. Table 2.1. summarizes classification of wind turbines depending on the size of blades.

Table 2.1 classification of wind turbine depending on the size of blade

Wind turbine type (size)	Blade diameter (m)	Generated power (kw)
Small scale	up to 6	up to 20
Medium scale	7-20	up to 300
Large scale	above 126	≥ 9500

2.2 Wind Turbine Aerodynamics

The wind turbine rotor interacts with the wind stream, resulting in a behavior named aerodynamics, which greatly depends on the blade profile. The analysis of the aerodynamic behavior of a wind turbine can be done, in a generic manner, by considering the extraction process. Consider an actuator disc (Figure 2.2) and an air mass passing across, creating a stream-tube. The conditions (velocity and pressure) in front of the actuator disc are denoted with subscript u/a , the ones at the disc are denoted with 0 and, finally, the conditions behind the disc are denoted with w/b .

Betz's law demonstrates the theoretical maximum power that can be extracted from the wind. The wind turbine extracts energy from the kinetic energy of the wind. Higher wind speeds result in higher extracted energy. It should be noted that the wind speed after passing through the turbine is much lower than before reaching the turbine (before energy is extracted). This means that there are two wind speeds: one before the wind approaches (in front of) the turbine and the other after (behind) the turbine. Figure 2.2 shows both speeds of the wind; after the turbine, the wind has a decreased speed.

The extracted power can be given by [6] and [13]

$$P_{extract} = \frac{1}{2} \rho \pi R^2 \frac{V_b + V_a}{2} (V_b^2 - V_a^2) \quad (2-1)$$

Where

P_{extr} is the maximum power can be extracted from the wind.

V_a is the wind speed after passing the turbine.

V_b is the wind speed before passing the turbine and ρ and R are the air density and radius of the blade respectively.

Then the efficiency can be calculated as

$$efficiency = \frac{P_{extract}}{P_{wind}} \quad (2-2)$$

Where

$$P_{wind} = \frac{1}{2} \rho \pi R^2 V_b^3 \quad (2-3)$$

From equation (2.1) and (2.3) the ratio of the extracted power to the available is

$$\frac{P_{extract}}{P_{wind}} = \frac{\frac{V_a + V_b}{2}}{V_b^3} (V_b^2 - V_a^2) = \frac{1}{2} \left(1 - \frac{V_a^2}{V_b^2}\right) \left(1 + \frac{V_a}{V_b}\right) \quad (2-4)$$

From maximum power extraction

$$\frac{d(P_{extract}/P_{wind})}{d(V_a/V_b)} = \frac{1}{2} \left(-3 \frac{V_a^2}{V_b^2} - 2 \frac{V_a}{V_b} + 1 \right) = 0 \quad (2-5)$$

Solving the quadratic equation $3a^2 + 2a - 1$, where $a = V_a/V_b$ from equation (2-5) for a yields.

$$a = \frac{V_a}{V_b} = \frac{1}{3}$$

Then substituting the values $\frac{V_a}{V_b} = \frac{1}{3}$ equation (2.4) we get

$$\frac{P_{extract}}{P_{wind}} = \frac{1}{2} \left(1 - \left(\frac{1}{3}\right)^2\right) \left(1 + \frac{1}{3}\right) = \frac{16}{27} = 0.593 = 59.3\% \quad (2-6)$$

This indicates that it is not possible to extract all wind energy available from wind since the wind speed after the turbine cannot be zero. The constant 0.593 is commonly known as the optimal power coefficient.

2.3 Fixed and Variable Pitch /Speed Wind Turbine

In **fixed pitch** type wind turbines, it is possible to extract maximum power especially when the wind speed is below rated value. But the main problem is using a fixed pitch wind turbine cause hard fatigue and damage on the entire system of the turbine system when the wind speed gets above the rated value. Due to this reason a **variable pitch** wind turbine is preferable currently. The pitch angle control is usually applied for medium to large type wind turbines [16].

The performance coefficient, C_p and therefore power production from the turbine is strongly influenced by variation of the blade pitch relative to the direction of the wind or the plane of rotation [17]. This provides the degree of control of the blade to improve the efficiency of the power conversion or to protect the generator as well as the turbine from fatigue and damage. When the wind speed is at rated and below, then the optimal angle of attack of the blade is taken so that to expose the blade fully to the upcoming wind speed in order to extract maximum power from the wind available. For a wind speed above the nominal value, the pitch control mechanism is activated to limit and regulate the output power. A pitch range of 20-25 degree is usually sufficient [15].

The pitch control mechanism can be either hydraulic or electric. The electric pitch actuator is more common nowadays, since they are simpler and require less maintenance and it is proposed for this work. The pitch servo transfer function is modelled with a first order system with a time constant, T_d . Usually T_d is ranging from 0.2 sec to 0.25 sec [18]. The pitch rate commanded by the actuator is physically limited usually between ± 10 °/s.

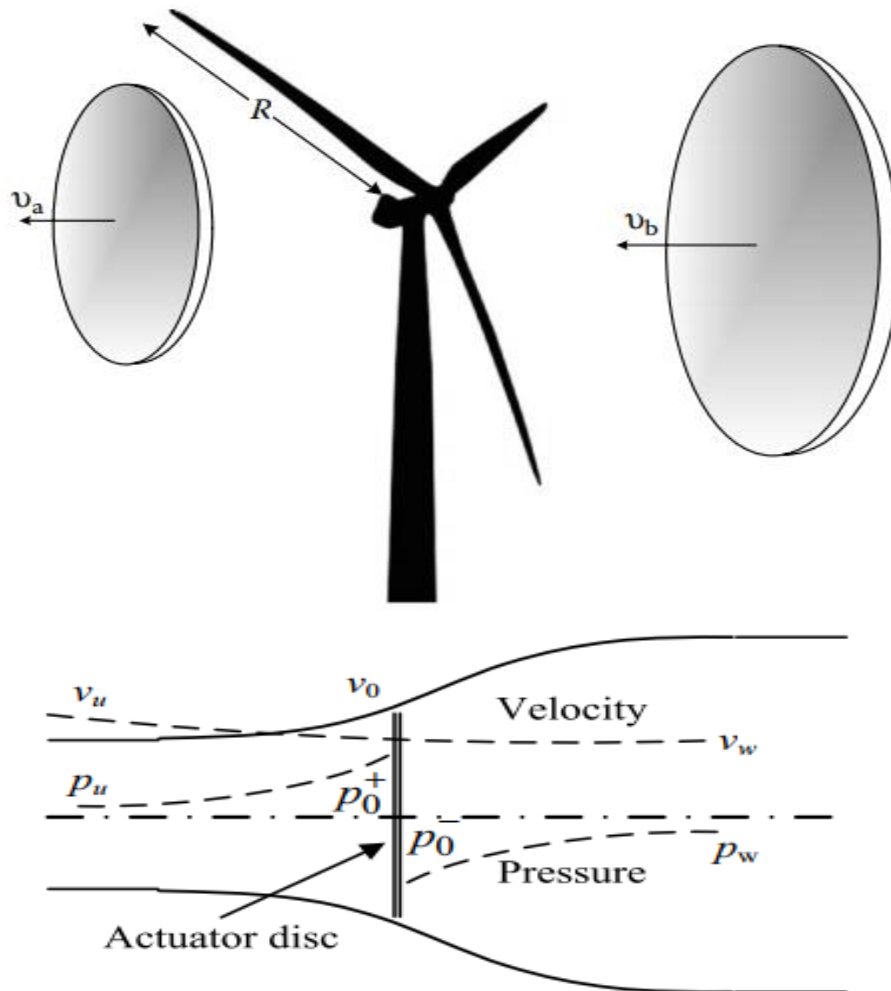


Figure 2.2 :Energy extracting actuator disc [6], [13]

Fixed-speed wind turbines: are the pioneers of the wind turbine industry. They are simple, reliable and use low-cost electrical parts. They use induction generators and they are connected directly to the grid, giving them an almost constant rotor speed stuck to the grid frequency, regardless of the wind speed [6].

Variable-speed wind turbines are currently the most used WECS. Their advantages, compared to fixed-speed wind turbines, are numerous. First of all, and most important, the decoupling between the generating system and the grid frequency makes them more flexible in terms of control and optimal operation. Of course, this comes at a price, namely the use of power electronic converters, which are the interfaces between the electrical generator and the grid and thus they actually make the variable-speed operation possible. But still, the high controllability offered by

the variable-speed operation is a powerful advantage in achieving higher and higher wind energy penetration levels.

The variable-speed operation allows the rotational speed of the wind turbine to be continuously adapted (accelerated or decelerated) in such a manner that the wind turbine operates constantly at its highest level of aerodynamic efficiency. While fixed-speed wind turbines are designed to achieve maximum aerodynamic efficiency at one wind speed, variable-speed wind turbines achieve maximum aerodynamic efficiency over a wide range of wind speeds. Furthermore, variable speed operation allows the use of advanced control methods, with different objectives: reduced mechanical stress, reduced acoustical noise, increased power capture, etc. [6].

2.4 Horizontal and Vertical Axis Wind Turbine

Depending on the axis position in figure 2.3, a wind turbine is classified as horizontal axis and vertical axis. Horizontal axis wind turbine is more common and have a horizontal positioned shaft which helps ease the conversion of the wind's linear energy into a rotational one. However, a vertical axis wind turbine has a vertical positioned shaft [13]. Table 2.2 summarizes the comparison of vertical axis versus horizontal axis wind turbine.

2.4.1 Wind Turbine components

Let's take HAWT, in order to get the desired power, the turbine must have shaped for good way of structure [19] - [20]. It has different components:

Tower foundation: In order to guarantee the stability of a wind turbine a pile or flat foundation is used, depending on the consistency of the underlying ground. The tower construction doesn't just carry the weight of the nacelle and the rotor blades, but must also absorb the huge static loads caused by the varying power of the wind. Generally, a tubular construction of concrete or steel is used. An alternative to this is the lattice tower form.

Rotor blades: The rotor is the component, which, with the help of the blades, converts the energy from the wind into rotary mechanical movement. Currently, the three-blade, horizontal axis rotor dominates. The rotor blades are mainly made of glass-fiber or carbon-fiber reinforced plastics (GRP, CFRP). The blade profile is similar to that of an airplane wing. They use the same principle of lift: on the lower side of the wing the passing air generates higher pressure, while the upper side

generates a pull. These forces cause the rotor to move forwards, i.e. to rotate. The pitch refers to turning the angle of attack of the blades into or out of the wind.

Pitch mechanism: The pitch mechanism in large wind turbines enables the rotation of the blades on their longitudinal axis. It can change the angle of attack of the blades with respect to the wind, by which the aerodynamic characteristics of the blade can be adjusted, as described in Figure 2.3. This provides a degree of control over the captured power to improve conversion efficiency or to protect the turbine.

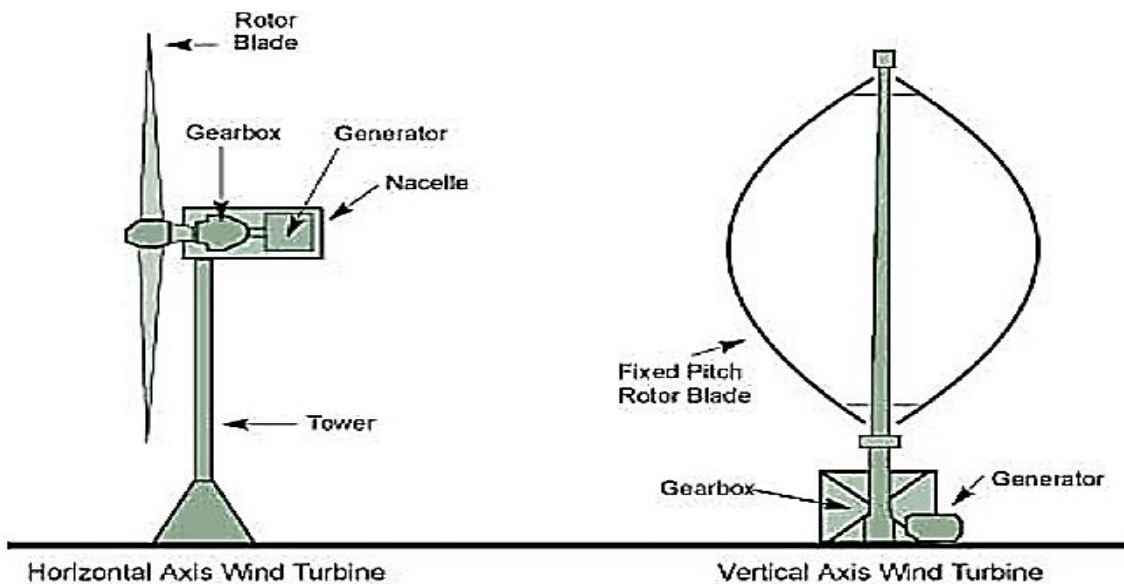


Figure 2.3: Type of wind turbine based on axis position [21]

When the wind speed is at or below its rated value, the angle of attack of the blades is kept at an optimal value, at which the turbine can capture the maximum power available from the wind. When the wind speed exceeds the rated value, the pitch mechanism is activated to regulate and limit the output power, thus keeping the power output within the designed capability. For this purpose, a pitch range of around 20 to 25 degrees is usually sufficient. When the wind speed increases further and reaches the limit of the turbine, the blades are completely pitched out of the wind (fully pitched or feathering), and no power will be captured by the blades. The wind turbine is then shut down and protected.

