

Maximum Power Point Tracking (MPPT) Method in Wind Power System

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ABSTRACT: Wind energy systems are being closely studied because of its benefits as an environmentally friendly and renewable source of energy. Because of its unpredictable availability, power management concepts are essential to extract as much power as possible from the wind when it becomes available. The purpose of this thesis is to presents a new adaptive control algorithm for maximum power point tracking (MPPT) in wind energy systems. The proposed control algorithm allows the generator to track the optimal operation points of the wind turbine system under fluctuating wind conditions and the tracking process speeds up over time. This algorithm does not require the knowledge of intangible turbine mechanical characteristics such as its power coefficient curve, power characteristic or torque characteristic. The algorithm uses its memory feature to adapt to any given wind turbine and to infer the optimum rotor speeds for wind speeds that have not occurred before. The proposed algorithm uses a modified version of Hill Climb Search (HCS) and intelligent memory to implement its power management scheme. This algorithm is most suitable for smaller grid or battery connected wind energy systems.

KEYWORDS: Wind generation, dc-converter, maximum power point tracking (MPPT), induction motor,

I. INTRODUCTION

As one of the most commonly used renewable energy sources, wind is the most promising one for replacing the fossil fuel in the near future. To achieve high efficiency in a wind power conversion system, the maximum power point tracking (MPPT) in variable-speed operation systems, like doubly fed induction generator (DFIG) and permanent magnet synchronous generator systems, attracts a lot of attention. The studied MPPT methods in the history include three strategies, namely:

- Methods relying on wind speed;
- Methods relying on output power measurement and calculation; and
- Methods relying on characteristic power curve.

Most wind energy control systems are based on the wind speed measurement. In these systems, anemometers are typically required to measure the wind speed. Such systems suffer from additional cost of sensors and complexity. To solve this problem, wind speed estimation methods have been reported. Relying on complex software algorithms, the wind speed can be captured for controlling the optimal tip-speed ratio so that the MPPT can be implemented. In addition, tracking the maximum power could also be implemented through measuring the output power directly. The idea of this method is the online measurement of the output power and checking the rate of change of power with respect to speed, i.e., $\frac{dP}{d\omega}$ to extract maximum power from the wind turbine system. MPPT can be achieved when $\frac{dP}{d\omega} = 0$, through adjusting either the rotor speed or duty cycle of the converter.

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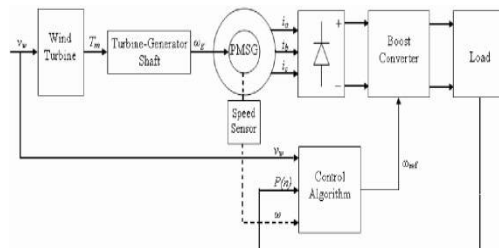


Figure: 1 Wind Energy Conversion System Block Diagram

This method relies on a large amount of online computation, and thus, it would be difficult to achieve MPPT for fast-varying wind speeds. Although the varying tracking step could be used to improve computation speed, this disadvantage cannot be eliminated. Recently, a proposed method of employing the power versus rotor speed characteristic curve is frequently used due to its simplicity in hardware and software. The optimal reference power curve is constructed according to experimental tests and programmed in a microcontroller memory.

One could either measure the rotor speed or obtain the power reference to regulate the power or measure the wind speed and obtain the rotor speed reference to regulate the rotor speed. The former produces more accurate output power while the latter will have faster control response. Aside from an accurate reference power curve, analysis is necessary to verify the stability of the method in terms of varying wind speed and output power. Few publications just address the stability issue of such method, but more detailed quantitative analysis should be conducted. This paper studies the performance of wind turbine under reference power curve MPPT power control. In particular, it presents a small-signal analysis on generator speed dynamics induced by variable wind speed. Also, an experimental setup to emulate the wind turbine operation in torque control mode is presented. Both steady-state and dynamic responses are implemented to verify the proposed analysis and conclusions. Section II will present how to obtain the optimal reference power curve and analyze the stability of this method by conducting the small-signal.

