MPPT of a Standalone Wind Energy Conversion System using Magnetostrictive Amorphous Wire Speed Sensor and Fuzzy Logic

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***Abstract*—This paper details the design and implementation of a Fuzzy Logic based controller for Maximum Power Point Tracking (MPPT) of a case study standalone wind energy conversion system(WECS). A magnetostrictive amorphous wire speed sensor is used for rotational speed measurement to provide an inexpensive, fast and robust solution to speed measurement.The designed MPPT algorithm includes a peak detection feature and a self-tuning capability which makes it intelligent and generic. The designed fuzzy logic controller determines the appropriate duty cycle D that yields optimum speed for maximum power extraction from the WECS for various wind speeds. It then applies this D to the DC-DC boost converter to control the speed of rotation of the PMSG to track maximum power point curve. The designed system was implemented on a real case study wind turbine under controlled conditions. Experimental results show that the designed system was able to significantly increase the maximum electrical power extracted for varying wind speeds.**

***Index Terms*—WECS, Magnetostrictive Amorphous wire speed sensor, PMSG, Fuzzy Logic Controller, MPPT.**

I. INTRODUCTION

WIND capacity is growing very quickly due to its increasingly competitive prices. Rapidly increasing demand for electrical energy and the issues associated with limited reserves and the rising cost of fossil fuels such as oil, coal, and natural gas are responsible for the growth and rise of renewable energy application. Environmental concerns in energy generation from the conventional sources also make fast development of renewable energy sources such as wind, solar, fuel cell [1]. Small-scale standalone WECS provides a good alternative in urban areas and residential applications in remote places where connection to grid is very expensive or not feasible [2]. Permanent magnet synchronous generators (PMSG) is often chosen for standalone WECS because of its advantages: higher reliability, less maintenance and more effectiveness [3]. Wind power depends mainly on geographical conditions and weather conditions. The output power from a fixed pitch WECS is a function of rotor speed that changes with the variation of wind speed. There is always an optimum rotor speed for a particular wind speed at which maximum power can be extracted from the system [2]. Maximum power point tracking (MPPT) involves optimizing the generator speed for a particular wind velocity intercepted by wind turbine such that the power extracted is maximized [4]. Various methods for MPPT have been studied [1].

The methods that use known turbine characteristics include Tip speed ratio (TSR) method [5], Optimal Torque (OT), Power signal feedback (PSF) [6] and Optimal relationship based (ORB) [7] methods. Methods that do not require knowledge of turbine characteristics include Hill climbing search (HCS) method [8], and its various variants. Advantages of MPPT methods that employ known turbine characteristics include [9] good performance with fast response and high efficiency, capability of efficiently tracking the maximum power point, simple design and easily implemented where turbine characteristics are known. The disadvantages of these methods include limitation to systems with known turbine characteristics, heavy reliance on sensor accuracy and efficiency, seasonal variation of stored optimal curve due to changes in nominal air density and drift of parameters due to aging [10].On the other hand, advantages of MPPT methods that do not require knowledge of turbine characteristics are that they can be adapted to any turbine since they do not require knowledge of turbine characteristics. One disadvantage is trade-off between the control efficiency and the tracking speeds. Larger perturbation step size increases the speed of convergence but causes oscillation around maximum power point affecting the efficiency of the system, while on other hand a smaller step size boosts the efficiency but the controller then becomes slower. Another critical shortcoming is that the Hill Climbing Search (HCS) control might lose its tracking under changing winds conditions resulting in travelling downhill instead of the uphill and vice versa [11].

There is need to come up with an MPPT control strategy that combines the advantages of both classes of methods and at the same time providing innovative ways of overcoming their shortcomings. This is the approach taken in this paper. In this paper, a Fuzzy Logic Controller (FLC) is used for maximum power point tracking. Fuzzy control works as well for complex non-linear multi-dimensional systems, systems with parameter variation problem or where the sensor signals are not precise. It is basically non-linear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect [12]. It has been shown that a properly designed direct fuzzy controller can outperform conventional proportional integral derivative (PID) controllers offering the following advantages: It can work with less precise inputs, does not need fast processors, more robust than other non-linear controllers and has better stability, small overshoot, and fast response [13]. The proposed controller does not require a wind speed sensor hence reducing the system complexity. It also features a self-tuning capability to adapt to changes in air density or ageing of the system.

