PERTURB AND OBSERVE BASED MAXIMUM POWER POINT TRACKING OF WIND POWER SYSTEM

By

Murad Hossain
20261006

A project submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Masters of Engineering

Department of Electrical and Electronic Engineering
Brac University
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Declaration

It is hereby declared that

1. The Project report submitted is my own original work while completing degree at Brac University.
2. The report does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project report does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

Student's Full Name & Signature:

Murad Hossain
ID: 20261006

Approval

The project titled "Perturb and Observe based maximum power point tracking of wind power system" submitted by

Murad Hossain (20261006)

of Spring, 2022 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Masters of Electrical and Electronic Engineering on 16th May 2023.

Examining Committee:

Supervisor:
(Chair)

Prof. Dr. Abu Hamed M. Abdur Rahim
Professor
Department of Electrical and Electronic Engineering
BRAC University

Internal Expert Examiner:
(Member)

Dr. A.S. Nazmul Huda
Associate Professor
Department of Electrical and Electronic Engineering
BRAC University

Departmental Head:
(Ex-officio)

Dr. Md. Mosaddequr Rahman
Professor and Chairperson
Department of Electrical and Electronic Engineering
BRAC University

Ethics Statement

This is to certify that this Project titled "Perturb & Observe Based Maximum Power Point Tracking of Wind Power System" is the result of my study for partially fulfilling the Master of Engineering in Electrical and Electronic Engineering degree, under the supervision of Dr. Abu Hamed M. Abdur Rahim, Professor, Department of Electrical and Electronic Engineering, Brac University. I confirm that the content of this work has been checked for plagiarism, and the similarity index is 20%, which falls within an acceptable range. Furthermore, no part of this work has been submitted elsewhere partially or fully, for the award of any other degree or diploma.

Abstract

Maximum power obtainable from a wind generator depends on the wind speeds. So, for varying wind speed conditions, tracking the maximum power point is essential for efficient power transfer to the grid. There are several gradient based search methods which are employed in maximum power point tracking (MPPT) of the wind generator. There are steepest descent method, hill climbing method, etc. The Perturb and Observe (P&O) method is one of the simple gradient techniques, which have been used in this work. The perturb and observe (P&O) method identifies the maximum power point (MPP) by adjusting the rotor speed of a wind turbine. The algorithm works by perturbing the rotor speed of the wind turbine and observing the change of power output for a certain wind speed. If the power output increases, the algorithm will continue to perturb the rotor speed in the same direction until the power output decreases. At this point, the algorithm changes direction and starts to perturb the rotor speed in the opposite direction. This process is repeated continuously, and the rotor speed is adjusted as necessary to track the maximum power point. Also, the corresponding rotor and power errors are measured by calculating differences between their estimate and actual values. The proposed algorithm entire process has been simulated by using MATLAB and tested under varying wind speed conditions. The simulation results show that the rotor speed followed the change in wind speed properly, indicating the effectiveness of the algorithm in tracking maximum power output. Also, the rotor speed and corresponding power errors have been measured, which is to very negligible errors. So, this algorithm is utilized to obtain the maximum power point (MPP) with easy computational effort.

Keywords: maximum power point tracking, perturb & observe method, gradient direction, wind generator.

بسم الله الرحمن الرحيم

Dedicated to

My Dearest Mother and Father

And

My respected Teachers

Acknowledgement

I would like to express my deepest appreciation to provide me with the possibility to complete this report. Special gratitude is given to the final year project Supervisor, I would to thank my research and academic supervisor Prof. Dr. Abu Hamed Abdur Rahim sir for his continuous supervision, advice, and guidance from the very beginning of this research. He taught me how to think, analyze and solve problems independently in a professional and friendly manner. Acknowledgments are due to Brac University which gave me the opportunity to pursue a graduate degree and also for all the support I received in carrying out this project research.

Last, of all, I would like to show my deepest gratitude and respect to my family, especially my parents, the ones to whom I owe all the success in my life. No words can express my gratitude to them, but I pray to Allah to bless them and reward them. Any success in my life so far is mostly charged to them and consequently, any success in the future will have their signature as well.

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List of Acronyms

DC	Directional Current
AC	Alternating Current
PMSG	Permanent Magnet Synchronous Generator
P_m	Turbine mechanical power
V_w	Wind speed
ρ	Air density
A	Wind turbine blades swept area
C_p	Coefficient of power
λ	Tip speed ratio
λ_{opt}	Optimum tip speed ratio
β	Blade pitch angle
R	Radius of wind turbine rotor
ω	Mechanical angular velocity of the wind turbine rotor
ω_{opt}	Optimum rotor speed
MPP	Maximum Power Point
WT	Wind Turbine
RE	Renewable Energy
RES	Renewable Energy Source
DG	Distributed Generation
C_{pmax}	Maximum power coefficient
ω_r	Rotor Speed
ω^*	Rotor speed corresponding to the maximum power
HCS	Hill Climbing Search
SD	Steepest Descent
P&O	Perturb and Observe
MSE	Mean Squared Error
P_{max}	Maximum power
TSR	Tip Speed Ratio

Chapter 1

INTRODUCTION

1.1 Background

Bangladesh has been facing a severe electricity crisis due to the increasing demand for energy in recent times. Renewable energy, generated from natural sources like as wind, solar, hydropower, geothermal, and biomass, has emerged as a potential solution. Wind power has become an increasingly important source of renewable energy, especially since government bodies have recommended its use to reduce fuel consumption.

Bangladesh is experiencing a continuous increase in power demand, but the eastern region's power sector heavily relies on fossil fuels due to inadequate gas supply. As a solution, the government has established quick rental projects that mostly rely on diesel and furnace oil, exacerbating the dependence on non-renewable sources. Moreover, the government provides significant subsidies to the energy sector. Given the present situation, transitioning to renewable energy sources appears to be a feasible option for Bangladesh. Renewable sources offer not only cost free fuel but also environmentally friendly emissions. Among all available renewable sources, wind power stands out as the most promising.

There is now a significant social shift to reduce the demand for fossil fuels as renewable energy sources. Indeed, much research on various energy sources is being conducted, with wind energy being one of the most developed choices. Wind power, in particular, is the world's energy source with the fastest annual growth rate - 30% - and a penetration of 12% of global electricity consumption is expected by 2020. In reality, wind energy is a huge source of power worldwide; it has been calculated that utilizing 10% of the entire quantity of accessible wind power is sufficient to meet the world's electrical demands [1]. In 2013, China (91424 MW), USA (61091 MW), Germany (34250 MW), Spain (22959 MW), and India (20150 MW) are the top five nations harvesting wind energy using windmills [2]. Bangladesh is situated between the latitudes of 20.30 and 26.38 degrees North and the longitudes of 88.04 and 92.44 degrees East [3]. It extends for over 700 kilometers [4]. According to CWET India's analysis of upper air data, Bangladesh's wind energy supply is insufficient for grid-connected wind farms [5].

1.2 Wind energy

In recent years, the usage of renewable energy sources has rapidly expanded. Natural resources including wind, sun, hydropower, geothermal, and biomass are used to produce renewable energy. Wind energy is one of the most important renewable energy sources, and wind turbines work under a variety of wind conditions, all of which have an influence on how well they function. The maximum power point needs to be accurately tracked in order to maximize power output.

Renewable energy sources (RES) can be a key component of the energy mix to solve the issues related to the production of electricity from fossil fuels. Also, the use of renewable energy sources (RES) in power generation is expanding as a result of the regulation of electricity markets and the growth of distributed generation (DG) systems. The most promising RES is wind energy, and wind turbine systems offer a direct way to transform wind energy into electrical energy without polluting the environment [6, 7].

Wind power systems have reduced initial, replacement, and ongoing expenses than other renewable energy sources like solar power. Wind energy systems also have higher energy conversion efficiencies. Due to its long-term advantages and government incentives to promote the use of renewable energy sources, several nations have created various wind energy systems despite the unpredictable nature of wind speed (RES). Researchers are focusing on a number of topics linked to wind systems, such as wind generator modelling, MPPT algorithms, power electrical converters used for grid integration, and their effects on the power system, as wind energy deployment continues to expand quickly. In isolated or hilly places that are not wired for electricity, wind turbines are often constructed [7].

Grid-connected wind systems, which may be installed onshore, offshore, along roads, and in open areas with significant wind potential, now dominate the power market and provide energy to load demand and the electric grid [8].

The variable nature of wind speed, however, makes large-scale wind energy integration to the electrical energy grid potentially harmful to the transmission and distribution network and other associated generators. Particularly during disturbances, this might compromise the electrical system's safety and stability. Hence, to examine and assess the influence of wind energy on the utilities power system, an accurate wind generator model that can simulate its output characteristics under various wind conditions is needed [9].

1.3 Maximum power point tracking (MPPT)

The effectiveness of a wind power system is dependent on the efficiency of the turbines, converters, and MPPT algorithm. Yet, since it depends on the technology already in use, improving the efficiency of turbines and converters is a challenging undertaking. Updated components can improve efficiency, but they also drastically raise installation costs. A MPPT algorithm that tracks the maximum power point (MPP) of the turbine given wind speed and direction has been created to enhance the power output of wind turbines. It is simpler and less expensive to increase efficiency using an MPPT algorithm, and it may be added to a wind system that is already up and running. The MPPT controller is essential for increasing the effectiveness of the wind power conversion system, and MPPT algorithms are required to ensure that turbines run as efficiently as possible. There are several MPPT methods, including steepest-descent and hill climbing [10].

The P&O based MPPT in wind generating systems is improved using the steepest descent (SD) algorithm, a gradient based optimization method. The operating point is changed by the SD algorithm in accordance with the direction of the objective function's steepest slope, which is the wind turbine's power production. For wind turbines, the P&O method, a less complicated version of the hill climbing method, is a reasonable option [2].

The hill climbing method is straightforward and straightforward, repeatedly adjusting the generator speed until it achieves the MPP. The hill climbing algorithm has significant drawbacks, especially in terms of how sensitive it is to variations in wind speed. The algorithm may fluctuate about the MPP due to changes in wind speed, which would decrease power output [6]. In order to improve the power output of the wind turbine by tracking and sustaining the maximum power point (MPP) under varying wind conditions, the P&O method is also often employed in wind turbine systems. This method is easy to use, responds quickly, and finds the MPP with a high level of precision. The fundamental tenet of this MPPT algorithm is to alter the system's optimal position and track variations in output power. The operating point can be altered in the direction of the MPP based on variations in output power. Even until the necessary convergence is achieved, the procedure must be continued [7].

1.4 Project objectives

The main objective of the study is to develop a Maximum Power Point Tracking (MPPT) algorithm for a wind turbine based on perturb and observe (P&O) method. The proposed algorithm seeks to increase the efficiency of wind power systems by accurately measuring the optimal power point of the wind turbine under different wind speed conditions. The P&O algorithm's effects on the effectiveness and reliability of the wind power system will be the focus of this research. Wind turbines must be operated at the optimum position on their (P-ω) characteristic curve for the specified wind speeds in order to generate the optimum power.

The following are the major objectives that are focused on this project:

1. To develop a P&O-based MPPT algorithm of a wind power system for variable wind speed.
2. To analyze the performance of the P&O algorithm in terms of tracking MPP and enhancing the efficiency of the wind power system.
3. To determine the optimum power and corresponding rotor speed using the P&O-based MPPT algorithm.
4. To determine the tracking error of rotor speed and corresponding power.

1.5 Report organization

The following outline is used to structure the project report:

Chapter-2 contains the brief description of wind turbine and literature review on maximum power point tracking (MPPT) method.

Chapter-3 contains the brief description of the theory of wind turbine and maximum power point tracking (MPPT) method.

Chapter-4 explores the methodology of the steepest ascent/descent, hill climbing, and perturb and observe methods for the MPPT algorithm based on wind turbines.

Chapter-5 presents the simulation results of the system under variable wind speeds. Various graphical plots are presented to show the competence of the proposed Perturb & observe (P&O) based MPPT controller. The MATLAB program simulation is used to verify the effectiveness and accuracy of the proposed algorithm.

Finally, chapter-6 is summarized the project work and its conclusions with suggestions for future work.

Chapter 2

THEORY OF WIND TURBINE TECHNOLOGY

2.1 Introduction

Wind power systems are widely preferred for producing renewable energy in remote locations, primarily due to their cost-effective and eco-friendly nature compared to fossil fuel-based systems. Small wind power system modeling and optimization have been the subject of several research articles [11]. One of the most reliable and efficient renewable energy sources is usually regarded as wind power. Yet, the construction of wind power systems in areas with sufficient wind speeds is crucial to ensuring their performance. At the moment, wind generators (WGs) are utilized in both remote hybrid power systems and grid-connected applications. The cost of installing WGs is less than that of photovoltaic systems.. A MPPT controller is needed to ensure that wind power systems function at their maximum power point (MPP) under a variety of weather situations. The research has discovered two MPPT algorithm: both direct and indirect. Direct methods, such as hill climbing search (HCS) and fuzzy logic controllers (FLC) don't need to be aware of the features of the generator or the weather. In contrast, indirect techniques based on the features of the generator include Optimal Torque Control (OTC) and Power Signal Feedback (PSF) [12 – 14]. The MPPT method for determining the maximum power point (MPPT) while dealing with variable wind speeds is proposed in this project effort. An MPPT algorithm was developed to track the optimum rotor speed, and multiple MPPT algorithms were evaluated and compared to improve their performance for the system in order to maximize the efficiency of the wind energy system. The next part further examines the body of knowledge on MPPT for wind turbines [15].

2.2 Principles of wind energy conversion

Kinetic energy may be used to calculate the power of wind energy. Wind kinetic energy is transformed into mechanical energy by the wind turbine. The graph below shows the kinetic energy of wind (2.1)

$$\text{Kinetic energy } = \frac{1}{2}\rho A V_w^3 \quad \text{watts} \tag{2.1}$$

where A is the swept area by the turbine blades, ρ is the air density, and V_w is the wind speed. The kinetic energy equation shows that the relationship between wind energy and swept area is proportional. The cubic function of wind velocity, which is seen in Fig. 2.1, is connected to the properties of wind power.

2.3 Modeling of wind turbines

The power coefficient(C_p), that is proportionate to the power collected from the wind impacting the turbine blades, determines how much wind a wind turbine can catch. One way to represent(C_p), is to (2.2),

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{2.2}$$

The value of (C_p) is related to tip speed ratio (λ). The λ is defined in (2.3). Here β is the blade pitch angle.

