MODELLING OF SENSORLESS MPPT CONTROLLER FOR VARIABLE SPEED PMSG WIND TURBINE STAND-ALONE SYSTEM

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by

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ABSTRAK

Tesis ini membincangkan tentang penilaian potensi tenaga angin di Pulau Pinang, Malaysia dan juga pemodelan sistem penukaran tenaga angin (WECS) dengan menggunakan Matlab/Simulink. Sistem keseluruhan pemodelan menggambarkan simulasi starategi kawalan pengesanan titik kuasa maksimum tanpa deria (MPPT) yang dipermudahkan bagi merekod tenaga maksimum daripada angin berubah-ubah dalam sistem penjana turbin angin laju boleh ubah bebas yang berskala kecil (VSWTGS) dengan menggunakan penjana segerak magnet kekal (PMSG) dan suatu pengawal penyongsang iaitu pengawal modulasi lebar denyut sinus (SPWM) rentak mati berasaskan kadaran-kamiran (PI) juga digunakan bagi penyongsang punca voltan satu fasa bebas (VSI) untuk menghantar kuasa ke beban tunggal. Pengawal MPPT tanpa deria yang dicadangkan bagi pacuan terus PMSG WTGS tunggal yang berskala kecil juga disimulasikan untuk kegunaan bateri pengecasan dalam sistem tenaga penyimpanan. Sistem penyongsang telah menerangkan simulasi bagi PI rentak mati pengawal SPWM VSI yang menggunakan sel bateri sebagai sumber tenaga utama. Data angin dianalisis secara statistik dengan menggunakan fungsi taburan Rayleigh dalam penilaian potensi tenaga angin. Keputusan telah menunjukkan bahawa tapak pengukuran tergolong di bawah Kelas 1 dalam Klasifikasi Sistem Angin Antarabangsa. Iklim di Pulau Pinang sangat dipengaruhi oleh musim tengkujuh timur laut (NE) dan barat daya (SW). Purata ketumpatan kuasa angin tahunan (WPD) dan purata ketumpatan tenaga angin tahunan (WED) adalah masing-masing dianggarkan kira-kira 24.54 Wm^{-2} dan 17.98 $kWhm^{-2}bulan^{-1}$. Jumlah ketumpatan tenaga angin tahunan adalah 216 $kWhm^{-2}tahun^{-1}$. Oleh itu, satu sistem penjana turbin angin yang berskala kecil (WTGS) adalah lebih sesuai dan lestari di Pulau Pinang. Pengawal tanpa deria MPPT yang dipermudahkan telah dibangunkan untuk berfungsi sebagai satu penganggar kelajuan angin dan ia juga menunjukkan kebolehannya dalam mendapatkan kuasa maksimum daripada kelajuan angin yang berubah-ubah. Penukar kuasa boleh mengecaskan bateri dan juga penapis arus terus (DC) boleh mencegah pengaliran arus dan voltan puncak ke dalam bateri. Pengawal penyongsang tersebut telah menghasilkan bentuk gelombang voltan keluaran sinus yang baik dengan 50 Hz, 230 V_{rms}, dan hanya 3.24% THD_v terhasil apabila disambungkan kepada beban 500 W 0.85 PF. Penukar kuasa dan penapis menunjukkan prestasi yang baik dalam mengecas bateri asid plumbum dalam sistem tenaga penyimpanan. Voltan keluaran penyongsang dalam sistem penyongsang boleh dikesan dan dikekalkan pada 230 V_{rms}, 50 Hz dalam beberapa kitaran sahaja semasa beban berubah secara mendadak i.e. 400 W - 500 W and 400 W - 500 W 0.85 power factor (PF) lagging dengan jumlah kandungan herotan harmonik seluruh (THD_v) masing-masing 1.53% dan 2.78% dan seterusnya membuktikan kemantapan dan kekukuhan pengawal tersebut.

