ANALYSIS OF MAXIMUM POWER POINT TRACKING FOR SMALL SCALE WIND ENERGY CONVERSION SYSTEM USING DIRECT POWER CONTROL

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DEDICATION

This thesis is dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time. Also, to my lovely wife, who taught me that the best kind of knowledge to have is that which is learned for its own sake.

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ABSTRACT

Wind Energy Conversion System (WECS) is a promising Renewable Energy Source (RES) to generate electricity closer to the consumers in the area with suitable wind pattern. However, the Maximum Power Point Tracking (MPPT) algorithm design is a challenging task due to the random and unpredictable nature of the wind. Therefore, an efficient MPPT controller is essential to detect, track and extract the maximum extractable wind power at the optimal operating region of the Wind Turbine (WT). Direct Power Control (DPC) MPPT analyses the electrical properties of the power converter's output to track the maximum power point (MPP). Perturb and Observe (P&O), and Incremental Conductance (INC) are the most commonly used DPC type algorithms for MPPT. P&O algorithm design is simple but the selection of perturbation step-size is cumbersome and affects the MPP settling time and oscillation significantly if it is too large or too small. The INC algorithm design has better performance in detecting MPP. But there is a lack of research data available on INC MPPT performance for WECS application which is a gap that is addressed in this thesis. The objectives of this research are to design a small scale WECS using fixed and variable step-size P&O and INC MPPT algorithms. The design is simulated using the MATLAB/Simulink tool. Finally, the MPP performance of each algorithm is analysed and compared in terms of MPPT convergence time, oscillation and accuracy. The WECS design comprises a Wind Turbine (WT), a three phase Permanent Magnet Synchronous Generator, a full bridge diode rectifier, a DC-DC buck converter and MPPT controllers. The MPPT control scheme uses the relationship between the converter current values and generator's electromagnetic torque by increasing/decreasing the duty cycle to track the optimal power point. The steady state and dynamic response of the MPPT algorithms is observed and analysed through simulation. Larger step-size has high oscillation rate at the MPP. Smaller step-size takes longer to reach the maximum operating point. INC and Variable step-size P&O MPPT technique proves to achieve better efficiency and accuracy in terms of MPP tracking with relatively shorter convergence duration against conventional P&O MPPT. MPPT efficiency increases by 13.8% and 10.6% from Conventional P&O and INC to 96.4% with Variable P&O at rated condition.

ABSTRAK

Sistem Penukaran Tenaga Angin (WECS) adalah salah satu Sumber Tenaga Boleh Diperbaharui (RES) menjanjikan penjanaan elektrik yang lebih efisien untuk pengguna. Walau bagaimanapun, reka bentuk Penjejakan Titik Daya Maksimum (MPPT) untuk WECS mencabar kerana sifat angin yang rawak dan tidak dapat diramalkan. Oleh itu, pengawal MPPT yang berkesan sangat penting untuk mengesan, menjejak dan mengekstrak tenaga angin maksimum yang dapat diekstrak di kawasan operasi optimum Turbin Angin (WT). *Direct Power Control* (DPC) MPPT menganalisis sifat elektrik output penukar kuasa untuk mengesan Titik Kuasa Maksimum (MPP). *Perturb and Observe* (P&O) dan *Incremental Conductance* (INC) adalah jenis algoritma DPC yang paling biasa digunakan untuk MPPT. Reka bentuk algoritma P&O adalah mudah tetapi pemilihan ukuran langkah gangguan adalah membebankan dan memberi kesan kepada masa dan ayunan MPP dengan ketara jika terlalu besar atau terlalu kecil. Reka bentuk algoritma INC mempunyai keupayaan ketepatan yang lebih baik dalam mengesan MPP. Terdapat kekurangan data penyelidikan mengenai prestasi INC MPPT untuk aplikasi WECS yang merupakan jurang yang ditangani dalam tesis ini. Objektif penyelidikan ini dicapai melalui reka bentuk WECS skala kecil menggunakan algoritma P&O dan INC MPPT ukuran tetap dan berubah-ubah. Seterusnya, reka bentuk disimulasikan menggunakan program Matlab / Simulink. Akhirnya, prestasi MPP setiap algoritma dari segi masa penumpuan MPPT, ayunan dan ketepatan dianalisis dan dibandingkan dengan algoritma P&O MPPT ukuran tetap konvensional. Reka bentuk WECS terdiri daripada Turbin Angin (WT), Penjana Segerak Magnet Tetap tiga fasa, penerus ‘diode rectifier’ penuh, penukar ‘buck’ DC-DC dan pengawal MPPT. Skema kawalan MPPT menggunakan hubungan antara nilai arus penukar dan tork elektromagnetik penjana dengan meningkatkan atau menurunkan kitaran tugas untuk mengesan titik daya optimum. Keadaan stabil dan tindak balas dinamik algoritma MPPT diperhatikan dan dianalisis melalui simulasi. Ukuran langkah yang lebih besar mempunyai kadar ayunan yang tinggi di MPP. Ukuran langkah yang lebih kecil memerlukan masa yang lebih lama untuk mencapai titik operasi maksimum. Teknik INC dan P&O MPPT ukuran langkah yang berubah-ubah terbukti dapat mencapai kecekapan dan ketepatan yang lebih baik dari segi penjejakan MPP dengan jangka masa penumpuan yang agak pendek berbanding dengan MPPT P&O konvensional. P&O MPPT ukuran langkah berubah-ubah boleh mencapai kadar kecekapan 13.8% dan 10.6% lebih tinggi berbanding P&O konvensional dan INC.