Gearbox: The rotor of a large three-blade wind turbine usually operates in a speed range from 6-20 rpm. This is much slower than a standard 4- or 6-pole wind generator with a rated speed of

1500 or 1000 rpm for a 50 Hz stator frequency and 1800 or 1200 rpm for a 60 Hz stator frequency. Therefore, a gearbox is necessary to adapt the low speed of the turbine rotor to the high speed of the generator. The gearbox conversion ratio (N_g), is defined as the ratio of generator speed to low-speed turbine blades. Single-stage gearboxes have also been used in practical wind turbines. This is achieved by using a special medium-speed generator that has a proper number of poles and operates at certain stator frequencies. Compared with the multistage gearbox, the single-stage gearbox is more reliable and costs less.

Rotor Mechanical Brake: A mechanical brake is normally placed on the high-speed shaft between the gearbox and the generator. The main advantage of placing the brake on the high-speed shaft is that it handles much lower braking torque. The brake is normally used to aid the aerodynamic power control (stall or pitch) to stop the turbine during high speed winds or to lock the turbine into a parking mode during maintenance. To minimize the wear and tear on the brake and reduce the stress on drive train during the braking process, most large wind turbines use the aerodynamic power control to reduce the turbine speed to a certain level or zero, and then the mechanical brake to stop or lock the wind turbine.

Generator: The conversion of rotational mechanical energy to electric energy is performed by the generator. Different generator types have been used in wind energy systems over the years. These include the squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG), and synchronous generator (SG) (wound rotor and permanent magnet) with power ratings from a few kilowatts to several megawatts.

The DFIG is the current workhorse of the wind energy industry. The stator of the generator is connected to the grid directly, while the rotor is interfaced with the grid through a power converter system with reduced power capacity. The DFIG typically operates about 30% above and below synchronous speed, sufficient for most wind speed conditions. It also enables generator-side active power control and grid-side re- active power control. The reduced-capacity converter is less expensive and requires less space, which makes the DFIG WECS popular in today's market.

Nacelle with drivetrain: The nacelle holds all the turbine machinery. Because it must be able to rotate to follow the wind direction, it is connected to the tower via bearings. The build-up of the

nacelle shows how the manufacturer has decided to position the drive train components (rotor shaft with bearings, transmission, generator, coupling and brake) above this machine bearing.

Yaw Drive: The main function of the yaw drive is to maximize the captured wind energy by keeping the turbine facing into the wind. It usually consists of more than one electric motor drive, yaw gear, gear rim, and bearing. A set of yaw brakes are disposed around the yaw rim to lock the position of the turbine when facing the wind or during maintenance. The yaw drive uses a planetary gear to lower the rotating speed of the yaw gear. All the motors are commanded by the same signals and lock after turning the wind turbine into the desired position. The yaw system typically needs to generate torque from 10,000 to 70,000 Nm to turn the nacelle.

Wind Sensors (Anemometers): The pitch/stall and yaw control systems require wind speed and direction measurements, respectively. The pitch/stall control needs the wind speed to determine the angle of attack of the blade for optimal operation. The yaw control requires the wind direction to face the turbine into the wind for maximum wind power capture. In addition, in variable speed turbines, the wind speed is needed to determine the generator speed for maximum power extraction. The wind speed sensor is usually made of a three-cup vertical-axis microturbine driving an optoelectronic rotational speed transducer. The wind direction is measured by a wind vane connected to an optoelectronic angle transducer. These are the main components of a wind measurement system, and are usually located on the top back part of the nacelle. More than one sensor system may be used in a wind turbine for more reliable and accurate measurements.

Ultrasonic anemometers are also used in practical wind turbines. They measure the wind speed by emitting and receiving acoustic signals through the air and monitoring the transmission time. Several emitters and receptors are disposed in such a way that a three-dimensional measurement can be made. The transmission time is affected by both wind speed and direction. With a given physical distribution of the sensors, the wind speed and direction can be computed from the propagation times. The ultrasonic anemometers are more accurate and reliable than the mechanical ones with moving parts. However, they are more expensive.

2.5 Power Characteristic of a Wind Turbine

In [20], the power characteristics of a wind turbine are defined by the power curve, which relates the mechanical power of the turbine to the wind speed. A typical power curve is characterized by three wind speeds: cut-in wind speed, rated wind speed, and cut-out wind speed, as described in Figure 2.6. Where P_m is the mechanical power generated by the turbine and v_w is the wind speed. The cut-in wind speed, as the name suggests, is the wind speed at which the turbine starts to operate and deliver power. The blade should be able to capture enough power to compensate for the turbine power losses. The rated wind speed is the speed at which the system produces nominal power, which is also the rated output power of the generator. The region between cut-in wind speed and rated wind also commonly called region two operation of wind turbine system. At this region, the main objective is to maximize power/energy capture until to get rated power. The cut-out wind speed is the highest wind speed at which the turbine is allowed to operate before it is shut down. For wind speeds above the cut-out speed, the turbine must be stopped, preventing damage from excessive wind.

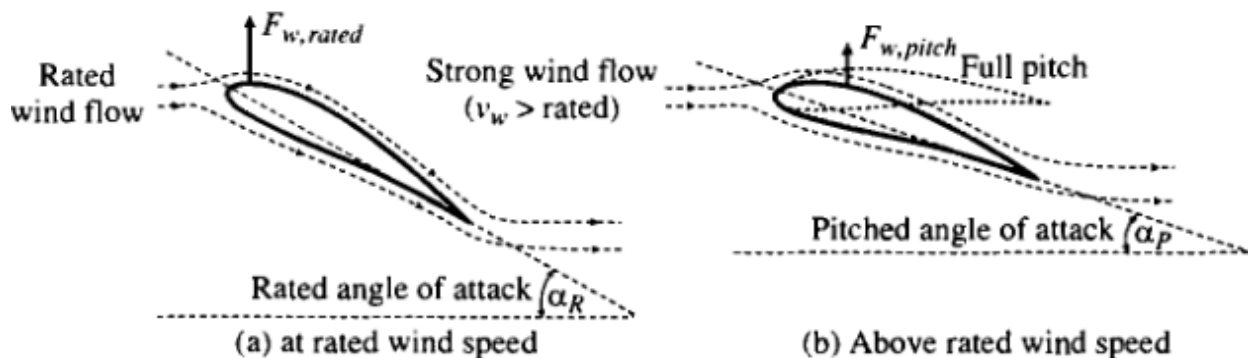


Figure 2.4: Aerodynamic pitch-control principle [15].

2.6 Related Control Techniques to Maximize Wind Energy Capture

Research geared towards increasing wind energy capture has focused on exploring control algorithms to improve wind turbine efficiency, particularly for operation in the partial load region, where the generator operates below its rated power and the turbine speed varies significantly. Several maximum power point tracking (MPPT) methods have been developed to track the optimal TSR.

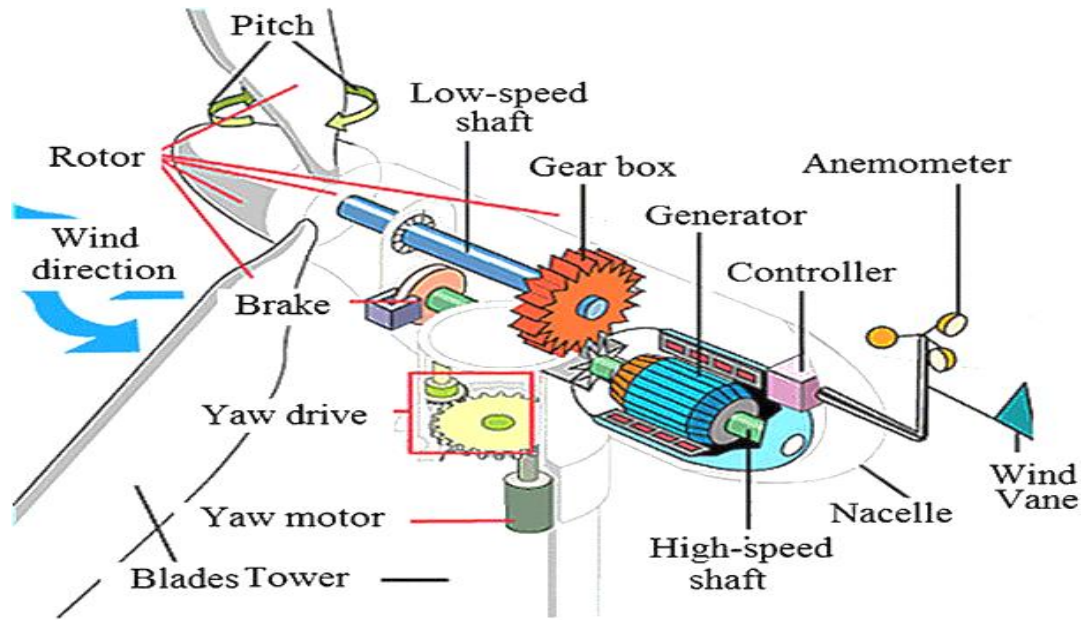


Figure 2.5: HAWT Component/Structure [22]

Table 2.2 Comparison between VAWT and HAWT [3], [13]

Turbine type	Advantage	Disadvantage
Horizontal axis	<ul style="list-style-type: none"> • Higher wind energy conversion efficiency • Access to stronger wind due to high power • Power regulation by pitch angle control 	<ul style="list-style-type: none"> • Higher installation cost, • stronger tower to support heavy weight of nacelle • Longer cable from the top of tower to ground
Vertical axis	<ul style="list-style-type: none"> • Lower installation and easier maintenance due to the ground level gearbox and generator • Operation independent of wind direction. 	<ul style="list-style-type: none"> • Lower wind energy conversion efficiency • Limited options for power regulation at high wind speeds

TSR feedback control is designed for direct optimal TSR tracking. This controller is intuitive and simple for implementation. However, the direct TSR feedback approach does not consider the

system nonlinearity which often leads to poor tracking performance. A standard torque controller (STC) has been developed and widely used for commercial wind turbines during partial load operation [23].

The commanded generator torque of STC is proportional to the square of generator speed with a proportional control gain that is determined based on the wind turbine model. With an ideal wind turbine model, an optimal control gain can be obtained. The STC will allow the wind turbine to track the corresponding optimal reference tip speed ratio (TSR) that maximizes energy capture [24]. However, the STC does not consider the wind speed measurement in its control design and takes long time to converge to its optimal operating condition. Therefore, the STC does not effectively track the reference TSR under highly varying wind inflow.

To accelerate the controller's convergence to the turbine reference TSR, an optimally [25] tracking rotor (OTR) controller was proposed. Based on different wind speed measurements, the OTR adjusts the generator torque to assist in rotor acceleration and deceleration, thereby expediting the turbine's response under highly varying wind speed. A direct speed controller (DSC) was also developed using wind inflow information to improve the tracking performance of the reference TSR [26].

Despite their effectiveness in accelerating turbine's response under high wind speed variation, the control gain and reference TSR employed by OTR and DSC are derived based on an ideal wind turbine model. It has been found that the simulation-derived reference TSR and torque control gain can deviate from their actual optimal values due to the aero-elastic response of turbine blades and the stochastic non-uniform wind inflow.

There are a few algorithms that have been developed to avoid relying upon the global maximum power coefficient, such as adaptive torque control [11] and Hill-Climb Search methods [12]. These methods greatly enhance wind turbine efficiency in the partial load region, but generally take a long time to converge and are more suitable for applications where the wind speed input is steady or slowly changing. When the wind speed is more variable, the energy capture capability is not fully realized with these methods.