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{2.3}$$

The power coefficient (C_p) and turbine power output have a significant relationship. The power coefficient, which depends on the TSR (λ), is what regulates the amount of power produced by wind turbines. The power coefficient against TSR is turbine-specific and heavily dependent on the Fig. 2.1 turbine blade design. When the tip speed ratio is approximately 8, the power coefficient reaches its highest value of about 0.48.

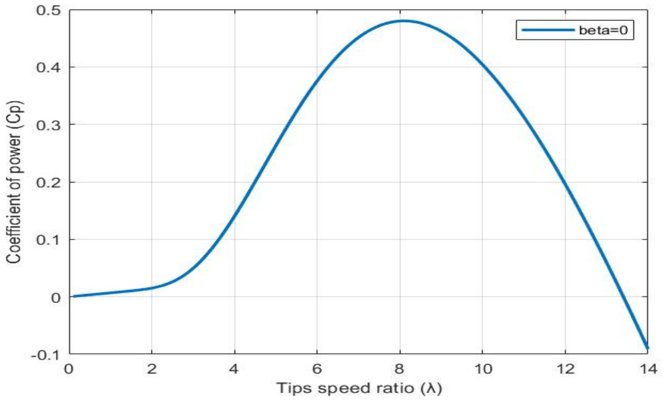


Figure 2.1: TSR vs Cp curve with 0 beta angle

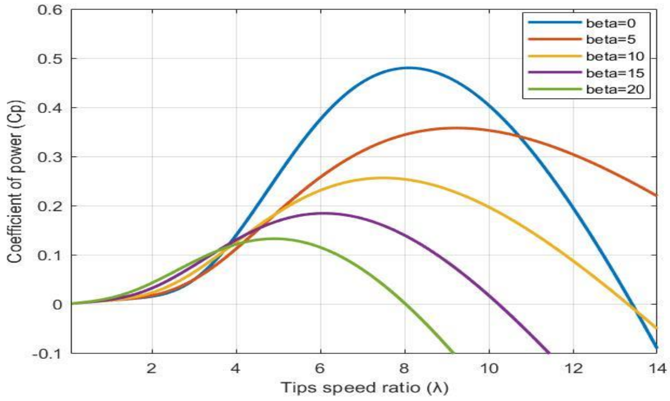


Figure 2.2: Tip speed ratio vs power coefficient curve with various pitch angle β values 0 to 20

The value of λ can be calculated by using equation (2.4).

$$\lambda = \frac{\omega_r R}{V_W} \tag{2.4}$$

2.4 Wind turbine system

In general, there are two main types of wind power conversion systems. The "Danish Idea" [16] refers to the first group, which runs at almost consistent rate (with changes restricted to roughly 1%). The generator and drive train are directly connected in this kind of system. In response to even slight changes in wind speed or load, this arrangement only permits tiny changes in rotor shaft speed, increasing mechanical stress and decreasing turbine lifetime [16 – 19].

The optimal TSR only occurs at particular wind speed; therefore, the steady speed design is unable to harvest the greatest amount of power from changing wind speeds [17 – 19]. On the other hand, a variable speed arrangement permits rotor speed management, allowing the wind turbine to run continuously close to the ideal TSR and enabling maximum power point tracking (MPPT) to be practical.

Variable speed configurations provide a number of advantages over fixed speed ones, including;

- The potential for up to 10% greater yearly energy collection depending on the wind regime and turbine aerodynamics [17].
- Longer machine longevity due to reduced mechanical stress and torque pulsations caused by turbulence [16, 20].
- The capacity to use the mechanical system's inertia and increased rotor speed to absorb extra energy from wind gusts.
- A higher power injection into the grid results in better power quality. Power pulsations are reduced to improve power quality and keep voltage deviation in check [16, 20].
- In adjustable speed designs, longer pitch control time constants, which reduce pitch control complexity. Moreover, these designs make less acoustic noise [16].

2.5 Maximum power extraction

The conversion of wind energy power is simple, but the process of obtaining the maximum power is challenging and includes a number of closely associated variables, including the C_P, TSR, wind speed, and rotor speed. It is clear from of the wind turbine's $P - \omega$ curve in Section 2.1 that there are several operational rotor speeds that correlate to various wind speeds at which maximum power extraction may be achieved. Owing to the wind turbine's aerodynamics, even a minor variation in rotor speed may have a big impact on how much power is generated from wind energy. Wind speed variations and generator loads both affect the rotor speed. As a result, wind generators might not run at the optimal rotor speed for a certain wind speed, resulting in a large loss of wind power. The quantity of energy extracted determines how cost-effective wind power is. The cost-effectiveness of the wind generators grows with the quantity of energy we can harvest. This is possible with today's electrical device improvements thanks to a variety of converter and maximum power point tracking (MPPT) algorithms. When it comes to other renewable energy sources for the production of electricity, wind turbine system capital costs are quite competitive. For wind power conversion systems to operate more efficiently and profitably, an efficient and affordable MPPT algorithm is required (WECS). As a result, during the last twenty years, the maximum power extract approach has attracted a lot of study attention. The MPP may be tracked using a number of algorithms based on tip speed ratio (TSR) control [21 – 23], power signal feedback (PSF) control [24 – 26], and hill-climb search (HCS) control [27, 28]. While being often employed for MPPT, the Perturb and Observe (P&O) approach demonstrates sluggish tracking performance and constant oscillation around the maximum power point [29], [30]. In [31 – 34], several MPPT control methods that calculate wind speed using air density and mechanical wind turbine system characteristics have been presented. Neural networks may be employed for the MPPT problem based on the mechanical power to turbine rotation speed ratio to get rid of unclear parameters and prevent oscillation [35]. In conclusion, the MPPT of a grid-connected PMSG wind turbine system is possible using SD, HCS, and fuzzy logic, and the P&O-based MPPT has superior efficiency and good performance with quick reaction. The fuzzy-control-based MPPT technique is effective, but it is difficult to implement [36, 37]. The main use of wind turbine systems is to provide electricity to mountainous or rural places that are cut off from the grid and where power grid is not practical financially. The fact that wind turbine systems require little to no maintenance is another important benefit. Popular MPPT methods are especially useful for small wind installations. At any wind speed, there will only be one rotor speed that offers the maximum power possible; this speed is known as the MPPT [38]. Variable-frequency mode operating for wind turbine generators is essential to perform maximum power extraction. Due to their higher capacity for capturing energy, variable speed wind turbine systems have recently gained in popularity relative to fixed-speed systems. Mechanical stress and poor power quality are problems with fixed speed systems. The disadvantages of fixed speed systems are lessened by variable speed systems, which enable MPPT algorithms and may run at their maximum power coefficient throughout a larger range of wind speeds [39 – 42]. For wind turbine generating systems, a peak detection approach based on the ideal power curve was created in [43] utilizing a perturbation step size determined by the reference. Despite the fact that most wind turbine systems employ anemometers to monitor wind speed [43 – 46], their errors might reduce the dependability of the wind energy conversion system. The wind power coefficient may be calculated using a polynomial, and the wind speed can then be calculated online by computing the roots of the polynomial using an iterative algorithm (such as Newton's method or the bisection technique). However, real-time polynomial root calculation is a highly difficult and drawn-out procedure, which affects system performance. When the wind system ages, the ideal tip speed ratio changes, producing inaccurate results [47], [48].

The MPPT controller is an essential component of the wind system, and its concept is not new; the literature review discusses several MPPT approaches that have been reported by researchers [49]. The major goal of this study is to create a P&O-based MPPT algorithm for a wind power system that can operate in fluctuating wind speeds and to evaluate how well the P&O MPPT system performs in terms of tracking the MPP and increasing the wind power system's efficiency [50].

2.6 Application of P&O-based MPPT algorithm

The efficient operation of wind power systems relies heavily on the accurate tracking of the maximum power point (MPP) of the wind turbine. MPP tracking algorithms play a crucial role in extracting the maximum available power from wind turbines under varying wind conditions. Among the various MPP tracking techniques, the Perturb and Observe (P&O) algorithm has gained significant attention due to its simplicity and effectiveness.

The P&O algorithm is an iterative technique commonly used for MPP tracking in wind power systems. It operates by perturbing the operating point of the wind turbine and observing the corresponding change in power output. Based on the direction of power change, the algorithm adjusts the operating point until it reaches the MPP. The simplicity and low computational requirements of the P&O algorithm make it an attractive choice for real-time MPP tracking [51]. Numerous studies have focused on enhancing the performance of the P&O algorithm to address its inherent drawbacks, such as oscillations around the MPP and slow convergence speed. Researchers have proposed various modifications to the P&O algorithm to mitigate these issues. For instance, adaptive step size control, variable step size algorithms, and hybrid algorithms that combine. These modifications aim to improve tracking accuracy, reduce oscillations, and enhance convergence speed [52, 53]. Wind variability and turbulence pose challenges for MPP tracking algorithms, including P&O. Fluctuations in wind speed and direction can affect the accuracy and stability of the tracking algorithm. Researchers have explored different strategies to handle wind variability and turbulence, such as employing filtering techniques, advanced wind speed prediction models, and data-driven approaches. These approaches aim to enhance the reliability and robustness of the P&O algorithm under varying wind conditions [54]. To assess the effectiveness of the P&O algorithm, numerous studies have conducted comparative analyses with other MPP tracking algorithms commonly used in wind power systems, such as steepest decent, hill climbing search (HCS), These studies evaluate the performance of different algorithms in terms of tracking accuracy, response time, efficiency, and robustness. The results highlight the advantages and limitations of the P&O algorithm compared to alternative methods [55]. The P&O algorithm has proven to be a widely effective technique for maximum power point tracking in wind power systems.

2.7 Maximum power point tracking (MPPT) strategy

In Fig. 2.3 gives an excellent representation of the MPPT idea with a change in wind velocity. The turbine power curve adapts to variations in wind speed. The MPP for that wind speed is B, and the associated rotor speed is ω_r^*, so let's assume that the wind speed is known and the turbine is running at point A. The generator's rotor speed will then be adjusted until it hits ω_r^*, the point at which the turbine power is at its peak.

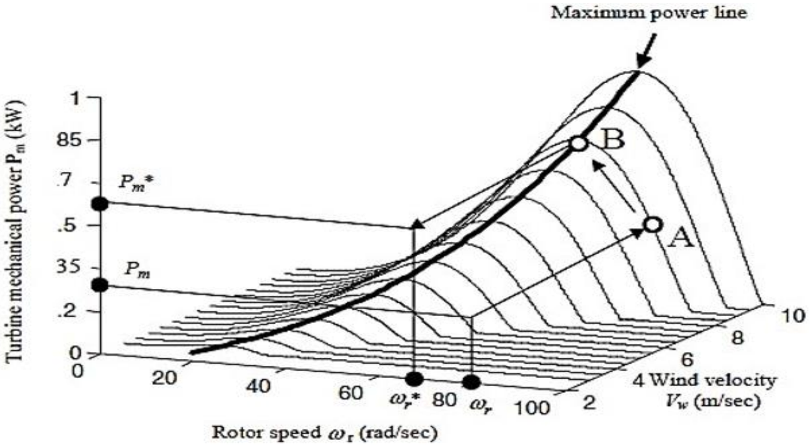


Figure 2.3: Three dimensional turbine speed vs power curve

Hence, utilizing the operation, we must first determine the wind speed. Using an anemometer, which is quite expensive, makes it simple to perform. So, it is more economical to use a sensor-free wind speed measuring approach. For this problem, it is possible to use Steepest Descent (SD). The operational turbine power and rotor speed will fluctuate together with the wind velocity. Power and rotor speed data can be exact, but they will only be used as inputs to the HC network. HC will determine the wind speed, maximum power proportional to the predicted wind velocity, and the turbine's ideal rotor speed for attaining maximum power based on the inputs provided. Despite the fact that the relationship between turbine power and rotor speed is nonlinear with regard to changes in wind speed, nonlinear objective functions can be handled by both HC and SD, allowing for the estimate of wind speed and MPPT tracking using SD.

Chapter 3

GRADIENT TECHNIQUES FOR MPPT

3.1 Maximum power point tracking (MPPT) algorithm

Kinetic energy may be used to calculate the power of wind energy. A wind turbine is a rotating machine that converts the kinetic energy in wind into mechanical energy. The graph below shows the kinetic energy of wind (3.1)

$$\text{Kinetic energy, Ke} = \frac{1}{2}\rho A V_w^3 \tag{3.1}$$

$$\text{Mechanical energy, } P_m = \frac{1}{2}\rho A C_p V_w^3$$

where A is the swept area by the turbine blades, ρ is the air density, and V_w is the wind speed.

- **Power coefficient**

The power coefficient (C_P) represents the aerodynamic efficiency of the wind turbine, which is dependent on TSR (tips speed ratio) λ and the particular pitch angle of the blade β. One way to represent(C_p), is to (3.2),

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{3.2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.3}$$

There is a strong relationship between the power output and power coefficient(C_p). The power coefficient, which depends on the TSR (λ), is what regulates the amount of power produced by wind turbines. When the tip speed ratio is approximately 8, the power coefficient reaches its highest value of about 0.48.

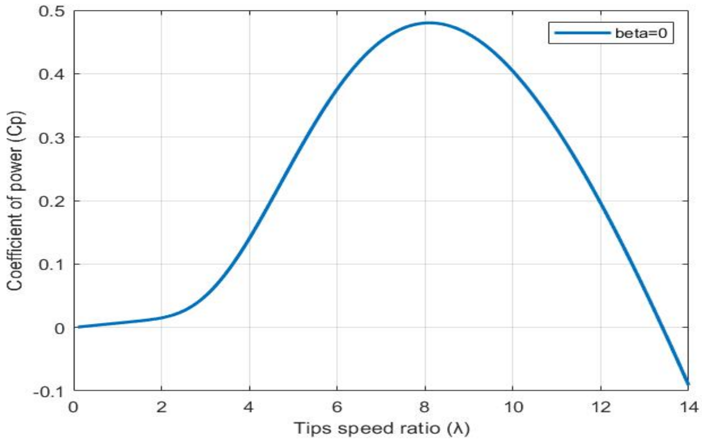


Figure 3.1: Tip speed ratio vs power coefficient curve with 0 beta angle

The value of λ can be calculated by using equation (3.4).

$$\lambda = \frac{\omega_r R}{V_W} \tag{3.4}$$

The value of ω_r can be calculated,

$$\lambda = \frac{\omega_r \times R}{V_w} \quad \Rightarrow \omega_r = \frac{\lambda \times V_w}{R} \quad \omega_r = \text{rotor speed}$$

The mechanical power of a wind turbine is dependent on wind speed V_w and is represented as (3.5).

