DESIGN AND PERFORMANCE ANALYSIS OF PITCHED-PLATE VERTICAL AXIS WIND TURBINE FOR DOMESTIC POWER GENERATION

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ABSTRACT

Wind energy is identified a promising energy resource in Sri Lanka. Therefore, it is important to use proper technologies for efficient energy capturing in order to minimize cost of energy. Small scale wind turbines are usually installed in constricted places (particularly in urban areas) where wind flow is turbulent and difficult to predict. Savonious type vertical axis wind turbines are important due to several reasons such as good response to turbulent winds, high initial torque, low cost, low noise, less maintenance.

In this study, a modified flat plate type Savonius wind rotor was proposed to cost effectively harness wind energy in constricted places. Generally, vertical axis wind turbines (VAWT) are less efficient than horizontal axis wind turbines, one reason behind this issue is wind force difference between the 2 sides of the axis is small and due to this reason torque is small and power generation capacity is less.

A prototype of the proposed VAWT was fabricated and the performance was determined by acquiring experimental data. Artificial wind blow which was generated by a huge fan was used to measure rotational speed and torque characteristics at varying wind speeds. Data were collected with 1-second sampling time and a data acquisition system was developed under this study. In the proposed design one side of the turbine blades are facing the wind direction in order to capture maximum force while other side is edging the blades to have minimum opposite torque. With this concept it is expected to maximize the torque of the axis and generate more power. A sort of a passive pitch mechanism is therefore utilized in order to save energy and simplify the system. Turbine blades are simple flat plates and it eliminates usage of complex aero foils. Due to the simplicity of this design it would be possible to use this turbine for domestic electricity generation at affordable costs.

Nowadays, net metering systems are being promoted in Sri Lanka and it would be beneficial to introduce low cost VAWT which operates at low winds as well as turbulent wind conditions. Based on typical household hourly load profile, viability of proposed vertical axis wind turbine was evaluated by considering rural and urban wind regimes in Sri Lanka. The costs of wind energy at two selected locations were determined in the context of net metering.
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CHAPTER 1 : INTRODUCTION

1.1 Background

There are two types of vertical axis wind turbines (VAWT) mainly used in wind power generation. Those are Savonius and Darrieus. Savonius type turbines operate on drag forces while Darrieus turbines use lift forces. VAWT are not widely used due to their generally lower efficiency compared with horizontal axis wind turbines (HAWT). The main drawback of Darrieus type wind turbines is low starting torque and then it cannot be self started. As Savonius wind turbines are operated by using drag force, their starting torque is high. However, they have limited rotational speed due to rotor blades not being able to move faster than the wind speed.

1.1.1 Savonius turbine

The model that we are going to examine in this experiment is also operating on drag force and therefore in this introduction we discuss Savonius turbine and its features.

Advantages of Savonius wind turbines:

- Simple and low cost design
- Ability to operate at high wind speeds due to its low rotational speed operation. Generally most of the HAWTs are required to stop at high winds for safety precautions.
- High starting torque which enables to operate at low wind speeds (low cut-in speed).
- Lower noise levels than HAWTs due to low rotational speed.

Despite of the abovementioned advantages Savonius type turbines also exhibit some important disadvantages:

![Savonius wind turbine](image1.png)  ![Darrieus wind turbine](image2.png)
• Low rotational speeds, which prevent efficient usage for electricity generation (generally electricity generators are operated at high rotational speeds or required specially designed generators with large number of poles).

• Small VAWTs are often installed near the ground, while the wind speed is low in the boundary layer near the ground level.

• Low efficiency (theoretically Savonius reaches a power coefficient of 20% but in practical situations it is around 10%).

Due to these disadvantages Savonius turbines are not suitable for large wind power generators but they are possible to use for small scale domestic applications, which are the focus of this study.

1.1.2 Improvements of the Savonius turbine

There are number of improvements and studies done by numerous researchers and developers since the 1920s. Some of the successful improvements are discussed below.

1.1.2.1 Improvement by blade twisting

A study has been carried out by attempting to improve performance by twisted type blades as compared to common semicircular blades [1].

![Figure 1: Typical performance of conventional wind conversion systems, given as power coefficient vs. tip speed ratio [2]](image)

Due to these disadvantages Savonius turbines are not suitable for large wind power generators but they are possible to use for small scale domestic applications, which are the focus of this study.
According to the research outcome, the twisted Savonius rotor coefficient of power was improved by around 3% and self-starting capabilities were also improved, see Figs. 4 and 5.

1.1.2.2 Improvement by changing overlap ratio e/d

Static simulation has been carried out to investigate the effect of varying e/d ratio on the turbine torque coefficient, see Fig. 6 and Table 1.[2]

![Figure 6: Savonius rotor dimensions](image)

**Table 1: Influence of the overlap ratio on the torque coefficient**[2]

<table>
<thead>
<tr>
<th>Overlap ratio: e/d</th>
<th>0.1</th>
<th>0.13</th>
<th>0.16</th>
<th>0.22</th>
<th>0.242</th>
<th>0.28</th>
<th>0.32</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque coefficient : Cm</td>
<td>0.24</td>
<td>0.27</td>
<td>0.28</td>
<td>0.29</td>
<td>0.33</td>
<td>0.27</td>
<td>0.24</td>
<td>0.18</td>
</tr>
</tbody>
</table>

As a result, the e/d value of 0.242 gives an optimum torque coefficient.
1.2 Project Aim and Research Objectives

Main objective of this work is to develop a cost effective flat plate type Savonius wind rotor for small scale wind power generation. Performance analysis of the proposed system was done by experimental measurements by using a prototype model. To evaluate the viability of this proposed system in different wind regimes in Sri Lanka, typical domestic electrical load profile and wind data were used and cost of wind energy was calculated by considering net present value of the total investment and maintenance cost throughout the lifetime of the proposed system.

1.3 Original Contribution by the author

The main idea which inspired this new flat plate turbine was to overcome the disadvantage of low efficiency of conventional drag-force turbines. The reason behind low efficiency of that when the turbine rotates, one half of the rotor moves towards the wind and therefore opposing wind generates counter-torque (drag) which reduces the resultant torque on the shaft. The new design would attempt to decrease the counter-torque.