The main challenge with the available optical, magnetic and hall effect speed sensors is their high cost compared to the unit cost of a small scale wind energy conversion system [14]. There is need to develop an inexpensive and accurate speed sensor especially for small scale standalone applications, in order to reap the advantages of sensor based methods.

Magnetostrictive amorphous wire based sensors have the following advantages [15] high signal to noise ratio, quick response with cut-off frequency of more than several kilohertz, High stability against temperature variations, insensitivity to mechanical vibrations, small size (wire diameter in the order of micrometers), high reliability and small aging for long time usage, digital output for good matching with microcomputer, good corrosion resistance and excellent electromagnetic properties. A magnetostrictive amorphous wire has been successfully used as a speed sensor in this paper to provide an inexpensive, stable and reliable solution to wind turbine speed measurement.

II. SYSTEM DESCRIPTION

The WECS proposed in this paper consists of a wind turbine coupled to a PMSG to power a stand-alone system. A three-phase diode bridge rectifier is used for the AC/DC conversion. A DC-DC boost converter is used to vary the rotor speed while an amorphous wire speed sensor is employed for wind turbine speed measurement. The proposed MPPT strategy uses a fuzzy logic controller to track the maximum power point curve of the WECS by varying the duty cycle of the DC-DC boost converter. The block diagram of the proposed system is shown in Figure 1. With the boost converter in the circuit, the expression for the resistance R_g seen by the generator is given by [16]

$$R_g = \frac{\pi^2}{18}(1-D)^2 R_L \tag{1}$$

where R_L is the load resistance connected at the output of the DC-DC boost converter in Ohms and D is the duty ratio.From the viewpoint of the rectifier, the boost converter and the load resistance R_L can be considered a variable resistance varied by changing the duty ratio D. From the analysis, it can be appreciated that the PMSG sees the rectifier and boost converter as a variable load resistance R_g which is a function of the duty ratio D. By varying the load resistance the generator output voltage V_g can be controlled. Since V_g is proportional to speed of rotation ω, [2] then by controlling the duty ratio D we can be able to control the speed of rotation ω

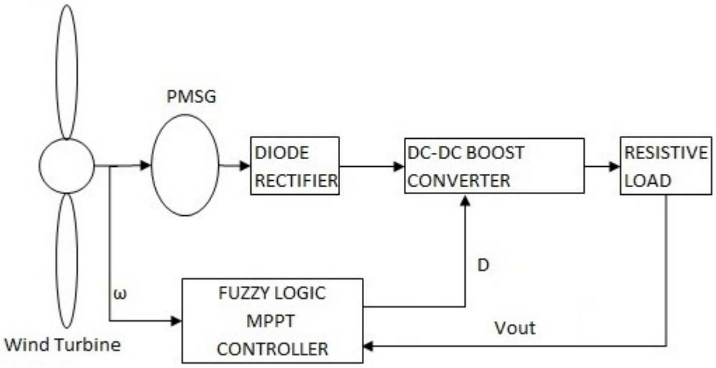

Figure 1. Block diagram of the proposed system

A. Wind Turbine Aerodynamic Model

The mechanical power extracted by the turbine is given by [16]

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p \tag{2}$$

where:P_m= Mechanical Power(W), ρ= Air density in kg/m3, R= Radius of the turbine blade in m, v = wind speed in m/s and C_p = power coefficient. C_p is a function of the tip speed ratio(TSR) as well as the blade pitch angle β for pitch controlled wind turbine [16]. In this work,the case study wind turbine has a fixed pitch hence β is set to zero. Hence $C_p = C_p(\lambda)$ and $\lambda = \frac{R\omega}{v}$ where ω = rotation speed of the rotor. C_p has a maximum value of 0.593 known as Beltz limit. From equation (1), when controlling the wind turbine, C_p is useful as it is the only variable and controllable parameter. Wind speed v is a variable but not controllable. There is a value of $\lambda = \lambda_{opt}$ for which C_p is maximum. If λ is maintained at its optimal value λ_{opt} the power coefficient is at its maximum value $C_{pmax} = C_p(\lambda_{opt})$ thus delivering maximum power for a given wind speed v.

$$P_{max} = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda_{opt}) \tag{3}$$

where

$$\lambda_{opt} = \frac{\omega R}{v} \quad \rightarrow \omega_{opt} = \frac{\lambda_{opt} v}{R}$$