STC maximizes wind energy capture based on global maximum assumption of aerodynamic power coefficient. Despite their good performance and simple implementation, these controllers assume

the knowledge of the global maximum power coefficient is always available. Unfortunately, this assumption does not apply to all wind turbine systems, especially because requirements for long service lives and inexpensive electronic components impose limits on generator speeds [4] , [9].

In [16], conventional controller like proportional derivative (PD) based MPPT is presented. However, a number of short comings have been encountered. The trial-and-error design procedure used to determine the P, I, and D gains presents a possibility for poorly tuned controller gains, which reduces the accuracy and the dynamic performance of the entire control system [1].

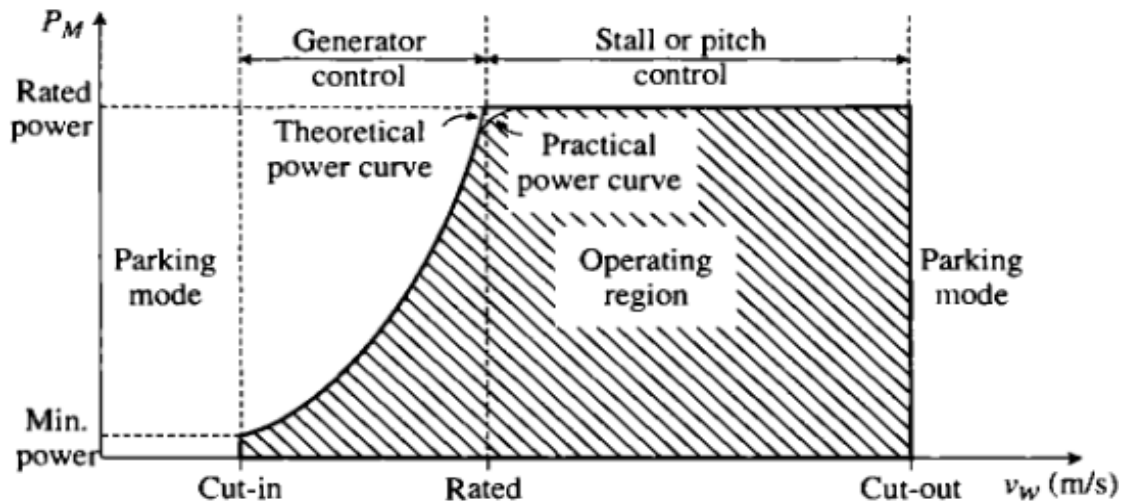


Figure 2.6: Qualitative turbine mechanical power versus wind speed curve [27].

CHAPTER THREE

System Modelling

3.1 Wind Turbine System Model

Wind speed, or wind flow speed, is a fundamental atmospheric quantity caused by air moving from high to low pressure, usually due to changes in temperature. Wind speed is affected by a number of factors and situations, operating on varying scales (from micro to macro scales). These include the pressure gradient, Rossby waves and jet streams, and local weather conditions. The energy available in the wind varies as the cube of wind speed [6].

In order to efficiently capture wind energy, several key parameters need to be considered: air density, diameter of the blades, wind speed, and the area covered when the blade rotates. The force of the wind is stronger at higher air densities. Wind force generates torque, which causes the blades of the wind turbine to rotate. Therefore, the kinetic energy of the wind depends on air density. The other parameter is the wind speed. It is expected that wind kinetic energy rises as wind speed increases.

The kinetic energy of the wind can be expressed as

$$K_E = \frac{1}{2} m v_w^2 \quad (3-1)$$

But air density $\rho = \frac{m}{v}$ this implies $m = \rho v$, then kenteic energy is rearranged

$$K_E = \frac{1}{2} \rho v v_w^2 \quad (3-2)$$

Where volume, $v = Ad = \pi R^2 d$

Therefore, the kenteic energy has the form

$$K_E = \frac{1}{2} \rho \pi R^2 d v_w^2 \quad (3-3)$$

Where KE is kenteic energy, v_w is wind speed, v is volume, R is radius of turbine blade, ρ is air density and d is the thicknesses of air disk. Then the theoretical overall power of wind can be given as follows:

$$p_w = \frac{K_E}{t} = \frac{\frac{1}{2} \rho \pi R^2 d v_w^2}{t} = \frac{1}{2} \rho \pi R^2 (d/t) v_w^2 = \frac{1}{2} \rho \pi R^2 v_w^3 \quad (3-4)$$

It implies that the power content of the wind varies with cube of the average wind speed [13].

3.2 Turbine Dynamics

A model that describes the wind turbine dynamics and has been used for control design. Assuming the drivetrain is rigid and its energy loss is negligible, in [28] the dynamics of the wind turbine can be represented by:

$$\dot{\omega} = \frac{1}{J_r} (\tau_{aero} - \tau_c) \quad (3-5)$$

Where J_r is the combined rotational inertia of the rotor, gearbox, generator and shafts, τ_{aero} is aerodynamic torque, which drives the turbine, and τ_c is the reactive torque.

$$\tau_{aero} = \frac{P_{cap}}{\omega_r} \quad (3-6)$$

P_{cap} represents the captured wind power.

The relation between the captured wind power P_{cap} and the available wind powers (P_{wind}) is defined by the aerodynamic power coefficient C_p . This coefficient measures how effectively change wind energy into mechanical energy. It can be defined as

$$C_p = \frac{P_{cap}}{P_{wind}} \quad (3-7)$$

The aerodynamic power coefficient C_p is a nonlinear function of the blade pitch angle (β) and the tip speed ratio λ .

$$C_p = f(\lambda, \beta) \quad (3-8)$$

The tip speed ratio is defined as the linear velocity of the rotor over wind speed given

$$\lambda = \frac{w_r D_r}{2v_w} \quad (3-9)$$

The aerodynamic power coefficient formula is developed as follows:

$$C_p = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{\frac{C_5}{\lambda_i}} \quad (3-10)$$

Where

$$\lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3-11}$$

The value from C₁ to C₆ and x are constant.

Table 3.1 value of aerodynamic power coefficient

Variable	C1	C2	C3	C4	C5
Value	0.5176	116	0.4	5	21

The reactive torque:

$$\tau_c = \tau_g N_g \tag{3-12}$$

Where τ_g is the turbine generator torque and N_g is gear box ratio defined as generator shaft speed over the wind turbine rotor speed.

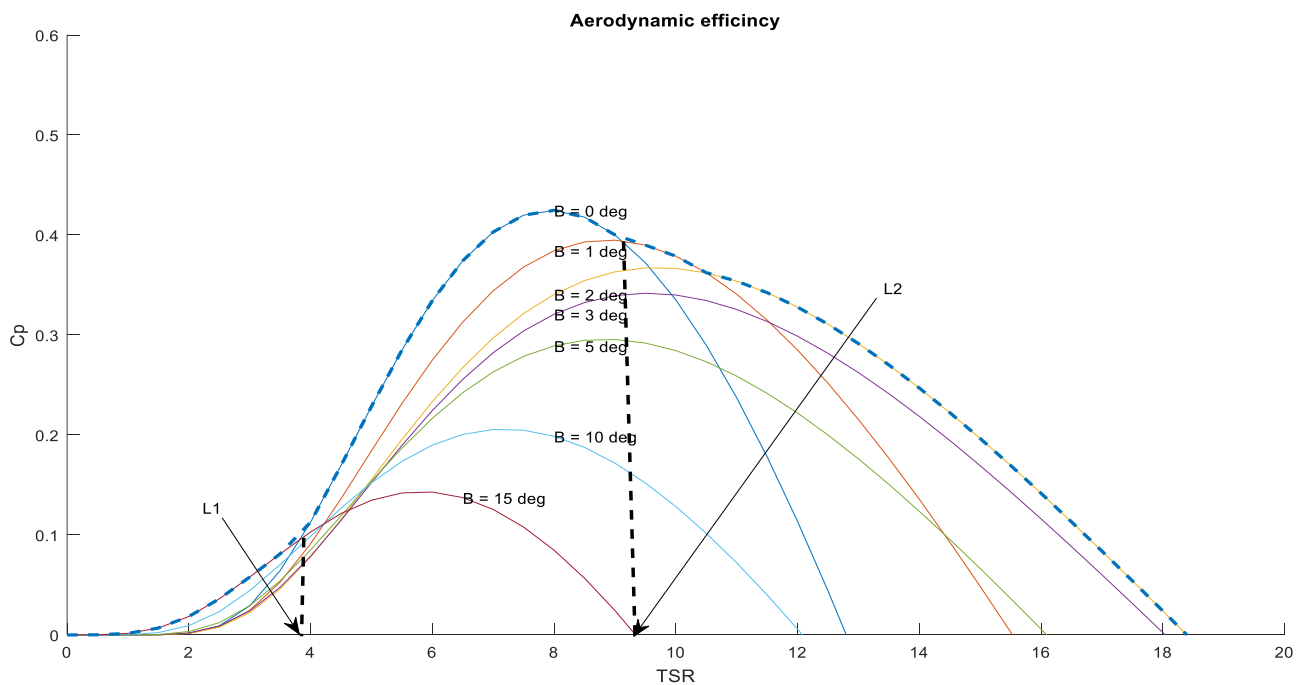


Figure 3.1 Cp vs TSR with different pitch angle.

By combining the above equation, the dynamics of wind turbine can be derived.

$$\dot{w} = \frac{1}{J_r} \left(\frac{\pi}{8} D_r^2 \rho C_p \frac{v_w^3}{w_r} - \tau_g N_g \right) \quad (3-13)$$

$$\tau_g = \left(\frac{\frac{\pi}{2} R^2 \rho C_p(\lambda, \beta) v_w^3}{w_r} - J_r \frac{dw}{dt} \right) / N_g \quad (3-14)$$

The total wind energy capture over a time interval can be calculated as

$$E_{cap} = \int_{t_0}^{t_f} P_{cap} dt = \int_{t_0}^{t_f} P_{wind} \cdot C_p dt = \frac{\pi}{8} \rho D_r^2 \cdot \int_{t_0}^{t_f} v_w^3 \cdot C_p dt \quad (3-15)$$

A two-dimensional plot (Appendix D) of C_p as a function of λ and β is shown in Fig.3.1. Each C_p curve corresponds to a different value of β . The dash blue curve consists of multiple segments that represent the maximum possible values of C_p over the ranges of λ and β . Each segment may correspond to a different β depending on the value of λ .

The plot shows that a pitch angle of $15^\circ - 25^\circ$ produces the maximum achievable power coefficient at low values of λ , i.e., $\lambda < \lambda_1(L1)$. for high values of λ , i.e., $\lambda > \lambda_2(L2)$, achievable maxima of C_p are generated by pitch angles of 1° or 2° . For the range of λ between λ_1 and λ_2 all of the achievable maxima of C_p are on the 0° pitch angle curve, including the global maximum of C_p , $(C_p)_{max}$. Due to constraints governed by the rotor speed and wind speed, the global maximum of C_p is not always achievable. In this case, the achievable maximum of C_p can only be obtained by tuning β appropriately.

The magnitude of the power is increased for a corresponding increase of a wind speed. Figure 3.2 shows the relation of mechanical energy extracted from wind for a three different wind speeds (10m/s, 11 m/s, and 12 m/s) with to rotor speed (see Appendix E).

3.3 Controller Design

3.3.1 STC Controller

Maximizing wind energy capture is equivalent to maximizing the integral term in equation (3-14) for the case of steady-state operation C_p should be kept as its global maximum value to maximize the wind energy capture. However, due to the variation in wind speed or the constraint on rotor speed, the transient of the turbine may cause λ to fall into any region of C_p graph (figure 3.1). In

order to maximize the integral term, β needs to be tuned to make the turbine always pursue the achievable maximum of C_p during its transient.