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LIST OF ABBREVIATIONS

AC - Alternating Current
DC - Direct Current
DPC - Direct Power Control
DFIG - Doubly-fed induction generator
GHG - Greenhouse gases
HCS - Hill Climb Searching
HAWT - Horizontal Axis Wind Turbine
INC - Incremental Conductance
IPC - Indirect Power Control
IPCC - Intergovernmental Panel on Climate Change
MPPT - Maximum Power Point Tracking
ORB - Optimum Relation Based
PMSG - Permanent Magnet Synchronous Generator
P&O - Perturb and Observe
PV - Photovoltaic
RES - Renewable Energy Source
SCIG - Squirrel Cage Induction Generator
TSR - Tip Speed Ratio
VAWT - Vertical Axis Wind Turbine
VPO - Variable P&O
WECS - Wind Energy Conversion System

LIST OF SYMBOLS

δ - Minimal error

D, d - Diameter

F - Force

v - Velocity

p - Pressure

I - Moment of Inertia

r - Radius

Re - Reynold Number

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

Due to the fact of increasing population, the energy demand has grown rapidly over the years. The current non-renewable energy reserve based on fossilized hydrocarbon is depleting and causing harm to the environment which has direct consequences towards climate change. Thus, Wind Energy Conversion System (WECS) has gained attention as a potential and profitable alternative energy source around the globe to address global issues such as the greenhouse effect faced with fossil fuel. Net-zero energy concepts for urban high-rise buildings and sub-urban houses using small-scale wind turbines are being actively studied by engineers, technologists, and researchers. The current trend shows that small scale wind turbine is slowly becoming the alternate choice for urban renewable energy solution to the solar power system. The simplicity, versatility, and low cut-in speed capability allow the small scale wind energy system to be installed closer to the consumer in urban terrains as part of the distributed generation system. The nature of wind is unpredictable, chaotic, and turbulent near the ground and in urban surroundings. To extract the maximum possible energy from the wind, a Maximum Power Point Tracking (MPPT) algorithm is used to control the wind energy conversion circuitry. The accuracy of the power peak detection capability of the MPPT algorithm determines the amount of wind power being captured by the wind energy conversion system [1] [2].

Direct Power Control (DPC) MPPT algorithms such as Perturb and Observe (P&O) or sometimes referred to as Hill Climb Searching (HCS) in some literature, Incremental Conductance (INC) and Optimum Relation Based (ORB) are being utilized widely in renewable energy conversion systems due to their simplicity and flexibility. These DPC MPPT algorithms control the wind energy conversion system output power directly. The MPPT algorithms under DPC that are commonly used are P&O and INC. The P&O MPPT algorithm is widely adopted in most wind energy conversion systems due to its simple power tracking methodology structure. However, the selection of suitable step size has direct consequences to the performance of the MPPT capability where a trade-off has to be made the convergence speed and accuracy which is determined based on the amplitude of the oscillation at the maximum power point. Large step-size could lead to high tracking oscillation at MPP meanwhile smaller step-size slows the tracking speed hence reduces the efficiency of the wind energy conversion system. INC MPPT algorithm is being studied widely and tested in photovoltaic (PV) systems in the industry due to its accurate MPP tracking capability and faster response to rapid wind condition changes. However, INC algorithm is much more complex compared to P&O and less common among the wind energy research community.