MODELLING OF SENSORLESS MPPT CONTROLLER FOR VARIABLE SPEED PMSG WIND TURBINE STAND-ALONE SYSTEM

ABSTRACT

This thesis presents an assessment of the wind energy potential at Bayan Lepas in Penang Island, Malaysia and also the modelling of wind energy conversion systems (WECS) by using Matlab/Simulink. An overall modeling system illustrates the simulation of a simplified sensorless maximum power point tracking (MPPT) control strategy for capturing maximum energy from the fluctuating wind-speed in stand-alone small scale variable speed wind turbine generator system (VSWTGS) using permanent magnet synchronous generator (PMSG) and an inverter controller of a deadbeat-based proportional-integral (PI) sinusoidal pulse-width-modulation (SPWM) controller is applied in single-phase voltage source inverter (VSI) for sending power to stand-alone load. The proposed sensorless MPPT controller for a stand-alone small scale direct-driven PMSG WTGS also has been simulated in energy storage system. In addition, an inverter system describes the simulation of a deadbeat-based PI SPWM controller for stand-alone VSI using battery cell as primary energy sources. The wind data were statistically analyzed using Rayleigh distribution function in wind energy potential assessment. The results show that the measurement site falls under Class 1 of the International System Wind Classification. The climate in Penang Island is highly influenced by the Northeast (NE) and Southwest (SW) monsoon seasons. The mean annual wind power density (WPD) and mean annual wind energy density (WED) are estimated to be about 24.54 Wm^{-2} and 17.98 $kWhm^{-2}month^{-1}$, respectively. The total annual WED is 216 $kWhm^{-2}year^{-1}$. Thus, a small-scale wind turbine generator system (WTGS) is more suitable and sustainable in Penang Island. Besides that, a simplified sensorless MPPT controller has been developed to function as wind-speed estimator shows to be capable of extracting the maximum power from the fluctuating wind-speed. Additionally, power converter can charge the battery as well as the DC filter can prevent high-sparking current and voltage from being injected back to the battery. Moreover, the inverter controller is producing a good sinusoidal output voltage waveform of 230 V_{rms} with only 3.24% THD_v when connected to a 500 W 0.85 PF lagging load. Meanwhile, the power converter and filters are showing good performance in charging the lead acid battery in energy storage system. Furthermore, the inverter output voltage of the inverter system can be tracked and maintained at 230 V_{rms}, 50 Hz within few cycles from the instant the load is changed i.e. 400 W - 500 W and 400 W - 500 W 0.85 power factor (PF) lagging with low total harmonic distortion (THD_v) content of 1.53 % and 2.78 %, respectively, proving the robustness and stiffness characteristic of the controller.

CHAPTER 1

INTRODUCTION

1.1 Overview of WECSs

Global energy consumption in the last half century has increased rapidly and is expected to continue to grow over the next 50 years. Of the total primary energy demand, the fossil fuels that provide the energy are oil, coal and natural gas. The major sectors using primary energy sources include electrical power, transportation, heating, industrial and others such as cooking. For electrical power, the coal is essentially has been used to generate electricity. It will certainly increase worldwide carbon dioxide (CO_2) emissions, and further increase global warming. In transportation, this sector has increased its relative share of primary energy. It contributes to the significant source of CO_2 emissions and other airborne pollutants and it is totally based on oil as its energy source (Kreith & Goswami, 2007).

Coal and oil, which are the buried products of several hundred million years of solar energy, photosynthesis, and geological pressure, have fuelled the industries and transport systems. The obtaining of the energy from the oil, coal and gas will continue to put CO_2 into the atmosphere at levels which it is widely acknowledged are elevating the average temperature on the planet. CO_2 molecules are a good heat absorber and it resonates strongly with infrared radiation causing it to be trapped as heat instead of all being transmitted into space. This will cause global warming which is already causing the polar ice caps to melt and it is inevitable that there will be higher sea levels resulting in less land for an increasing population, along with changes in climate. These changes are not easy to predict and may be difficult to reverse (Armstrong & Blundell, 2007). As a result, since there are depletion of fossil fuels reserves and the need to arrest global warming caused by the combustion of fossil fuels, an alternative to the fossil fuel power is renewable energy technologies.

Renewable energy technologies consists of the hydro, wind, solar, biomass, geothermal and ocean. Large scale hydroelectric projects have become increasingly difficult to carry through in recent years because of competing use of land and water. Relicensing requirements of existing hydro plants may even lead to removal of some dams to protect or restore wildlife habitats. Among the other renewable power sources, wind and solar have recently experienced a rapid growth around the world. Having wide geographical spread, it can be generated near to the load centers, thus simultaneously eliminating the need of high voltage transmission lines running through rural and urban landscapes. Besides, the conventional power sources have reached fully matured technologies however the renewable power sources are rapidly developing (Patel, 1999). Wind energy is the one of the most available and exploitable forms of renewable energy. Winds blow from a region of higher atmospheric pressure to one of lower atmospheric pressure. The difference in the pressure is caused by the fact that the earth's surface is not uniformly heated by the Sun and the earth's rotation. Essentially, wind energy is a by-product of solar energy, available in the form of that kinetic energy of air (Bhadra, Kastha, & Banerjee, 2005).

Wind has been known to man as natural source of mechanical power for long time. The technology of wind powers has evolved over this long period. Of the various renewable energy sources, wind energy has emerged as the most viable source of electrical power, and is economically competitive with the conventional sources (Bhadra, et al., 2005).

There are some advantages and disadvantages by using the wind turbine system. For the advantages, it does not emit CO_2 or produce any wasted products. The wind is also an infinite resource that cannot be exhausted. A small home wind turbines cuts reliance on traditional fossil fuel resources by using the power of the wind to create electricity. Besides that, small domestic wind turbines can potentially provide 30 to 35 % of an average home's electricity needs, and pay back in 8-10 years. This is much quicker payback than most solar-power generated electricity systems. The wind turbines also rely on simple mechanical processes. The large-scale wind farms can be built at sea without cluttering the landscape.