Substituting ω_{opt} and rearranging gives:

$$P_{max} = \frac{1}{2}\rho\pi R^5 \frac{C_{pmax}}{\lambda_{opt}^3}.\frac{\lambda_{opt}^3 v^3}{R^3} \tag{4}$$

This equation can be expressed as:

$$P_{max} = K_{opt}\omega_{opt}^3 \tag{5}$$

where

$$K_{opt} = \frac{0.5\rho\pi C_{pmax}R^5}{\lambda_{opt}^3} \quad \text{and} \quad \omega_{opt} = \frac{\lambda_{opt}v}{R} \tag{6}$$

B. Proposed Speed Sensor

The sensor employed in this paper is a magnetostrictive amorphous wire with the composition (Fe50Co50)78Si9B13 and 25mm diameter, placed in a pick-up coil [14]. The operation of the sensor is based on Large Barkhausen Jump; sudden reversal (change) of magnetization at a single value of magnetic field. Due to LBJ, amorphous magnetostrictive wires generate very sharp and stable voltage spikes in ac fields. When a permanent magnet is attached on the wind turbine and a pick- up coil placed near it with the amorphous wire inside the coil, as the permanent magnet rotates due to rotation of the rotor, voltage spikes are induced in the coil due to the sudden reversal of magnetic flux in the amorphous wire core. The block diagram of the speed sensing system is shown in Figure 2.

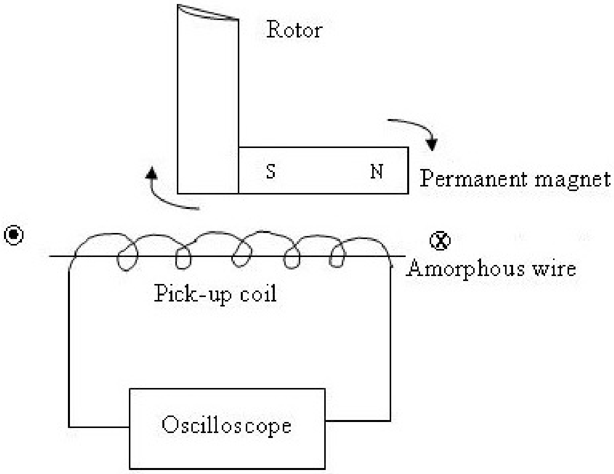

Figure 2. Set up of magnetostrictive amorphous wire speed sensor

The voltage spikes are induced every time the north pole of the magnet comes close to the wire. The frequency of the induced voltage spikes is equivalent to the number of times the North Pole passes close to the wire per second, hence the wind turbine rotational speed in revolutions per second. The wind turbine speed in revolutions per minute can then be deduced.

Critical design issues of the speed sensor system are determination of the critical length of the wire, optimal positioning of the wire relative to the wind turbine and performance of the sensor at different speeds of the turbine. For implementation,signal conditioning of the sensor output involves amplification of the signal and TTL conversion to enable interfacing with a microcontroller or other digital circuit.

C. Proposed MPPT Method

Mechanical power P_m has a unique optimal power curve P_{opt} which exhibits a cubic function of the generator speed [17]. Therefore, the optimal curve of a wind turbine's mechanical power is characterized by a unique constant K_{opt}

$$P_{opt} = K_{opt}\omega_{opt}^3 \tag{7}$$

where $K_{opt} = \frac{0.5\rho\pi C_{pmax}R^5}{\lambda_{opt}^3}$ and $\omega_{opt} = \frac{\lambda_{opt}v}{R}$
C_p = power coefficient
R = radius of blades
λ_{opt} = Optimum tip speed ratio

From the above equations, it is noted that K_{opt}, is associated with the captured mechanical power P_m, whereas the power being actually measured and subjected to maximization is the output electrical power P_o supplied to the load. The mechanical power is related to output electrical power by [17].

$$P_o = \eta_g\eta_c \times P_m \tag{8}$$

The mechanical and electrical power coefficients are then related by:

$$(K_{opt})_o = \eta_g\eta_c \times (K_{opt})_m \tag{9}$$

where η_g = generator efficiency, η_c = converter efficiency.