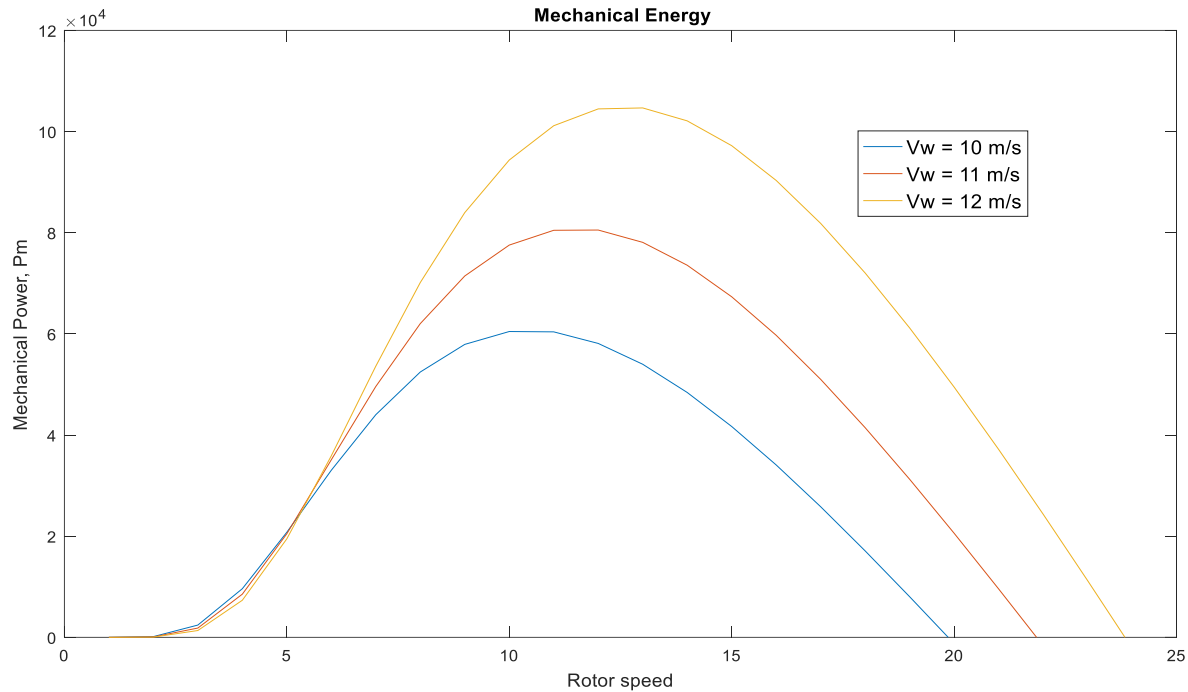


Figure 3.2 mechanical power vs rotor speed for different wind speed

STC control method relies on the feedback of the global maximum power coefficient and assume the knowledge of the global maximum power coefficient is always attainable. It is considered as a benchmark in this research and its performance will be compared with proposed optimal controller. For this control method, the turbine generator torque is controlled according to a feedback control law [29], described as follows

$$\tau_c = \tau_g N_g = k_\tau \omega_r^2 \quad (3-16)$$

Where N_g is number of gear ratio and

$$k_\tau = \frac{1}{2} \rho_{air} \pi R_r^5 \frac{(C_p)_{max}}{\lambda_*^3} = \frac{1}{2} \rho_{air} \pi R_r^5 \frac{C_p(\lambda_*, \beta_*)}{\lambda_*^3} \quad (3-17)$$

When substitute this in equation (3-13), the model has the following forms.

$$\dot{\omega} = \frac{1}{2J_r} \rho_{air} \pi R_r^5 \omega_r^2 \left[\frac{C_p}{\lambda^3} - \frac{(C_p)_{max}}{\lambda_*^3} \right] \quad (3-18)$$

Thus

$$\dot{\omega} < 0, \text{ when } C_p < \frac{C_{pmax}}{\lambda_*} \lambda^3 \text{ and } \dot{\omega} > 0, \text{ when } C_p > \frac{C_{pmax}}{\lambda_*} \lambda^3$$

Where $(c_p)_{max}$ is the maximum power coefficient achievable by the turbine, and λ_* and β_* is the tip speed ratio and pitch angle at the maximum power coefficient and J_r is rotational inertia of the system.

Thus, this control law given by (3-16) and (3-17) causes the turbine to accelerate toward the desired set point when the rotor speed is too slow and decelerate when the rotor speed is too fast. As a result, this generator torque control law will balance the aerodynamic and load torques to regulate the speed of the turbine to the optimal tip speed ratio in steady-state conditions. On the other hand, the blade pitch angle is controlled to track β_* as follows

$$\frac{d\beta}{dt} = T_\beta(\beta_* - \beta) \quad (3-19)$$

where T_β is a positive gain which can be tuned to control the speed of tracking.

Even if standard control of region two wind turbine is widely used/adapted due to its ease of implementation and satisfactory performance, but it has several shortcomings leads to significant power losses. The first of these is that there is no accurate way to determine the gain k_τ ; modeling programs are not accurate enough to represent all of the complex aerodynamics, and these aerodynamics change over time. Furthermore, it is not certain whether the value of k_τ used in the standard control even provides for the maximum energy capture under real-world turbulent conditions. Second, even when it is assumed that k_τ can be accurately determined via simulation or experiments, wind speed fluctuations force the turbine to operate off the peak of its C_p - λ curve much of the time, resulting in less energy capture [28].

3.3.2 Optimal controller design

Optimization is a very desirable feature in day-to-day life. We like to work and use our time in an optimum manner, use resources optimally and so on. The subject of optimization is quite general in the sense that it can be viewed in different ways depending on the approach (algebraic or geometric), the interest (single or multiple), the nature of the signals (deterministic or stochastic), and the stage (single or multiple) used in optimization. This is shown in Figure 3.3. As we notice

that the calculus of variations is one small area of the big picture of the optimization field, and it forms the basis for the study of optimal control systems. Further, optimization can be classified as static optimization and dynamic optimization [30].

1. Static Optimization is concerns with controlling a plant under steady state conditions, i.e., the system variables are not changing with respect to time. The plant is then described by algebraic equations. Techniques used are ordinary calculus, Lagrange multipliers, linear and nonlinear programming.

2. Dynamic Optimization is concerns with the optimal control of plants under dynamic conditions, i.e., the system variables are changing with respect to time and thus the time is involved in system description. Then the plant is described by differential or difference) equations. Techniques used are search techniques, dynamic programming, variational calculus (or calculus of variations) and Pontryagin principle.

Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A control problem includes a cost functional that is a function of state and control variables. The main objective of optimal control is to determine control signals that will cause a process (plant) to satisfy some physical constraints and at the same time extremize (maximize or minimize) a chosen performance criterion (performance index or cost function) [30]. The formulation of optimal control problem requires: -

1. a mathematical description (model) of the system to be controlled (in state variable form),
2. a specification of the performance index (cost-function), and
3. a statement of boundary conditions and the physical constraints on the states and/or controls.

For the purpose of optimization, we describe a physical system by a set of linear or nonlinear differential or difference equations. A nonlinear system is characterized by

$$\dot{x}(t) = f(x(t), u(t), t) \quad (3-20)$$

$$y(t) = g(x(t), u(t), t) \quad (3-21)$$

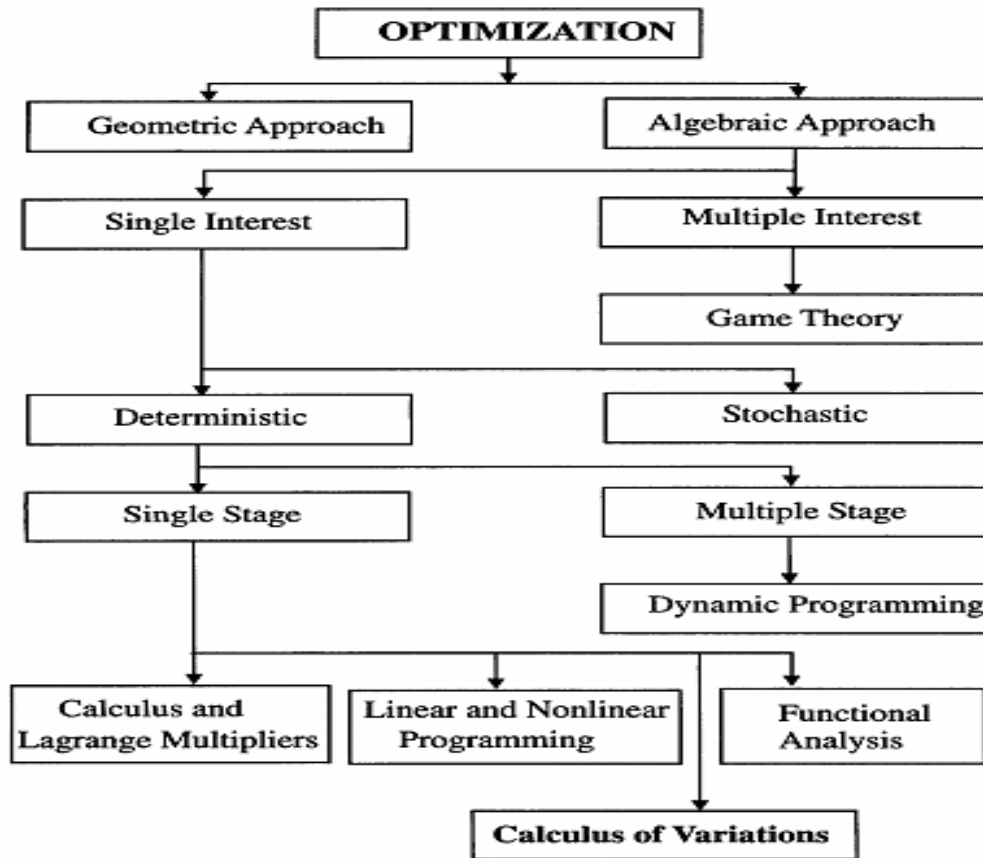


Figure 3.3 Overview of Optimization [30]

3.3.3 Formal Statement of Optimal Control System

Let's state formal statement of optimal control system. The optimal control problem is to find the optimal control $u^*(t)$ (* indicates extremal or optimal value) which causes the nonlinear plant (system)

$$\dot{x}(t) = f(x(t), u(t), t)$$

to give the state $x^*(t)$ that optimizes the general performance index

$$J = S(x(t_f), t_f) + \int_{t_0}^{t_f} V(x(t), u(t), t) dt \quad (3-22)$$

with some constraints on the control variables $u(t)$ and/or the state variables $x(t)$ given by

$$X_- \leq x(t) \leq X_+ \quad (3-23)$$

Control input constraint

$$U_+ \leq u(t) \leq U_- \quad (3-24)$$

where, +, and - indicate the maximum and minimum values the variables can attain.

3.3.4 Dynamic programming

Given a dynamical process or plant and the corresponding performance index there are basically two ways of solving for the optimal control of the problem, one is the Pontryagin maximum principle and the other is Bellman's dynamic programming (DP) [31]. For this thesis the latter method is concentrate due to more suitable for dynamic system. Dynamic programming is a method for the optimization or mathematical representation of systems in which one works by stages or sequences. The basic idea of DP is a discrete, multistage optimization problem in the sense that at each of the finite set of times, a decision is chosen from a finite number of decisions based on some optimization criterion.

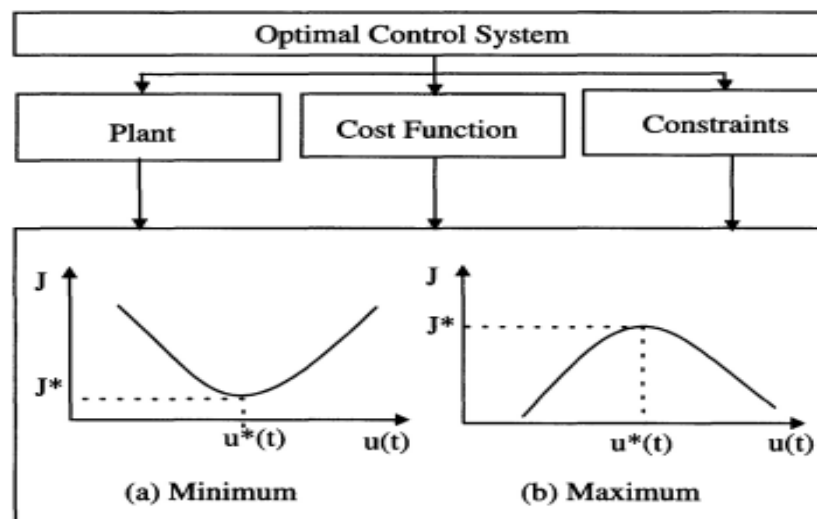


Figure 3.4 Optimal Control Problem [30]

Dynamic programming (DP) is a numerical algorithm based on Bellman's optimality principle that finds the control law, which provides the globally maximum value for the given objective function while satisfying the system constraints. It divides a complex optimization problem into simple sub-problems [32]. The important feature of the dynamic programming approach is structuring of optimization problems into multistage decision problem, which are solved sequentially one stage at a time. Each subproblem is solved as an optimization problem and its solution helps to define

the characteristics of the next sub-problem in the sequence. The central theme of DP is based on a simple intuitive concept called principle of optimality [30], stated as follows

“An optimal policy has the property that whatever the previous state and decision (control), the remaining decisions must constitute an optimal policy with regard to the state resulting from the previous decision.”