To increase the output power of the turbine we need to remove the backward force acting on the rotor when moving towards the wind. A simple mechanism was introduced using self-pitchable vane flat plates. In this design one blade of the rotor is subdivided into several strips and these strips are hinged to move freely and so that when the wind blows the plates are locked for achieving highest forces, while at the other half of the rotor these plates move freely and edging towards the wind for lowest possible drag. The force acting on the rotor half moving towards the wind will be minimized and therefore resultant shaft torque will be maximized.

1.4 Outline of the Thesis report

- Chapter 2
In this chapter aerodynamic behavior of flat plate turbine will be discussed through mathematical modeling based on momentum theory and dimension analysis. Other power requirements based on same aspect ratio will also be studied.

- Chapter 3
This chapter discusses the new design of flat plate rotor and mechanism used to eliminate backward drag. The practical implementation of the test model and the data acquisition system for the performed experiments are also discussed.
- Chapter 4
Experimental set up and methods of testing. Result observations, data handling and analysis are discussed in this chapter.

- Chapter 5
The viability of using the hereby proposed VAWT for domestic electricity generation and water pumping was studied. Implementing net metering was also examined and evaluated for two VAWT applications in Colombo and Hambantota districts in Sri Lanka.

- Chapter 6
Further developments and future work are discussed. Two improvements have been identified which can enhance the Savonius rotor performance if applied to the initially proposed and tested design.
CHAPTER 2 : AERODYNAMIC BEHAVIOUR OF VAWT

2.1 Introduction

Momentum theory [3] and blade element [4] theories are the most common and fundamental methods to evaluate aerodynamic forces on the wind rotor as well as to analyse the flow field. Aerodynamic characteristics and varying lift and drag coefficients (\(C_l\) and \(C_d\)) with varying angle of attack for a rotating flat plate are needed to evaluate rotor performance. Therefore, an empirical method was proposed in this study to determine rotor performance. Linear momentum theory neglects all wake losses and flow field interaction and this leads to deviation of expected performance from the experimental results. The empirical model was developed by experiments and the aspect ratio of the proposed VAWT was used in its dimensioning for the different power outputs and applications.

2.2 Mathematical modeling

In the initial stage blade element theory was implemented by using simple flat plate theory with the assumption of low rotational speed for modeling the wind rotor performance. Due to mismatch with experimental data, linear momentum theory was used to guide the experiment, while the empirical model was used for analysing the rotor performance. Assumptions when using momentum theory:

- Flow is incompressible.
- Flow is steady, inviscid, irrotational.
- Flow is one-dimensional and uniform through the rotor.
- No flow interactions between flow layers or streamlines.

The linear momentum theory gives the maximum possible power that can theoretically be produced by a wind turbine. Actual power is lower than the calculated because in this theory most of the losses are neglected such as friction losses, wake losses, tip losses, non-uniform flow errors etc.
List of symbols:

\( \theta \): Angle of attack of wind

\( U_1 \): Wind speed approaching the turbine (undisturbed wind)

\( m \): Mass of the selected wind strip of width \( dr \)

\( L \): Length of blades (third dimension, not visible in the figure)

\( R \): Radius of turbine

\( r \): Distance to the selected point from the center

\( \omega \): Rotational speed \( \) (Rad/s)

\( \lambda \): Tip speed ratio

\( T \): Torque

\( A \): Area of turbine faced to wind

**Figure 7: Mathematical model of a drag-force VAWT**
Tip Speed Ratio is defined as
\[ \lambda = \frac{\omega R}{U_1} \]  

(1)

The rotor area is divided into thin flat strips along the span of the turbine and linear momentum theory is applied to each wind strip, see Fig. 7.

By linear momentum theory it can be found that the momentum change of each wind strip colliding on the blade at distance \( r \) from the shaft which is rotating at the angular speed of \( \omega \) (see Fig. 7) would be
\[ F = m(U_1 - r\omega) \]  

(2)

Mass flow of wind strip at velocity \( U_1 \) length \( L \) and width of \( dr \), in kg/s, is
\[ m = \rho \cdot U_1 \cdot L \cdot dr \]  

(3)

Force acting on the turbine blade due to momentum change of each wind strip, is
\[ F(r) = \rho \cdot U_1 \cdot L \cdot (U_1 - r\omega) \cdot dr \]  

(4)

Torque on the shaft
\[ T(r) = \rho \cdot U_1 \cdot L \cdot (U_1 - r\omega) \cdot r \cdot dr \]  

(5)

By integrating torque for \( r=0 \) to \( r=R \), the resultant force on the rotor due to the wind is obtained as
\[ T = \int_{0}^{R} T(r) \cdot dr \]  

(6)

\[ T = \rho L \left[ \frac{U_1^2 R^2}{2} - U_1 \cdot \omega \cdot \frac{R^3}{3} \right] \]  

(7)

\[ T = \rho L \left[ \frac{U_1^2 R^2}{2} - U_1 \cdot \omega \cdot \frac{R^3}{3} \right] \]  

(8)

Power equals the torque multiplied with the rotational speed
\[ \text{Turbine Power} = T \cdot \omega \]  

(9)

Power coefficient represents the turbine aerodynamic efficiency
\[ C_p = \frac{\text{Turbine Power}}{\frac{1}{2} \cdot \rho \cdot U_1^3 \cdot A} \]  

(10)

Where
\[ A = 2R \cdot L \]  

(11)
2.2.1 Mathematical solution

The mathematical model was solved using Matlab script, shown in Annex I. In this calculation the skin drag force was neglected.

![Figure 8: Cp vs tip speed ratio for the mathematical model](image)

![Figure 9: Turbine power vs wind speed, for R = 500 mm](image)

2.3 Dimension analysis with experimental results

Experimental results were obtained for a turbine model with dimensions of 1 m rotor length and 0.5 m rotor radius. It was important to study the relation of dimensions of the test model to its Cp value, and how to use this Cp value for improved dimensioning. Buckingham’s pi theorem was applied to examine the relation of Cp to other parameters.
Buckingham’s pi theorem [6]

If there are \( n \) variables in a problem and these variables contain \( m \) primary dimensions (for example M, L, T) the equation relating all the variables will have \((n-m)\) dimensionless groups.