However, for the disadvantages, both small- and large-scale wind energy installations need planning permission. Many developments are consequently blocked by other local residents. Besides, the wind turbine costs are high. Large-scale wind farms also require a significant start-up investment from industry. In addition, the amount of electricity generated is dependent on the speed and direction of the wind. The wind-speed itself depends on a number of factors, such as location, height of the turbine and nearby obstructions. Furthermore, many people dislike the appearance and sound of wind turbines on the landscape although noise pollution is less significant for micro-wind turbines. Anti-wind farm groups also argue that wind farms damage habitats and harm birds and marine ecology. Besides that, the wind is an unpredictable energy source and requires the back up of more traditional and polluting method of energy generation. Since the significance of the advantages of the wind energy is more than that of the disadvantages, the wind energy would be preferred to be used to generate the electricity.

Generally, the wind turbine is a rotating machine which converts the kinetic energy in wind into mechanical energy. If the mechanical energy is then converted to electricity, the machine is called wind turbine. In the case of hydro, gas or steam, and diesel power stations, the delivery of energy can be regulated and adjusted to match demand by end users. In contrast, the conversion system of a wind turbine is subject to external forces. The delivery of energy can be affected by changes in wind-speed, by machine-dependent factors such as disruption of the airstream around the tower or by load variations on the consumer side in weak grids (Heier, 2006).

The wind power system is comprised of one or more units, operating electrically in parallel, having the components such as the tower, the wind turbine with two or three blades, the yaw mechanism, the mechanical gear, the electrical generator, and the speed sensors and control. The modern system often has the additional components such as the power electronics, the control electronics which incorporating with a computer, the battery for improving the load availability in stand-alone mode, and the transmission link connecting to the area grid (Patel, 1999).

Basically, the blades of a wind turbine rotor extract some of the flow energy from moving air, convert it into rotational energy and then deliver it via a mechanical drive unit such as shafts, clutches and gears to the rotor of a generator and hence to the stator by mechanical-electrical conversion. The electrical energy from the generator is fed via a system of switching and protection devices, lines and if necessary transformer to the grid, consumers or an energy storage device (Patel, 1999).

Besides that, the wind energy conversion devices can be broadly categorized into two types according to its axis alignment. There are two types of wind turbines i.e. horizontal-axis wind turbine (HAWT) and vertical-axis wind turbines (VAWT). HAWT can be further divided into three types. There are ‘Dutch-type’ grain-grinding windmills, multi-blade water pumping windmills and high-speed propeller type windmills. For VAWT, it comes in two different designs i.e. the Savonius rotor and the Darrieus rotor (Bhadra, et al., 2005).

Furthermore, the generation schemes for wind electrical conversion systems depend primarily on the type of output required as well as the mode of operation of the turbine. In present-day practice, two types of generators generally find application in wind power plants i.e. the synchronous generator and the induction generator. Synchronous generators may have Direct Current (DC) field excitation or a permanent magnet (PM) field. Systems using line-frequency excited alternators and Alternating Current (AC) commutator generators have been suggested for constant-frequency output from an aero turbine operated in the variable-speed mode, but they are not preferred over synchronous and induction generators. For the induction generators, there are two types of induction machines i.e. the squirrel cage type and the wound rotor (slip ring) type. For the synchronous generators, it can be wound-field synchronous machine and PMSG (Bhadra, et al., 2005).

Wind power is characterized by its stochastic nature. Wind-speed changes continuously, and along with it the energy flow. A variable-speed wind machine is able to extract significantly more energy than a constant-speed machine. However, the generated power, voltage and frequency from a variable-speed wind machine changes with the wind-speed. In such a situation, the most significant potential for the advancement of wind power technology lies in the area of power-electronics-controlled variable-speed operation. The developments in power electronics have not only increased the energy productivity but have also resulted in the quality control operation of both fixed and variable-speed wind turbines (Bhadra, et al., 2005).

In broad terms, the task of power electronics is to control the flow of electrical power efficiently by shaping the input voltage/current using power semiconductor devices so that the output voltage/current conforms to the load requirement. There are many criteria for classifying converters used in power electronics. It classifies power electronic converters based on the nature of the input and the output such as rectifier, DC-DC converter or chopper, cycloconverter and inverter. In power electronic converters, ideal switches are approximated by semiconductor devices with high switching speed, low on-state drop and low off-state current. However, semiconductor switches are generally unidirectional (Bhadra, et al., 2005).

Power semiconductor switches also can be classified into several categories i.e. uncontrolled, semi-controlled, and fully controlled. The uncontrolled semiconductor devices are diode and diac, the semi-controlled semiconductor devices are thyristors and triacs and the fully controlled devices are bipolar junction transistor (BJT), gate turn-off thyristor (GTO), power metal oxide semiconductor field effect transistor (MOSFET) and insulated gate bipolar transistor (IGBT) (Bhadra, et al., 2005).

As a result, wind energy is plentiful, renewable and it can reduce the greenhouse gas emissions instead of electricity generated from fossil fuels. The wind power system also can be built with a various type of components easily.

1.2 Problem Statement

The fossil fuels reserved that provide the energy including electrical power which are oil, coal and natural gas are depleted from time to time. Meanwhile, harmful phenomenon of global warming become more critical and obvious that causing the polar ice caps to melt and higher sea levels resulting in less land for an increasing population, along with changes in climate. As a result, an alternative to the fossil fuel power is renewable energy technologies.