Notice that the dynamic programming approach is naturally a discrete-time system. Also, it can be easily applied to either linear or nonlinear systems, whereas the optimal control of a nonlinear system using Pontryagin principle leads to nonlinear two-point boundary value problem (TPBVP) which is usually very difficult to solve for optimal solutions.

As we know wind turbine mathematical model is completed and cannot be solve or get its optimal point of the variable by using analytical method but it can achieve by numerical based computation. Due to its nonlinear model of aerodynamic behavior. it is hard to optimize it by using simple mathematical derivation. To get the desired amount of energy from wind, numerical based global optimization method can be used. So, let see how to optimize wind energy capture by using dynamic programming. The basic definition about optimization, optimal control, dynamic programming, and the constraint of states and control inputs are defined in the above description. To maximize wind energy capture by using such control algorithm, the general optimal control problem mentioned on the above are arranged based on wind turbine system state, control input and performance index (objective/cost) function.

In [30], Optimal control can be classified based on the structure of the performance index. If the PI (3-21) contains the terminal cost function $S(x(t), u(t), t)$ only, it is called the Mayer problem, if the PI (3-21) has only the integral cost term, it is called the Lagrange problem, and the problem is of the Bolza type, if the PI contains both the terminal cost term and the integral cost term as in (3-21). For this thesis, Bolza type optimal control problem to be used. So, the performance index is derived from equation (3-1) up to (3-13)

$$\max J = E(N) + \frac{\pi}{8} \rho D_r^2 \sum_{k=0}^{N-1} \int_{t_0}^{t_f} v_w^3 \cdot C_p\left(\frac{R\omega_r}{v_w}, \beta\right) dt \quad (3-25)$$

Subject to:

$$\dot{\omega}_r = \frac{1}{J_r} \left(\frac{\pi}{8} D_r^2 \rho C_p(\lambda, \beta) \frac{v_w^3}{\omega_r} - \tau_g N_g \right) \quad (3-26)$$

$$x(0) = x_0 \quad (3-27)$$

$$(\omega_r)_{min} \leq \omega_r \leq (\omega_r)_{max} \quad (3-28)$$

$$(\tau_g)_{min} \leq \tau_g \leq (\tau_g)_{max} \quad (3-29)$$

$$\beta_{min} \leq \beta \leq \beta_{min} \quad (3-30)$$

$E(N)$ denotes, final time wind energy capture. The state of the wind turbine system is ω_r (turbine rotor speed), the control inputs are τ_g (generator torque) and β (pitch angle). Performance index is the total energy capture from wind, in equation (3-24). This is continuous optimal control problem form. Since for this thesis, assume that wind speed is determined. Deterministic dynamic programming can be used to get optimal state trajectory and control trajectory.

When developing causal suboptimal controllers, it is an advantage if the optimal controller is known, even if this controller is not causal. In many cases, such optimal controllers can be found using the deterministic dynamic programming (DP) algorithm introduced in [31]. Of course, this optimal controller can be found only if all future disturbance and reference inputs are known. In this sense, this solution is not causal.

In deterministic dynamic programming (DP) models, the transition between states following a decision is completely predictable. Knowledge of the triple ‘‘stage, state, decision’’ allows the modeler to know the subsequent state and the single-stage cost associated with the decision and transition. The cost of a decision is the appropriate combination of single stage cost and the cost of the subsequent optimal policy. A policy is any rule for making decisions which yields an allowable sequence of decisions; and an optimal policy is a policy which maximizes a preassigned function of the final state variables [31]. The optimal policy for the current state and stage can then be found by finding the best cost, taken over all possible decisions.

When implementing the deterministic DP algorithm on a computer there are many numerical issues that arise that have, so far, not yet received sufficient attention. Also, since the computational complexity of every DP algorithm is exponential in the number of states and inputs, special attention must be given to minimizing the overall computational cost. The implementation

of suitable numerical algorithms that efficiently solve a given DP problem is, therefore, a nontrivial part of a design process [33].

3.3.5 Dynamic programming algorithm

Since DP can be used here to solve a continuous-time control problem, the continuous-time model must be discretized in time first. So, Let the system be described by

$$x(k+1) = F(x(k), u(k), k), \quad k = 0, 1, \dots, N-1 \quad (3-31)$$

$$x(k+1) = T_s * \frac{1}{J_r} \left(\frac{\pi}{8} D_r^2 \rho C_p \left(\frac{R * x(k)}{v_w}, u(k) \right) \frac{v_w^3}{x(k)} - \tau_g(k) N_g \right) + x(k) \quad (3-32)$$

with the state variable $x_k \in X_k$ and the control signal $u_k \in U_k$. And the cost function be

$$J_k(x(k)) = J = E(x(k_f), k_f) + \sum_{k=0}^{N-1} E(x(k), u(k)) \quad (3-33)$$

where, $x(k)$, $u(k)$ are the n and r dimensional state and control vectors, respectively. By using the principle of optimality to find the optimal control $u^*(k)$ which applied to the plant (3-31) gives optimal state $x^*(k)$. Let us assume that we evaluated the *optimal* control, state and cost for all values starting from $k+1$ to N . Then, at any time or stage k , we use the principle of optimality to write.

$$E_k^*(x(k)) = \max[E[x(k), u(k)] + E_{k+1}^*(x^*(k+1))] \quad (3-34)$$

$$J_k^*(x(k)) = \max(E_{k+1}(k+1)) + \frac{\pi}{8} D_r^2 \rho \sum_{k=0}^{N-1} T_s * C_p \left(R * \frac{x(k)}{v_w}, u_2(k) \right) * \frac{v_w^3}{x(k)} \quad (3-35)$$

The previous relation is the mathematical form of the principle of optimality as applied to optimal control system. It is also called functional equation of dynamic programming. Thus, it means that if one had found the optimal control, state and cost from any stage $k+1$ to the final stage N then one can find the optimal values for a single stage from k to $k+1$.

For this system, the admissible control policy is the combination of the pitch angle and the generator torque. The pitch control input is used to assist the startup process as three bladed wind turbines have relatively low starting torque, and to limit the rotational speed, when the wind speed

exceeds the rated wind speed. The pitch control method is active more when the wind speed exceeds the rated value to limit the aerodynamic power to rated one. The generator torque control is used in the partial load wind system to maximize the energy capture from the wind by continuously accelerating or decelerating the generator speed in such way that the optimum tip speed ratio is tracked. This control mechanism generally limits the generator speed at rated wind speed and deals the power conversion efficiency optimization.

Let $U = \{\mu_0, \mu_1, \dots, \mu_{N-1}\}$ be a control policy, and the discretized cost of in eq (3-34) using U with the initial state $x(0) = x_0$, the first part (3-34) of cost function is the final time energy capture from wind. The remaining part is the cost of applying the control $\mu_k(x_k)$ at state (x_k) . The control applying on the cost function is the combination of generator torque and pitch angle that maximize aerodynamic power coefficient. When power conversion efficiency is improving, the energy capture from available wind speed is optimized. The selection of combination of this control input for each discretized node/time is maximize the cost function.

$$U = [\beta_1 \beta_2 \dots \beta_N (\tau_g)_1 (\tau_g)_2 \dots (\tau_g)_N] \quad (3-36)$$

Based on the principle of optimality [31], the DP algorithm evaluates the optimal cost-to-go function $J_k(x^i)$ at every node in the discretized state-time space by proceeding *backward* in time.

- End cost calculation step

$$J_N(x^i) = E_N(x^i) + p_N(x^i) \quad (3-37)$$

This is $p_N(x^i)$ penalty function that can be used to enforce a constraint on the final state. And i is number of discretized nodes.

- Intermediate calculation step for $k = N - 1$ to 0

$$J_k(x^i) = \max_{u_k \in U_k} \{E_k(x^i, u_k) + p_k(x^i) + J_{k+1}(F_k(x^i, u_k))\} \quad (3-38)$$

The optimal control is given by the argument that maximizes the right-hand side of equation (3-37) for each x^i at time index k of the discretized state-time space. The cost-to-go function $J_{k+1}(x)$ used in (3-37) is evaluated only on discretized points in the state space. the output of the model function $F_k(x^i, u_k)$ is a continuous variable in the state space which can be between the nodes of the state grid. the last term in (3-37), namely $J_{k+1}(F_k(x^i, u_k))$ must be evaluated appropriately. In the dpm function introduced in [33], linear interpolation of the cost-to-go J_{k+1} is used. Since the

state and the input grids are equally spaced, the computational cost of this interpolation is low compared to the cost induced by the model evaluations.

linear interpolation is a method of curve fitting using linear polynomials to construct new data points within the range of a discrete set of known data points. This interpolation is algorithms are select due to its simplicity and low computational cost. When using a linear interpolation, the control input , state trajectory, and cost between nodes has the following similar form.

$$U(T) = U_k + \frac{U_k - U_{k+1}}{T_{k+1} - T_k} (T - T_k), \quad T_k \leq T \leq T_{k+1} \quad (3-39)$$

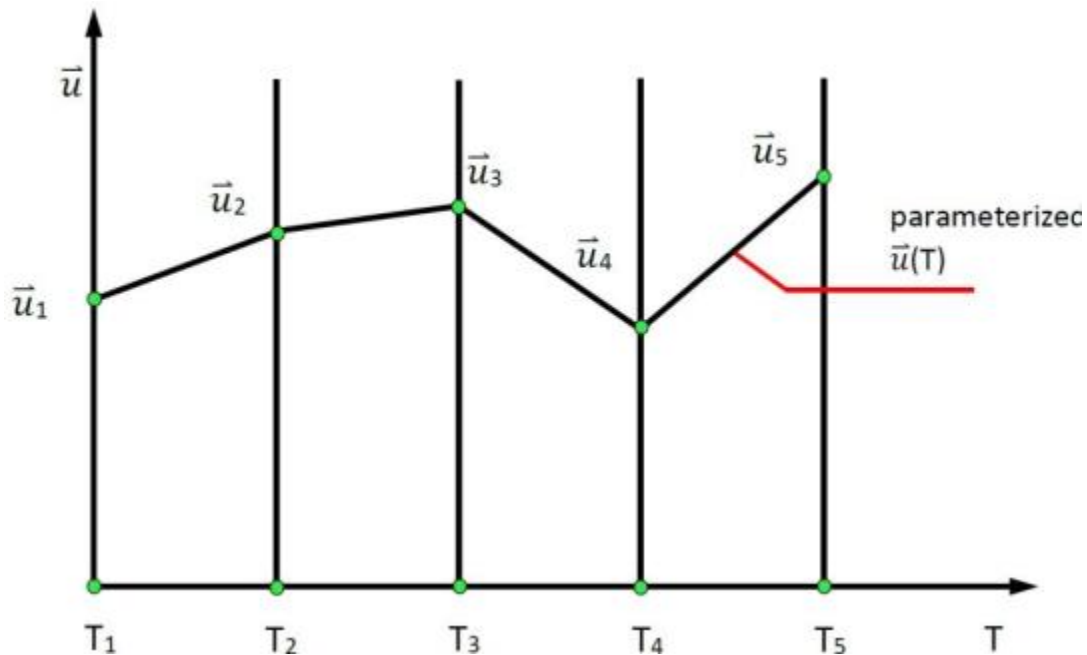


Figure 3.5: Visualization of linear interpolation between nodes.

The output of the algorithm (3-36) - (3-37) is an optimal control signal map. This map is used to find the optimal control signal during a forward simulation of the model (3-25), starting from a given initial state x_0 , to generate the optimal state trajectory. In the optimal control signal map, the control signal is only given for the discrete points in the state space grid. The control signal, therefore, must be interpolated when the actual state does not coincide with the points in the state grid. In general, the complexity of the DP algorithm is exponential in the number of state and input variables.

3.3.6 Dynamic programming method(dpm)

The dpm function solves the discretized version of the optimal control problem (3.24) – (3-29) using the dynamic programming algorithm. This section shows the syntax and commands for solving such problems. When solving discrete-time optimal control problems the dpm function is normally called using the structures in the dpm listed below and more details see the Appendix A – Appendix C.

- Problems

In the problem structure all necessary parameters that define the problem are given. The important parameters are the time step T_s of the model description, the problem length N , wind speed $w\{1\}$. Moreover, in the problem structure an optional cell array can be defined, which contains time variant information relevant for the problem description. For example, if the model explicitly depends on the time the cell array $T\{1\}$ would contain a time vector with N elements. The corresponding elements in these time-variant vectors are forwarded to the model function throughout the problem. The problem structure can also contain a starting time index where the forward simulation starts. This can be helpful when searching for a time optimal solution.