These groups are called \( \pi \) groups.

Final equation can be written as

\[ \pi_1 = f(\pi_2, \pi_3 ... \pi_{n-m}) \]

The \( \pi \) groups are independent of each other and no one group should be formed by multiplying together powers of other groups. This method offers the advantage of being simpler than the method of solving simultaneous equations for obtaining the values of the indices (the exponent values of the variables).

In this method of solving the equation, there are 2 conditions:

- Each of the fundamental dimensions must appear in at least one of the \( m \) variables
- It must not be possible to form a dimensionless group from one of the variables within a recurring set. A recurring set is a group of variables forming a dimensionless group.

Relation of turbine power output and other parameters is given as

\[ C_p = \frac{\omega.T}{(0.5\rho.D.L.U^3)} \]

\[ C_p = f(\omega,T,\rho,D,L,U) \]

\( \omega \) – Angular velocity
\( \rho \) – Density of air
\( D \) - Diameter of turbine rotor (2R)
\( L \) - Length of the turbine
\( U \) – Wind velocity
\( T \) – Torque

Number of variables \( n= 6 \).
Number of fundamental dimensions \( m = 3 \) (M, L, T).

By Buckingham’s theorem, the number of dimensionless groups would be \( n - m = 6 - 3 = 3 \). The variables \( \omega \), \( \rho \) and \( L \) are chosen as the recurring set.
The dimensions of these variables are:

\[ \omega = [T^{-1}] \]
\[ \rho = [ML^{-3}] \]
\[ l = [L] \]

The dimensionless groups are formed by taking each of the remaining variables T, D and U in turn.

Torque has dimensions of \( ML^2T^{-2}T \), therefore \( T.M^{-1}L^{-2}T^2 \) is dimensionless.
Substituting dimensions in terms of variables, gives
\[ \pi_1 = T \cdot \rho^{-1}l^{-3} \cdot l^{-2} \cdot \omega^{-2} \]

\( D \) has dimensions of \( L \), therefore \( DL^{-1} \) is dimensionless
\[ \pi_2 = D / l \]

\( U \) has dimensions of \( LT^{-2} \), therefore \( U.L^{-1}.T^2 \) is dimensionless
\[ \pi_3 = U \cdot l^{-1} \cdot \omega^{-2} \]

By Buckingham’s theorem
\[ T \cdot \rho^{-1}l^{3} \cdot l^{2} \cdot \omega^{-2} = f( D / L, \ U \cdot l^{-1} \cdot \omega^{-2} ) \]
\[ T \cdot \omega \cdot \rho^{-1}l^{5} \cdot \omega^{-3} = f( D / L, \ U \cdot l^{-1} \cdot \omega^{-2} ) \]

According to the above solution, turbine power (\( T \cdot \omega \)) is a function of aspect ratio (\( D/L \)). Therefore dimensioning of these types of turbines with the same aspect ratio of experimental setup can be used with the results obtained from the experiment (\( Cp \) vs tip speed ratio plot).
CHAPTER 3 : THE PROPOSED FLAT PLATE TYPE SAVONIUS WIND ROTOR

3.1 Introduction

Key feature of this new flat plate pitching wind turbine is to reduce opposing torque applied on the one half of the turbine during rotation against wind. In this new design the blade can move around its own axis in order to edge itself towards the wind. This is achieved by using simple stopper attached to the rotor arm. Turbine blades are pushed against this stopper and locked by wind forces on the downwind side of the rotor. On the upwind side of the rotor the blades are pushed away from the stopper and freely rotate around their hinged axis thus decreasing the drag forces.

*Figure 10: Pitched-plate controlling mechanism*

Figures 10 and 11 explain the concept and visualise the orientation of blades at different angles during one rotation of the turbine.

*Figure 11: Blade assembly and orientation*
The major advantages of this flat plate pitching design, adding to the abovementioned advantages of VAWTs, are the following:

- Simple and low cost design, can be produced in small workshops;
- Minimum maintenance;
- Safe at high wind speeds, cannot spin too fast;
- High starting torque, can easily start with the load connected;
- Promises higher efficiency than other drag-force VAWTs.

### 3.2 Model design and development

#### 3.2.1 Design objectives

After calculations of $C_p$ and torque, the below criterion was established in order to design and produce the prototype model to obtain maximum performance at lowest cost.

In order to achieve good self-starting capabilities, easy balancing of the rotor and maximum torque, four blades were introduced. Low cost components and simplified mechanical solutions were used to keep system cost at minimum and to make this turbine viable for micro power generation competitive with other sources of energy. For the initial model, plywood blades were used for the rotor but in a future manufacturing stage fiberglass or aluminum blades are recommended for higher reliability.

Simplicity is a major factor when implementing the model and if attempting mass production. Therefore special attention was paid to designing the blades and mounting of the blade strips. Blades were mounted in between 2 “L”-shape iron bars with 2 drill holes and thin shaft fixed to each blade as shown in Figures 12 and 13.

The 4 flat plate rectangular shape blades are each divided and hinged into 3 parallel strips to allow for a self-pitching ability at the downwind position while achieving a high drag coefficient at the locked (upwind) position.
### 3.2.2 Model development

Blade assembly and mounting method are presented in the figures below.

**Figure 2: Blade design and mounting**

Dimensions of the model:
- Length = 1000 mm
- Width = 500 mm

Dimensions are selected to comply with available experimental capacity and desired turbine power output. Each blade was divided into 3 strips as shown below.

**Figure 3: Blade structure and dimensions**
Turbine model is implemented according to the above dimensions with wooden frame and plywood blades. [8]

3.3 Data acquisition and control system

Data acquisition system consists of 4 main components

- Hardware units
- RS485 communication line
- Application software
- Database

The hardware consists of torque measuring setup and interfacing circuits for RPM sensor and anemometer. The RPM and anemometer interface, calibration data and specifications are described in Annex III.

All interfacing circuits are connected to a single RS 485 communication bus and each unit consists of unique address. Application software periodically polls data from each unit and stores all the data in the database with time stamps.