Both P&O and INC algorithms are amply researched in their respective field of application independently, but there is very little information available on the inter-MPPT analysis between them to understand more about their MPPT capability and to compare the tracking performances for the same system to determine the most optimal MPPT solution for small scale wind application.

1.2 Research Background

1.2.1 World Energy Market

Based on NASA’s Earth Observatory data shown in Figure 1.1, the Earth’s surface temperature is increasing towards an alarming level due to the Greenhouse Gases (GHG) that disrupts Earth’s natural cooling mechanism by trapping the heat within the surface which is known as the Global Warming Phenomenon [3]. The energy industry contributes to the most GHG emission into the atmosphere as per the Intergovernmental Panel on Climate Change (IPCC) assessment finding [4]. The rapid growth in global energy demand has a direct correlation with the increase in human population and industrialization. Referring to statistical data shown in Figure 1.2, fossil fuel dominates more than 50% of the energy market as the source of fuel to produce electricity [1] [5]. However, the energy transition to Renewable Energy Sources (RES) has started in many developed and even developing countries such as the United States, United Kingdom, Europe, Australia, and China as per the trend shown below.

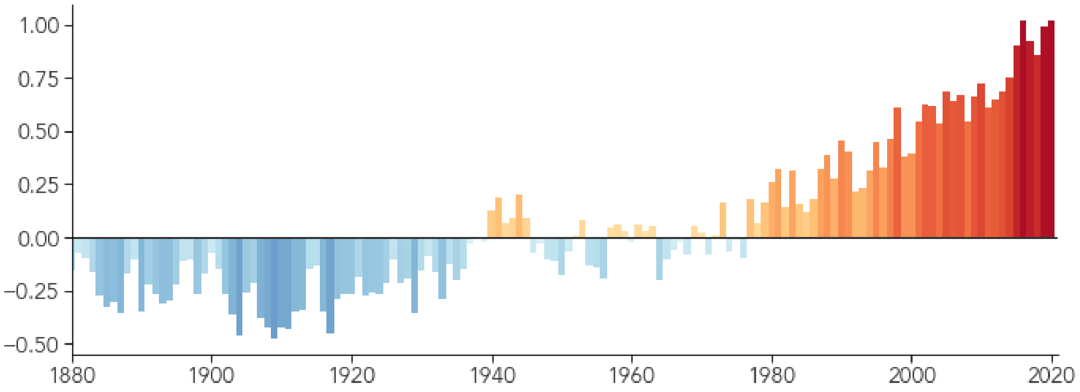

Figure 1.1 Global Temperature Anomaly Statistic compared to 1951 – 1980 average [3]