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_w^3 \tag{3.5}$$

When the TSR is adjusted to its optimum value λ_{opt} then the power coefficient C_P will be its maximum value C_{Pmax} and the maximum power extraction will be achieved. The relationship between turbine power (Pm) and rotor speed (ω_r) may be expressed as in by rearranging equations (3.4) and (3.5). (3.6)

$$P_m = \frac{1}{2}\rho A C_{p_{opt}} \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 \tag{3.6}$$

The maximum power generated, as indicated in (3.6), is proportional to the cube of the rotating speed (3.7).

$$P_m \propto \omega_r{}^3 \tag{3.7}$$

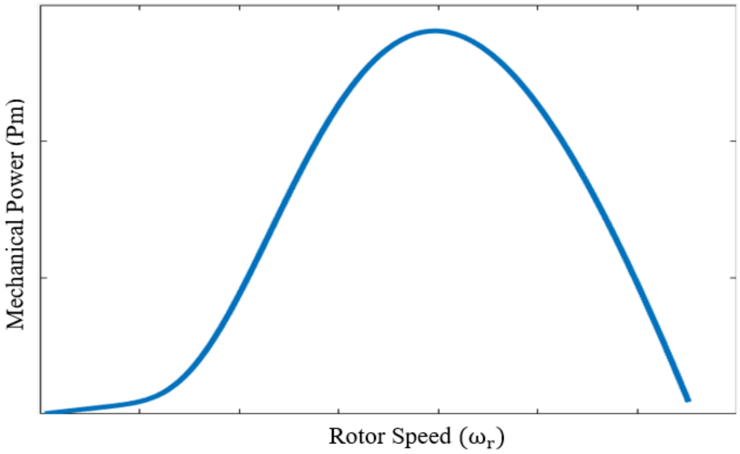


Figure 3.2: (P - ω) characteristic curve

During wind speed variation, the captured wind power relates to the specific operating region within a wind speed range restricted between V_{cut_in} and V_{cut_out}. Otherwise, WT must be prevented to operate below the V_{cut_in} or above V_{cut_out} for safety necessities. The operating wind speed regions are classified as follows:

Regions 1 and 4: For safety reasons, the WT has been prevented and disconnected from the utility grid.

Region 2: In the middle region, maximum power point tracking (MPPT) methods are used to gather the most wind energy in the middle area.

Region 3: The produced power is limited to the rated power by applying pitch angle control to reduce mechanical strains on the WT blades at high wind speeds.

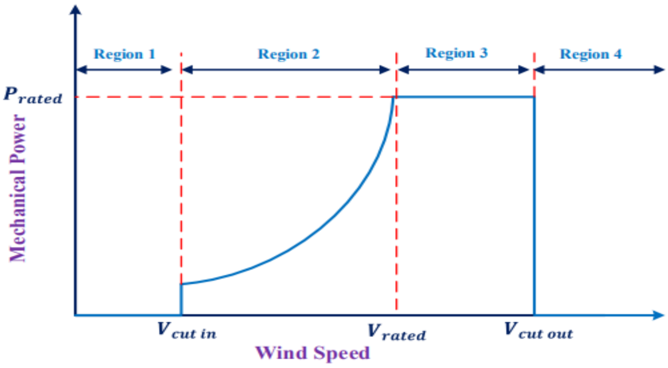


Figure 3.3: WT operating regions [56]

The MPPT algorithm is used to ensure that the wind turbine operates at its maximum power point below the rated wind speed, which allows for maximum power generated at different wind speed. To optimize the power output, an efficient MPPT algorithm will be controlled by the rotor speed. The maximum power point is determined by operating the wind turbine at the optimal values of λ_{opt} and C_{p_opt} , which are 8.1 and 0.48, respectively.

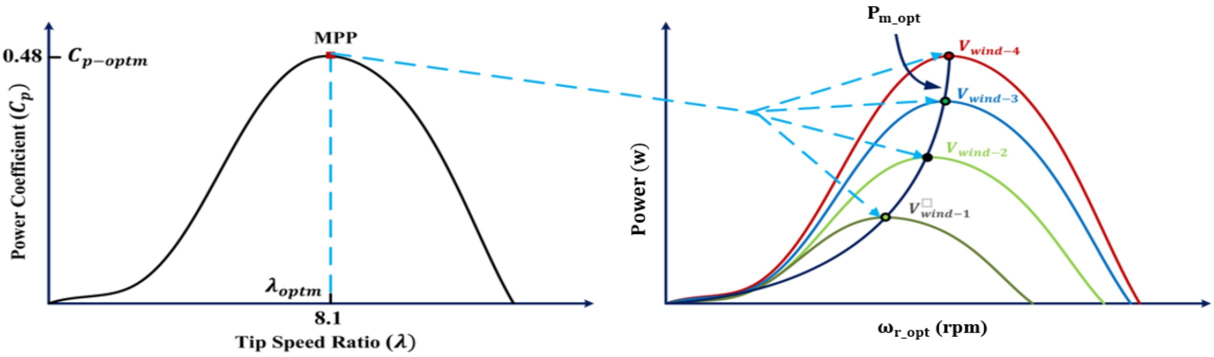


Figure 3.4: WT power characteristics curve [56]

The gradient methods for maximum power point in the literature are steepest descent, hill climbing and perturb & observe. These methods are discussed in the following sections briefly.

3.2 Steepest Descent (SD) method

A well-known and well-established search strategy for minimizing or maximizing multivariable unconstrained optimization problems is the steepest descent method. The development of powerful optimization techniques has greatly benefited from this technique. It is an iterative first-order derivative optimization algorithm that, for quadratic functions, demonstrates linear convergence. Gradient descent is the method for finding a local minimum point when steps are required in the direction of a negative gradient of the function at the present position. Gradient ascent, on the other hand, is the process of moving the search point in the direction of a positive gradient in order to locate a local maximum point. The starting point selection has a significant impact on how effective the steepest descent approach is. The procedure converges quickly when starting from a distance from the optimal, but as it gets closer to the ideal, it becomes more slowly [57]. Note that it is wise to look for non - linear function objective functions in the gradient's negative direction. Take into account the next objective function:

where $x \in \mathbb{R}^n$, our objective is to find the minimizer of the above function. In proceed as follows: Let $x^{(0)}$ be a starting point, and consider the point$(x^{(0)} - \alpha\nabla f(x^{(0)}))$, where α > 0 is sufficiently small, and $\nabla f(x^{(0)})$ is the gradient of f at $x^{(0)}$. Set

$$\phi(\alpha) = f(x^{(0)} - \alpha\nabla(f^{(0)}))$$

If $\alpha = 0$, then

$$\phi(0) = f(x^{(0)})$$

Applying Taylor's theorem to $\phi(\alpha)$at $\alpha = 0$, then

$$\phi(\alpha) = \phi(0) + \alpha\phi'(0) + 0(\alpha)$$

that is

$$\begin{aligned} f(x^{(0)} - \alpha\nabla(f^{(0)})) - f(x^{(0)}) &= \alpha\frac{d}{d\alpha} f(x^{(0)} - \alpha\nabla(f^{(0)})) + 0(\alpha) \\ &= -(\nabla(f^{(0)}))^T \alpha\nabla f^{(0)})) + 0(\alpha) \\ &= -\alpha\left\|\nabla f(x^{(0)})\right\|^2 + 0(\alpha) \end{aligned}$$

Since$\left\|\nabla f(x^{(0)})\right\|^2$is positive, α > 0 and $\nabla f(x^{(0)}) \neq 0$, therefore

$$f(x^{(0)} - \alpha\nabla(f^{(0)})) - f(x^{(0)}) < 0 \tag{3.9}$$

that is,

$$f(x^{(0)} - \alpha\nabla(f^{(0)})) < f(x^{(0)})$$

This concludes that the new point $f(x^{(0)} - \alpha\nabla f(x^0))$ is an improvement point over the initial point $x^{(0)}$, if we are searching for the minimizer. This idea has been used to develop an algorithm.

- **Basics of Steepest Descent Method**

The steepest descent method is a natural iterative procedure used to generate a sequence of iterates. Suppose that we are given an initial point x (k). To find the next point $x^{(k+1)}$, we begin from $x^{(k)}$, and move by an amount of $-\alpha_k\nabla f(x^{(k)})$ where $-\alpha_k$ a positive scalar is called the step length or step size. In this method, we choose α_k to achieve the maximum amount of decrease of the objective function at every step. Definitely, α_k is chosen to minimize

$$\phi_k(\alpha) = f(x^{(k)} - \alpha\nabla f(x^{(k)}))$$

that is,

$$\alpha_k = \underset{\alpha\geq 0}{\arg\min}\, f(x^{(k)} - \alpha\nabla f(x^{(k)})) \tag{3.10}$$

At each step from the point $x^{(k)}$, we conduct a line search to move in the direction $-\nabla f(x^{(k)})$, which follows a zig-zag pattern as depicted in Fig. 3.5. The following iterative algorithm is provided by this procedure:

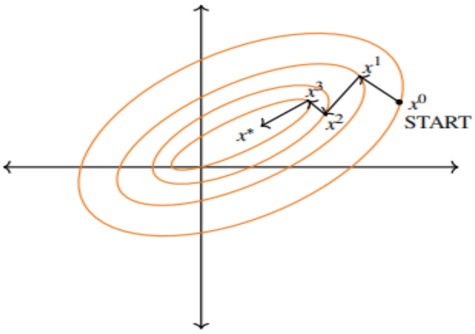


Figure 3.5: SD method operation and algorithm explanation [57]

$$x^{(k+1)} = x^{(k)} - \alpha_k \nabla f(x^{(k)}) \tag{3.11}$$

In essence, for each iteration, consecutive directions preserve the orthogonal property but the gradient of the function shifts as the search moves forward. When we proceed in the direction of the negative gradient, the function value drops off the most, and when the gradient decreases to zero, we reach the minimizer x* of the function.

- **Steepest Descent Method for Quadratic Functions**

Consider the following quadratic function:

$$f(x) = \frac{1}{2} x^T Q x - b^T x \tag{3.12}$$

where $Q \in \mathbb{R}^{n \times n}$ is a symmetric positive definite matrix, $b \in \mathbb{R}^n$, and $x \in \mathbb{R}^n$. The gradient of above function is given as

For the sake of simplicity, we express

$$\nabla f(x) = Qx - b \tag{3.13}$$

that is,

$$g^{(k)} = \nabla f(x^{(k)}) \tag{3.14}$$

$$g^{(k)} = Qx^{(k)} - b \tag{3.15}$$

Taking transpose on both sides, we get

$$(g^{(k)})^T = (x^{(k)})^T Q - b^T \tag{3.16}$$

The steepest descent algorithm for a quadratic function is:

$$x^{(k+1)} = x^{(k)} - \alpha_k g^{(k)} \tag{3.17}$$

where α_k is the minimizer of $f(x^{(k)} - \alpha_k g^{(k)}), \forall\, \alpha \geq 0$. In other words, α_k is minimizer of

$$\phi_k(\alpha_k) = \frac{1}{2}(x^{(k)} - \alpha_k g^{(k)})^T Q (x^{(k)} - \alpha_k g^{(k)}) - b^T (x^{(k)} - \alpha_k g^{(k)}) \tag{3.18}$$

We can find an explicit formula for α_k to minimize the quadratic functions. Assume that then $g^{(k)} \neq 0$, otherwise if $g^{(k)} = 0$,

$$x^{(k+1)} = x^*$$

and the algorithm will stop. Note that

$$\phi_k'(\alpha) = \frac{d}{d\alpha} f(x^{(k)} - \alpha g^{(k)}) = (\nabla f(x^{(k)} - \alpha g^{(k)}))^T(-g^{(k)})$$

Since $\nabla f\big(x^{(k)} - \alpha g^{(k)}\big) = Q(\big(x^{(k)} - \alpha g^{(k)}\big) - b$ then,

$$\phi_k' = [Q(x^{(k)} - \alpha g^{(k)}) - b]^T(-g^{(k)})$$

Therefore,

$$\phi_k' = [Q(x^{(k)} - \alpha g^{(k)}) - b]^T(-g^{(k)})$$

Since $\alpha_k \geq 0$ is a minimizer $\phi_k(\alpha)$ and from fifirst order necessary condition to $\phi_k(\alpha)$, then,

$$\phi_k'(\alpha_k) = 0 \tag{3.19}$$

thus,

$$-(x^{(k)} - \alpha_k g^{(k)})^T Q g^{(k)} - g^{(k)} b^T$$

Which implies that

$$-(x^{(k)})^T Q g^{(k)} + \alpha_k (g^{(k)})^T Q g^{(k)} + g^{(k)} b^T = 0$$

that is,

$$\alpha_k (g^{(k)})^T Q g^{(k)} = [(x^{(k)})^T Q - b^T] g^{(k)} \tag{3.20}$$

Since $(x^{(k)})^T Q - b^T = \big(g^{(k)}\big)^T$, from (3.20), we get

$$\alpha_k (g^{(k)})^T Q g^{(k)} = (g^{(k)})^T g^{(k)}$$

Which leads to

$$\alpha_k = \frac{(g^{(k)})^T g^{(k)}}{(g^{(k)})^T Q g^{(k)}} \tag{3.21}$$

The explicit step length $\alpha_{k\,,}$ formula, which only applies to quadratic functions, is now available. The method of steepest descent for quadratic functions is expressed as follows:

$$x^{(k+1)} = x^{(k)} - \frac{(g^{(k)})^T g^{(k)}}{(g^{(k)})^T Q g^{(k)}} \tag{3.22}$$

- **Convergence Analysis of Steepest Descent Algorithm**

The method of steepest descent is an iterative algorithm, which generates a sequence of points with each point computed based on the previous one. This method is referred to as a descent method because each new point produced by the algorithm aims to yield a decreased value of an objective function. An iterative algorithm is considered globally convergent if it satisfies the first order necessary condition for a minimizer, regardless of the starting point. However, if the algorithm is not globally convergent, it may still generate a sequence of points that converge to a point satisfying the first-order necessary condition, provided that the initial point is close enough to the point. The rate of convergence indicates how quickly the algorithm converges to a solution point. Using gradient descent techniques to quadratic problems, including the steepest descent technique, analyses the convergence characteristics of these techniques:

$$f(x) = \frac{1}{2}x^TQx - b^Tx$$

but analyzing the convergence properties is more convenient if deal with

$$V(x) = f(x) + \frac{1}{2}x^{*T}Qx^* \tag{3.23}$$

where $x^* = Q^{-1}b$ is a solution of $Qx = b$. Note that $V(x)$ differs from $f(x)$ only by a constant $\frac{1}{2}x^{*T}Qx^*$

$$V(x) = \frac{1}{2}x^{*T}Qx^* - b^Tx + \frac{1}{2}x^{*T}Qx^*$$

Simplifying the above-given formula for V(x), we reach the following conclusion:

$$V(x) = \frac{1}{2}(x - x^*)^TQ(x - x^*)$$

We can prove the above as follows:

$$V(x) = \frac{1}{2}x^TQx^* - b^Tx + \frac{1}{2}x^{*T}Qx^*$$

$$= \frac{1}{2}[x^TQx - 2b^Tx + x^{*T}Qx^*]$$

$$= \frac{1}{2}[x^TQx - b^Tx - b^Tx + x^{*T}Qx^*]$$

Since $b = Qx^*$, therefore

$$V(x) = \frac{1}{2}[x^TQx - (Qx^*)^Tx - (Qx^*)^Tx + x^{*T}Qx^*$$

$$= \frac{1}{2}[x^TQx - x^{*T}Qx - x^{*T}Q + x^{*T}Qx^*]$$

$$= \frac{1}{2}[(x - x^*)^TQx - x^{*T}Q(x - x^*)]$$

$$= \frac{1}{2}[(x - x^*)^TQx - (x - x^*)^TQx^*]$$

Which gives

$$V(x) = \frac{1}{2}[(x - x^*)^TQ(x - x^*)] \tag{3.24}$$

A theorem attributed to Kantorovich that can be found in Luenberger2 is used to compute a bound. We may show the following, in particular, by using the method of steepest descent with accurate line searches on a strongly convex quadratic function:

$$f(x_{k+1}) - f(x^*) \leq \left[\frac{k(Q) - 1}{k(Q) + 1}\right]^2 (x_k) - f(x^*) \tag{3.25}$$

where $k(Q) = \frac{\lambda_n}{\lambda_1}$ is the condition number of the matrix Q.