Common PDU format was implemented to maintain communication between the application software and each hardware unit. All the data received to the server and hardware unit checks for error detection using an 8-bit CRC calculation and omits erroneous data. The PDU format is given in Table 2.
In the PDU, a preamble is used to identify starting of new data packet. Device ID comes as the second byte. Inverse ID is included to avoid miscommunication and verification of data to and from the particular device. Control byte specifies data type e.g.: data packet, empty packet, calibration data, etc. CRC byte contains the calculated CRC value for the data packet.

### Table 2: PDU format for the data application software

<table>
<thead>
<tr>
<th>Preamble</th>
<th>ID</th>
<th>Inverse ID</th>
<th>Control byte</th>
<th>Data (8 bytes)</th>
<th>CRC</th>
</tr>
</thead>
</table>

3.3.1 Torque sensor

Turbine torque was measured using a load cell and braking mechanism attached to the shaft and load cell. The load cell and braking mechanism are shown in Figure 16.
Brake controlling is done via cable attached to the braking pads and cable tightening and loosing is controlled via motorised screw mechanism. This mechanism is controlled via application software using MPPT algorithm [8] [7] [3] implemented to keep turbine power at its maximum point.

During the operation, load cell output value is transferred to the application software and database via the RS485 communication link. Load cell interfacing and calibration is described in Annex IV.
3.3.2 RS 485 communication line

RS 485 communication was implemented in order to minimise effects from external interferences and to allow long length of wire connections. RS485 is capable of sending data through copper wires up to 1 km distance.

Level converter is used to interface the device with PC serial port. This converts RS485 voltage levels into RS232 levels. In this communication line, MAX3089 and MAX232 ICs were used. Datasheets are shown in Annex V.

3.3.3 Sampling rate

Sampling rate of data acquisition system depends on several factors, which are:

- Baud rate of data communication;
- Application software data processing speed;
- Database connection and storage delay.

To get a complete sample the application software has to communicate with 3 devices (RPM, Torque, Anemometer interfacing units). To take data from one device, the application sends 13 bytes and receives a reply of 13 bytes. Therefore, number of bytes for one complete data sample are

\[ 13 \times 2 \times 3 = 78 \text{ bytes} \]

Baud rate of data communication \( = 9600 \text{ bps} \)

Time taken to send 78 bytes \( = 0.065 \text{ s} \)

Time required for one device \( = 0.0325 \text{ s} \)

Therefore, to allow other delays a 935 ms delay for all three devices was configured. Then actual sampling time will be 1 s.

3.3.4 Application software

Application software is developed using “C#.Net” and it is capable of communicating with the RPM sensor, anemometer and torque monitoring units via the RS485 communication link. All the data communication packets are subjected to 8-bit CRC check for error detection at both ends.
During the operation the application software sends data polling packets to the assigned IDs (ID of RPM sensor, anemometer and load cell circuits) and waits for a reply from each unit. Once a reply is received without errors received data packet will be decoded and experimental data extracted and stored in the database.

![WT Mon application software user interface](image)

**Figure 8: WT Mon application software user interface**

In the application software user interface, turbine shaft power is displayed in the textbox so that the operator can view the power rating during the MPPT tracking in the manual mode and adjust the brake in order to keep the power at the desired value.

### 3.3.5 Database

“My sql” database is used to store the real time system data and wind speed with a time stamp. Data sampling rate can be multiple of 1 second. The reason to use “my sql” database is that its free and easy to implement, and there are freely available data connectors to interface with the “.Net” framework.
The table structure of “my sql” database is given in Table 3.

### Table 3: Database table structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>TimeStamp</td>
<td>datetime</td>
</tr>
<tr>
<td>V_Out</td>
<td>double</td>
</tr>
<tr>
<td>I_Out</td>
<td>double</td>
</tr>
<tr>
<td>V_in</td>
<td>double</td>
</tr>
<tr>
<td>Wind_Speed</td>
<td>float</td>
</tr>
<tr>
<td>Turbine_RPM</td>
<td>float</td>
</tr>
<tr>
<td>Torque</td>
<td>float</td>
</tr>
<tr>
<td>Turbine_Power</td>
<td>float</td>
</tr>
<tr>
<td>Electrical_Power</td>
<td>float</td>
</tr>
</tbody>
</table>

Figure 9: Database view using client application

### 3.4 Operation

When the turbine rotates, the anemometer, rotational speed and load cell interfacing units are polled by application software, which requests data with predefined interval. In this experiment, the data request interval was 1 second.
When polling, the application software sends data request packet with device ID and only the device with the same ID will reply with data. When the device receives the request it checks the CRC for error detection and if errors are detected the packet will ignore the request and will send a NAK (negative acknowledge) to the server. When software reads reply packet it decodes data and stores them in the database, or if NAK is received it will send previous packet again. Application also checks CRC for errors and if error is detected it will ignore data received and will send a NAK to device to send data again. If no error is detected, the application sends an ACK (acknowledgement) with the next packet. The device keeps sent data in the RAM until it receives an ACK from the server.

In the MPPT operation application calculates turbine power by multiplying turbine RPM and torque (calculated by multiplying load cell value and distance to the force acting point from the shaft). Then the application software issues command to the brake controlling motor to tighten or loosen the brake according to the previous value of power. Hill climbing [7] method was implemented to find and maintain the maximum power point.
CHAPTER 4  : EXPERIMENTAL VALIDATION

4.1 Introduction

A prototype of the proposed wind turbine was built under this project. During the period of this project it was hard to find and access a wind site with considerable wind speed. Therefore it was decided to use artificially generated wind speeds to test the wind turbine. With the limited resources available to the project, performance monitoring and testing were carried out by applying wind forces to the turbine in two ways:

- Mount the turbine on a vehicle and drive at different speeds in a calm and quiet environment.
- Use a large industrial fan to generate required wind speeds, resembling a wind tunnel setup.