- State/Input Grids and Constraints

The grid structure `grd` contains all the information about the state (wind turbine rotor speed) and input grids (pitch angle and generator input torque) and constraints (upper and lower limit of states and control inputs). The `grd` structure is composed by cell arrays, where there is a cell for each state variable and each input variable. For example, for a problem with two state variables the `grd` structure contains `grd.X{1}`, `grd.X{2}`, `grd.Xn{1}.lo`, `grd.Xn{2}.lo`, and so on. The input grid is used in a similar way depending on the number of input variables of the problem.

- Options

The DP approach can be used for many different problem settings and the options structure defines how to use the algorithm. The `HideWaitbar` options decides if wait bars are shown or not when running the DP algorithm. The `SaveMap` option determines if the optimal cost-to-go is saved and returned. Note that the memory requirements increase when `SaveMap=1`. An important option is the `UseLine` option, which decides if the boundary line method, is used or not. The boundary line method is very useful for increasing the accuracy of problems with final state constraints.

- Output

The outputs of the `dpm` function are two structures, namely `res` and `dyn`. The `res` structure contains the results from the forward simulation of the model (wind turbine rotor trajectory) when applying the optimal control input map. The `dyn` structure is associated with the dynamic programming algorithm, the optimal cost-to-go (Energy capture from wind), and the optimal control input map (optimal trajectory of pitch angle and generator input torque). When the boundary line method is used the `dyn` structure also contains the boundary lines (with the states, inputs, and costs).

- Model

The equations describing the model (system) must be implemented in a correct format in order to be used with the `dpm` function. where the model input structure `inp` is generated by the `dpm`-function and contains the elements in appendix A. The structure `par` contains air density, diameter of wind turbine blades, the combined rotational inertia of the rotor, gearbox, generator and shafts, and gear ratio parameters necessary in the wind turbine model function. It is important that the model function preserves the size of the inputs to the outputs. Consequently, the elements `inp.X{.}`, `inp.U{.}` and the outputs `X{.}`, `C{.}`, and `I` must have the same size. The structure `signals` contain optimal state (turbine rotor speed) trajectory and optimal value of tip speed ratio, pitch angle, generator input torque, aerodynamic power coefficient (efficiency) and optimal value of captured energy based on define time and wind speed. These signals are stored during the forward simulation and returned in the `res` structure when calling the `dpm`-function.

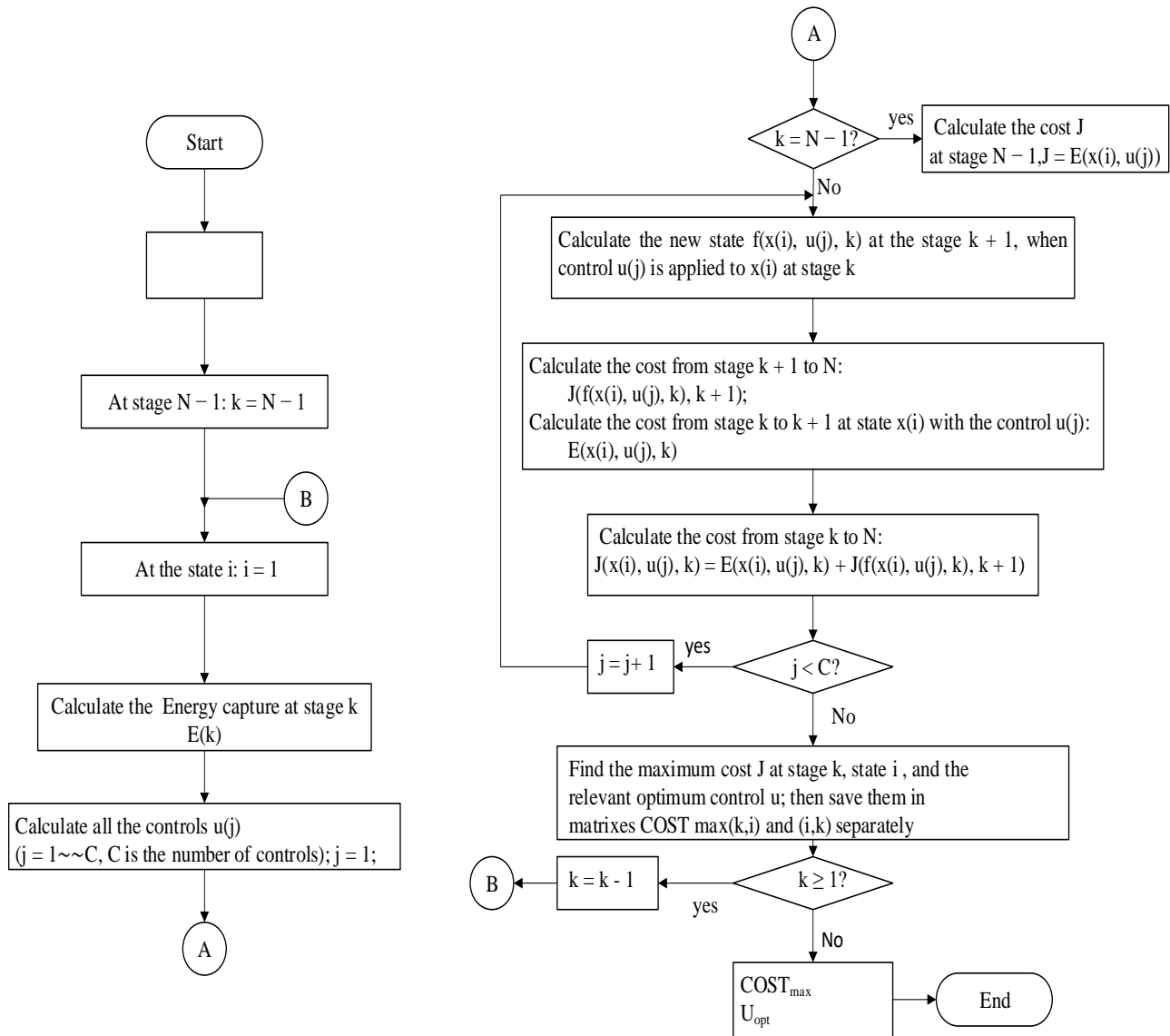


Figure 3.6: Recursive dynamic programming algorithm flow chart.

CHAPTER FOUR

Results and Discussion

4.1 Wind speed

The extraction of energy from wind highly depend on the speed of winds. It have cubic relation ship to the available wind speeds. In this Theses, piecewise step input and sine function wind speeds' are used for MATLAB simulation (see Appendix A).

4.2 Piecewise Step input

$$v_w(t) = 6 + 2.125 * \text{fix}\left(\frac{t-1}{15}\right) \quad (4-1)$$

Piecewise function defined wind speed was used to check the performance of optimal control by dynamic programming algorithm and standard torque control via feedback control of torque with respect to turbine rotor speed. For former control method, since it is optimal control, it has cost function to be maximized and constraints to be satisfied. And for the later control method, the aerodynamic power coefficient is set at maximum operating point and the pitch angle is set to zero degree. To maximize the captured energy, the aerodynamic power coefficient (C_p) has to be maximized. This can be done by forcing the system variables such as TSR (λ), pitch angle and generator input torque and turbine rotor speed to follow optimal trajectories.

Let the wind speed be between 6 m/s and 12.375 m/s and stay constant for 15 sec during the duration between 0 and 60 sec and let the discretization time step be 0.8 secondes. In figure 4.1, wind speed used as input, wind turbine rotor speed, tip-speed ratio, pitch angle, generator control torque, total energy capture and power generated are plotted for both STC and optimal controller.

The state variable (wind turbine rotor speed) depends on how much wind speed interreacts with the turbine blades. So, when wind speed is increasing the rotor speed also increases but it also depends on the radius of the blade. even if, radius has fixed value, the tip-speed ratio to be maximum, when the available wind speed dosn't correctly interact with the blade of the wind turbine. The state trajectory(ω_r) in the numerical optimization is bounded by upper and lower constraints. This can be simulated by forward dp algorithm. The optimal controller via dynamic programming works as follows:

First the optimal input policy will be compute using the backward recursive computation stage of the DP algorithm. This stage computes the inputs to the plant that will result in maximum energy capture while satisfying system constraints. These constraints are defined as shown in eq. (3-25) to (3-29). After the optimal policy input sequence are computed the algorithm simulates the system. In this stage the previously computed inputs will be applied for the specified amount of time to observe the system response.

Based on the intial turbine speed and wind speed, the TSR value starts from five and increases until wind speed changes. But further increase of TSR causes out of optimal point. This leads to change the angle of attack of wind in the turbine blades. When the wind speed is further increased, the TSR gets the optimal operation point. The blade angle also goes to its optimal value.

From this result, STC control method seems to converge to the optimal point better than the optimal one. However, the reason for this is the fact that the STC method computation is based on only the global optimal point of the pitch angel and C_p . Thus, this method will not be much useful when wind speed is varying continuously. After the wind speed gets the value above 6 m/s, numerical optimal control mechanism has more performance than STC control method.

Aerodynamic power coefficient measures how much of wind energy is converted to mechanical energy. The optimal value of this variable according to the wind speed located in this figure also. It is depends on the optimal value of Tip-speed ratio, generator torque, pitch angele and optimal state trajectory. From the simulation result, numerical optimization of this efficiency are greater than standard torque control.

Generator torque, being one of the plant inputs, also affects computation of the optimal C_p value. Because this input torque is inversely related to turbine rotor speed. When the turbine speed has small change the generator input torque also has to change. Using equation (3-14), the required generator torque can be easily calculated. The result of the calculation in both optimal controller and standard torque control, used as input to aerodynamic power cofficent to maximize the energy capture and power generated with respect to the availabel wind speed. From the figure, The numerical way of manipulating this torque is highly sensitive to small change of turbine speed.

During extraction of energy from wind, if there is the sudden change of torque, it leads mechanical damage. Even if it is difficult to eliminate all changes of torque that cause fatigue, but this can be

minimize by using optimal control method. Since, it is numerical and evaluate each fraction of torque with respect to turbine rotor speed, its constraint and related wind turbine system variables.

From figure it can be observed that the total captured energy is using the optimal numerical method is larger than that of the STC method. This is the result of the numerical method being superior at finding the optimal point for every value of the wind speed in contrast to the STC method which assumes the global optimal point only. Above 11 m/s, the numerical optimal control and standard torque control have approximately the similar performance. But due to the state constraint the numerical way of optimization tries to achieve the final state limits. That is why the DPM type state have greater value than STC.

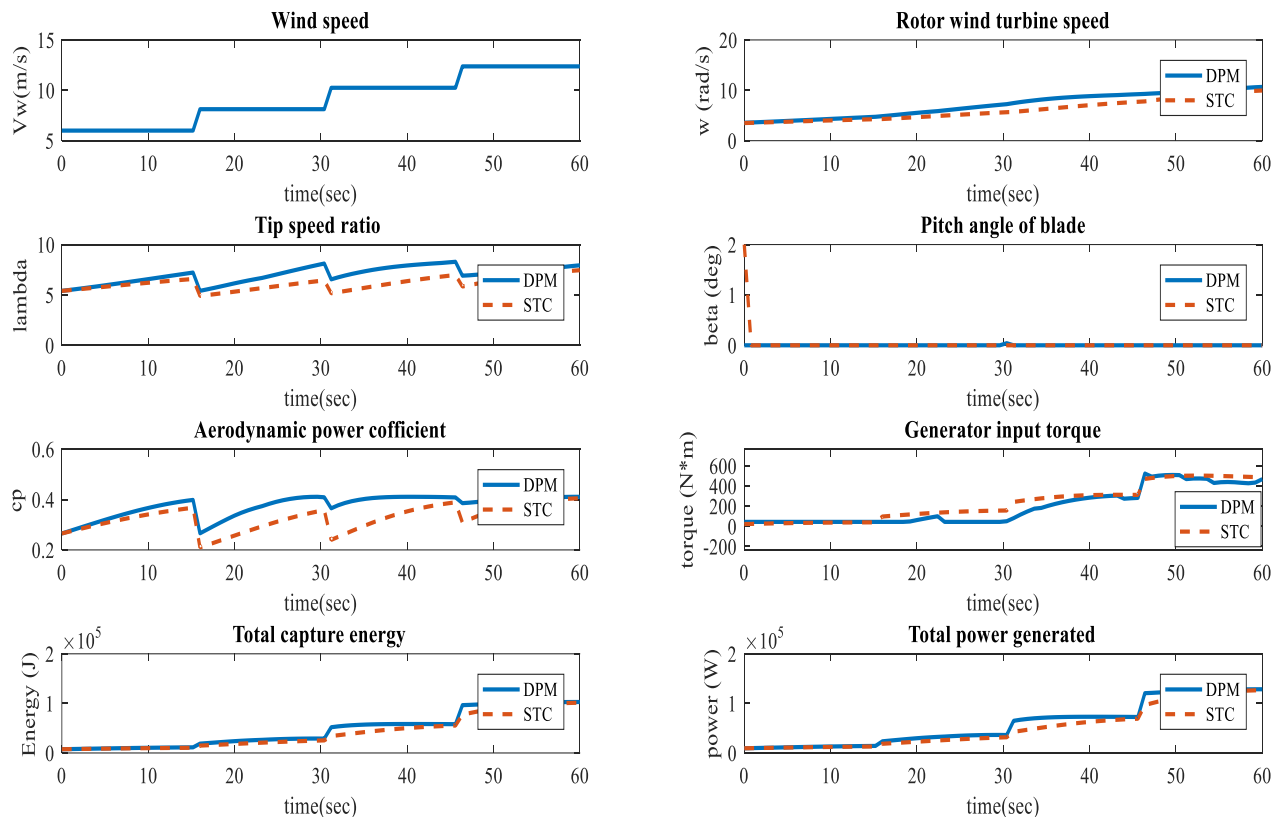


Figure 4.1: DPM and STC wind energy capture using piecewise wind speed

Generally, it is clear that the optimal control method gives better result than the STC method. Even if it is uncommon that the variation of natural wind speed behavior will be described in step response, the capture energy from the wind is more optimized by numerical way of optimization than feedback control of torque. Optimal control method uses small number of elements in the