If we assume that α_k is the global minimizer along the search direction, a similar bound can be derived for the case of a general nonlinear objective function [57].

A gradient-based optimization technique called steepest descent is used to determine a function's minimum or maximum. This approach travels iteratively in the direction of the steepest descent, which is the positive or negative gradient of the function at the current point. The procedure starts at a starting point. A line search technique or a fixed step size is used to determine the step size, and the procedure is repeated until the convergence requirement is achieved. In machine learning and optimization issues when the objective function is differentiable, this approach is frequently utilized. Wind generators can use the steepest descent (SD) approach for the best power point tracking (MPPT). By altering the turbine rotor speed and blade pitch angle, the steepest descent method may be employed in the context of wind generators to monitor the maximum power point of the wind turbine. The power function's gradient with respect to the rotor speed and blade pitch angle is calculated using the steepest descent technique, and this gradient is used to change the rotor speed and blade pitch angle in order to maximize power. This method is a well option for MPPT in wind turbines since it is computationally effective and quite easy to implement.

3.3 Hill climbing (HC) method

The hill climbing method analyzes variations in wind power output and is utilized for MPPT if there is any increase or reduction in power. Without using the hill climbing approach, large or medium-sized wind turbines may not be able to attain the MPP during varied wind changes. In hill climbing, the step size of the measured variable is essential for efficient MPPT. Since bigger step sizes did not mirror the precise MPPT as seen in Fig. 3.6, they resulted in rapid responses and decreased accuracy. A smaller step size lengthens the amount of time needed to reach the precise MPP, but because it tracks the exact MPP as illustrated in Fig. 3.7, it improves efficiency. The parameters' initialization may have an impact on how well the system works.

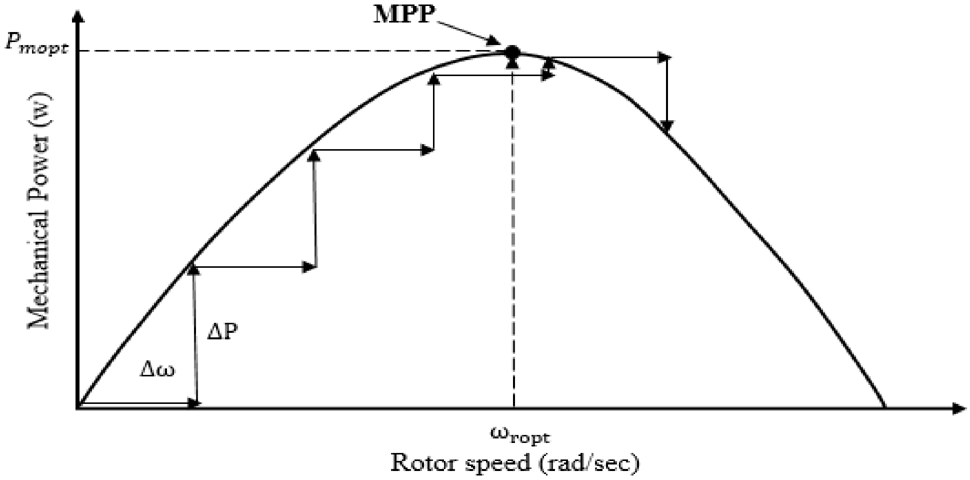


Figure 3.6: Larger perturbation

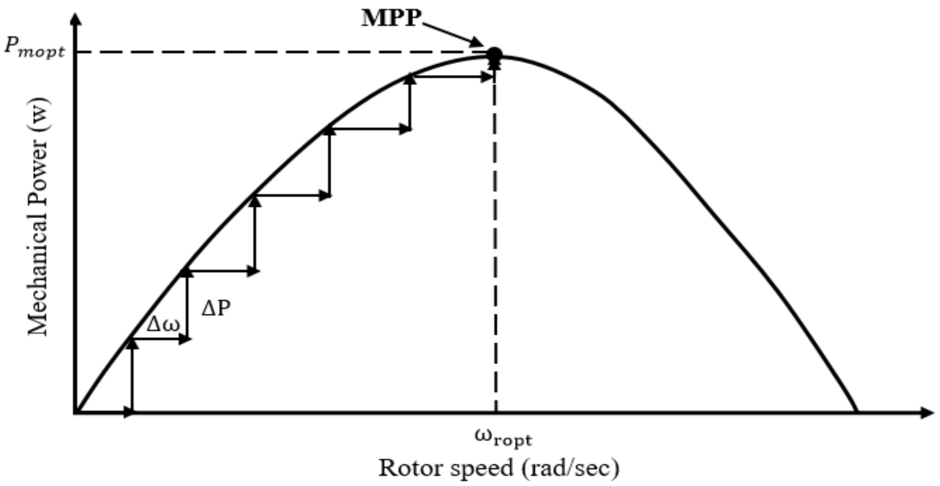


Figure 3.7: Smaller perturbation

The hill climbing search (HCS) method is a most useful techniques for maximum power point tracking (MPPT) in wind power systems due to its simplicity and independence from wind turbine characteristics, such as the maximal power coefficient C_{p-opt} and the optimal tip speed ratio λ_{opt}. The HCS method's basic idea is frequently changing (increasing or decreasing) the wind turbine's rotor speed in tiny stages and evaluating the impact on the power production P by comparing it to the prior value. The algorithm, shown in the flow chart in Fig. 3.9, continues the perturbation in the same direction if a small increase in rotor speed leads to an increase in output power $\left(\text{case } \frac{\Delta P}{\Delta \omega} > 0\right)$, otherwise it changes the direction of perturbation (case $\frac{\Delta P}{\Delta \omega} < 0$). This process is repeated until the maximum power point is reached, when the slope $\frac{\Delta P}{\Delta \omega} = 0$. The HCS method adjusts the generator speed iteratively until it reaches the MPP, as shown in Fig. 3.8. The hill climbing algorithm does, however, have certain limitations, most notably its susceptibility to variations in wind speed, which can result in oscillations about the MPP and lower power output.

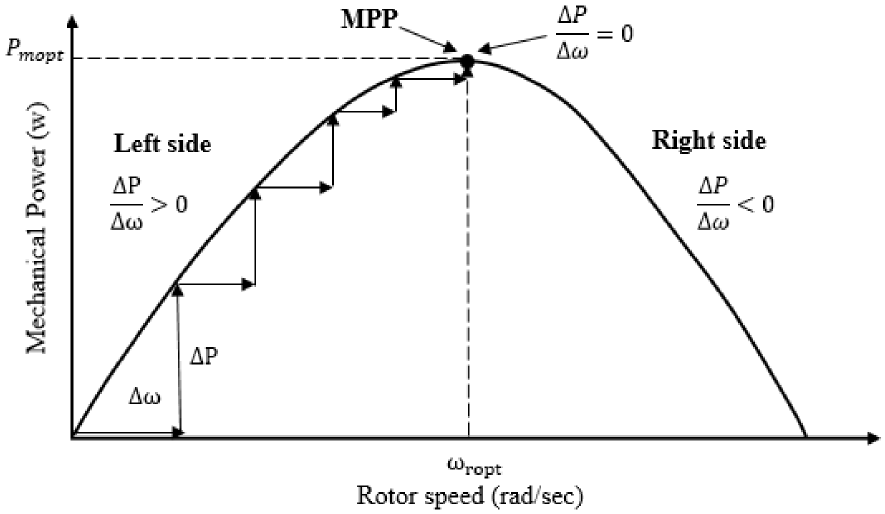


Figure 3.8: Hill climbing search method operation & algorithm explanation [58]

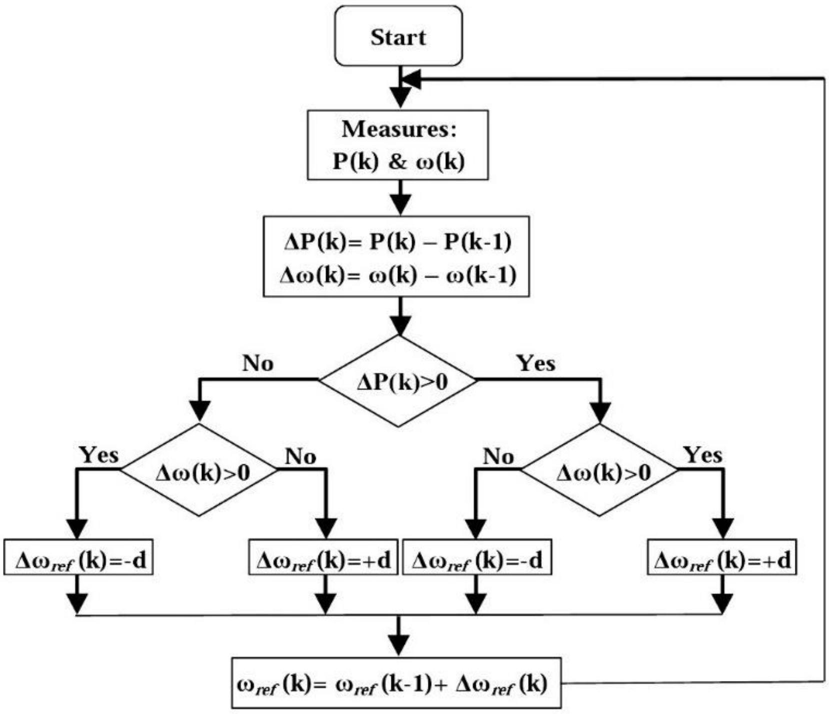


Figure 3.9: Hill climbing search method flowchart [58]

The hill climbing is a search point optimization method used to find the maximum point of a function. It starts at an initial solution and iteratively moves to the adjacent solutions that improve the objective function until a maximum is reached. The choice of the next solution depends on the heuristic rule used, such as choosing the steepest ascent, the first ascent, or a random ascent [58]. In the area of numerical optimization, the SD technique and the hill climbing method are two widely used optimization methods. These techniques include repeatedly going in the direction of the sharpest drop or climb to determine the minimum or maximum value of a function. The SD method is a first-order technique that chooses whether to proceed in the direction of the minimum or maximum based on the function's gradient, which can be either positive or negative. The procedure begins at a starting point within the domain of the function and advances in either the positive or negative gradient until it reaches a minimum or maximum.

The HC method, on the other hand, is a heuristic search algorithm that iteratively moves to a higher value in the function's domain to find the maximum value. The algorithm starts at an initial point in the function's domain and moves to a neighboring point with a higher function value. This process is repeated until a maximum point is found.

Overall, SD & HC methods are all same technique but they are working principle is different. Their main objective is to track the maximum point. The SD method and the HC method are powerful optimization algorithms that can be used in various applications, either alone or in combination with other methods.

3.4 Differences between perturb and observe, steepest descent, and hill climbing methods

The SD method, also known as gradient descent, is a mathematical optimization algorithm that works by finding the direction of steepest descent of a function and moving in that direction to minimize the function. In wind turbine control, the function being minimized is typically the difference between the actual power output of the turbine and the desired power output. The algorithm adjusts the rotor speed in the direction of steepest decrease in power output until a minimum is reached. This process is repeated continuously, and the rotor speed is adjusted as necessary to minimize the difference between actual and desired power output. The advantage of the steepest descent method is that it is computationally efficient and can converge quickly to a minimum.

The HC method is a heuristic optimization algorithm that works by repeatedly making small adjustments to the turbine's rotor speed and observing the resulting power output. The algorithm then moves in the direction of increasing power output, effectively "climbing the hill" of power output until a peak is reached. This process is repeated continuously, and the rotor speed is adjusted as necessary to maximize power output. The advantage of the hill climbing method is that it can be effective at finding the global maximum of the power output function, even in the presence of noise or other disturbances that may affect the turbine's performance.

The P&O method works by adjusting the turbine's rotor speed in the direction of the highest power output. The algorithm starts by perturbing the rotor speed in small step size and observing the resulting power output. If the power output increases, the algorithm continues to perturb the rotor speed in the same direction until the power output starts to decrease. At this point, the algorithm changes direction and starts to perturb the rotor speed in the opposite direction. This process is repeated continuously, and the rotor speed is adjusted as necessary to maximize power output. The P&O method is advantageous due to its simplicity and minimal requirement for information about the turbine's performance characteristics.

Overall, the major difference between these algorithms is the direction in which the rotor speed is adjusted. The proposed method adjusts rotor speed in the direction of the optimum power output, the steepest descent method adjusts the rotor speed in the direction of minimizing the difference between actual and desired power output, and the hill-climbing method adjusts the rotor speed in the direction of increasing power output. Every method is its own advantages and disadvantages and should be selected based on the specific application and requirements.