4.2 Experimental setup I

In this setup the turbine was mounted on a vehicle and driven at different speeds. It was assumed that the vehicle speed equals the wind speed, which is applied to the wind turbine. This method of experiment was not successful due to some important reasons, which are:

- Surrounding air movements disturb the wind profile.
- Front area and cabin of the vehicle creates turbulence.
- Not good road conditions, bumpy roads, heavy traffic.

Therefore readings taken from this experimental setup were omitted and not used for the analysis.

Figure 10: Turbine testing by mounting on a vehicle and driving at variable speeds
4.3 Experimental setup II

The turbine was tested similar to a wind tunnel condition by applying wind generated from a large engine-driven fan operating at variable rotational speeds. The maximum output power from the turbine is usually obtained by controlling the system such that the relevant points of wind rotor torque and break load operating characteristic coincide. In order to achieve this, it is necessary to drive the turbine at optimal rotor speeds for a particular wind speed value. The hill climbing method maximum power point tracking (MPPT) controlling was used to achieve this. During this experiment it was observed that the maximum power point tracking was not responsive enough to follow the changes of wind speed due to high momentum of inertia of rotating parts, therefore it was decided to operate the braking system manually to find the maximum power point.

Figure 24: Experimental setup using a fan
Figure 25: Wind generator (industrial fan)
This was an open environment testing and thus the natural wind speed disturbances were again relevant. Main drawback of using a fan as a wind generator is the wake and swirl generated by fan rotation. Therefore it is vital to minimize the effect of swirl by placing the turbine at some distance to the fan. In this experiment the turbine was kept at a distance of 10 m away from the fan. This distance was selected by practical means, for example by observing and minimising the magnitude of anemometer reading variations.

In this experimental setup, wind velocity was measured by a cup-type anemometer. The anemometer was fixed near to the turbine rotor and it captures only the horizontal component of the wind velocity. Apart from the swirl of wind there can be fluctuation of wind speed due to engine rotational speed fluctuations and natural wind at the site, which both are ignored in this experiment, assuming that they are infinitesimal.

Despite the imperfect conditions and possible deviations of wind speed, this experimental method was successful for the purposes of this study. Most fluctuations and swirl effects were possible to eliminate by averaging and filtering the collected measurement data.

Figure 12: Minimising the swirl effect on the turbine
4.4 Observations

All the data from the database were extracted to a Microsoft Excel file and these data are analyzed using Matlab and Simulink models in different methods in order to obtain the performance map of the turbine with respect to the tip speed ratio. Data analysis methods are explained below. The power coefficient $C_p$ of the wind turbine was used as primary parameter for the performance analysis. Definition of $C_p$ is given in equation 10.

4.4.1 Data analysis I

During the experimental campaign a number of maximum power points were recorded in the data base. Initially the total test duration was divided into 2 samples, from which the maximum power points and related tip speed ratios were obtained.

Test sample 1

Turbine efficiency vs different parameters is plotted in the graphs below. Several maximum power points can be observed. Tip speed ratio for maximum efficiency was found to be around 0.5.

![Figure 13: Test data sample 1, $C_p$ vs Time](image-url)
Figure 14: Test data sample 1, $C_p$ vs $\lambda$

The maximum efficiency recorded in this sample was 25%. Some deviations have been caused by erroneous readings.

Test sample 2

Figure 15: Test data sample 2, $C_p$ vs Time
The maximum efficiency recorded in this sample was 20%, occurring at around 0.45 tip speed ratio. A violent spread of readings caused some illogical results for the Cp values, which need to be neglected.

**Table 4: Data analysis I summary of results**

<table>
<thead>
<tr>
<th></th>
<th>Tip speed ratio</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample 1</td>
<td>0.5</td>
<td>25</td>
</tr>
<tr>
<td>sample 2</td>
<td>0.45</td>
<td>20</td>
</tr>
<tr>
<td>average</td>
<td>0.475</td>
<td>22</td>
</tr>
</tbody>
</table>

Experimental tip speed ratio value (0.475) does not match the calculated value of 0.75. The mathematical model is simplified, while the experiment involves uneven flow field and other losses. The uncertainties cause the appearance of irrelevant Cp values above the Betz limit.

### 4.4.2 Data analysis II

In this method several MPPT points are extracted with time span before and after the point. When analysing raw data from the database and plotting graphs we observed that there are sudden variations of Cp value. The reason behind this spikes in the Cp is variation of wind speed at the measuring point. Because the wind generated from the fan is not always constant and the flow is uneven, it gives sudden variations of wind speed.
speed readings and leads to high measurement uncertainties. In order to minimise these variations, $C_p$ values were obtained by averaging the values around maximum power points.

Figure 17: $C_p$ (Average) vs Time for total test duration

![Figure 17](image17.png)

Figure 18: $C_p$ (Average) vs Lambda for total test duration

![Figure 18](image18.png)

From the above graph we can observe that maximum power point occurs at 0.4 tip speed ratio and its $C_p$ value varies from 0.15 to 0.3.
MPPT extract I

*Figure 19: MPPT extract 1, $C_p$ vs Time*

Result average: $C_p = 0.16$

From the trend line in Figure 34: Average $C_p = 0.15$ at $\lambda = 0.32$

*Figure 20: MPPT extract 1, $C_p$ Vs $\lambda$*
MPPT extract II

**Figure 21: MPPT extract 2, Cp vs Time**

Result average: \( \text{Cp} = 0.17 \)

From the trend line in Figure 36: Average \( \text{Cp} = 0.16 \) at \( \lambda = 0.24 \)

**Figure 22: MPPT extract 2, Cp vs Lambda**
**MPPT extract III**

![Graph: Cp vs Time](image)

**Figure 23: MPPT extract 3, Cp vs Time**

Result average: $C_p = 0.0624$

From the trend line in Figure 38: Average $C_p = 0.06$ at $\lambda = 0.19$

![Graph: Cp vs Lambda](image)

**Figure 24: MPPT extract 3, Cp vs Lambda**
MPPT extract IV

**Figure 25: MPPT extract 4, Cp vs Time**

Result average: \( \text{Cp} = 0.18 \)

From the trend line in Figure 40: Average \( \text{Cp} = 0.18 \) at \( \lambda = 0.28 \)