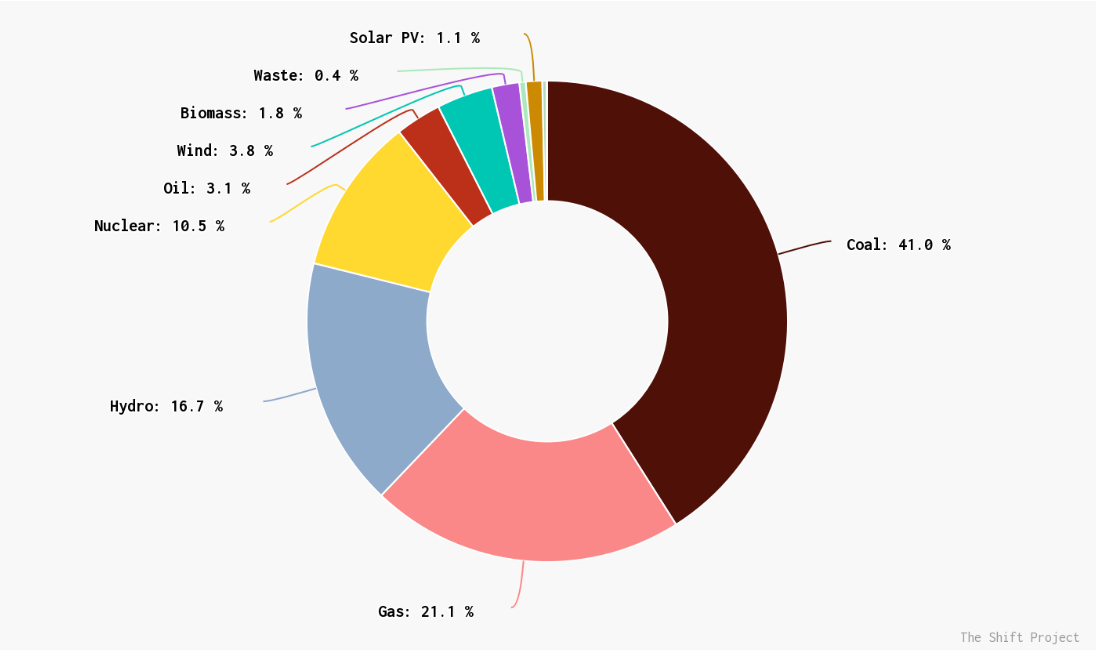

Figure 1.2 Global Electricity Generation by Fuel Source, 2015 [5]

RES are naturally occurring energy sources that are available in abundances such as wind, geothermal, water, biomass, and the sun. The wind exists everywhere and is the resultant of dissimilarities in energy density distribution across the Earth’s surface. U.S Department of Energy states that a one (1) megawatt capacity wind turbine electricity production offsets approximately two (2) kilotons of CO_2 mass in the atmosphere [6]. The wind turbine installation has increased six (6) folds in the last ten (10) years due to high global demand [7].

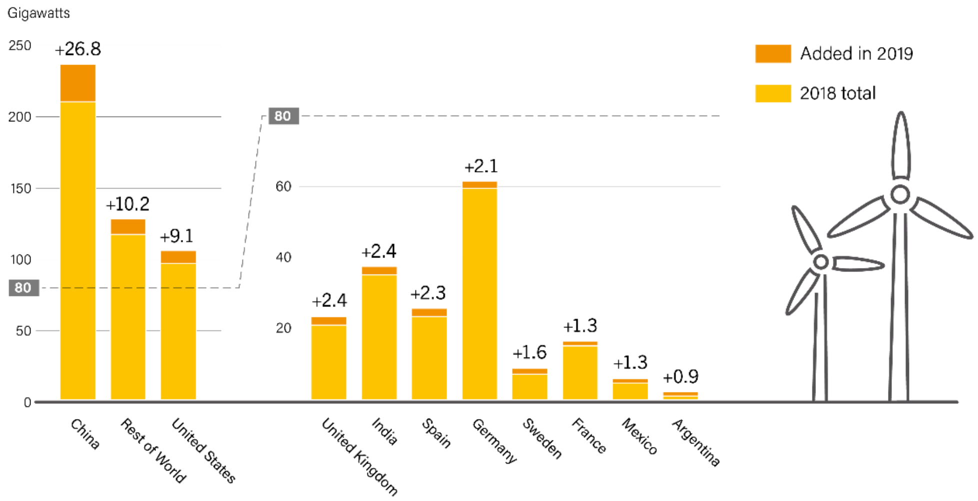

Figure 1.3 Wind Power Capacity Trend by Top 10 Countries [7]

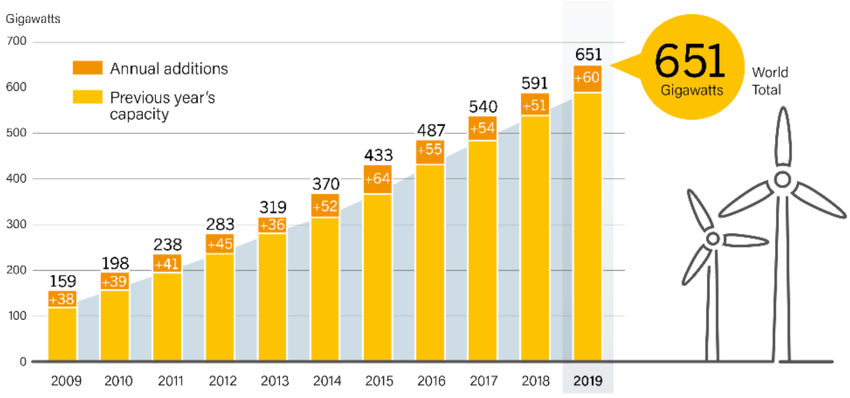

Figure 1.4 Global Wind Power Capacity Growth from 2009 – 2019 [7]

1.2.2 History of Wind Energy

Wind energy was harnessed using vertical axis type design during the early 10th century by the Persians for mechanical work such as lifting the water and grinding the wheat or corn. The Dutch invented the first windmills using the horizontal axis type design in the early 15th century for agricultural use. And, the Americans improvised the design to pump water to their homes. The first horizontal axis wind turbine used to produce electricity was built in 1888 in Cleveland, Ohio. And, the first vertical axis wind turbine was constructed more than a century later in California [8].