However, the overall efficiency of a WECS is not constant under wind and load variations. According to [17]there does not exist a unique optimal curve constant (K_{opt})o for Po and the maximum of the $P_o\omega$ curve does not coincide with the peak of the $P_m - \omega$ curve.This justifies the need for self-tuning to update K_{opt}.The designed MPPT algorithm aimed to maximize electrical power delivered to the load by driving the wind turbine at the optimal speed of rotation for maximum power production at various wind speeds. This was implemented by varying the duty cycle of the DC-DC boost converter according to the error between the reference power and the measured power output delivered to the load. The change in duty cycle ΔD was set adaptively using a Fuzzy Logic controller. The flowchart of the designed algorithm is shown in Figure 4.

D. Proposed Fuzzy Logic Controller(FLC)

The inputs to the Fuzzy Logic Controller were Error (E) in electrical output power and the change in Error ΔE where : Error $E(k) = P_{ref} - P_{measured}$ and change in this error $\Delta E(k) = E(k) - E(k-1)$. The output of the FLC was the change in duty cycle ΔD of the switch controlling the DC-DC boost converter. The membership functions for Error (E), Change in Error (ΔE) and change in duty cycle ΔD were constructed as Figure 3. The structure of the fuzzy logic controller is as Figure 3.

The rule base was designed as in Table I.

III. EXPERIMENTAL VERIFICATION AND RESULTS

The implementation of the system was done with a real WECS consisting of a fixed pitch, variable speed wind turbine directly coupled to a permanent magnet synchronous generator

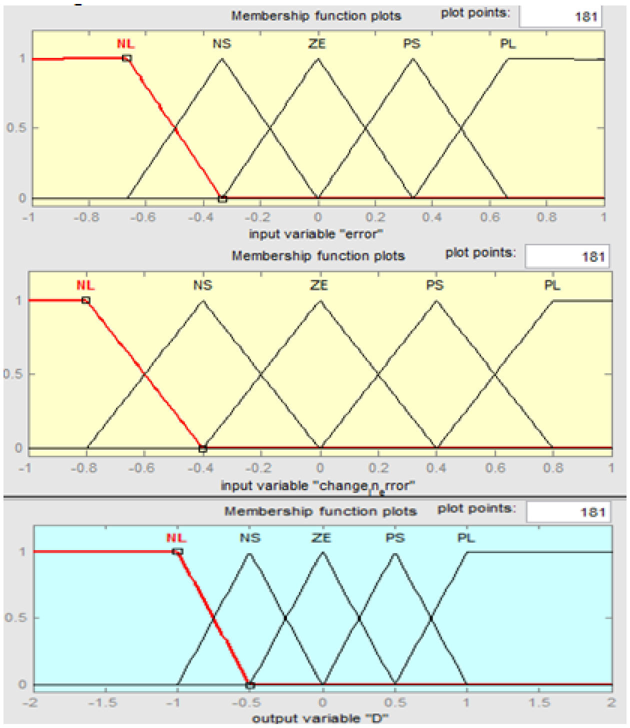

Figure 3. Membership function for Error (E),Chnage in Error (ΔE) and Duty Ratio (D)

Table I
RULEBASE FOR FUZZY LOGIC CONTROLLER

ΔD		Error				
		NL	**NS**	**ZE**	**PS**	**PL**
ΔError	**NL**	NL	NL	NS	NS	ZE
	NS	NL	NS	NS	ZE	PS
	ZE	NS	NS	ZE	PS	PS
	PS	NS	ZE	PS	PS	PL
	PL	ZE	PS	PS	PL	PL