**Figure 26: MPPT extract 4, Cp vs Lambda**
MPPT extract V

\[ y(x) = cste \]
\[ cste = 0.15488 \]
\[ R = 1.3899e-005 \text{ (lin)} \]

**Figure 27: MPPT extract 5, \( C_p \) vs Time**

Result average: \( C_p = 0.155 \)
From the trend line in Figure 42: Average \( C_p = 0.15 \) at \( \lambda = 0.28 \)

**Figure 28: MPPT extract 4, \( C_p \) vs Lambda**
Observed results after data averaging and filtering:

**Table 5: Data analysis II summary of results**

<table>
<thead>
<tr>
<th></th>
<th>Cp</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extract 1</td>
<td>0.15</td>
<td>0.31</td>
</tr>
<tr>
<td>Extract 2</td>
<td>0.16</td>
<td>0.24</td>
</tr>
<tr>
<td>Extract 3</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>Extract 4</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>Extract 5</td>
<td>0.15</td>
<td>0.29</td>
</tr>
<tr>
<td>Average</td>
<td>0.16</td>
<td>0.262</td>
</tr>
</tbody>
</table>

### 4.4.3 Data analysis III

Results from the above data analysis differ again from the mathematically obtained Cp. Therefore it was decided to further analyze the data set.

Turbine torque can be written as sum of torque generated by wind and the torque due to moment of inertia and angular acceleration.

The relation if given in the equation below

$$T_{turbine} = T_{wind} - J\dot{\omega}$$

In this experiment we are actually going to find out instantaneous power output values, therefore it is important to eliminate torque due to moment of inertia. According to the equation above it is possible to eliminate the $J\dot{\omega}$ by filtering higher $\dot{\omega}$ values. This is carried out by a Matlab Simulink model which delivers filtered data set for further analysis.

After the initial filtering a sudden increment of Cp values was observed again. This behavior can again be explained with fluctuations of anemometer readings due to swirl effects and unsteady wind profile coming out from the fan. Despite that, the data analysis in this series can be represented by the mathematical expression given below.

$$Cp = \frac{\text{Measured Torque} \cdot \text{Measured Angular Speed}}{0.5 \cdot A \cdot \rho \cdot (\text{Measured Wind Speed})^3}$$

When the turbine rotates the torque and angular speed variations are not significant and only very strong sudden changes of the wind speed are erroneously recorded due to the low moment of inertia of the anemometer. Therefore, when the turbine rotates at certain angular velocity, any sudden
variation of the wind speed at anemometer would lead to large variation of the Cp value because Cp depends on the cube of the wind speed. It was thus decided to filter abnormal Cp values by setting maximum reference value as an upper limit to the deducted Cp. This value of Cp was selected from the mathematical result, which is 0.18. According to the mathematical modeling most of the losses are omitted and the result obtained was the maximum Cp attainable for this turbine. All practical results must be less than this value.

After the data filtering it could be observed that the data series contain several wind speed readings and it was decided to separate these data into wind speed blocks for clarity of the analysis. Finally, Cp as a function of tip speed ratio (lambda) was plotted for different wind speed blocks and performance graphs for the turbine were obtained by averaging Cp and lambda values.

Figure 29: Matlab Simulink model for data filtering
Wind speed block between 3 - 4 ms$^{-1}$

Figure 30: $C_p$ vs $\lambda$ for wind speed 3-4 ms$^{-1}$

Wind speed block between 4 - 5 ms$^{-1}$

Figure 31: $C_p$ vs $\lambda$ for wind speed 4-5 ms$^{-1}$
Wind speed block between 5 - 6 ms$^{-1}$

![Figure 32: Cp vs \( \lambda \) for wind speed 5-6 ms$^{-1}$](image)

Wind speed block between 6 - 7 ms$^{-1}$

![Figure 33: Cp vs \( \lambda \) for wind speed 6-7 ms$^{-1}$](image)
Design and performance analysis of pitched-plate VAWT for domestic power generation.
MSc thesis, EKV947, August 2012

Wind speed block between 7 - 8 ms\(^{-1}\)

\[ y(x) = a_0 + a_1 x + a_2 x^2 \]
\[ a_0 = 3.963 \times 10^{-3} \]
\[ a_1 = 0.090297 \]
\[ a_2 = 0.08099 \]
\[ R = 0.92247 \] \( (\text{in}) \)

**Figure 34: \( Cp \) vs \( \lambda \) for wind speed 7-8 ms\(^{-1}\)**

Wind speed block between 8 - 9 ms\(^{-1}\)

\[ y(x) = a_0 + a_1 x + a_2 x^2 \]
\[ a_0 = 6.3198 \times 10^{-3} \]
\[ a_1 = 0.22284 \]
\[ a_2 = 0.14553 \]
\[ R = 0.9703 \] \( (\text{in}) \)

**Figure 35: \( Cp \) vs \( \lambda \) for wind speed 8-9 ms\(^{-1}\)**
Observed results after the latest data corrections and filtering:

**Table 6: Data analysis III summary of results**

<table>
<thead>
<tr>
<th>Wind speed (ms⁻¹)</th>
<th>Lambda</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>0.387</td>
<td>0.096</td>
</tr>
<tr>
<td>4-5</td>
<td>0.361</td>
<td>0.096</td>
</tr>
<tr>
<td>5-6</td>
<td>0.35</td>
<td>0.0982</td>
</tr>
<tr>
<td>6-7</td>
<td>0.34</td>
<td>0.1</td>
</tr>
<tr>
<td>7-8</td>
<td>0.32</td>
<td>0.11</td>
</tr>
<tr>
<td>Average</td>
<td>0.3516</td>
<td>0.10004</td>
</tr>
</tbody>
</table>

**4.4.4 Final result from experiments and data analysis**

As a conclusion after applying the data analysis methods presented above, method III which was based on filtering of higher Cp and angular acceleration is taken as most accurate, and thus agreed to represent the final outcome of this experiment as given below:

- Aspect ratio of the turbine (D/L) = 1
- Average experimental Cp value = 0.1 (10%)
- Tip speed ratio at these conditions = 0.352

Figure 50 shows the Cp characteristic curve of the tested flat plate VAWT.
Figure 36: Wind Turbine characteristic curve