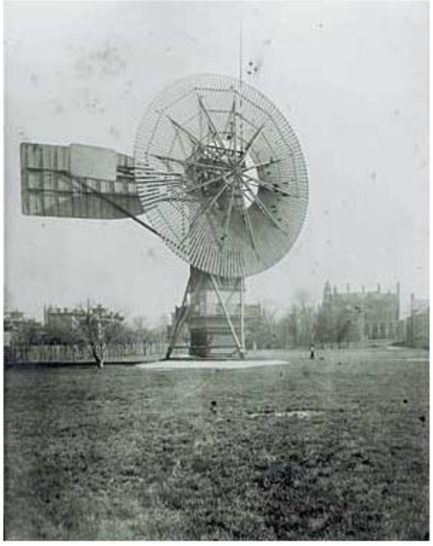

Figure 1.5 First electricity production wind turbine, 1888 in Cleveland, Ohio [9]

Even though the concept of wind energy has started earlier, it was not popular as compared to fossil fuel which had monopolized power generation in Europe and the United States (US) during the industrial revolution. The wind power conversion system was back in the picture in the later 1970s after the oil crisis hit the economy badly. Large scale wind energy technology companies emerged in the United Kingdom, Germany, Denmark, and the US. In the last decade, the Europeans have emerged as the front liners in wind energy installation followed by China and the US [6] [7].

According to market analysts, increasing the global investment in wind energy shows huge potential for wind energy application as one of primary sources of renewable energy and is predicted to continue to grow exponentially in the next five years by the market analyst [7] as shown in Figure 1.6. In the past, wind turbines were mostly constructed on the land. However, technology innovation has enabled offshore wind installation to address some of the hurdles faced by onshore wind turbines such as noise pollution and aesthetic concern raised by the public [10]. Alternatively, Vertical Axis Wind Turbine (VAWT) has been predicted as a potential solution for the implementation of WTs in urban and semi-urban areas [11] [12].

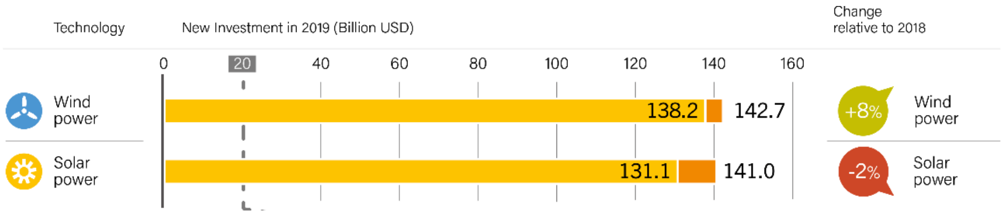

Figure 1.6 Global Investment in Renewable Energy (Wind and Solar), 2019 [7]

1.2.3 Wind Turbine Technology

The wind turbines are commonly classified based on the axis of the turbine rotation; the Horizontal-Axis Wind Turbine (HAWT) and Vertical-Axis Wind Turbine (VAWT).

1.2.3.1 Horizontal-Axis Wind Turbine (HAWT)

The HAWT rotors are designed to face parallel to the headwind. The basic components of HAWT are the tower, rotor blade, wind sensors, and nacelle which encloses the generator, gearbox, yaw, and pitch control motors, power conversion, and control system. The airfoil-shaped turbine rotor blade has an engineered aerodynamic design that converts the linear motion of the wind into rotational mechanical energy and drives the generator through a gearbox. The air pressure difference created in the upper and lower region of the airfoils creates an aerodynamic lift force similar to an airplane’s design which turns the rotor when the wind speed exceeds a certain starting velocity. Modern HAWT rotor designs are three (3) blade system which has the balance between cost and optimal efficiency in terms of lift to drag ratio. The main advantage of HAWT is its capability of self-starting and higher wind-to-mechanical energy conversion efficiency. HAWT construction is durable which enables access to strong winds at high elevations on land and offshore. However, the production and installation cost of HAWT is relatively high due to stronger construction to support the nacelle and rotor blades at the top of the tower. High voltage cables run from the top of the tower to the ground add up to the overall CAPEX of the HAWT [13] [14].