state grid (turbine rotor speed), and relatively a greater number of elements in the control inputs grid (pitch angle and generator input torque) based on piecewise step input of wind speed of the system. But the torque and pitch angle are depending on the discretization step of rotor turbine speed, to track optimal trajectory. Therefore, a more realistic wind speed model based on frequency data from a typical wind variation is used to observe the behavior of the controller in actual real-world situations.

4.3 Random wind speed generation

Due to its irregular nature of the wind speed, the wind generation has many fluctuations. In this thesis, the applied wind speed is approximated in to equation (4.1) using sine functions through trial and error (see Appendix C for MATLAB syntax)

$$\begin{aligned}
 v_w(t) = & 10 + 0.87 \sin\left(\frac{2}{25}t\right) + 0.5 \sin\left(\frac{2}{30}t\right) - 0.625 \sin\left(\frac{2}{65}t\right) \\
 & + 0.75 \sin\left(\frac{2}{135}t\right) + 0.65 \sin\left(\frac{2}{235}t\right) \\
 & + 0.125 \sin\left(\frac{2}{575}t\right)
 \end{aligned} \tag{4-2}$$

Wind speed varies between 8 m/s up to 12.34 m/s and the simulation duration is 800 sec with time step time is 8 sec. Rotor turbine speed in figure 4.2 is generated from the sinusoidal windspeed. Since wind speed is varying continuously, the turbine speed also varies although it is limited by constraints and number of grid elements. The TSR is directly related to wind turbine rotor speed and inversely relate to wind speed. By combing this two wind turbine system variables, the TSR can be evaluated as shown below in the some figure. For maximizing wind energy capture, the tip speed ratio values follow optimal path to relate turbine rotor speed and the available wind speed.

As shown in figure 3.1, the optimal value of TSR that help to capture maximum wind energy is between 7 up to 9 amounts of value. From the figure below the TSR value is located between around 7.8 up to 8.5, this value indicates the incoming wind speed mostly interact with turbine blades. As result of this, the pitch angle is also at optimal value of angle of attack, i.e. at zero degree. Due to these two most important variables, used to formulate aerodynamic nature of the blades.

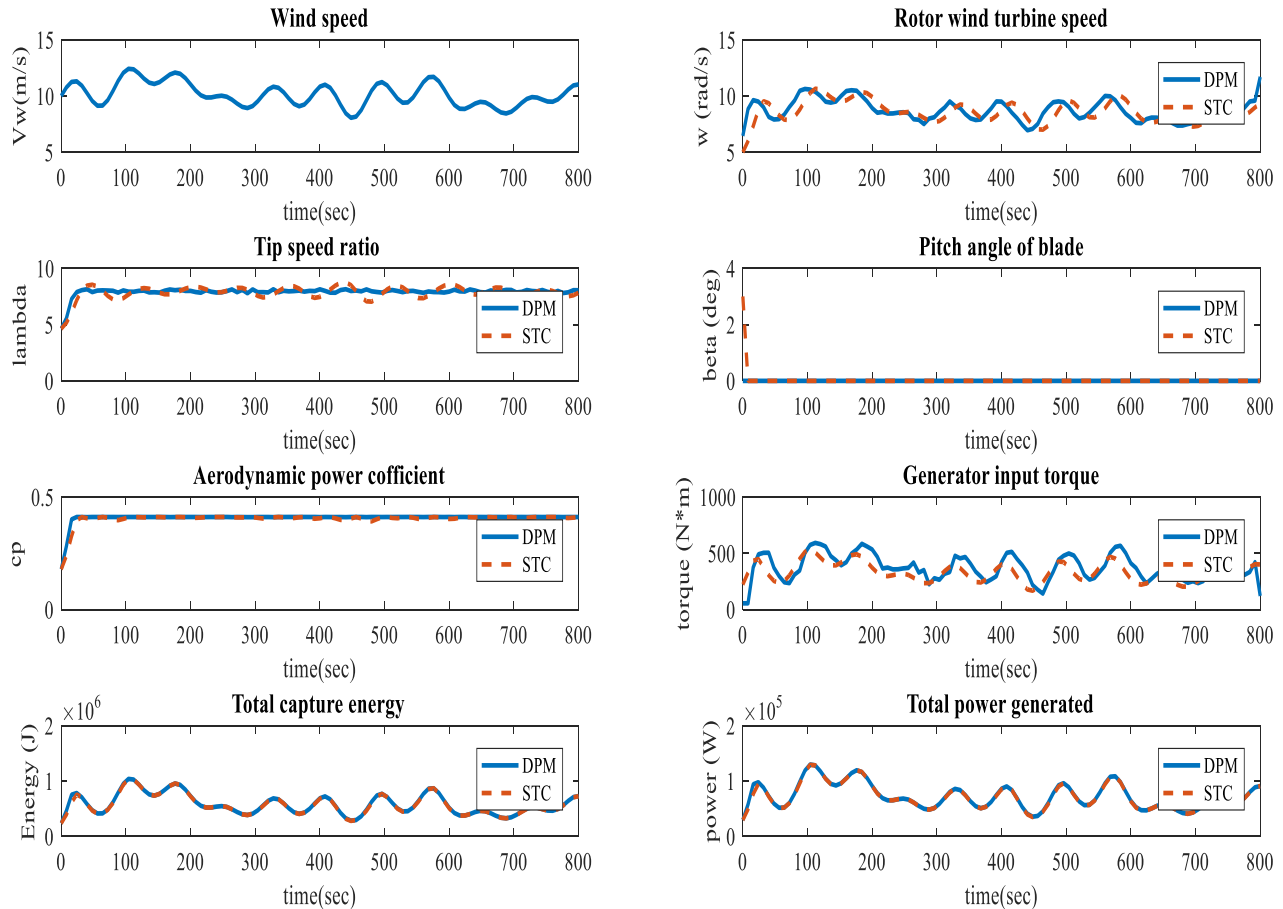


Figure 4.2: DPM and STC wind energy capture using random generation wind speed

The aerodynamic coefficient used to measure how much wind energy is converted to mechanical energy. So, maximization of aerodynamic coefficient is directly maximizing wind energy capture. This maximum value of C_p is achieved when TSR and pitch angle has its optimal value. From the figure, both values are located, but numerical control method gives better result than standard torque control.

Numerical optimization by DPM algorithm is clearly superior to STC but it requires more computational time than STC. This is due to large number of state grid and control input grids. Since it is more applicable for dynamic system including their nonlinear model and constraints, this way of optimization or control method in wind turbine system is more efficient than torque feedback control in terms of turbine rotor speed.

all necessary wind turbine system elements, wind speed, turbine rotor speed, TSR, pitch angle, generator input torque, and aerodynamic power coefficient are located in figure 4.2. This result leads to maximize wind energy capture from available wind speed. The figure above energy extraction and power generated have the from wind. Because, It has the cubic relation-ship to the available wind speed.

Generally, from the result, the numerical algorithm of dynamic programming method evaluation of dynamic model of nonlinear wind turbine system has better performance. Additionally, such numerical algorithm is more applicable for dynamic, complex nonlinear systems, with constraints. The other benefit from numerical algorithm is the fact that it can be used to optimize the system globally. Even if, it requires more computational time, it gives attractive result more than standard torque control. Standard torque control method has easy implementation by assuming aerodynamic power coefficient is at global maximum value, and angle of attack is at zero degree, but due to irregular nature of wind, this assumption is no further applicable to capture wind energy and to generated maximum power. This is reason STC has less performance than DPM method.

CHAPTER FIVE

Conclusion and Recommendation

5.1 Conclusion

A wind energy conversion system (WECS) transforms wind kinetic energy to mechanical energy by using rotor blades. This is done by the blades mounted on the rotor hub. The rotor hub is installed on the main shaft, also known as the low-speed shaft. The mechanical energy is transmitted through the drive train (shafts, bearings, and gearbox) to the generator.

In this Theses work, optimal controller design by using numerical algorithm for HAWT orientation wind energy conversion system is investigated. Since, WT has complex non-linear dynamic system and the wind speed is determined by piecewise step input and sine function, Deterministic dynamic programming of numerical algorithm has to be used. This type of numerical algorithm solves continuous optimal control problem by converting it to discrete time system form. Additionally, dynamic programming algorithm is applicable for highly constrained and nonlinear system model, and it is used to optimize the cost function globally.

The optimal values of wind turbine variables such as turbine rotor speed trajectory, tip speed ratio, pitch angle, generator input torque, and aerodynamic efficiency are computed by preceding backward in time. From the simulation result, all wind turbine variables for both piecewise step and sine function-based input gives optimal values. For piecewise step input method, the pitch angle optimal value shows little difference from the optimal point due to small element of state grid. However, for try and error (sine function) input method, all variables of the system have the values to satisfy the objective.

Generally from the simulation result the system have 7.5 up to 8.5 tip speed ratio optimal value and the aerodynamic efficiency mostly has 0.411 efficiency value. And also the optimal controller captured 13.841% more energy and power than STC for the piecewise step input wind speed. For the randomly generated wind speed pattern, the optimal controller captured 1.15% more energy and power than the STC. The lower percentage improvement in this case is due to the limited range of the wind speed value given for the simulation.

5.2 Recommendation

In this thesis, the study of wind energy focuses on one mass model of wind turbine system and conversion of energy from kinetic energy of wind to mechanical energy. But, for future work, all losses, during wind energy conversion, two mass and FAST model and electrical energy conversion system also included.

In this work, the wind speed used is considered as measured directly through an expensive anemometer due to time to analysis or estimate the wind speeds from other parameters of the turbine. However, for a future work it is recommended to estimate the wind speed in order to avoid the expensive cost of a mechanical sensor which has an advantage to minimizing the initial cost during implementation

Also, in this thesis, among four region of wind energy conversion system, region two are studied, however, by considering all region of operation, it is recommended to increase total energy capture using optimal controller design by using dynamic programming.

In this thesis, the applied pitch angle control strategy is common for all the three blades. However, by considering the model of all the three blades independently, it is recommended to use individual pitch control method along with the optimal controller to improve the overall performance of the system. In addition to this, this thesis work only shows the effectiveness of the proposed system only in MATLAB/Simulink computer simulation. But it is recommended that to show the effectiveness again by implementing the real system for future works.

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Appendices

#Parameters of wind turbine system.

Rated power, P_{rated}	100KW
Rotor moment of inertia, J_r	$2.6 \times 10^4 \text{ Kg.m}^2$
Rotor diameter, D_r	18 m
Gear ratio, G_r	21.5858
Maximum turbine rotor speed, $(\omega_r)_{\text{max}}$	12 rad/sec
Minimum turbine rotor speed, $(\omega_g)_{\text{min}}$	2.75 rad/sec
Maximum blade pitch angle, β_{max}	25 degree
Minimum blade pitch angle, β_{min}	0 degree
Maximum Generator input torque, $(\tau_g)_{\text{max}}$	1500 Nm
Minimum Generator input torque, $(\tau_g)_{\text{min}}$	0Nm
Global maximum value of C_p $(C_p)_{\text{max}}$	0.4212
Value of λ corresponding to $(C_p)_{\text{max}}$, λ^*	8.0
Value of β corresponding to $(C_p)_{\text{max}}$, β^*	0 degree
Rated wind speed	12.5 m/s

Appendix A

General description of dynamic programming.