II. OPTIMAL REFERENCE POWER CURVE AND STABILITY ANALYSIS

The first important issue in characteristic power curve MPPT is how to obtain the reference power curve. The second issue is whether the generator speed and output power will converge to the points along this reference power curve regardless of the wind variations, i.e., “whether this method is stable with respect to the varying wind speed.” Section II-A will first capture the optimal reference operation points from the experimental tests when power variation rate is zero through varying the generator speed and the measurements of power. Then, a reference power curve $P_{e(\omega_m)}$ for the fitting curve of connection of all the optimal operation points is constructed, where a simple mechanical model is utilized to do small-signal analysis and a transfer function is proposed based on the optimal reference power curve $P_{e(\omega_m)}$. The transfer function reveals the relationship between the variation of wind speed and that of generator speed and helps in predicting the stability and dynamic responses.

A. Optimal Reference Power Curve $P_{e(\omega_m)}$ The optimal reference power curve $P_{e(\omega_m)}$ is obtained by finding the optimal power (P_{opt}) and optimal generator speed (ω_{mpot}) for any given wind speed (V_w). For a given, V_w the generator speed ω_m is swept, and the output power P is observed. The ω_m and P that would give the $\frac{dP}{d\omega_m} = 0$ are selected as ω_{mpot} and P_{opt} for the specific V_w . By repeating the same procedure for different V_w , a fitting curve can be obtained by connecting all optimal operating points (ω_{mpot}, P_{opt}). The fitting curve is then used as reference power curve $P_{e(\omega_m)}$. The procedure for preparing the $P_{e(\omega_m)}$ curve is summarized, where k and i are the indices of operating point and wind speed. Since this is an offline procedure, the measurement and calculation will not affect the online system operation speed.

- **Dynamic Stability Analysis:**

Once the reference power curve $P_{e(\omega_m)}$ is obtained, the stability of reference operating points (ω_{mpot}, P_{opt}) is investigated. Whether the system (generator speed and output power) would converge to the $P_{e(\omega_m)}$ or not is a dynamic

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stability issue. We have developed a small-signal model of the wind turbine system to investigate this issue. In the MPPT method discussed in this paper, the reference electrical power P_e is dependent on ω_m according to the polynomial.

$$P_e = b_1 \omega_m^3 + b_2 \omega_m^2 + b_3 \omega_m + b_4 \quad (1)$$

where the coefficients b_1 to b_4 are determined by the fitting curve of optimal operation point connection. The mechanical model that connects the wind turbine shaft and generator rotor can be written as

$$J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \quad (2)$$

where J denotes the inertia of the combined system, B is the damping coefficient, ω_m is the generator rotor speed, and T_m and T_e represent the turbine and generator torques, respectively.

Combining the relationship between torque and power, (2) can be rewritten in terms of power as

$$J \frac{d\omega_m}{dt} = \frac{P_\omega}{\omega_m} - \frac{P_e}{\omega_m} - B\omega_m \quad (3)$$

where P_ω and P_e are the turbine and generator powers, respectively. P_ω is determined by wind speed V_w , generator speed

ω_m , air density ρ , and blade swept area

$A = \pi R^2$ as

$$P_\omega = 0.5 A V_w^3 C_p(\omega_m, V_w) \quad (4)$$

where is $C_p(\omega_m, V_w)$ the turbine performance coefficient and is expressed as follows [4]:

$$C_p(\omega_m, V_w) = C_1 \left(\frac{C_2}{\lambda p} - C_3 \beta - C_4 \right) e^{C_5 / \lambda i} + C_6 \lambda \quad (5)$$

III. WIND ENERGY CONVERSION SYSTEMS

- **Wind Turbine Technology**

The wind turbine is the first and foremost element of wind power systems. There are two main types of wind turbines, the horizontal-axis and vertical-axis turbines.

- **Horizontal-axis Turbines**

Horizontal-axis turbines are primarily composed of a tower and a nacelle mounted on top of tower. The generator and gearbox are normally located in the nacelle. It has a high wind energy conversion efficiency, self-starting capability, and access to stronger winds due to its elevation from the tower.