Chapter 4

PROPOSED METHODOLOGY

4.1 Perturb and observe (P&O) method

The P&O method is an algorithm used to ensure that a wind generator operates at its maximum power point (MPP) under varying wind conditions. The MPP represents the optimal operating point where the power output is maximized. The P&O method works by continuously adjusting the rotor speed of the wind generator to track the MPP for a certain wind speed. The direction of power change is then used to adjust the rotor speed in the next iteration. The algorithm starts by perturbing the rotor speed and measuring the power output. If the power output increases, the algorithm continues in the same direction. If the power output decreases, the algorithm reverses the direction in the next iteration. This iterative process continues until the power output reaches a maximum, indicating the MPP.

In the perturb and observe (P&O) method, the step size refers to the magnitude of the perturbation applied to the rotor speed of the wind generator in each iteration. It determines how much the operating point is adjusted to track the maximum power point (MPP) accurately. The rotor speed step size has to be adjusted depending on the convergence criterion selected. The selection of an appropriate step size is crucial for the effectiveness and efficiency of the P&O method. If the step size is too small, the algorithm may take longer to converge to the MPP, especially under rapidly changing wind conditions. On the other hand, if the step size is too large, the algorithm may overshoot the MPP, leading to oscillations around the optimal operating point. Selecting the appropriate step size in the P&O method requires considering the specific characteristics of the wind generator system and finding the right balance between accuracy, convergence speed, and stability to ensure effective maximum power point tracking.

Firstly, the power-speed ($P - \omega$) characteristic curve is generated from a power equation. The power equation relates the optimum power coefficient, tip speed ratio and the specific wind speed. The theoretical power P_m is calculated from eqn. 3.5 which equals the optimal extracted mechanical power,

$$P_m = \frac{1}{2}\rho A C_p V_w^3$$

Here P_m is mechanical power in watt, ρ is air density in, Kg/m^3 A is the swept area by the turbine blades, C_p power coefficient.

To obtain an accurate power output P_m at each corresponding rotor speed point ω_r, a 12th order polynomial function is applied for curve fitting the power and corresponding rotor speed. This function makes it easy to obtain the power output P_m at any given point of rotor speed ω_r.

$$f(x) = a_0 + a_1 x^1 + a_2 x^2 + a_3 x^3 + \cdots + a_{11} x^{11}$$

$$P_m = f(x)$$

$$P_m = a_0 + a_1 \omega_r^1 + a_2 \omega_r^2 + a_3 \omega_r^3 + \cdots + a_{11} \omega_r^{11}$$

where P_m is the mechanical power and ω_r is corresponding rotor speed.

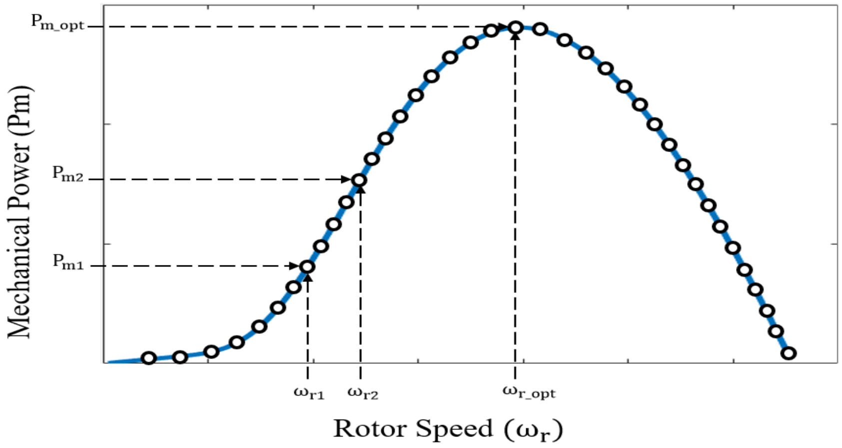


Figure 4.1: (P - ω) characteristic curve fitting technique

Secondly, a special synthesized speed is calculated as,

Forward, $\omega_{r\_ref}(n+1) = \omega_{r\_ref}(n) + \Delta\omega_r$ and $P_\omega = P_{\omega\_ref}(n+1) = \omega_{r\_ref}(n) + \Delta P_\omega$

Reverse, $\omega_{r\_ref}(n+1) = \omega_{r\_ref}(n) - \Delta\omega_r$ and $P_\omega = P_{\omega\_ref}(n+1) = \omega_{r\_ref}(n) - \Delta P_\omega$

The algorithm scheme is summarized as:

- Measuring P_ω (n) and ω_r (n) also estimating the wind speed.
- Calculating $\Delta P_\omega(n)$, $\Delta\omega_r(n)$, $P_\omega(n)$, $P_m(n)$.
- Selecting forward or reverse operating point.
- Perturb the rotor speed with the specified point step size.
- Updating operating point.

This 12th order polynomial function makes it easy to obtain the power output P_m at any given point of rotor speed ω_r. The n denotes the total number of differential order of polynomial function. The rotor speed step size has to be adjusted depending on the convergence criterion selected. If the new power point is observed to be below point C, the step size is reversed. The selection of step size depends on the number of point and the operating point, which is shown in Fig. 4.2. The complete process multi point flow chart of the proposed algorithm is depicted in Fig. 4.3.

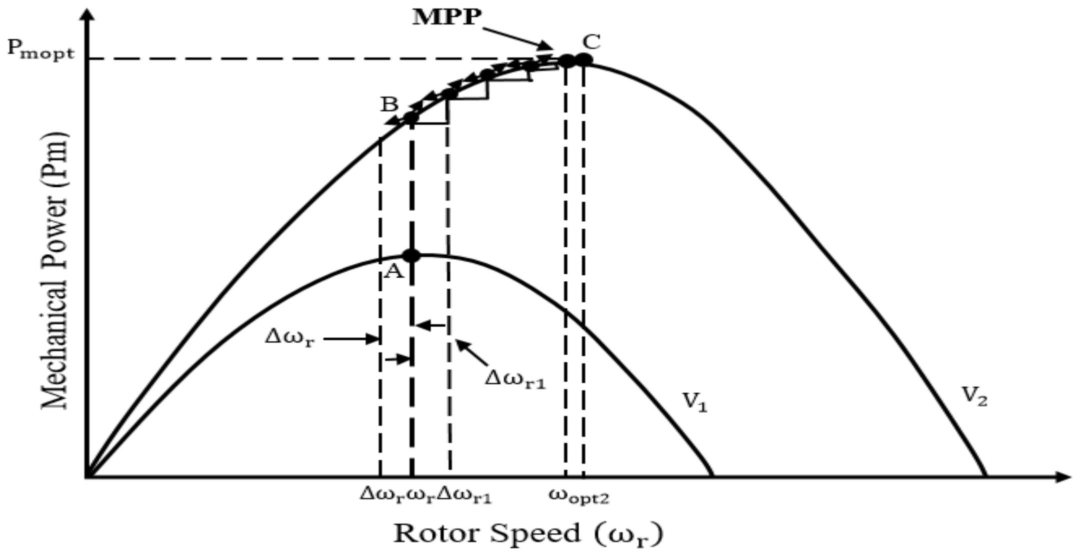


Figure 4.2: P&O based MPPT algorithm operation [59]

The proposed Perturb and Observe (P&O) algorithm is explained through the following step:

Step-1: Referring to Fig. 4.2, (V_1) and (V_2) curves are ($P - \omega$) characteristic curves, which is the theoretical estimate value that is computed based on the power equation. Consider the initial operating point is A corresponding to pre-disturbance wind speed (V_1). If the wind speed changes, the mechanical power output also changes. As a result in generated new curve (V_2) and consider new operating curve is B, starting from the previous optimum point A. Now the identify the maximum power point C for wind speed V_2.

Step-2: Now, consider the new operating point B, which is located at a given point on the power-speed curve. Since it is not known whether point C is above or below the curve, a small change in the new operating point B is made $\Delta\omega_r$ to $\Delta\omega_{r1}$ and the corresponding power is calculated from the generated power – speed ($P - \omega$) characteristic and the corresponding change in power is observed. Every perturbation point of the rotor speed step size is checked to determine the correct peak point direction of the power speed curve. To obtain an accurate power output at each step size, the rotor speed perturbation point is checked to find the highest and lowest points. The highest point is chosen from these highest and lowest points to reach the peak point of the power – speed curve. With the correct slope, the new rotor speed and corresponding power are determined. The speed step size has to be adjusted depending on the convergence criterion selected. If the new power point is observed to be below point C, the step size is reversed.

Step-3: The process is continued until point C is obtained. Notice that computations have to be carried out beyond point C also in order to verify the correct peak point. After the operating point is in close proximity to the optimum point C, if there is no significant wind speed change, the algorithm will track the maximum power point C.

After convergence the error in maximum power point and corresponding rotor speed have to be recorded. Since the wind speed may be continuously changing, the process has to be repeated for every wind speed variation. The complete process of the proposed algorithm is explained in the flowchart that is shown in Fig. 4.3.

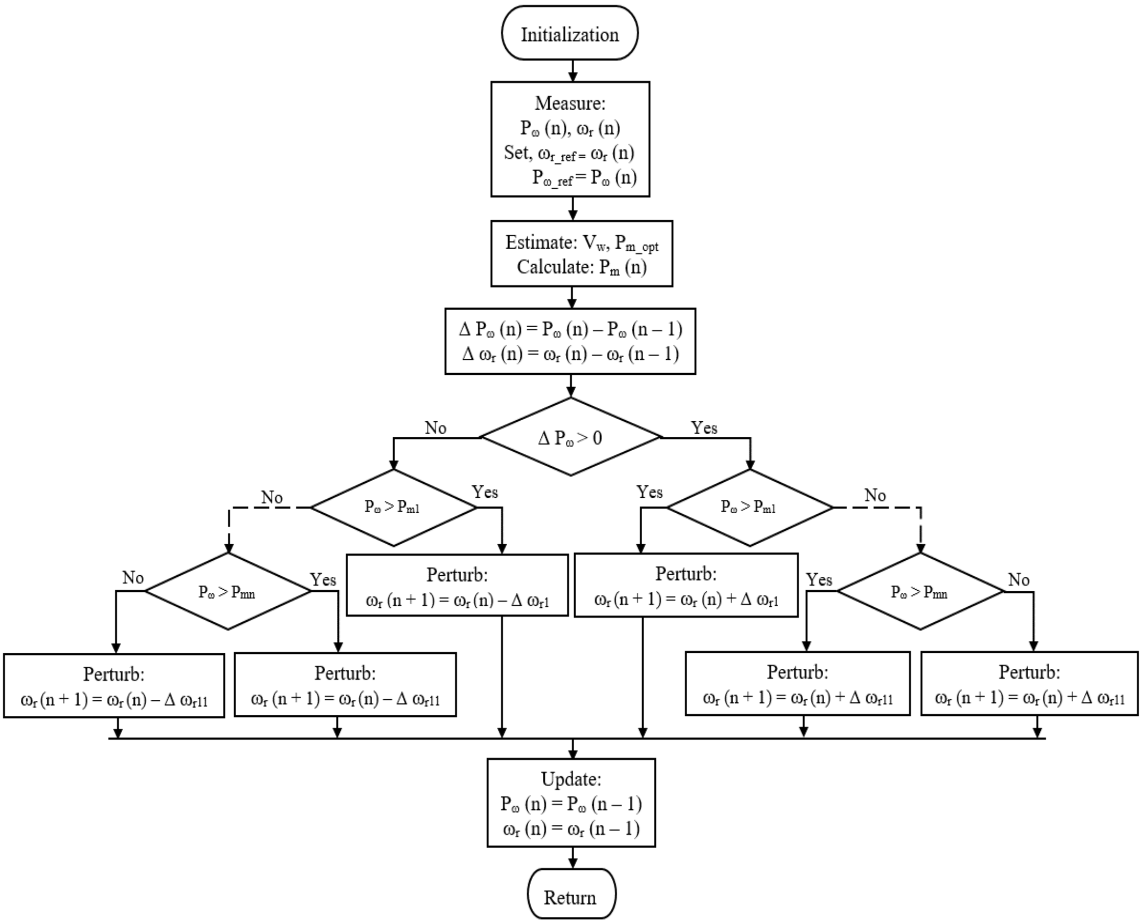


Figure 4.3: Flowchart of the P&O based MPPT algorithm [59]

Now, the error values of rotor speed and corresponding power have to be calculated. The rotor speed and corresponding power error are measured by calculating difference between estimate and actual values. The rotor speed perturbation step size has to be adjusted depending on the convergence criterion selected. If the rotor speed perturbation step size is observed to be large and below the optimum point, then reduced the step size smaller until the optimum point is reached, as a result in reduces the error in power. The rotor speed and corresponding power error are calculated by comparing each step size perturbation estimate point, such as $\omega_1, \omega_2, \omega_3, \omega_4$and ω_5, with their respective actual step size perturbation points, $\omega_1, \omega_2, \omega_3, \omega_4$and ω_5.

The rotor speed and corresponding power error average are very negligible, such as rotor speed error is 0.04666 rpm and power error is 50 watt which is shown in Fig. 4.4. On the other hand, if the step size is too large, the average error in the rotor speed and the corresponding power will be too high. This error is higher than the previous small step size perturbation error value. Also, the error of rotor speed is obtained, which is higher than the previous rotor speed error which is shown in Fig. 4.5.