1.3 Scope of the Research

The scopes of the research work basically covers two major studies. First part of the studies is wind data analyses that will focus on the investigation and assessment as well as evaluation of the wind energy potential in Penang Island. The wind data bought from the meteorological weather station at Bayan Lepas will be analyzed by using the specific statistical analysis tools. Hence, the study would be carried out based on the particular principals, calculations and theories in analyzing the wind data such as power law of estimating the wind-speed at various heights, WPD, air density and WED at Bayan Lepas. Besides that, the wind data are statistically analyzed using Rayleigh distribution function. There are several outcomes from the analyses which are the mean monthly wind-speed, maximum wind-speed, monthly mean hourly wind-speed in three quarters, wind direction, and mean wind power analysis. The wind data will be analyzed using Matlab programming to plot all of the various trends and graphs.

Next, the second study will be done in this research work is building the Simulink model of WECS and performing the simulation on that model. The Simulink model is used to develop the MPPT control strategy in tracking the maximum generated output power from the PMSG wind turbine system. Basically, the research focuses on the principals of power energy conversion systems from AC to DC and then converted back to AC sending power to the load. The scope of the study also covers four important parts which are mechanical system, machines, power electronics and the controllers. Those important parts are wind turbine, PMSG, rectifier, filters, DC-DC boost converter, inverter, MPPT controller and inverter controller with deadbeat-based PI SPWM switching scheme. This research project has been divided into three system simulation studies i.e. overall system: designing a sensorless MPPT control method for variable speed PMSG WTGS in supplying electricity for stand-alone load; energy storage system: designing a sensorless MPPT control in WTGS for battery charging application; inverter system: designing a deadbeat-based PI controller in single-phase inverter applying in stand-alone loads.

Moreover, analyzing and evaluating the proposed MPPT controller in tracking the maximum energy from the fluctuating wind as well as assessing and validating the inverter controller for producing a constant sinusoidal output voltage sending to the stand-alone load will be carried out in overall system. In addition, capturing the maximum power from the fluctuating wind in charging the battery energy storage by using the proposed sensorless MPPT control approach in the WTGS will be analyzed and certified in energy storage system. Next, in inverter system, the deadbeat-based PI controller associated with SPWM switching scheme will be analyzed and validated in controlling the single-phase inverter system for supplying a low THD_v to the loads. Last but not least, all Simulink models of the WECS will be built and simulated using Matlab/Simulink/SimPowerSystem software.

1.4 Objectives of the Research

The objectives of this project are listed below:-

(a) To investigate, analyze and assess the wind energy potential in Bayan Lepas, Pinang Island.

(b) To design and validate the sensorless MPPT control method and inverter controller in WECS supplying electricity to a stand-alone load using Matlab/Simulink platform.

(c) To develop a sensorless MPPT control strategy in order to maximize the generated output power from the PMSG WTGS for battery charging application in Matlab/Simulink environment and to design and verify the Simulink model of a deadbeat-based PI controller with SPWM switching scheme for controlling the single-phase inverter system in delivering power to several loads.

1.5 Contributions of the Thesis

One of the contributions in this research study is the wind energy potential could be evaluated at Bayan Lepas in Penang Island for future implementing WECS purposes. Another contribution is a novel and simplified MPPT controller can be used to capture the maximum power from the fluctuating wind in WECS for supplying electrical power.

1.6 Outline of the Thesis

The thesis is divided into six main chapters which are introduction, literature survey on wind regime analysis, literature survey on WTGS, methodology and design, analysis results, simulation results and discussions as well as conclusions and recommendations.

In Chapter 1, the content provides reader with the general overview of the wind energy and WECS as well as the problem statement. It also shows the scope of the research and objectives of the research that to be accomplished. The contributions of the thesis have also been described in this chapter.

Chapter 2 will show the theories on the wind regime analysis. It provides in-depth knowledge on the measurement of wind and wind data analysis. It also describes the calculation and formulas on power law for estimates of wind-speed at various heights, mean WPD, air density and mean WED. In addition, the literature review on the work of researchers will be discussed.

In Chapter 3, the study of WTGS will be discussed. It would provide in-depth derivation of formula as well as the theories in every single components which include wind turbine characteristic, PMSG, rectifier, DC-DC boost converter, lead acid battery, Butterworth low-pass filter, single-phase inverter, SPWM switching technique and PI controller. Its operation of major components such as DC-DC boost converter and single-phase inverter will be devoted. Review of the work of previous researches is discussed in this chapter as well.

In Chapter 4, the methodology and design of the project will be described. The flow chart and the description of the procedures involved in this project will be discussed. First, the methodology of wind data analysis will be explained. Then, the system design methodology and the parameters calculation will be clarified and validated in the Simulink model of sensorless MPPT control strategy and inverter control technique for supplying electricity to a stand-alone load. Besides that, the procedure of designing and calculating the parameters in the project of sensorless MPPT control in WTGS for battery energy storage will be discussed. In addition, step by step designing the Simulink model of a deadbeat-based PI controller with SPWM switching scheme in single-phase inverter system transferring electricity to several loads would be verified.