- **Vertical-axis Turbines**

A vertical axis turbines' spin axis is perpendicular to the ground. The wind turbine is vertically mounted, and its generator and gearbox is located at its base. Compared to horizontal-axis turbines, it has reduced installation cost, and maintenance is easier, because of the ground level gear box and generator installation. Another advantage of the vertical axis turbine is that its operation is independent of wind direction. The blades and its attachments in vertical axis turbines are also lower in cost and more rugged during operation.

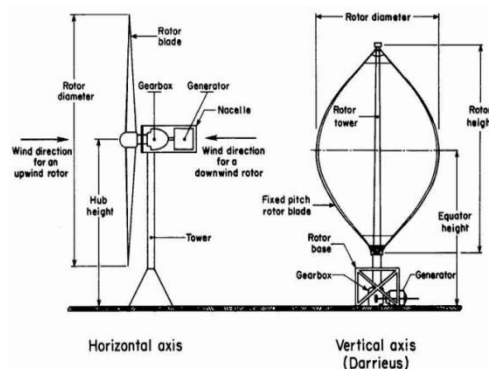


Figure: 2 Illustrations of a horizontal axis and a vertical axis wind turbine.

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However, one major drawback of the vertical wind turbine is that it has low wind energy conversion efficiency and there are limited options for speed regulation in high winds. Its efficiency is around half of the efficiency of horizontal axis wind turbines. Vertical axis turbines also have high torque fluctuations with each revolution, and are not self-starting. Mainly the other hand, it includes high installation cost, the need of a strong tower to support the nacelle and rotor blade, and longer cables to connect the top of the tower to the ground. Due to efficiency issue, horizontal wind turbines are primarily used. Consequently, the wind turbine considered in this thesis is a horizontal axis turbine.

IV. TYPES OF HORIZONTAL-AXIS WIND TURBINES

• Pitched Controlled Wind Turbines

Pitch controlled wind turbines change the orientation of the rotor blades along its longitudinal axis to control the output power. These turbines have controllers to check the output power several times per second, and when the output power reaches a maximum threshold, an order is sent to the blade hydraulic pitch mechanism of the turbine to pitch (or to turn) the rotor slightly out of wind to slow down the turbine. Conversely, when the wind slows down, then the blades are turned (or also known as pitched) back into the wind. During operation, the blades are pitched a few degrees with each change in wind to keep the rotor blades at the optimum angle to maximum power capture.

• Stalled Controlled Wind Turbines

The rotor blades of a stall controlled wind turbine are bolted onto the hub at a fixed angle. The blades are aerodynamically designed to slow down the blades when winds are too strong. The stall phenomenon caused by turbulence on rotor blade prevents the lifting force to act on the rotor. The rotor blades are twisted slightly along the longitudinal axis so that the rotor blade stalls gradually rather than suddenly when the wind reaches the turbines' critical value.

• Active Stall Controlled Wind Turbines

Active stall turbines are very similar to the pitch controlled turbine because they operate the same way at low wind speeds. However, once the machine has reached its rated power, active stall turbines will turn its blades in the opposite direction from what a pitch controlled machine would. By doing this, the blades induces stall on its rotor blades and consequently waste the excess energy in the wind to prevent the generator from being overloaded. This mechanism is usually either realized by hydraulic systems or electric stepper motors.

V. PROPOSED ALGORITHM

• Algorithm Concept and Features

The proposed algorithm uses the HCS methodology along with intelligent memory and power management to track the maximum power points of wind energy systems under fluctuating wind conditions. The main problems in existing power extraction methods are:

- Customization,
- Speed, and
- Wasted power

The proposed algorithm provides a solution to these problems. In order to avoid the customization problems in some of the existing algorithms, the proposed technique does not re-quire the characteristics of the turbine to be preprogrammed. Instead, the algorithm initially uses a general estimate of the turbine characteristics and then determines the actual characteristics through operation. By doing this, the algorithm can be easily used for a wide range of wind turbines. The turbine adaptation feature of the algorithm allows it to immediately make fairly accurate estimations on the maximum power points of the system following the determinations of the maximum power points. The estimations allow the system to immediately operate near to the maximum power point, where the change in speed corresponds to small changes in power. Therefore, the estimations lead to less wasted potential power and speed up the determination process. The closer the operating point is to the maximum power point, the fewer adjustments necessary. The proposed algorithm has two main concepts to enable flexible, fast and efficient maximum power extraction.