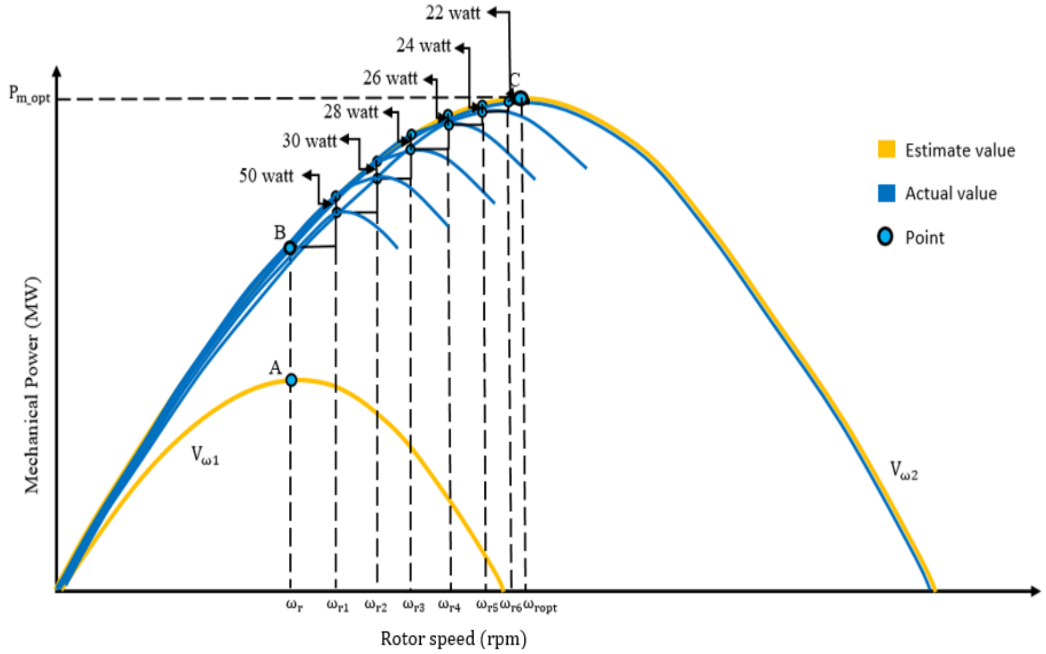


Figure 4.4: Error in P&O based MPPT algorithm for small step size perturbation

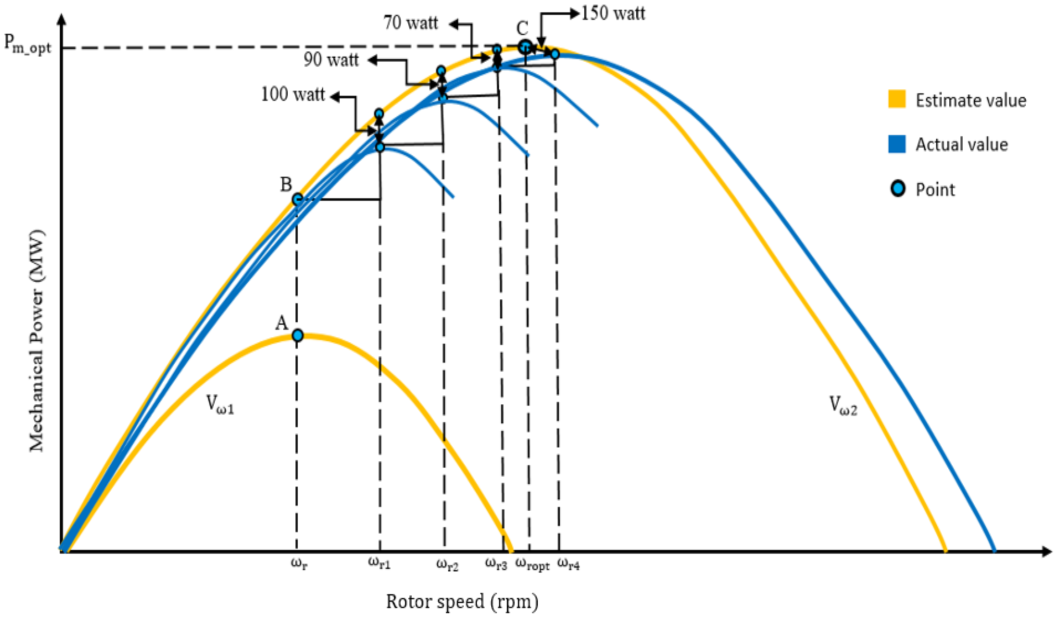


Figure 4.5: Error in P&O based MPPT algorithm for large step size perturbation

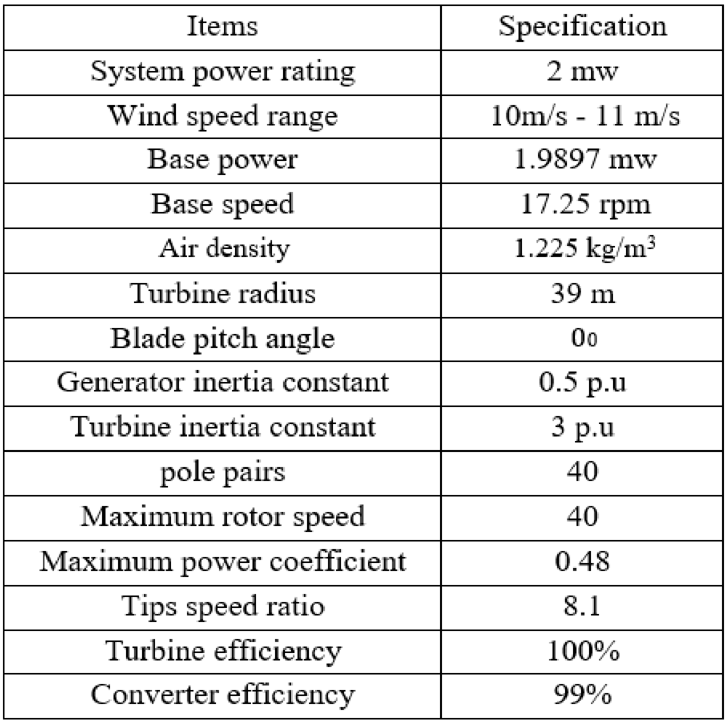
Chapter 5

SIMULATION RESULT

5.1 Simulation results of P&O based MPPT algorithm

The proposed MPPT algorithm is used to obtain the maximum power point from a 2 MW wind turbine generator and this algorithm is simulated by using the MATLAB. The proposed algorithm perturbs the rotor speed of a wind generator and observes the change of power output for a certain wind speed. The analysis of the algorithm's performance has shown that it can accurately determine the optimum power point and corresponding rotor speed. Also, the rotor speed and corresponding power errors have been measured. The results of the proposed algorithm approach under 3 different step and random changes in wind speed are shown in Fig. 5.1 to 5.18. The wind generator system parameters are shown in Table 5.1, respectively.

Table 5.1: Wind generator system parameters



Items	Specification
System power rating	2 mw
Wind speed range	10m/s - 11 m/s
Base power	1.9897 mw
Base speed	17.25 rpm
Air density	1.225 kg/m^3
Turbine radius	39 m
Blade pitch angle	0_0
Generator inertia constant	0.5 p.u
Turbine inertia constant	3 p.u
pole pairs	40
Maximum rotor speed	40
Maximum power coefficient	0.48
Tips speed ratio	8.1
Turbine efficiency	100%
Converter efficiency	99%

5.1.1 Step variation

5.1.1.1 Wind speed

In Fig. 5.1 shows the 3 different step wind speed are considered over a period of 120 second. Consider the wind speeds 10, 10.5, and 11 m/s, respectively. Here 0 to 20, 20 to 40, 40 to 60, and 100 to 120 second wind speeds are slowly increasing and 60 to 80, 80 to 100 second wind speeds are slowly decreasing.

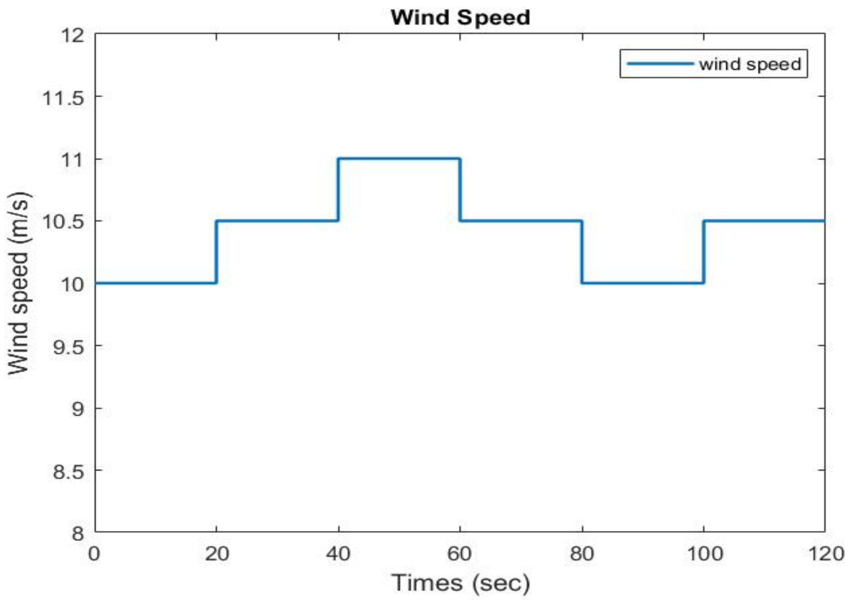


Figure 5.1: Wind speed variation over a duration of 120 sec

5.1.1.2 Rotor speed (in rpm)

In Fig. 5.2, the estimated and actual optimal rotor speed are together. The solid line show that the estimate optimum rotor speed and dash line show that the actual optimum rotor speed. The estimated and actual optimum value are overlapping start from 2 second. During the 120 second period, 0 to 20, 20 to 40, 40 to 60, and 100 to 120 second rotor speed slowly increases and 60 to 80, 80 to 100 second rotor speed slowly decreases, through the algorithm using the different wind speed conditions. The result shown that the rotor speed followed the change in wind speed properly and indicated the effectiveness of the algorithm in tracking optimum rotor speed. So, it is possible to track the optimum rotor speed of wind turbine generator through algorithm using different wind speed conditions.

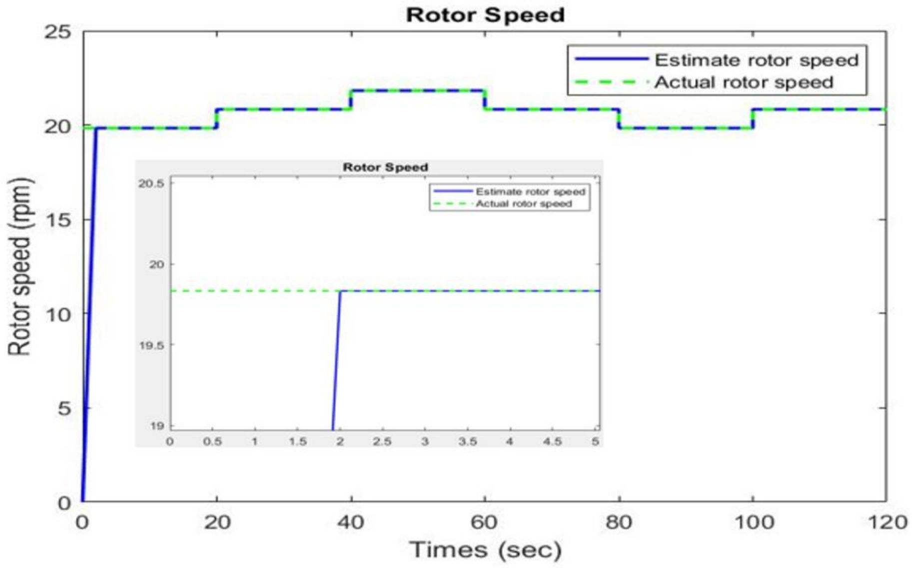


Figure 5.2: Rotor speed variation over a duration of 120 sec

5.1.1.3 Rotor speed error (in rpm)

In Fig. 5.3, the rotor speed error is determined by calculating the difference between the estimated and actual optimum rotor speed. The optimal rotor speed error is 0.04666, 0.04166, and -0.03566 rpm, respectively.

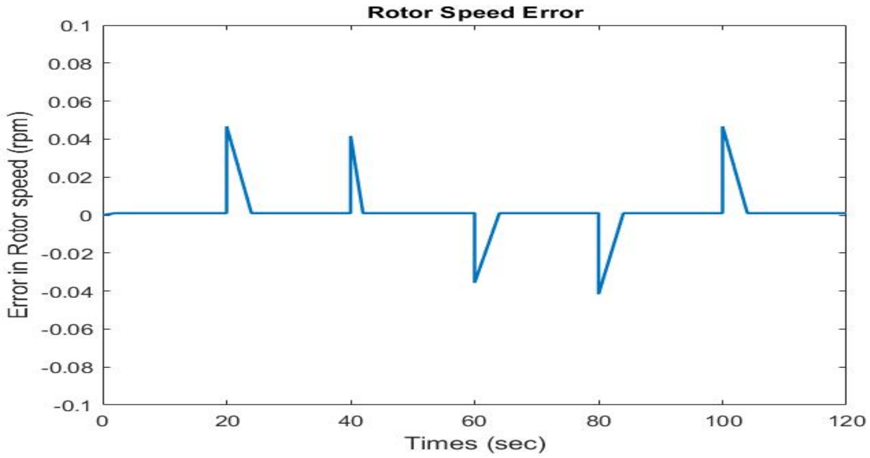


Figure 5.3: Rotor speed error over a duration of 120 sec

5.1.1.4 Mechanical power (in watt)

In Fig. 5.4, when the wind speed and rotor speed are changes the mechanical power proportionally changes. The estimated and actual optimum power are together. The solid line show that the estimate maximum power and dash line show that the actual maximum power. The estimated and actual maximum power are overlapping start from 2 second. During the 120 second period, 0 to 20, 20 to 40, 40 to 60, and 100 to 120 second power slowly increases and 60 to 80, 80 to 100 second power slowly decreases, through the algorithm using the different wind speed conditions. The result shows that the power followed the change in wind speed properly and indicated the effectiveness of the algorithm in tracking maximum power. So, it is possible to track the maximum power of wind turbine generator through algorithm using different wind speed conditions.

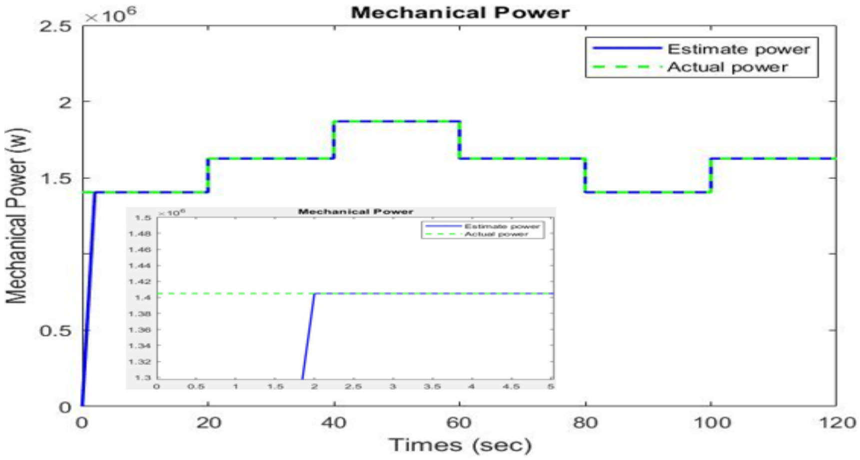


Figure 5.4: Mechanical power variation over a duration of 120 sec

5.1.1.5 Power error (in watt)

In Fig. 5.5, the power error is determined by calculating the difference between the estimated and actual maximum power. The average maximum power error is 50 watt.