Chapter 5 describes the analysis results and simulation results of the entire research work. Firstly, the wind data analysis results will be discussed. Those analyses illustrate the mean monthly wind-speed as well as the maximum wind-speed of the wind data at Bayan Lepas. Meanwhile, the monthly mean hourly wind-speed in three quarters and Rayleigh distribution function of the wind-speed obtained from the wind data analyses will be elucidated. The analyses of wind direction and the mean WPD will also give in detail in this chapter. Besides that, the simulation results and discussion on WECS will be revealed in the chapter. The simulation results of the PMSG WTGS using MPPT controller in boost converter and deadbeat-based PI controller in single-phase inverter sending power to stand-alone load will be discussed in this chapter. Moreover, the simulation results obtained from the sensorless MPPT control approach in the WTGS for application in battery charging will be elaborated. Finally, the explanation will be carried out on the simulation results of controlling single-phase inverter using deadbeat-based PI controller applying in stand-alone loads.

Lastly, Chapter 6 would summarize the thesis with the conclusions and suggestions as well as recommendations to be used for further research on this topic in the future.

CHAPTER 2

LITERATURE SURVEY ON WIND REGIMES ANALYSIS

Chapter 2 describes on the study of the principal of the wind regime analysis. It will describe in-depth knowledge on the measurement of wind and wind data analysis. It also presents the calculation and formulas on power law for prediction of wind-speed at various heights, mean WPD, air density and mean WED. Besides that, the reviews and outcomes as well as the results on the work of previous researchers will be also discussed.

2.1 Background of Wind Regime Analysis

The depletion of fossil fuel reserves and the need to fulfill an increasing global energy demand have accelerated the efforts to seek alternative fuel sources such as wind power, solar energy, liquid biofuel, solid biomass, biogas and geothermal energy (Armstrong & Blundell, 2007).

Many countries worldwide recognize that the current energy trends are not sustainable and that a better balance must be found among energy preservation, economic development and protection of the environment (Fyrippis, Axaopoulos, & Panayiotou, 2010) especially in Malaysia. One of these sources is wind energy. The global wind energy market among other renewable sources has been experiencing a rapid growth especially during the last two decades (Gokcek & Genc, 2009). In addition, wind is a fuel-free, inexhaustible energy source and does not cause pollution in electricity production. Hence, the first step in planning a wind energy project is to identify a suitable site, having strong and impressive wind spectra (Mathew, 2006).

In fact, wind is stochastic in nature. The most critical factor influencing the power developed by a WECS is the wind velocity since even a small variation in the wind-speed may result in significant change in power. Besides that, speed and direction of wind at a location vary randomly with time. Hence, the behavior of the wind at a prospective site should be properly analyzed. Furthermore, the average wind velocity gives us a preliminary indication on a site's wind energy potential. However, its distribution is also play an important role. As a result, the statistical models are being used for defining the distribution of wind velocity in a regime, over a given period of time, so that it can proceed further with the assessment of the energy potential (Mathew, 2006).

2.2 Measurement of Wind and Wind Data Analysis

A precise knowledge of the wind characteristics at the certain regime is essential for the successful planning and implementation of WECS. The basic information required for such an analysis is the speed and direction of the prevailing wind at different time scales. Wind data from the nearby meteorological stations can provide better understanding on the wind spectra available at the site. However, for a precise analysis, the wind velocity and direction at the specific site has to be measured with the help of accurate and reliable instruments such as anemometers and wind vanes (Mathew, 2006).

The wind data from the meteorological stations can provide an idea on the suitability of a given site for wind energy extraction that can be made on the basis of short term field measurements. Anemometers fitted on tall masts are used for such wind measurements. As the power is sensitive to the wind-speed, good quality anemometers which are sensitive, reliable and properly calibrated should be used for wind measurements. Basically, there are different types of anemometers. Based on the working principle, it can be classified as rotational anemometers (cup anemometers and propeller anemometers), pressure anemometers (pressure tube anemometers, pressure plate anemometers and sphere anemometers), thermoelectric anemometers (hot wire anemometers and hot plate anemometers) and phase shift anemometers (ultra sonic anemometers and laser doppler anemometers). Meanwhile, direction of wind is an important factor in the sitting of a WECS that can predict major share of energy available from a certain direction. Hence, wind vanes will be used to identify the wind direction (Mathew, 2006).

Furthermore, for estimating the wind energy potential of a site, the wind data collected from the location should be properly analyzed and interpreted. Long term wind data from the meteorological stations near to the candidate site can be used for making preliminary estimate. It represents the wind profile at the potential site. In general, modern wind measurements systems will provide the mean wind-speed at the site in average over a pre-fixed time period such as five minutes basis, ten minutes basis or hourly basis (Mathew, 2006). Meanwhile, one year wind data recorded at the site is sufficient to characterize the long term variations in the wind profile within an accuracy level of 10 % (Guzzi & Justus, 1988; Jamil, Parsa, & Majidi, 1995).