The first concept is to quickly determine the maximum power point by using the turbine fundamental tip-speed ratio equation in conjunction with the HCS methodology. The second concept is to enable immediate maximum point

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retrieval for reoccurring wind speeds and determination of the given turbine's internal actual TSR. Recall that the TSR is the ratio of the wind speed and the rotor speed, and for each turbine there is one TSR that will always result in maximum power transfer. The TSR characterizes the aerodynamic efficiency of a wind turbine and is unique. Please note that the dynamic response of the generator dictates the speed at which the algorithm can determine an optimum point. This is because the system will not make any decisions or adjustment to the speed reference until it has reached steady-state (i.e. reached the reference for a defined period of time).

- **Modified Hill Climb Search**

Due to the nature of wind energy systems described, the power available from the wind turbine is a function of both the wind speed and the rotor angular speed. The wind speed being uncontrollable, the only way to alter the operating point is to control the rotor speed. Rotor speed control can be achieved by using power electronics to control the loading of the generator. Without any given knowledge of the aerodynamics of any wind turbine, the HCS principle searches for the maximum power point by adjusting the operating point and observing the corresponding change in the output. The HCS concept is essentially an "observe and perturb" concept used to traverse the natural power curve of the turbine. With respect to wind energy systems, it monitors the changes in the output power of the turbine and rotor speed. The maximum power point is defined by the power curve, where $\Delta P/\Delta\omega=0$. Thus, the objective of HCS is to 'climb' the curve by changing the rotor angular speed and measuring the output power until the condition of $\Delta P/\Delta\omega=0$ is met. There are several different ways of implementing the HCS idea. In this thesis, the algorithm generates the reference speed by measuring the output power of the wind energy conversion system and adjusts the system's operating point accordingly. The $\Delta P/\Delta\omega=0$ condition is achieved when $\Delta P \approx 0$ because the amount of adjustment in the rotor speed is chosen to be proportional to the change in power; thus when $\Delta P/\Delta\omega \approx 0$. The HCS concept is described in detail in this section according to this thesis' implementation method.

Observing that there has been an increase in power due to an increase in speed, the algorithm signals to further increase the rotor speed. Since $\Delta P/\Delta\omega$ is positive, the system is 'climbing' up the power curve. With $\Delta P/\Delta\omega$ still positive, the system continues to increase the rotor speed. The algorithm notices that the change in power from negative, and it was due to an increase in speed. With $\Delta P/\Delta\omega$ now negative, the optimum point has been passed. As a result, the rotor speed is decreased. The slope of the power curve diminishes as the system approaches the peak power point (level of extracted power is less sensitive to the change in rotor speed, $\Delta P/\Delta\omega=0$). Therefore, it follows that as the operating point moves closer to the maximum power point, the magnitude of the speed adjustment should be smaller. The algorithm will oscillate and eventually settle at the maximum power point (which is defined to be where $\Delta P/\Delta\omega = 0$).

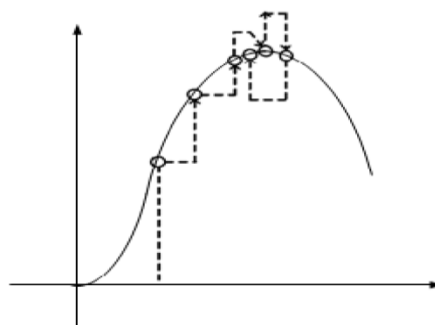


Figure: 3 Wind power curve for an arbitrary wind speed.

- **Adaptive Memory**

HCS gives the algorithm the ability to search for the maximum power point, but by also using the TSR relationship and memory, the search process is sped up considerably. An anemometer provides the algorithm with the knowledge of the wind conditions so that the system can quickly respond with the correct decisions. For each turbine, the operating point at which the maximum power is attained is defined by the wind speed and its corresponding rotor speed. In order to keep the system independent from the physical characteristics of the wind turbine, and thus keeping it easily modifiable to other turbines, an approximate "optimal" TSR is used initially. The memory feature of this algorithm not only allows immediate access to the maximum power points previously determined, it also enables the algorithm to adapt to its given turbine.