PROBLEM-STRUCTURE (PRB)

Ts time step (is passed to the model function).

N number of time steps in problem (integer that defines the problem length).

N0 (optional) start time index (only used in forward simulation).

W{.} (optional) vectors with length N containing time variant data for the model.

GRID-STRUCTURE (GRD)

Nx{.} number of grid points in state grid

Xn{.}.lo lower limits for each state (vector for time-variant or scalar for fixed)

Xn{.}.hi upper limits for each state (vector for time-variant or scalar for fixed)

XN{.}.lo final state lower constraints

XN{.}.hi final state upper constraints

X0{.} initial value (only used in forward sim)

Nu{.} number of grid points in input grid

Un{.}.lo upper limits for each input (vector for time variant or scalar for fixed)

Un{.}.hi upper limits for each input (vector for time variant or scalar for fixed)

OPTIONS-STRUCTURE (OPTIONS)

HideWaitbar hide waitbars (0/1)

Warnings show warnings (0/1)

SaveMap save cost-to-go map (0/1)

UseLine use boundary line method (0/1)

FixedGrid (used if UseLine=1) using the original grid as

specified in grd or adjust the grid to the boundary lines (0/1)

Iter (used if UseLine=1) maximum number of iterations when inverting model

Tol (used if UseLine=1) minimum tolerance when inverting model

InfCost a large cost for infeasible states (I=1)

Minimize minimizing (or maximizing) cost function (0/1) default is minimizing

InputType string with the same number of characters as number of inputs. Contains the character 'c' if input is continuous or 'd' if discrete (default is all continuous).

$gN\{1\}$ (optional) Cost matrix at the final time (must be of size($\text{options.gN}\{1\}$) =
[$\text{grd.Nx}\{1\}$ $\text{grd.Nx}\{2\}$... $\text{grd.Nx}\{. \}$])

DP OUTPUT-STRUCTURE (DYN)

$B.\text{hi } X_o, U_o\{. \}, J_o$ contains the cost, input, and state for the upper boundary line

$B.\text{lo } X_o, U_o\{. \}, J_o$ contains the cost, input, and state for the lower boundary line

$J_o\{. . . \}$ optimal cost-to-go (indexed by input number and time index)

$U_o\{. . . \}$ optimal control input (indexed by input number and time index)

RESULTS-STRUCTURE (RES)

$X\{. \}$ - state trajectories

$C\{. \}$ -cost trajectory

I - infeasible vector (problem is not solved if nonzero elements)

signals - structure containing all the signals that were saved in the model function

INPUT-STRUCTURE (INP)

$X\{. \}$ current states ($n+m$ dimensional matrix form depending on the number of inputs and state variables)

$U\{. \}$ current inputs ($n+m$ dimensional matrix form depending on the number of inputs and state variables)

$W\{. \}$ current time-variant data (scalar)

T_s time step

MODEL OUTPUTS

$X\{. \}$ resulting states after applying $\text{inp.U}\{. \}$ at $\text{inp.X}\{. \}$ (same size as $\text{inp.X}\{. \}$)

$C\{. \}$ resulting cost of applying $\text{inp.U}\{. \}$ at $\text{inp.X}\{. \}$ (same size as $\text{inp.X}\{. \}$)

I set with infeasible combinations (feasible=0, infeasible=1) (same size as $\text{inp.X}\{. \}$)

signals structure with user defined signals (same size as $\text{inp.X}\{. \}$)

Appendix B

The system model function and cost function

```
function [X, C, I, signals] = turb(inp,par )

% inp.X{i} states
% inp.U{i} inputs
% inp.W{i} disturbances (as defined in dis-struct)
% inp.Ts    time step
% par      struct including user defined parameters
Dr = 18.52;
Jr = 2.6e4;
Gr = 21.5858;
rho_air = 1.225;
A = pi*(Dr.^2)/4;
lam = (inp.X{1}.*Dr)./(2*inp.W{1});
coff = pi*rho_air*Dr.^5./(64.*lam.^3);
% state update (out.X{i} must be set within model function)
c_p = 0.5.*(116.*(1./(lam+0.08.*inp.U{2})-
0.035./(inp.U{2}.^3+1))-0.4.*inp.U{2}-5).*exp(-
21.*(1./(lam+0.08.*inp.U{2})-0.035./(inp.U{2}.^3+1)));
func = coff.*c_p;
X{1} = (inp.Ts.*(func.*(inp.X{1}.^2)- Gr.*inp.U{1})./Jr )+
inp.X{1};

% cost (out.C{1} must be set within model function)
C{1} = 0.5.*rho_air.*A.*inp.Ts.*c_p.*(inp.W{1}.^3);
% Infeasibility (out.I [zero=feasible/one=infeasible] must
be set within model function)
% The cost of these state-input combinations will be set to
I = 0;
% store signals (store any other signals in the out struct)
signals.U{1} = inp.U{1};
```

```
signals.U{2} = inp.U{2};  
signals.cp = func./coff;  
signals.lam = lam;
```

Appendix C

The main DPM and STC syntax for simulation

```
t = 0:0.8:60;  
% create grid  
grd.Nx{1} = 4;  
grd.Xn{1}.lo = 5;  
grd.Xn{1}.hi = 11.94;  
  
grd.Nu{1} = 101;  
grd.Un{1}.lo = 0;  
grd.Un{1}.hi = 1500;  
  
grd.Nu{2} = 26;  
grd.Un{2}.lo = 0;  
grd.Un{2}.hi = 25;  
  
% set initial state  
grd.X0{1} = 4;  
  
% set final state constraints  
grd.XN{1}.hi = 12;  
grd.XN{1}.lo = 11.94;  
% define problem  
clear prb  
prb.Ts = 0.8;  
prb.N = 60*1/prb.Ts+1;  
prb.W{1} = 6+2.5.*fix((t-1)/15);
```

```
% set options
options = dpm();
options.Minimize = 0;
options.BoundaryMethod = 'Line'; % also possible: 'none' or
'LevelSet';
if strcmp(options.BoundaryMethod,'Line')
    options.FixedGrid = 0;
    options.Iter = 10;
    options.Tol = 1e-6;
end
[res,dyn] = dpm(@turb,[],grd,prb,options);
%% standard torque control
t=0:0.8:60;
sz = size(t);
w_r = ones(size(t));
bet = ones(size(t));
v_w = 6+2.5.*fix((t-1)/15);
w_r(1) = 4;
bet(1) = 2;
R = 9.26;
K = 0.5;
Jr = 2.6e4;
rho =1.225;
Gr = 21.5858;
Ts =0.8;
for k=1:length(t)-1
    lambda = R*w_r(k)*(1./v_w(k));
    if lambda<=2.6
        B = 25;
        cp_max = 0.0547;
```

```

        l_star = 2.6;
        bet(k+1) = (B-bet(k))*K+bet(k);
elseif lambda>2.6&&lambda<=3.4
        B = 20;
        cp_max = 0.0807;
        l_star = 3.4;
        bet(k+1) = (B-bet(k))*K+bet(k);
elseif lambda>3.4&&lambda<=9
        B = 0;
        cp_max = 0.4244;
        l_star = 8;
        bet(k+1) = B;
elseif lambda>9&&lambda<=10.4
        B = 1;
        cp_max = 0.3935;
        l_star = 9.2;
        bet(k+1) = (B-bet(k))*K+bet(k);
else
        B = 2;
        cp_max = 0.3599;
        l_star = 10.65;
        bet(k+1) = (B-bet(k))*K+bet(k);
end
li = 1./(lambda+0.08*B)-0.035./(B^3+1);
cp = 0.5.*(116.*li - 0.4*B - 5).*exp(-21.*li);
w_r(k+1) =
(0.5*rho*pi*(R^5)*(w_r(k).^2))*(cp./lambda.^3-
cp_max/l_star^3)/Jr+w_r(k);
end
lam = R*w_r./v_w;
li = 1./(lam+0.08*B)-0.035./(B^3+1);

```

```

Cp = 0.5.*(116.*li - 0.4*B - 5).*exp(-21.*li);
T_aero = (0.5*rho*pi*Cp*R^2).*(v_w.^3)./w_r;
T_g = zeros(size(t));
for m=1:length(t)-1
T_g = (0.5*rho*pi*Cp*R^2.*v_w.^3)./(Gr.*w_r) - (w_r(m+1)-
w_r(m)).*Jr./(Ts.*Gr);
end
E_c = Ts.*0.5*rho*pi*(R^2).*(v_w).^3.*Cp;

```

Appendix D

#Cp versus tip speed ratio

```

B = [0:3 5:5:15];
R = 9.26;
L = 0:0.5:24;
cp = zeros(length(L),length(B));
hold on
for i=1:length(B)
li = 1./(L+0.08*B(i))-0.035./(B(i)^3+1);
cp(:,i) = 0.5167.*(116.*li - 0.4*B(i) - 5).*exp(-
21.*li);
plot(L,cp(:,i));
end
ylim([0 0.6])
maxi = max(cp,[],2);
plot(L,maxi, '--', 'LineWidth',2);
ylabel('Cp')
xlabel('TSR')
title('Aerodynamic efficiency')
text(8,0.4246,'B = 0 deg')
text(8,0.3843,'B = 1 deg')

```

```
text(8,0.3406,'B = 2 deg')
```

Appendix E

```
#Mechanical energy versus rotor speed
```

```
Cp=zeros();  
p=1.225;  
R=9.26;  
j=input('no of Vw')  
i=input('enter the number of d/t pitch angles')  
for k=1:j  
V=input('enter the value of wind speed, Vw')  
for j=1:i  
B=input('enter the value of pitch angle B')  
end  
for w=1:1:70;  
L=w*R/V;  
I=1/((1/(L+0.08*B))-0.035/(B^3+1));  
Cp(1,w)=(0.5176*((116/I)-0.4*B-5)*exp(-21/I));  
Pm(1,w)=0.5*p*pi*R^2*Cp(1,w)*(V^3);  
end  
plot(Pm)  
ylim([0 1.2*10^5]);  
hold on  
title(' Mechanical Energy') end
```

Backward loop of DPM

```

n = dis.N+1;
while n > 1
    n = n-1;
    previous_grd = current_grd;
    x_size = nan(1,length(grd.Nx));
    u_size = nan(1,length(grd.Nu));
    for i=1:length(grd.Nx)
        if options.UseLine && i==1 && ~options.FixedGrid
            if length(grd.Nx)==1
                current_grd.X{i} =
linspace(dyn.B.lo.Xo(n),dyn.B.hi.Xo(n),grd.Nx{i}(n));
            else
                current_grd.X{i} =
linspace(min(min(dyn.B.lo.Xo(1, :, n:n+1))),max(min(dyn.B.hi.
Xo(1, :, n:n+1))),grd.Nx{i}(n));
            end
            elseif ~options.CalcLine || i~=1
                current_grd.X{i} =
linspace(grd.Xn{i}.lo(n),grd.Xn{i}.hi(n),grd.Nx{i}(n));
            end
            x_size(i) = grd.Nx{i}(n);
        end
        for i=1:length(grd.Nu)
            current_grd.U{i} =
linspace(grd.Un{i}.lo(n),grd.Un{i}.hi(n),grd.Nu{i}(n));
            u_size(i) = grd.Nu{i}(n);
        end
    end
end

```

Forward simulation of DPM

```

for n=dis.N0:dis.N
    for i=1:length(grd.Nx)
        if options.UseLine && length(grd.Nx)==1 && i==1 &&
~options.FixedGrid
            current_grd.X{i} =
linspace(dyn.B.lo.Xo(n),dyn.B.hi.Xo(n),grd.Nx{i}(n))';
            elseif options.UseLine && ~options.FixedGrid
                current_grd.X{i} =
linspace(min(dyn.B.lo.Xo(:,n)),max(dyn.B.hi.Xo(:,n)),grd.Nx
{i}(n))';
            else
                current_grd.X{i} =
linspace(grd.Xn{i}.lo(n),grd.Xn{i}.hi(n),grd.Nx{i}(n))';
            end
        end
    end
    for i=1:length(grd.Nu)
        current_grd.U{i} =
linspace(grd.Un{i}.lo(n),grd.Un{i}.hi(n),grd.Nu{i}(n))';
    end
end

```