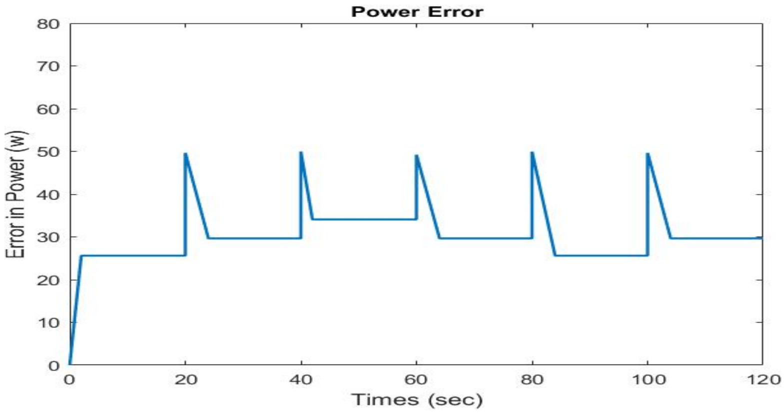


Figure 5.5: Power error over a duration of 120 sec

5.1.1.6 Rotor speed efficiency

In Fig. 5.6, the rotor speed efficiency is 99.9950 %.

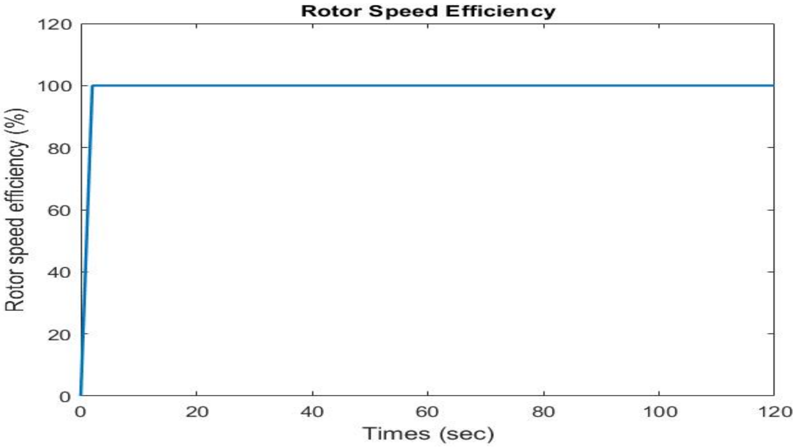


Figure 5.6: Rotor speed efficiency over a duration of 120 sec

5.1.1.7 Mechanical power efficiency

In Fig. 5.7, the mechanical power efficiency is 99.9982 %.

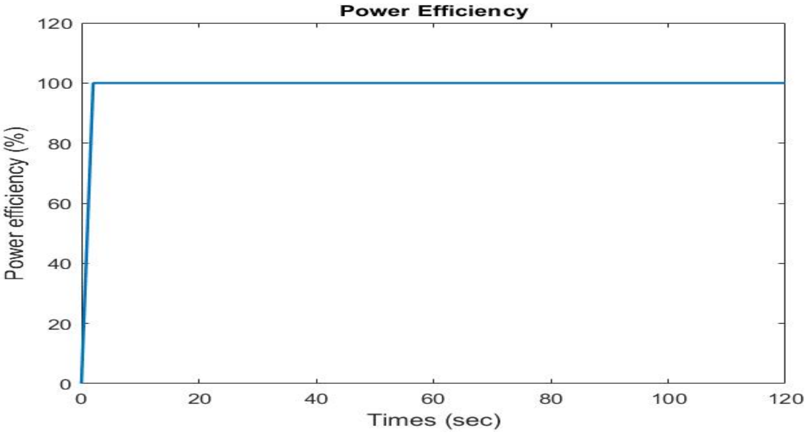
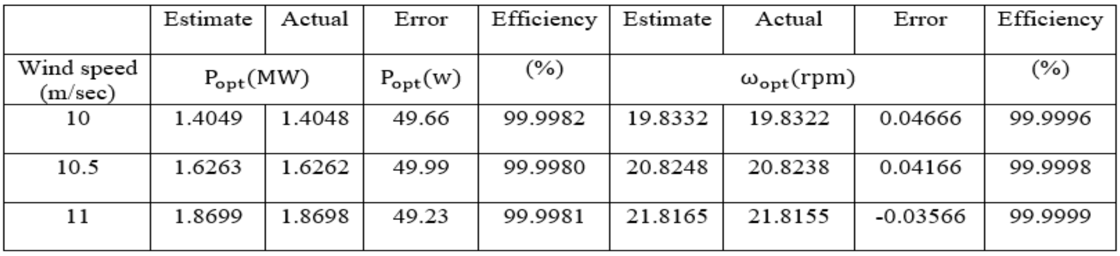


Figure 5.7: Mechanical power efficiency over a duration of 120 sec

5.1.1.8 Comparison data table

Table 5.2: comparison between the estimated values, actual values, and errors in MPPT for 3 different wind speeds.

Table 5.2: Comparison between the estimated values, actual values, and errors in MPPT for 3 different wind speeds (in watt and rpm)



	Estimate	Actual	Error	Efficiency	Estimate	Actual	Error	Efficiency
Wind speed (m/sec)	P_{opt}(MW)		P_{opt}(w)	(%)	ω_{opt}(rpm)			(%)
10	1.4049	1.4048	49.66	99.9982	19.8332	19.8322	0.04666	99.9996
10.5	1.6263	1.6262	49.99	99.9980	20.8248	20.8238	0.04166	99.9998
11	1.8699	1.8698	49.23	99.9981	21.8165	21.8155	-0.03566	99.9999

5.1.2 Random variation

5.1.2.1 Wind speed

In Fig. 5.8 shows the random wind speed are considered over a period of 120 second. Consider the random average wind speeds is 10 m/s, respectively.

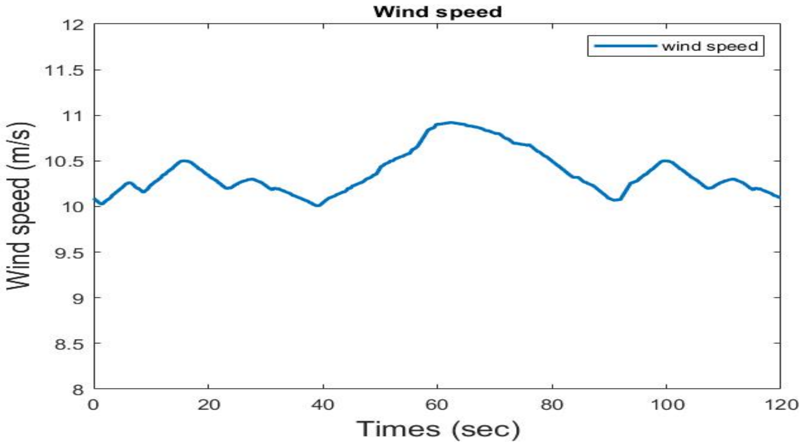


Figure 5.8: Random wind speed variation over a duration of 120 sec

5.1.2.2 Rotor speed (in rpm)

In Fig. 5.9, the estimated and actual optimum rotor speed are together. The solid line show that the estimate optimum rotor speed and dash line show that the actual optimum rotor speed. The estimated and actual optimum value are overlapping start from 0.2 second. During the 120-second period, the rotor speed undergoes random variations through an algorithm using random wind speed conditions. The result shown that the rotor speed followed the change in wind speed properly and indicated the effectiveness of the algorithm in tracking optimum rotor speed. So, it is possible to track the optimum rotor speed of wind turbine generator through algorithm using random wind speed conditions. The average optimum rotor speed is 20.5673 rpm.

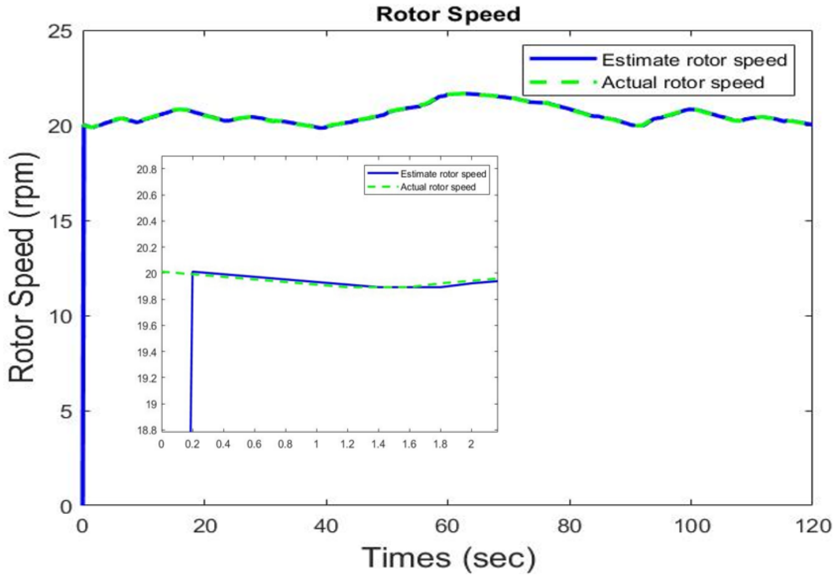


Figure 5.9: Random variation rotor speed variation over a duration of 120 sec

5.1.2.3 Rotor speed error (in rpm)

In Fig. 5.10, the rotor speed error is determined by calculating the difference between the estimated and actual optimum rotor speed. The average optimum rotor speed error is as 3×10^{-2} rpm.

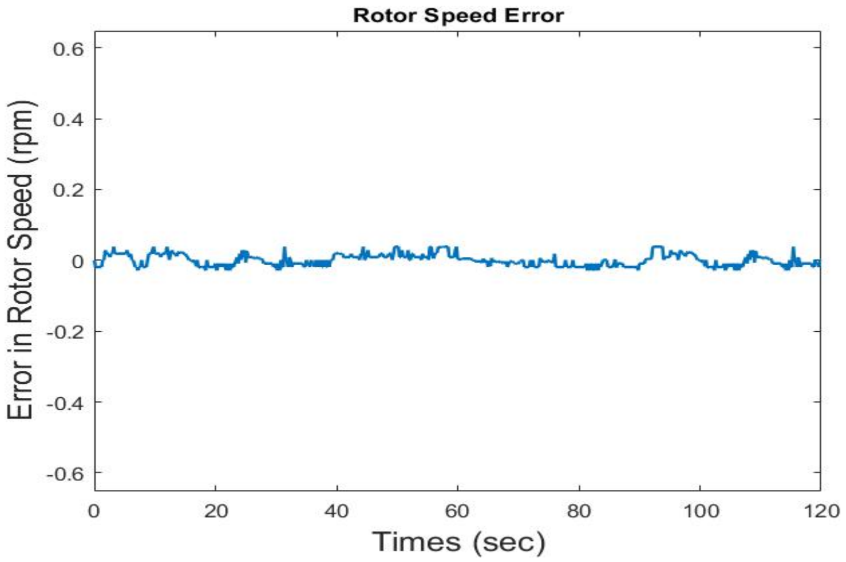


Figure 5.10: Random variation rotor speed error over a duration of 120 sec

5.1.2.4 Mechanical Power (in watt)

In Fig. 5.11, when the wind speed and rotor speed are changes the mechanical power proportionally changes. The estimated and actual optimum power are together. The solid line show that the estimate maximum power and dash line show that the actual maximum power. The estimated and actual maximum power are overlapping start from 0.2 second. During the 120-second period, the mechanical power undergoes random variations through an algorithm using random wind speed conditions. The result shows that the power followed the change in wind speed properly and indicated the effectiveness of the algorithm in tracking maximum power. So, it is possible to track the maximum power of wind turbine generator through algorithm using random wind speed conditions. The average optimum mechanical power is 1.57×10^6 watt.

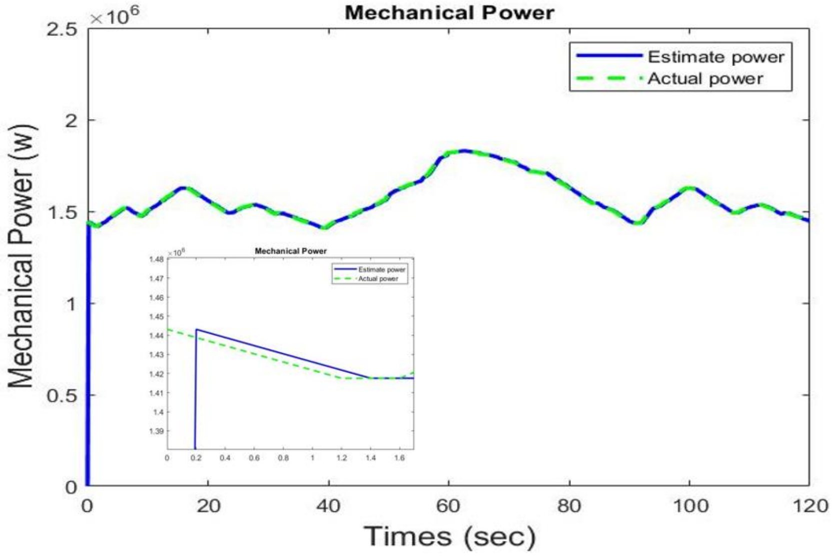


Figure 5.11: Random variation mechanical power variation over a duration of 120 sec

5.1.2.5 Power error (in watt)

In Fig. 5.12, the power error is determined by calculating the difference between the estimated and actual maximum power. The average maximum power error is 50 watt.

