Maximum Power Tracking in Horizontal Axis Wind Turbine Using Fuzzy Logic Controller

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Abstract—To make Wind energy a more attractive source of power, the design of a controller based on Fuzzy Logic is undertaken to facilitate the extraction of maximum power at any given wind speed while at the same time providing a control solution that requires minimal measurements to be taken, thus reducing costs spent on sensor purchase. The controller is applied to a model designed to simulate a Horizontal Axis Wind Turbine, and by continually making adjustments to the speed of the wind turbine rotor, it achieves output powers greater than what is achievable by a similar wind turbine under experimental conditions.

Keywords—Maximum Power Point Tracking; Fuzzy Logic; coefficient of power; Horizontal axis wind turbine.

I. INTRODUCTION

Renewable energy is an attractive alternative to traditional energy sources, mainly in order to safeguard the planet from depletion as well as to reduce carbon-based pollution. Wind energy has generated significant interest due to its viability as a clean, cost-effective source of energy. Horizontal axis wind turbines have been designed to make use of energy from the wind. One of the constraints facing the attractiveness of wind energy as a primary source of electrical power is the reliability of the wind, since one cannot control the wind speed. It is necessary to devise methods that will attempt to extract maximum power from the wind at a given wind speed. This is mainly done by manipulating the factors affecting the coefficient of power, a factor which determines how much energy a wind turbine will extract from the wind at a given wind speed.

II. THEORY

A. Horizontal Axis Wind Turbines

In a horizontal axis wind turbine, each blade section experiences a constant angle of attack during one revolution, under steady state conditions [1]. Horizontal Axis wind turbines have been used with different blade configurations such as fixed pitch [2] and variable pitch [3]. Variable pitch machines operate over a wider range of wind speeds than fixed pitch machines, but are more costly and more complex to control. Use of variable pitch turbines is necessitated by the need to decrease energy captured during wind storms, maximize energy captured at rated speeds and regulate and smooth the rated power [4].

B. Wind Turbine Characteristics

The power extracted from a wind turbine is a function of the wind power available, turbine characteristics and the ability of the machine to adjust to wind variations. Power and torque extracted from the wind (\(P_w\) and \(T_w\) respectively) can be expressed by equations (1) and (2) [5].

\[
P_w = \frac{1}{2} \rho C_p(\lambda, \beta) A V_w^3
\]

\[
T_w = \frac{1}{2} \rho C_t(\lambda, \beta) r_w A V_w^2
\]
where $\rho$ is the air density, $C_p$ is the coefficient of power, $C_T$ is the torque coefficient, $\lambda$ is the Tip Speed ratio, which is the ratio between the blade tip speed and the wind speed upstream of the rotor, $\beta$ is the blade pitch angle, $A$ is the wind swept area, $V_w$ is the wind speed and $r_m$ is the turbine radius.

For a constant pitch wind turbine, $C_p$ is expressed as a function of $\lambda$.

C. Maximum Power Point Tracking

Since the output power produced by a wind turbine at any particular wind speed is not constant, it is possible to manipulate the factors that affect the output power to ensure maximum power is attained. The factors that affect output power include blade size, air density and coefficient of power [6]. Blade size is optimized by selecting a wind turbine with the largest possible blades, subject to other factors such as location, energy requirements, location and cost considerations, and air density is optimized by careful site selection. Once the turbine is selected and installed, the only parameter that remains to be optimized is the coefficient of power.

Given that $C_p$ is a function of $\lambda$, the tip speed ratio, and $\beta$, the pitch angle, maximum power point trackers are designed to vary either $\lambda$, $\beta$ or both to obtain optimum performance. For fixed pitch wind turbines, maximum power point trackers operate by varying $\lambda$.

The value of $\lambda$ is obtained from equation (3).

$$\lambda = \frac{\omega r_m}{V_w}$$  \hspace{1cm} (3)

where $\omega$ is the rotational speed of the rotor of the wind turbine, $r_m$ is the turbine radius and $V_w$ is the wind speed. Maximum power point tracking in this case is done by continually adjusting the value of $\omega$ to obtain the optimum value of $\lambda$, which gives the optimum value of $C_p$ based on the relationship between $C_p$ and $\lambda$.

D. Fuzzy Logic Control

Fuzzy Logic is a form of multivalued logic that permits the evaluation, analysis and control of systems with vague or imprecise variables through the use of natural language in the definition of inputs, construction of control logic and generation of outputs. The nature of Fuzzy Logic allows for tolerance of suboptimal and imprecise data to give quick, simple and sufficiently good solutions [7].

The nature of Fuzzy Logic makes it particularly well suited to control of wind turbines because the operational characteristics of wind turbines, particularly the power coefficient are usually not generalizable across different wind turbine models. As a result, one has to rely on data from the manufacturer or from experimental results to predict power output. However, with Fuzzy Logic, it is possible to design a controller even with incomplete data, basing the control rules on the quantities that are measurable [8].

The steps undertaken in designing a Fuzzy Logic controller are:

- Identification of the Inputs and Outputs and their ranges
- Design of Membership Functions for all the Inputs and Outputs
- Design of Rule Base
- Determination of Inference System
- Testing and Implementation

The Membership Functions are curves that define how each point in the input or output space is mapped to a membership value (degree of membership) between 0 and 1. The input/output space is referred to as the universe of discourse. To reduce complexity in calculations during implementation, the most commonly used Membership functions are triangular or trapezoidal in shape, though it is possible to use a variety of other functions to divide the universe of discourse into subsets.