Apart from the average strength of wind over a period, its distribution is also a critical factor in wind resource assessment. The frequency distribution of the wind-speeds helps towards answering questions of how long is a wind power plant out of action and how often does the wind power plant achieve its rated output (Pashardes & Christofides, 1995). It is logical to represent the wind velocity distributions by standard statistical functions, for instance, Gamma distribution (Panda, Sarkar, & Bhattacharya, 1990), Log normal distribution (Garcia, Torres, Prieto, & De Francisco, 1998) and Logistic distribution (Guzzi & Justus, 1988). However, Weibull and Rayleigh distributions can be used to describe the wind variations in a regime with an acceptable accuracy level (Hennessey, 1977; Justus, Hargraves, Mikhail, & Graber, 1978; Stevens & Smulders, 1979).

2.3 Rayleigh Distribution Function of Wind-speed

The Weibull distribution function is a special case of the Pierson Class III distribution. The variations in the wind velocity are characterized by two functions i.e. probability density function (PDF) and cumulative density function (CDF). According to Mathew, the PDF, *f(V)*, indicates the fraction of time for which the wind is at a given velocity, *V* shown as,

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \tag{2.1}$$

where *k* is Weibull shape factor and *c* is scale factor (Mathew, 2006). The shape factor *k* indicates where the wind distribution will peak, while the scale factor *c* indicates how ‘windy’ the wind location under consideration is (Fyrippis, et al., 2010). Meanwhile, the CDF of the velocity *V* gives the fraction of time that the wind velocity is equal to or lower than *V*. The CDF, *F(V)*, is the integral of the PDF is expressed by (Mathew, 2006),

$$F(V) = \int_0^\alpha f(V)dV = 1 - e^{-\left(\frac{V}{c}\right)^k} \tag{2.2}$$

The common methods for determining parameters *k* and *c* are the graphical method, standard deviation method, moment method and maximum likelihood method as well as energy pattern factor method (Mathew, 2006). Although the methods aforementioned are widely used, nevertheless, the maximum likelihood approach has been used to estimate the parameters *k* and *c*. One reason is that this approach can provide a better estimate compared to other methods and it does not have problems for interpretation when compared to other methods.

The reliability of Weibull distribution in wind regime analysis depends on the accuracy in estimating *k* and *c*. For the precise calculation of *k* and *c*, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period (for example daily, monthly or yearly mean wind velocity). Under such situations, a simplified case of the Weibull model can be derived, approximating *k* as 2. This is known as the Rayleigh distribution. Hence, the equation (2.1) can be rewritten as

$$f(V) = \frac{\pi}{2}\frac{V}{V_m^2} e^{-\left[{\pi}/{4}\left({V}/{V_m}\right)^2\right]} \tag{2.3}$$

where V_m is average wind-speed of a regime. The *c* value of the wind location under consideration is given by

$$c = \left[\frac{1}{n}\sum_{i=1}^{n} V_i^k\right]^{1/k} = \frac{2V_m}{\sqrt{\pi}} \tag{2.4}$$

The most frequent wind-speed, V_f, can be determined by

$$V_f = \sqrt{\frac{2}{\pi}} V_m \tag{2.5}$$

Meanwhile, the CDF of the velocity in equation (2.2) can be rewrite as

$$F(V) = 1 - e^{-\left[\pi/4\left(V/V_m\right)^2\right]} \tag{2.6}$$

The probability of wind to exceed a velocity of V_x is given by (Mathew, 2006)

$$P(V > V_x) = 1 - \left\{1 - e^{-\frac{\pi}{4}(V_x/V_m)^2}\right\} = e^{-\frac{\pi}{4}(V_x/V_m)^2} \tag{2.7}$$

2.4 Power Law for Estimates of Wind-speed at Various Heights

In order to assess the wind energy for a certain height at the candidate site, the power law can be used to estimate the wind-speed. Basically, the power law equation can estimate the hub height wind-speeds at various potential sites. Therefore, the wind-speeds at one height can be predicted in terms of the measured speed at another height by (Kamau, Kinyua, & Gathua, 2010),

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{2.8}$$

where α is the power law exponent, v_2 is the extrapolated wind-speed at height z_2 and v_1 is the measured speed at z_1 (Kamau, et al., 2010).

The exponent α depends on the several factors such as nature of terrain which including the surface roughness, wind-speeds and temperature (Kamau, et al., 2010). According to Peterson and Hennessey, a power law exponent of 1/7 is adequate for realistic but conservative for estimating the available wind power (Peterson &

Hennessey Jr, 1978). Furthermore, the exponent value of 1/7 has widely been chosen as a good representative of the prevailing conditions for neutral stability (Kamau, et al., 2010).