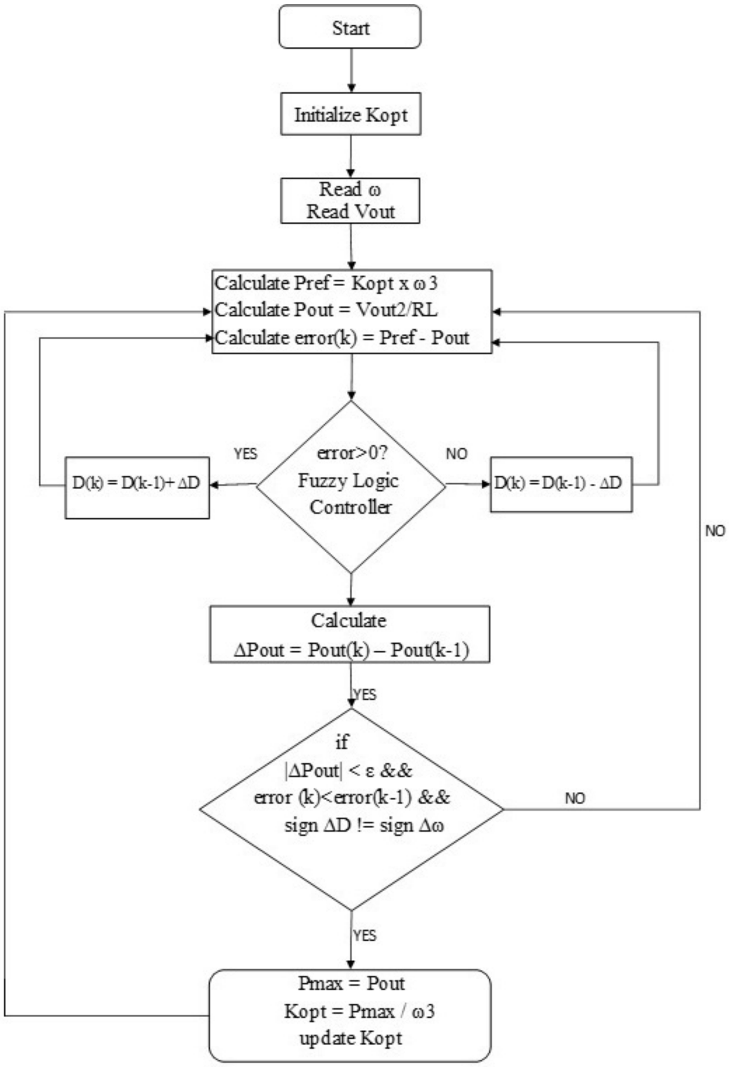

Figure 4. Flowchart of the designed MPPT algorithm

available at the University's research workshop. Arduino Mega 2560 Toolkit [18] was chosen to handle voltage and current measurement, implement the fuzzy logic control algorithm and output the duty cycle to drive the DC-DC boost converter. Its advantages includes an on board analog to digital converter and a PWM generation chip. A program code was written in the Arduino Mega 2560 Integrated development environment (IDE) and downloaded into microcontroller to perform the following tasks:Read speed of rotation and voltage output measurements from the sensors,implement the fuzzy logic maximum power point tracking control algorithm,output the required duty cycle to the DC-DC boost converter according to the Fuzzy Logic MPPT algorithm and extract maximum power point and update $Kopt$

The complete setup of the implemented system is shown in Figure 5.

The critical length of the sensor wire was experimentally found to be 7cm. This was due to the fact that Large Barkhausen Jump occurs at a given critical length of the wire, which for this case, was found to be to be 7cm.The optimal horizontal position of the wire relative to the wind turbine was experimentally found to be 4cm. It was also found that the wire should be centred relative to the position of the small magnet attached to the wind turbine for optimal performance of the sensor. The speed sensor's performance was tested at various speeds of rotation and the waveforms observed on an oscilloscope. The results were presented in the Figures 6 and 7.It can be seen that the magnetostrictive amorphous wire sensor was able to measure speed of rotation for a wide range of speeds from 1 to 5.5 Hz (63 to 326 rpm).

Test run at the various wind speeds were done by varying the duty cycle of the boost converter to obtain the Power vs speed of rotation curves for the implemented wind energy conversion system.Power vs speed of rotation curves were plotted as in Figure 8

From Figure 8 the electrical power output vs speed of rotation

Figure 5. Complete setup of the implemented system

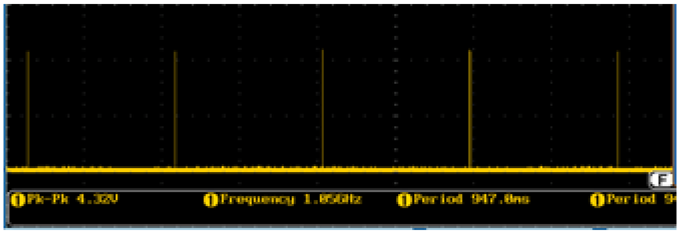

Figure 6. Sensor output waveform at 1.056 Hz (63.36 rpm)