Fuzzy Logic Controllers make use of IF...THEN type rules connected by logic operators such as AND, OR and NOT. The rules, expressed in natural language, consist of two parts. The antecedent is the first part and describes the input(s) that has been activated as a result of its having a value that falls within one or more of the subsets within the membership function of that input. The consequent part shows the resultant subset of the output membership function to be activated.

III. EXPERIMENTAL MODEL

The model used for simulation and analysis was based on a Hyacinth 100 Wind turbine with the following specifications:

- Rated Power: 100W
- Rated DC Voltage: 24V
• Rated Current: 4.4A
• Rated Speed: 860 rpm
• Maximum Power: 115W
• Cut-in Wind Speed: 3m/s
• Rated Wind Speed: 12 m/s
• Rotor Diameter: 1050 mm
• Over-speed wind protection: Tip stall protection, turned protection and electromagnetic brake

The wind turbine was tested using a wind tunnel with a speed range of 0 to 20.5 m/s, represented as 0 to 50Hz. The power output from 0 to 12 m/s was obtained experimentally. Higher wind speeds were avoided due to excessive vibrations, which destabilized the setup.

A. Uncontrolled Model of Wind Turbine

A SIMULINK® model was created to simulate the power output of the wind turbine, with the equivalent power output from the model being compared to the actual power output from the wind turbine. The SIMULINK® model is illustrated in Fig. 1. The lookup table for the coefficient of power was generated from the results obtained experimentally in order to match as closely as possible the output from the experimental setup.

![SIMULINK® model of Horizontal Axis Wind Turbine](image)

The model was subjected to a gradually increasing wind speed from 0 to 15 m/s in order to obtain the wind speed/ power characteristic. The results obtained were graphed in comparison with the experimental results previously obtained, and can be seen in Fig. 2.
B. Controlled Model

The model for the controlled Horizontal axis wind turbine required the design of the Fuzzy Logic Controller. The controller was designed in MATLAB®, with triangular membership functions used for all inputs as well as the output. The controller was initially designed with 15 control rules, excluding the wind speed as an input, but the rule base was later expanded to 25 rules to cater for conditions involving zero wind speed and high wind speeds. The rule surface summarizing the control rules generated is shown in Fig. 3.

The Fuzzy Logic controller was incorporated into the SIMULINK model, and a feedback loop incorporated, thus allowing the system to continually make adjustments to the turbine rotor speed until the maximum achievable wind power at that particular speed is realized and is stable.

For the lookup table in the controlled model, a different lookup table was designed from the initial lookup table to document relationship between tip speed ratio and power coefficient rather than wind speed and power coefficient as used in the uncontrolled setup.
C. Wind Speed Signal Simulation

In order to test the system’s performance under Fuzzy Logic control, it was necessary to simulate wind speed profiles. The following three kinds of speed profiles were used for testing:

- A constant wind speed of 8 m/s. This value was selected because it falls between the cut-in and rated speed, thus it was possible to see how the maximum power point tracking occurs below rated speed conditions.
- A stepwise varying profile, shown in Fig. 4.
- A ramp profile with a gradient of 1, varying from 0 m/s to 15 m/s.

The wind speed signals were generated using a signal builder with multiple output ports, thus it was possible to carry out simulations without redesigning the model.

IV. RESULTS AND DISCUSSION

The output from the maximum power tracking model was generated using a SIMULINK simulation with a sample time of 0.1 seconds. The results were plotted alongside the results obtained experimentally.

A. Constant Wind Speed (8m/s)

For constant wind speed, the resultant output is shown in comparison with experimental output in Fig. 5.
From the output profile generated, it is possible to see the result of maximum power tracking action by the controller. The output power is initially close to the output power obtained experimentally, but as the rotor speed is adjusted, the power output increases until it stabilizes at a value about 20W above the output obtained experimentally, which in a wind turbine rated at 100W is an increase of about 20%. The adjustment of the wind turbine rotor speed in subsequent cycles until it reached a stable value was also plotted, and is seen in Fig. 6.

B. Stepwise Increasing Wind Speed

The output achieved from the wind profile described in Fig. 4 was generated by simulation and compared to experimental results. The results are shown in Fig. 7.
The rotor adjustments that resulted in the output power shown in Fig. 7 are shown in Fig. 8.

The resultant output indicated that for higher wind speeds, the tracking time increased with greater fluctuations in turbine rotor speed involved. However, the power output is still significantly higher with maximum power tracking at each of the 3 wind speeds involved.

C. Wind Speed with a Ramp Profile

The ramp profile was used to investigate the overall shape of the wind turbine characteristic when subjected to maximum power point tracking. The resultant output power is shown in Fig. 9 and is shown in comparison with experimental results previously obtained.
Figure 9. Power-Wind Speed characteristic obtained with and without Maximum Power Point Tracking

The output curve indicates that below cut-in speed, the wind turbine with Fuzzy Logic control shows negative output power production. However, from cut-in speeds of 3 m/s, the output is consistently higher than that obtained experimentally. Also, the high speed regions close to rated speed show the fluctuations in output noticed when testing with the step profile, with maximum fluctuations between 12 and 13 m/s. However, the magnitude of the fluctuations reduces as the wind speed moves away from rated speed.

V. CONCLUSION

The Fuzzy Logic Controller showed remarkable ability to improve the performance of the Horizontal axis wind turbine, based on simulation results. The output power from the controlled model was consistently higher than that obtained experimentally. The model, however, showed notable fluctuations in output for wind speeds around the rated speed, and it is hoped that these fluctuations will be tackled in future controller designs.

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