2.5 WPD, Air Density and WED

Assessing the WPD available in the prevailing wind regime at a site is one of the preliminary steps in the planning of a wind energy project. WPD indicates how much energy per unit of time and swept area of the blades are available at the selected area for conversion to electricity by a wind turbine (Fyrippis, et al., 2010). In order to get the most accurate estimate of WPD, the summation using data taken over a time interval is performed which is given by,

$$WPD = \frac{1}{2}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\rho_i V_i^3 \qquad (2.9)$$

where n is the total number of wind-speed reading, ρ_i is the i^{th} reading of air density and V_i is the i^{th} reading of the wind-speed in 10 minute intervals (Mathew, 2006). The data have been analyzed by using Matlab software which can cope with a huge and complex data. As a result, the arithmetic mean of WPD can be carried out and analyzed in an efficient way.

WPD is proportional to the density of the air and to the cube of the wind-speed. However, air density is a function of temperature T and pressure p, both of which vary with altitude above sea level z. Therefore, whenever calculation regarding the wind potential at certain altitude z is performed, the corresponding air density ρ could be evaluated by,

$$\rho = \rho_0 \frac{T_0}{T}\left(1 - \frac{\Gamma Z}{T_0}\right)^{\left(\frac{g}{\Gamma R}\right)} \tag{2.10}$$

where g = 9.81 ms^{-2} is the gravitational acceleration, R = 287 $Jdeg^{-1}kg^{-1}$ is the gas constant, T is the temperature in Kelvin, T_0 = 298 K, ρ_0 = 1.225 kgm^{-3} is the standard sea level air density and Γ is the vertical temperature gradient (Fyrippis, et al., 2010). The air density may be taken as 1.225 kgm^{-3} for most of the practical study (Mathew, 2006).

One of important steps in assessing the wind potential of a selected site location is the WED that is available in the wind regime. In addition, the WED can be calculated once the WPD is known. WED and the energy available in the regime over a period are usually taken as the yardsticks for evaluating the energy potential. Hence, the WED is the energy available in the regime for a unit rotor area and time (Mathew, 2006). Thus, the total WED available that can be extracted is expressed as,

$$WED = WPD \times d \times t \tag{2.11}$$

where d is the number of days in the month and t is the time base.

2.6 Review on the Work of Previous Researchers in Malaysia

In the paper by Sopian, Othman and Wirsat, the wind data that were collected at ten stations in Malaysia had been analyzed for wind energy potential (Sopian, Othman, & Wirsat, 1995). The stations are located at Mersing, Kuala Terengganu, Alor Setar, Petaling Jaya, Cameron Highlands, Melaka, Kota Kinabalu, Tawau, Labuan, and Kuching. The data were collected over a ten-year period from 1982 till 1991. The results were represented as a Weibull distribution function. From the analyses, the station at Mersing has the greatest wind power potential, with a mean annual WPD of 85.61 Wm^{-2} and at 10 m above sea level.

Besides that, a case study of the wind energy potential at Pulau Perhentian (Perhentian Island) has also been carried out. Pulau Perhentian is one of the popular resort islands in Malaysia which consists of a cluster of islands off the East (E) coast of Malaysia which is about 21 km from the coast of Terengganu. In the study, a hybrid system integrated with a wind turbine and solar panel had been installed so as to minimize the use of diesel as a source of electricity in Pulau Perhentian (Darus, et al., 2008).

Furthermore, the wind-speed measurements at the Materials and Energy Research Centre (MERC) solar site were used to find out the WED and other wind characteristics with the help of the Weibull PDF. The study also emphasized that the Weibull and Rayleigh PDF are useful tools for WED (Jamil, et al., 1995).

In addition, the research of Zaharim also summarized that the numerical and graphical results obtained from the Weibull and Gamma distributions, which parameters are estimated using the maximum likelihood principle, provide the best fits for the wind data (Zaharim, Najid, Razali, & Sopian, 2009).

CHAPTER 3

LITERATURE SURVEY ON WTGS

The comprehensive review of WTGS will be discussed in Chapter 3. The derivation of formula and the theories in every single component are extensively explained. The components aforementioned are including the wind turbine characteristic, PMSG, rectifier, DC-DC boost converter, lead acid battery, Butterworth low-pass filter, single-phase inverter, SPWM switching technique and PI controller. In addition, the operation of major components such as DC-DC boost converter and single-phase inverter will be further expanded in details. Lastly, the previous works that have been done by other researchers are also included in this chapter.

3.1 Overview of WTGS

WTGS have transformed into various sizes, shapes and designs, to suite the intended applications. At the inception stage of the technology, wind machines were used for grinding grains. In 19^{th} century, so called "American wind mills" were introduced and designed with multi-bladed rotor, mechanically coupled with reciprocating piston pumps, which was appropriate for water pumping application. Next, the construction of the turbine driven wind electric generators in Denmark had been established in 1890 for meeting the rural electricity demand. Then, the modern wind turbine is started which is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. Size of these turbines ranges from a few Watts to several

Mega Watts. Most of the commercial machines are HAWT with three blades rotors instead of VAWT because it could not evolve as reliable alternative to the horizontal axis machines. Besides that, the turbines may be grouped into arrays, feeding power to a utility, with its own transformers, transmission lines and substations. Stand-alone systems are also catering the needs of smaller communities. As wind is an intermittent source of energy, hybrid systems with back up from diesel generators or photovoltaic (PV) panels are also popular in remote areas. For the efficient and reliable performance of a WECS, all its components are to be carefully designed, crafted and integrated (Mathew, 2006).