1.2.3.2 Vertical-Axis Wind Turbine (VAWT)

The VAWT rotates at the perpendicular axis to the ground. The generator and all power system equipment located on the ground at the base of the VAWT. There are two (2) popular VAWT designs which Darrieus and Savonius studied and developed in the market [15]. Due to the turbulent and chaotic nature of wind near the ground and in the urban environment, the HAWT solution becomes less effective. Thus, the VAWT has gained attention as a potential candidate for urban application because of its design to operate at lower wind speed, no noise concern and lower capital investment due to lesser support structures, and no yawing requirement [16]. Even though VAWT operates irrespective of the wind direction, the wind-to-mechanical rotational energy conversion efficiency is relatively lower and has limited room to regulate the speed at high wind scenarios compared to a small-scale HAWT design. Besides, VAWT design is mostly non-self-starting and requires high torque management which makes the cost-of-energy (COE) value higher compared to HAWT for urban application. Therefore, the wind turbine considered in this thesis is a small scale HAWT design [15] [17].

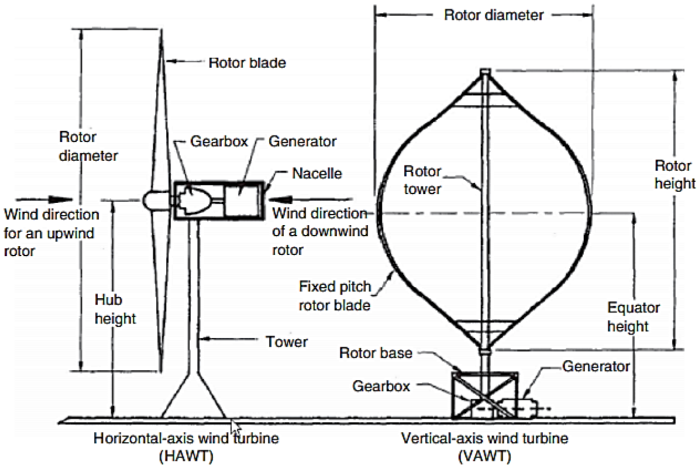

Figure 1.7 HAWT and VAWT Typical Configuration [18]

1.2.4 Maximum Power Extraction

Wind speed is unpredictable and changes stochastically at all times. Thus, a carefully designed tracking and control mechanism needs to be in place to enable the power conversion system to operate at optimal point at all time. Without proper optimization, a significant amount of wind energy will be wasted unnecessarily leading to efficiency decrement. One of the methods is using maximum power point tracking (MPPT) algorithms to track the power generated and control the power converter circuit to match the optimal operating point [19]. The MPPT algorithm controls the wind energy conversion circuit to operate at an optimal power point condition as shown in Figure 1.8. In this thesis, the focus will be analyzing the Direct Power Control (DPC) MPPT algorithm such as P&O and INC application to control the duty cycle of the DC-DC converter to achieve maximum power tracking capability at the highest efficiency possible. Details about the WECS and MPPT algorithms will be discussed in Chapter 2.

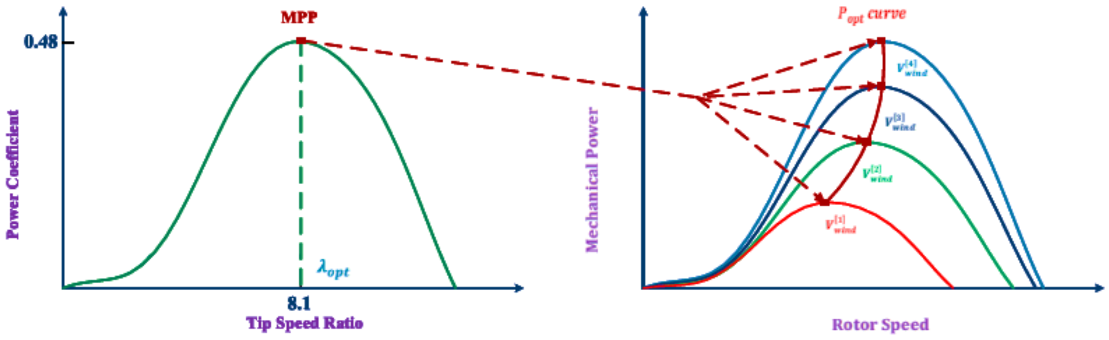

Figure 1.8 Wind Turbine Maximum Power Point (MPP) [20]