Error estimation for the final experimental results:

Cp = turbine power / available power in wind
Turbine power = T x Omega
Error in turbine power = ΔT . ΔOmega
Available wind power = ½ . ρ . A . V³
Error in Wind Power = Δ A . ΔV³
ΔT = 0.033 Nm
ΔOmega = 0.00044 Rad/s
ΔA = 0.001 * 0.001 m²
ΔV = 0.00066 ms⁻¹
Maximum Cp error at maximum power point
= \frac{(5.43+0.033)*(3.14+0.00044)}{(0.5*1.16*(1-0.000001)*(5.54-0.00066)^3)} - 0.1728
= 0.001128
CHAPTER 5 : VIABILITY OF VAWT FOR MICRO POWER GENERATION IN SRI LANKA

5.1 Introduction

When designing small-scale renewable energy systems efficiency is not the ultimate parameter that we should look into. One reason is that we can afford building a larger energy converter if that would allow the optimisation of other parameters. Another reason is that cost and simplicity of design are much more important than efficiency and productivity. The flatplate turbine design is much simpler than any other turbine and avoids the use of complex aerofoil shapes and structures. The cost of this turbine is at minimum when compared with conventional HAWT structures.

Practical applications of small VAWTs are primarily the following:

1. Water pumping

   Due to low rotational speed and high torque it is suitable to couple the hereby proposed wind rotor with a reciprocating pump that is mainly used for agricultural or household water pumping.

2. Domestic electricity generation

   Expected turbine rotational speed is around 50 rpm at 4 ms-1 wind speed, therefore a high gear ratio is required to generate electricity for domestic usage or to connect to the grid. Alternatively, multi-pole electrical generators can be used for direct coupling with the wind rotor.

5.2 Electricity generation

   A plausible design of domestic electrical system using a VAWT [9] is shown in Annex VI.

   In this study, the districts of Colombo and Hambantota in Sri Lanka were selected, and the viability of the proposed turbine for domestic electricity production was considered and assessed in terms of cost of electricity.

   Net metering configuration was selected to export extra energy to the national grid and import energy when wind power is not available. The experimental result of $C_p = 0.10$ was used for the calculation of the required turbine dimensions.

   HOMER software was used to model the system with the daily electricity load pattern and wind resource generated by a geospatial tool kit. HOMER
is a computer model that simplifies the task of designing distributed generation (DG) systems - both on- and off-grid [14].

5.2.1 Net metering

Net metering is a utility policy created to facilitate consumers who own alternative energy source converters, especially renewable energy systems, and who want to export excess electricity to the national grid. The word “Net” refers to that consumers pay only for the net power they consumed when locally produced electricity is measured against the consumed such. More accurately, in the net metering system the grid acts as a large energy storage, accepting the locally produced power whenever it is available and delivering power whenever it is needed and when local production is insufficient. The consumers only pay for the net amount of energy they imported from the grid. The net amount can be balanced on a per day or per month basis, or on any other time basis for finding a negative (import) or positive (export) energy balance for the local electricity generator.

![Net metering system overview](image)

**Figure 37: Net metering system overview**

In the net metering system, renewable energy power generation (in this case the wind turbine with a DC generator) is connected to the grid tie inverter which generates AC voltage and matches with the grid phase for a intertie to the grid with exactly the proper phase angle and output voltage. The in- or outflow of power is measured by a special energy meter which runs in both directions, balancing off the locally produced and exported power to the imported one when the wind turbine is not operating. At the end of each dedicated time period the consumer pays only for the portion
of imported power that has exceeded the exported one, or vice versa, the consumer (local producer) will get paid for the portion of exported power if local electricity production exceeds the consumption.

5.2.2 Wind resource

Wind resource data for the abovementioned areas were generated from the geospatial tool kit [8], which gives the winds speeds at 50 m height for any location in Sri Lanka.

5.2.2.1 Wind data extracted from Geospatial toolkit [8]

![Wind resource map of Sri Lanka](image)

**Figure 38: Wind resource map of Sri Lanka**

In this study hub height of the wind turbine was taken as 20 m which is the maximum practical height for small scale wind turbines. Logarithmic profile wind speed variation [10] was used for the conversion of wind resource data to the selected 20 meter height level (meaning that wind speed is proportional to the logarithm of height above ground).

The following equation [11] was used to calculate the wind speeds at the required height:
\[ \frac{\nu_{\text{hub}}}{\nu_{\text{anem}}} = \ln\left(\frac{h_{\text{hub}}}{z_0}\right)/\ln\left(\frac{h_{\text{anem}}}{z_0}\right) \]

- \(Z_{\text{hub}}\) = the hub height of the wind turbine [m]
- \(Z_{\text{anem}}\) = the anemometer height [m]
- \(Z_0\) = the surface roughness length [m]
- \(\nu_{\text{hub}}\) = wind speed at the hub height of the wind turbine [m/s]
- \(\nu_{\text{anem}}\) = wind speed at the anemometer height [m/s]
- \(\ln(\cdot)\) = the natural logarithm

In the geospatial tool kit wind data are predicted for 50 m height from the ground and by means of above equation it is possible to map the wind speeds at 20 m height.

The surface roughness for Colombo is assumed as 1.5 m \[12\] and for Hambantota it was taken as 0.25 m \[12\]. Hourly wind speeds are generated synthetically from monthly averages.