In WTGS, the wind power stations or other electricity supply sources of comparable output, it should be simple to use, having a long useful lifetime, having a low maintenance outlay and having as low as possible initial cost. To meet these requirements, a suitable generator must be chosen. Because of their robust construction, the generators used in WTGS for the conversion of mechanical energy to electrical energy should be almost exclusively synchronous or asynchronous. The asynchronous generator used in the conversion systems can be divided into two categories i.e. short-circuit rotor machines and slip-ring rotor machines. Similarly, two categories of synchronous generator also have been employed in the conversion systems which are machines with exciter and PM machines. Synchronous machines, often based on gearless, ring-type designs with controlled or machine-commutated rectifiers, DC links and self-commutated inverters, are favoured in these machines. Meanwhile, double-fed asynchronous generators permit similar speed-variation ranges with considerably smaller converter systems in reactive current adjustment ranges equivalent to the converter output. The gears necessary in these machines usually is stall-regulated turbines (Heier, 2006).

With regard to the transfer of energy to electrical supply installations, it can be categorized into systems with limited supply options that either operate in isolation or supply weak grid and unlimited connection with the rigid grid. The use of such system, even at high cost, is justified if, by adjusting the turbine speed to the prevailing wind-speed, the compatibility of the plant to the environment and to the grid can be improved, leading to a higher energy output and reduced drive-train loading. This type of system requires a converter system that is capable of conditioning the variable-frequency electrical energy from the turbine generator for supply to a grid of constant frequency and voltage. Hence, power electronic converters or power converters are the most common solution for the conversion and control of electrical energy. It is used to an increasing degree in WTGS to adjust the generator frequency and voltage to those of the grid, particularly in variables-speed systems (Heier, 2006).

Power converters have significant advantages over the rotating transformers which are low-loss energy conversion, rapid operator intervention and high dynamic response, wear-free operation, low maintenance requirement as well as low volume and weight. The main components of power conversions systems are the power section which is power converters valves that carries the electrical power and electronics signal processing unit to perform numerous controls, protective and regulating tasks. The power converters can also be divided into two categories i.e. direct converters and indirect converters. Direct converters are used particularly for the reduction of frequency that requires two complete anti-parallel power conversion bridges per phase to operate to consumer and supply systems. This will result in high costs for power gates and control elements. Meanwhile, indirect converters consist of a rectifier, constant-voltage or constant-current DC link and inverter. Particular characteristics of the link are the inductor for current smoothing and the capacitor for voltage smoothing. Indirect converters have achieved a clear dominance in WECS and the connection of variable-speed wind turbines to the grid. Direct converters have only been used in individual cases to supply the rotor circuit of double-fed asynchronous generators (Heier, 2006).

3.2 Wind Turbine Characteristic

3.2.1 Wind Turbine Power and Torque

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms. So, the kinetic energy of a stream of air with mass, *m*, and moving with a velocity, V_w, is given by (Mathew, 2006),

$$E = \frac{1}{2} m V_w^2 \tag{3.1}$$

Assuming a wind rotor of cross sectional area, *A*, exposed to the wind regime stream as shown in Figure 3.1.

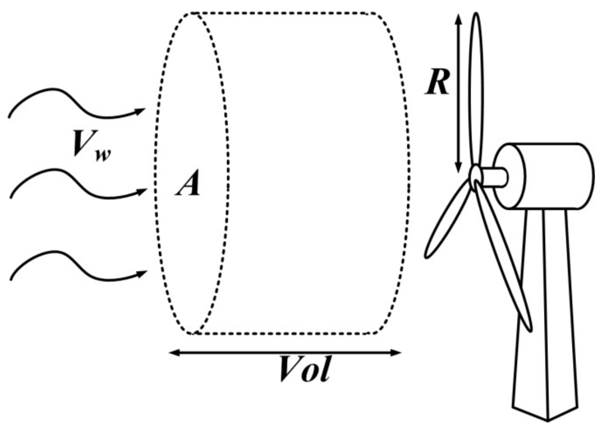

Figure 3.1 An airparcel moving towards a wind turbine

The kinetic energy of the air stream available for the turbine can be expressed as,

$$E = \frac{1}{2}\rho \times Vol \times V_w^2 \tag{3.2}$$

where ρ is the density of air and *Vol* is the volume of air parcel available to the rotor. The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor, A, and thickness equal to the wind velocity. Hence energy per unit time, that is power, *P*, can be expressed as (Mathew, 2006),

$$P = \frac{1}{2}\rho A V_w^3 \tag{3.3}$$

Equation (3.3) shows that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. The air density may be taken as 1.225 kgm^{-3} for most of the practical cases as discussed in section 2.5. Effect of the wind velocity is more prominent owing its cubic relationship with the power. When the wind velocity is doubled, the available power increases by 8 times (Mathew, 2006).

However, a turbine cannot extract the theoretical power completely from the wind as shown in equation (3.3). When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as power coefficient, c_p. Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind that express as,