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The adaptability of the algorithm allows the system to capture as much available power as possible under fast wind variations. The memory provides two major power management functions;

- Store the operating points as determined by the algorithm,
- To update the approximate TSR to a value nearer to the actual TSR.

The algorithm stores the determined operating points with respect to the wind speed. This allows the system to immediately jump to the optimal operating point, thereby bypassing the time-consuming searching procedure. In the case that the stored operating point is not ideal, after the determined maximum power point is reached, small adjustments are made to ensure the integrity of the stored data. With small adjustments, minimal power is wasted during this process because the system will be operating very close to its maximum efficiency.

With each successful determination of a maximum power point, the data is used to obtain a more accurate TSR. Since it is known that the maximum power point for a particular turbine always occurs at the same optimal TSR for all wind speeds, the TSR is updated to be the average TSR obtained from each data entry.

As a result, each time a new wind speed occurs, the approximate operating point, using the updated TSR, will become closer and closer to the actual maximum power point. Thus, the searching process is continuously shortened with each optimum point.

VI. DESIGN OF BOOST CONVERTER

Since the main scope of this thesis is to verify the functionality of the proposed adaptive control algorithm in MPPT applications for WECS, the boost converter is chosen as the front-end power converter connected between the PMSG and DC load side. The design specifications are listed in Table: 1. in this design example, the boost converter was designed for the highest rated wind speed of 9 m/s. The maximum boost inductor value (L_{max}) that can be used to operate the boost converter in DCM. Also, to achieve very low ripple output voltage, the minimum output capacitor value (C_{min}) is calculated, where ΔV is 0.5% of the rated output voltage.

Output power	20KW
Load Resistance (R)	20Ω
Switching Frequency(f_s)	5kHz
Output Voltage (V_o)	632V

Table: 1 Design Specification for boost Converter

$$L_{max} = \frac{T_s V_o}{2I_o} (D)(1 - D)^2$$

$$C_{min} = \frac{V_o}{\Delta V} \frac{DT_s}{R}$$

For the system used in this thesis, L_{max} is calculated to be 470μ Hand C_{min} is calculated to be 600μF. In the actual design, to ensure that the boost converter always operates in DCM under different wind conditions and that the output voltage has very low ripple, L is selected to be 200μH and C is 2000μF respectively.

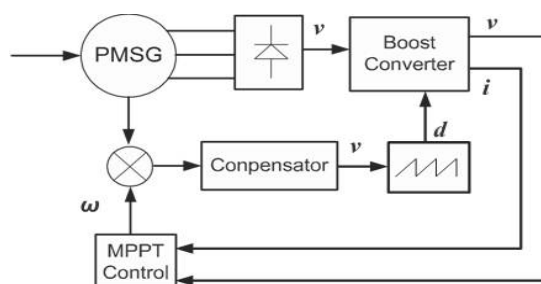


Figure: 4 Closed Loop System

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VII. SIMULATION

The algorithm requires the wind speed, generator speed, output voltage and output current as an input. Since the algorithm requires an anemometer to monitor the wind speed and calculate the turbine's internal TSR, the wind speed is directly fed into the algorithm in the simulation. The generator speed input allows the algorithm to determine whether the generator speed has reached the reference speed as desired. The output voltage and current together provides the algorithm with knowledge of the output power. Information regarding the output power, generator speed, and wind speed allow the algorithm to determine the system's maximum power points.