1.3 Problem Statement

The primary challenge of the P&O MPPT algorithm is the selection of suitable perturbation step-size. The conventional P&O (C-P&O) utilizes fixed step-size for all wind conditions which has several drawbacks. Smaller step-size leads to slower power tracking capability and becomes less efficient during rapid wind speed changes. Meanwhile, a bigger step-size tracks the maximum power point (MPP) faster but has a large oscillation near the MPP region that takes a long time for convergence which affects the accuracy of the system. Researchers are studying several variable step-size P&O (V-P&O) MPPT algorithms to overcome the drawbacks of C-P&O however, step-size selection is still one of the complex tasks for the P&O MPPT algorithm. On the other hand, INC MPPT is largely employed in solar PV systems and detects MPP with significant precision. However, the calculation and decision-making algorithm is relatively complex and takes more computing power. Besides, INC MPPT is less researched on WECS thus not much information available for reference. Thus, extensive research on P&O and INC MPPT algorithms and finding the most effective MPPT strategy that the has a balance in terms of system complexity and efficiency with relatively low computational power for small-scale WECS application are greatly necessary. Therefore, in this work, the MPPT performance between INC and P&O MPPT are analysed in terms of MPP tracking convergence time, oscillation and efficiency relative to conventional P&O MPPT.

1.4 Research Objectives

The objectives of the research are:

(a) To control the maximum power point tracking in wind energy conversion system using Perturb and Observe, and Incremental Conductance MPPT algorithms.

(b) To simulate the studied algorithm in MATLAB / Simulink environment under various input wind speeds.

(c) To analyze and compare the tracking performance of Incremental Conductance and Variable Step Perturb and Observe MPPT algorithms against conventional Perturb and Observe MPPT algorithm.

1.5 Scope

The main scopes of this work are the proposed algorithm analyzed for small scale WECS (≤10 kW) for off-grid DC load application in urban or sub-urban environments. Secondly, the proposed algorithm analyzed for a WECS using a fixed pitch wind turbine standard model, three-phase Permanent Magnet Synchronous Generator (PMSG), full-bridge diode rectifier, and DC-DC converter circuit. Next, the proposed algorithm will be implemented to control the duty cycle control of the load side DC-DC converter circuit. Also, the generator side control and/or mechanical means of control design is not the focus of this paper. Finally, this work will be simulated in a MATLAB environment using standard Simulink model for the wind turbine, rectifier, PMSG, and DC-DC converter provided by Mathworks.

1.6 Hypothesis

Step-size selection large or small has significant influence in the maximum power point tracking and control system. Optimal performance in maximum power point tracking in terms of speed and accuracy for a small-scale wind energy conversion system can be achieved using a variable step-size P&O MPPT algorithm.

1.7 Report Outline

The report is organized as follows:

(a) Chapter 1 introduces the concept and types of wind energy technology. The wind energy conversion system and its key components are discussed in this chapter. The research motivation, problem statement, research objectives, and scopes of study are discussed in this chapter.

(b) Chapter 2 presents a detailed literature review on the various MPPT algorithm schemes researched in the industry. The chapter highlights the limitations and assumptions of these researches and points out specific gaps that will be addressed in this report providing analysis and improvement to the mentioned MPPT algorithm in the literature.

(c) The methodology of simulation circuitry design and MPPT algorithm implementation is discussed in Chapter 3. The chapter briefly explains the thesis work methodology taken in this research. The research activities, progress and timeline will be presented in this chapter.

(d) Chapter 4 presents the result and discussion about this study. The simulation results and correlation between the studied algorithms and the MPPT algorithm performance is discussed in this chapter.

(e) Chapter 5 concludes the report on the studied approach and summarizes the outcome of the analyzed algorithms in terms of optimal accuracy and speed in tracking the maximum power point of the wind energy conversion system at the end of the research.

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