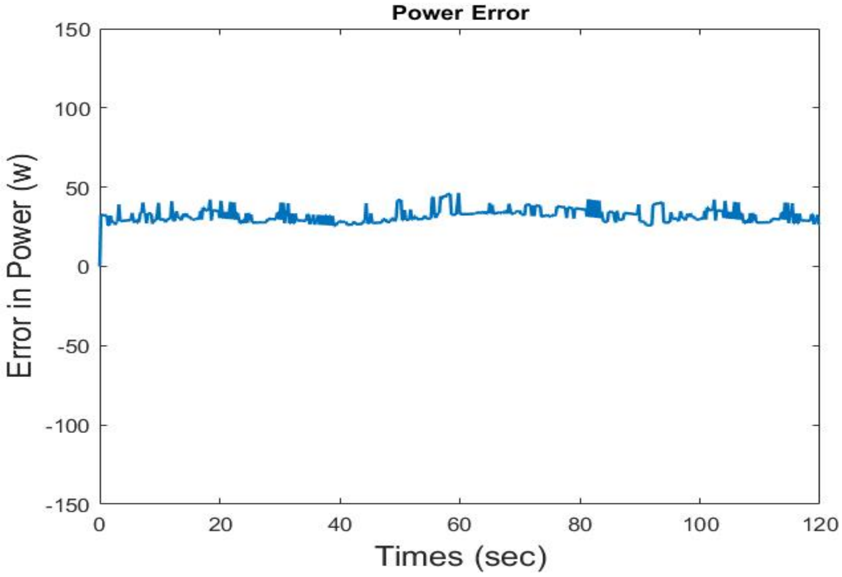


Figure 5.12: Random variation power error over a duration of 120 sec

5.1.2.6 Comparison data table (in watt and rpm)

Table 5.3 presents a comparison between the estimated values, actual values, and errors in MPPT in (watt and rpm) for random wind speeds.

Table 5.3: Comparison between the estimated values, actual values, and errors in MPPT for random wind speeds (in watt and rpm)

	Estimate	Actual	Error	Efficiency	Estimate	Actual	Error	Efficiency
Wind speed (m/sec)	P_{opt}(MW)		P_{opt}(W)	(%)	ω_{opt}(rpm)			(%)
10.01	1.409	1.408	42.21	100	19.85	19.84	0.0386	100
10.5	1.626	1.625	42.49	100	20.82	20.81	0.0384	100
10.92	1.829	1.828	45.83	100	21.66	21.65	0.0386	100

5.1.2.7 Rotor speed (in pu)

The average optimum rotor speed is 1.1923 pu, that is shown in Fig. 5.13.

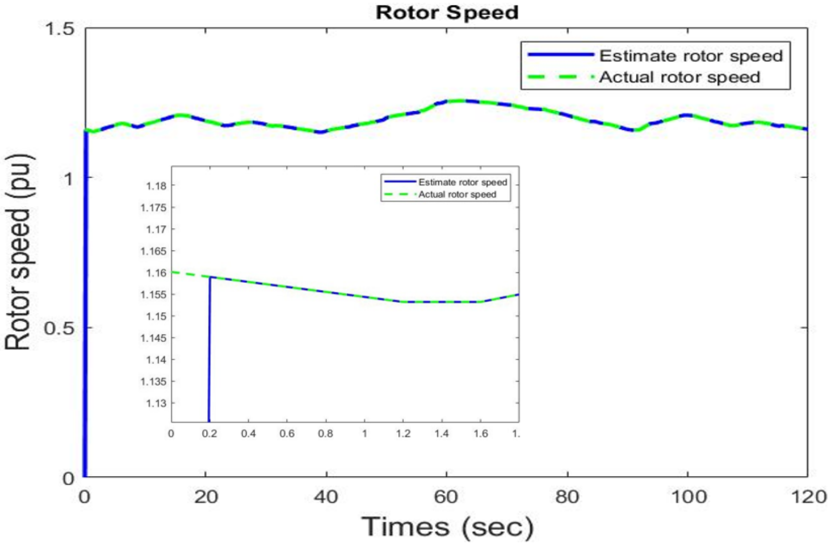


Figure 5.13: Rotor speed variation over a duration of 120 sec

5.1.2.8 Rotor speed error (in pu)

The average optimum rotor speed error is 1.29×10^{-3} pu that is shown in Fig. 5.14.

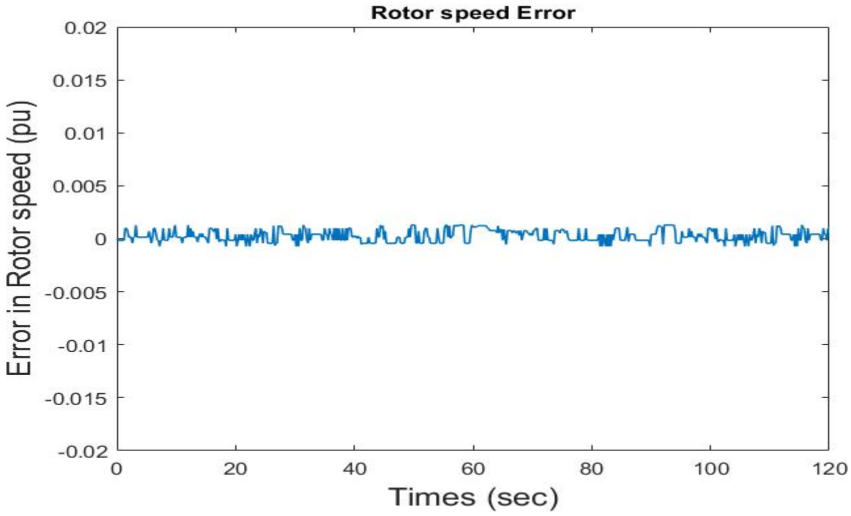


Figure 5.14: Rotor speed error over a duration of 120 sec

5.1.2.9 Mechanical power (in pu)

The average optimum mechanical power is 0.7678 pu, that is shown in Fig. 5.15

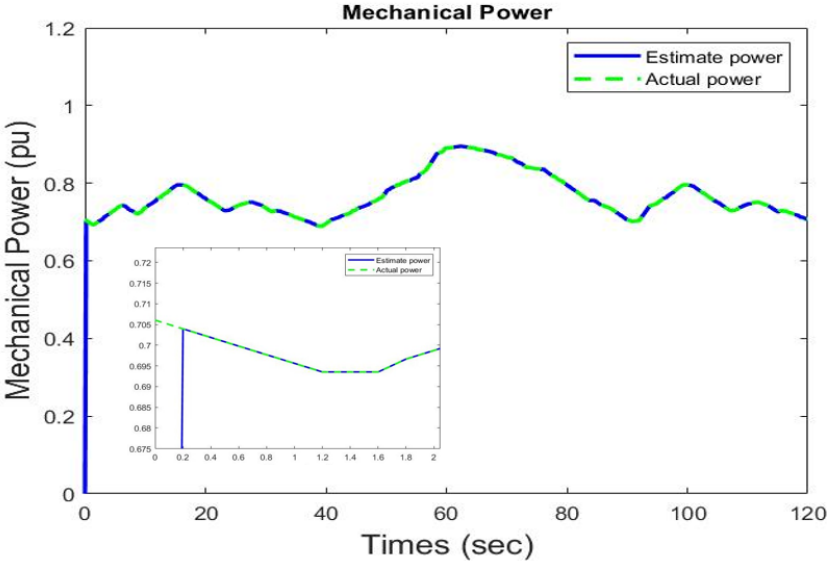


Figure 5.15: Mechanical power variation over a duration of 120 sec

5.1.2.10 Power error (in pu)

The optimum power error is as 2.271×10^{-5} pu, that is shown in Fig. 5.16.

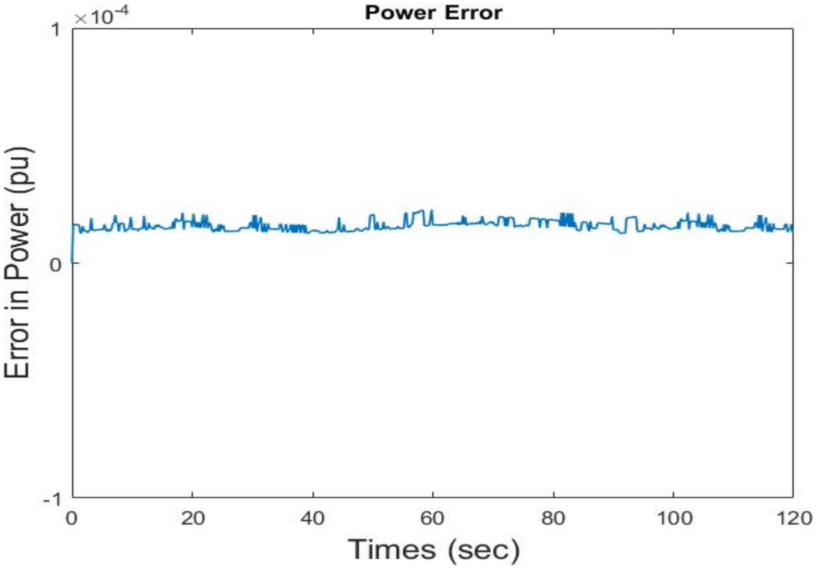


Figure 5.16: Power error over a duration of 120 sec

5.1.2.11 Rotor speed efficiency

In Fig. 5.17, the rotor speed efficiency is 99.8454 %

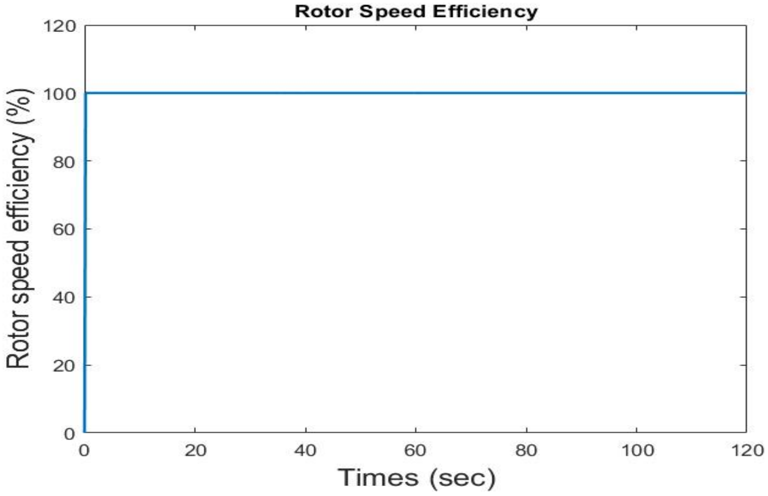


Figure 5.17: Rotor speed efficiency over a duration of 120 sec

5.1.2.12 Mechanical power efficiency

In Fig. 5.18, the mechanical power efficiency is 99.8666 %.

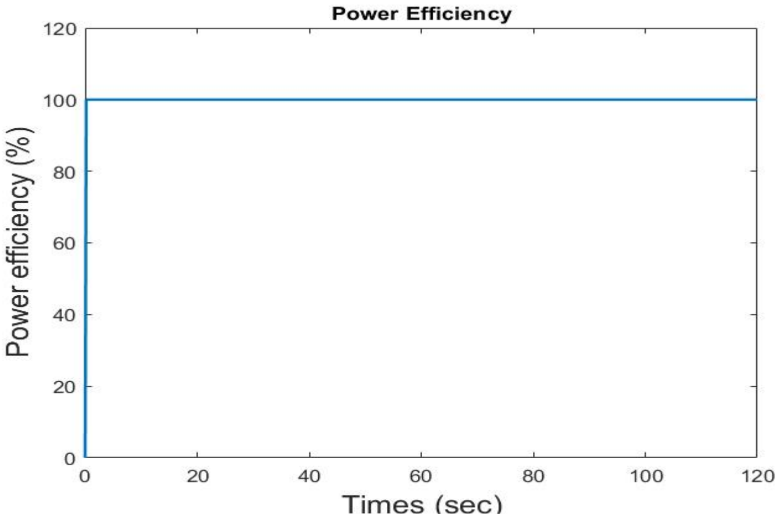


Figure 5.18: Mechanical power efficiency over a duration of 120 sec

5.1.2.13 Comparison data table (in pu)

Table 5.4 presents a comparison between the estimated values, actual values, and errors in MPPT in (pu) for random wind speeds.

Table 5.4: Comparison between the estimated values, actual values, and errors in MPPT for random wind speeds (in pu)

	Estimate	Actual	Error	Efficiency	Estimate	Actual	Error	Efficiency
Wind speed (m/sec)	$P_{opt}(pu)$		$P_{opt}(pu)$	(%)	$\omega_{opt}(pu)$			(%)
10.01	0.6894	0.6893	2.2×10^{-5}	100	1.151	1.150	0.001299	100
10.5	0.7957	0.7956	2.3×10^{-5}	100	1.207	1.206	0.001115	100
10.92	0.8945	0.8944	2.4×10^{-5}	100	1.255	1.255	0.001299	100

Chapter 6

CONCLUSION

6.1 Conclusion

The maximum power point at various wind speeds has been developed using the proposed P&O based MPPT algorithm. By maximizing the power output of the turbine, the algorithm has also increased the efficiency and dependability of the wind power system. The algorithm's performance study has demonstrated that it can precisely identify the optimum power and related rotor speed. Moreover, the rotor speed and power error have been evaluated.

It also explained how to modify the rotor speed to improve the performance of wind turbines using the three approaches of P&O, SD, and HC. The steepest descent method changes speed to minimize the difference between actual and desired power output, the P&O method adjusts speed to maximize power output, and the hill climbing method adjusts speed to increase power output. Every method has advantages and disadvantages of its own, thus the optimum one should be chosen depending on the application and specifications.

Also, the results demonstrated that the mechanical power output correctly followed changes in wind speeds, showing the efficiency of the algorithm in determining the optimum rotor speed. The corresponding rotor speed and power errors have been evaluated, and it has been discovered that they are quite small. The algorithm was used to get the maximum power point (MPP) with the least amount of computational effort.

The project has helped increase the amount of power generated by the wind, making wind power a more dependable and effective source of renewable energy. Overall, these results validate the efficacy of the proposed P&O-based MPPT algorithm for wind turbine generator. So, this algorithm has been utilized to obtain the maximum power point (MPP) with easy computational effort.

6.2 Future work

The following research may be carried out as extension of this project:

- It will be interesting to develop control strategies for variable speed wind turbines.
- Also it will be interesting to develop adaptive perturbation sizes for more accurate MPPT.
- Investigating the use of machine learning algorithms for MPPT in wind generators.
- Improving perturbation method to explore dynamic perturbation sizing for better accuracy and convergence speed.

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Appendix A

System parameter and operating values

Per unit:

Ra = 0.01 p.u.; Xd =1 p.u.; Xq = 0.7 p.u.;

Hg = 0.5 p.u.; Ht = 3 p.u.; Ks = 1 p.u.;

Ri=0.05 p.u.; Xi=0.1 p.u.;

Load and line:

Y11=0.2-j*0.4;

Zline=0.1+j*0.2;

Converter efficiency:

Etaturb=1.0;