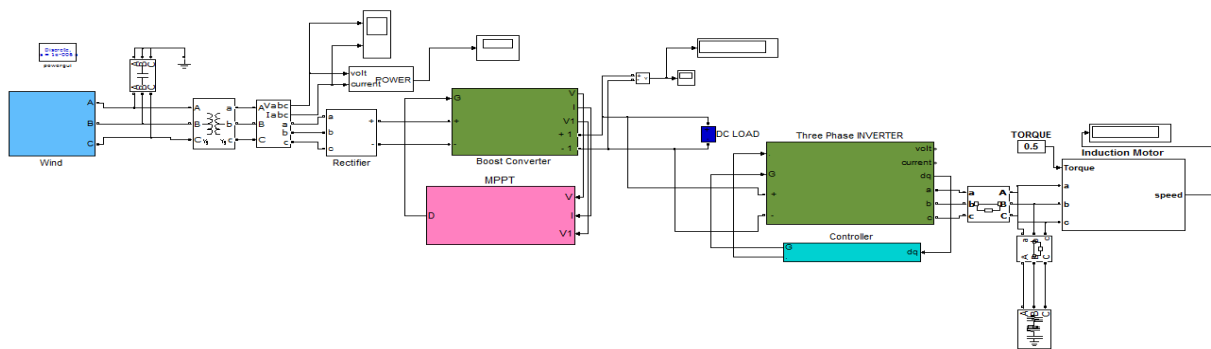


Figure: 5 Algorithm performance under wind speed of 1 m/s.

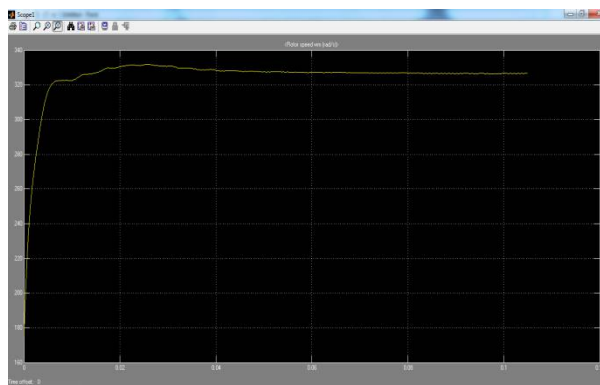


Figure: 6 Output Voltage

At a wind speed of 9 m/s, the algorithm was able to determine the generator speed to be 3381 rpm through its search procedure, while the actual maximum power point is at 3480 rpm. The corresponding rotor speeds are 11.8 rad/s and 12.1 rad/s. By substituting these speeds, the corresponding extracted mechanical power can be determined. The power extracted by the energy conversion system at the determined and actual speeds is 21709 W and 21766 W, respectively. The algorithm is successful in determining the maximum power point of the system because the difference in power between the actual and determined operating point is 57 W (approximately 0.1% of the maximum power). The power coefficient was at 0.45 using the generic TSR value, and eventually became 0.478 at the determined maximum power point. The turbine's TSR was determined to be 0.787 which is relatively close.

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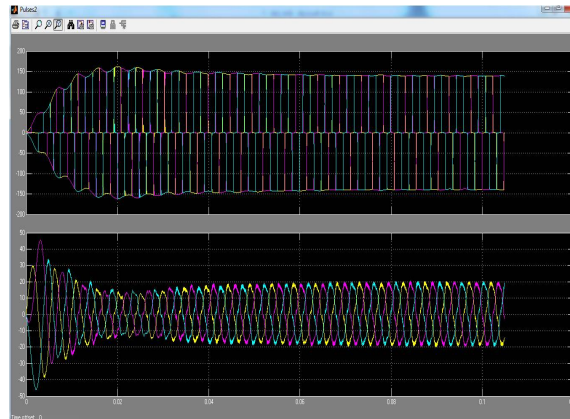


Figure: 7 Input Voltage and current

VIII. CONCLUSION

Due to wind's unpredictable nature, power management concepts are necessary to extract as much power as possible from the wind when it becomes available. The proposed algorithm has been developed to maintain the system at its highest possible efficiency by using its memory feature to infer the optimum rotor speeds for wind speeds that have not occurred before.

Another feature of the proposed algorithm is that it can be easily customized for various wind turbines since it is independent of turbine characteristics. The proposed algorithm uses a modified version of HCS and intelligent memory to implement its power management scheme. This algorithm is most suitable for smaller grid or battery connected wind energy systems. PSIM simulation studies have confirmed the effectiveness of the proposed algorithm

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