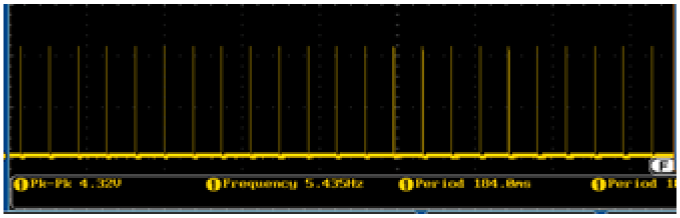

Figure 7. Sensor output waveform at 5.435 Hz (326.1 rpm)

curve has a single peak for each wind speed. This corresponds to the respective optimum speed of rotation.The experimental results for wind speeds of 2.7, 3.1 and 3.5m/s, with and without MPPT were tabulated in Table II

From Table II, it can be seen from the results that the introduction of the MPPT controller significantly increases the Power Output. The efficiency of the MPPT controller was also found to increase with increase in wind velocity. As the wind speed changed, the fuzzy logic controller changed the duty cycle of the DC-DC boost converter according to the error between the reference power and the measured power resulting in a variation of the load seen by the PMSG. As a result, the voltage at the terminals of the PMSG changed. Since the speed of rotation is proportional to the terminal voltage, it varied accordingly. Increase in duty cycle caused decrease in speed of rotation and vice versa. Consequently, the controller was able to track the reference maximum power for various wind speeds

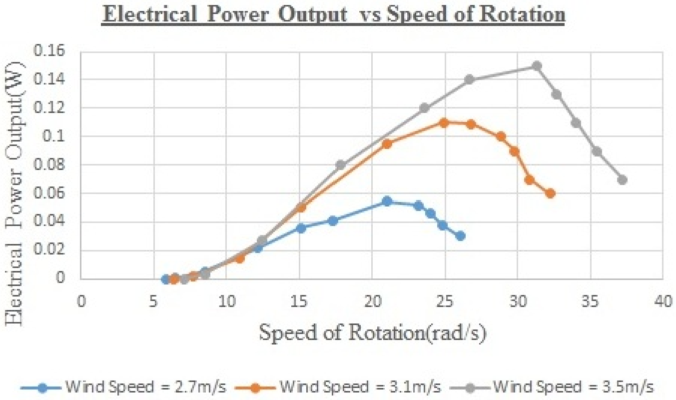

Figure 8. Power vs speed of rotation curves for various wind speeds

Table II
EXPERIMENTAL RESULTS

Without MPPT				With Fuzzy Logic MPPT Controller			
Wind Speed (m/s)	Rotational speed (rad/s)	V_{out}	P_{out}	Rotational speed (rad/s)	V_{out}	P_{out}	% Increase
2.7	25.2	5.6	0.09	20.3	26	28.8	39%
3.1	32.7	0.04	8.5	6.6	9.5	11.1	46%
3.5	35.2	7.85	0.10	0.06	0.13	0.17	71%

Using the values of K_{opt} obtained at respective maximum power points with for the various wind speeds maximum power point curves were plotted as in Figure 9

It can be appreciated from Figure 9 that the optimal curve constant K_{opt} for electrical power output is not unique for all wind speeds. Hence the need for self-tuning to arrive at the true maximum power point for various wind speeds. This is one of the novel features introduced into the MPPT algorithm.

IV. CONCLUSION

A simple, inexpensive and efficient magnetostrictive amorphous wire speed sensor was developed for the wind turbine. It was shown that the designed speed sensor was able to accurately measure the speed of rotation of the wind turbine for various speeds.

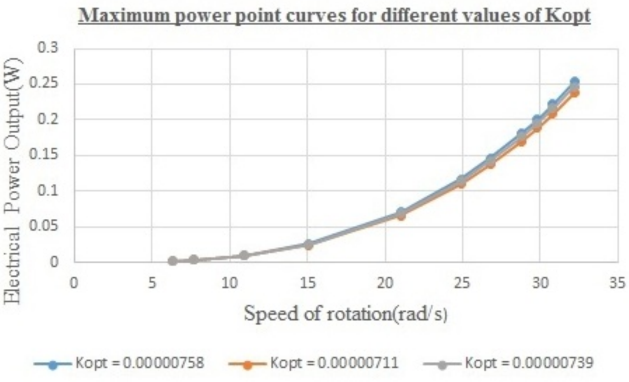

Figure 9. Maximum Power Oint Curves for different values of K_{opt})

A Fuzzy Logic MPPT Controller for the wind energy conversion system was designed and implemented. It was shown that the designed controller was able to track reference maximum power for the WECS with good accuracy for fluctuating wind velocities and thus maximize the electrical power delivered by the wind energy conversion system to the load.

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