**Table 7: Monthly averaged wind speed at 50m height**

<table>
<thead>
<tr>
<th>Month</th>
<th>Colombo (ms^{-1})</th>
<th>Hambantota (ms^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>4.09</td>
<td>7.47</td>
</tr>
<tr>
<td>Feb</td>
<td>2.75</td>
<td>6.53</td>
</tr>
<tr>
<td>Mar</td>
<td>3.35</td>
<td>5.62</td>
</tr>
<tr>
<td>Apr</td>
<td>3.82</td>
<td>4.2</td>
</tr>
<tr>
<td>May</td>
<td>6.69</td>
<td>7.86</td>
</tr>
<tr>
<td>Jun</td>
<td>7.23</td>
<td>8.14</td>
</tr>
<tr>
<td>Jul</td>
<td>6.79</td>
<td>8.51</td>
</tr>
<tr>
<td>Aug</td>
<td>7.12</td>
<td>9.16</td>
</tr>
<tr>
<td>Sep</td>
<td>6.38</td>
<td>6.22</td>
</tr>
<tr>
<td>Oct</td>
<td>5.1</td>
<td>7.06</td>
</tr>
<tr>
<td>Nov</td>
<td>3.8</td>
<td>3.16</td>
</tr>
<tr>
<td>Dec</td>
<td>4.1</td>
<td>3.82</td>
</tr>
</tbody>
</table>

**5.2.3 Wind turbine**

Flat plate type wind turbine with 200 W rated power and a grid tie inverter were considered as electricity generation system.
The turbine dimensions are given below:

Rotor Radius = 1 m  
Blade Length = 2 m  
Aspect ratio (L/D) = 1  
Mean Height = 20 m  
Cp = 0.10

Cost of turbine = 130,000.00 Rs

Annual maintenance cost is taken as 1.5% [13] of the total cost of turbine.

The actual power curve of the wind turbine was determined by coupling a suitable generator and applying relevant power converters to the system.

![Power Curve](image)

*Figure 39: Proposed wind turbine power curve*

Annual energy output of the wind turbine for both locations were calculated by using HOMER [14] and the results are:

Colombo – 814 kWh/year ; Hambantota – 2500 kWh/year.

The electrical load profile in a typical house in Sri Lanka is given in Fig. 54:

![Daily Profile](image)

*Figure 40: Typical load profile of a Sri Lanka household*
5.3 Summary Colombo

Table 1: Grid report for a house with a wind turbine in Colombo

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy Purchased (kWh)</th>
<th>Energy Sold (kWh)</th>
<th>Net Balance (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>149</td>
<td>0</td>
<td>149</td>
</tr>
<tr>
<td>Feb</td>
<td>129</td>
<td>0</td>
<td>129</td>
</tr>
<tr>
<td>Mar</td>
<td>160</td>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>Apr</td>
<td>148</td>
<td>0</td>
<td>148</td>
</tr>
<tr>
<td>May</td>
<td>127</td>
<td>0</td>
<td>127</td>
</tr>
<tr>
<td>Jun</td>
<td>130</td>
<td>0</td>
<td>130</td>
</tr>
<tr>
<td>Jul</td>
<td>132</td>
<td>0</td>
<td>132</td>
</tr>
<tr>
<td>Aug</td>
<td>146</td>
<td>0</td>
<td>146</td>
</tr>
<tr>
<td>Sep</td>
<td>138</td>
<td>0</td>
<td>138</td>
</tr>
<tr>
<td>Oct</td>
<td>139</td>
<td>0</td>
<td>139</td>
</tr>
<tr>
<td>Nov</td>
<td>140</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>Dec</td>
<td>148</td>
<td>0</td>
<td>148</td>
</tr>
<tr>
<td>Annual</td>
<td>1,686</td>
<td>0</td>
<td>1,686</td>
</tr>
</tbody>
</table>

Cost summary Colombo

Total net present cost            Rs 697190
Levelized cost of energy          Rs 27.43/kWh
Operating cost                    Rs 31070/yr
5.4 Summary Hambantota

Table 2: Grid report for a house with a wind turbine in Hambantota

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy Purchased (kWh)</th>
<th>Energy Sold (kWh)</th>
<th>Net Balance (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>132</td>
<td>4</td>
<td>128</td>
</tr>
<tr>
<td>Feb</td>
<td>124</td>
<td>1</td>
<td>123</td>
</tr>
<tr>
<td>Mar</td>
<td>154</td>
<td>0</td>
<td>154</td>
</tr>
<tr>
<td>Apr</td>
<td>157</td>
<td>0</td>
<td>157</td>
</tr>
<tr>
<td>May</td>
<td>121</td>
<td>5</td>
<td>117</td>
</tr>
<tr>
<td>Jun</td>
<td>121</td>
<td>5</td>
<td>115</td>
</tr>
<tr>
<td>Jul</td>
<td>117</td>
<td>6</td>
<td>111</td>
</tr>
<tr>
<td>Aug</td>
<td>118</td>
<td>7</td>
<td>111</td>
</tr>
<tr>
<td>Sep</td>
<td>141</td>
<td>1</td>
<td>140</td>
</tr>
<tr>
<td>Oct</td>
<td>135</td>
<td>2</td>
<td>133</td>
</tr>
<tr>
<td>Nov</td>
<td>158</td>
<td>0</td>
<td>158</td>
</tr>
<tr>
<td>Dec</td>
<td>163</td>
<td>0</td>
<td>163</td>
</tr>
<tr>
<td>Annual</td>
<td>1,640</td>
<td>31</td>
<td>1,609</td>
</tr>
</tbody>
</table>

Cost summary Hambantota

Total net present cost Rs 577330

Levelized cost of energy Rs 22.62/kWh

Operating cost Rs 24830/yr

According to the micro power optimization, the cost of wind energy in Colombo (urban site) is a bit higher than in Hambantota (rural site). The tier type tariff mechanism is applied in Sri Lanka for grid electricity sales [13] and monthly consumption of 164 kWh, mean electricity flat rate is 25 Rs/kWh. For net metering connections in Sri Lanka the consumer is not paid for export of energy, but is given credit (in kWh) for consumption of same amount of energy later. Therefore, same power prices are applied
for selling back power. The results show that the application of the wind turbine in Colombo is not competitive. If we increase the turbine size in order to match the power demand in Colombo, it would increase the cost of turbine and would still not be a practical solution for domestic usage. The comparison between cost of energy and operating costs gives a marginal advantage for a rural site like Hambantota.

Another parameter that was considered in this feasibility study was the capacity factor for the two selected sites.

Capacity factor is defined as:

\[
CF = \frac{\text{Energy produced by the system during one year}}{\text{Total energy which can be produced}}
\]

Capacity factor for Hambantota = 24.3
Capacity factor for Colombo = 7.63

According to the wind economics researches [13], viable capacity factor for a wind power system lies between 27 and 30. Therefore, in the Hambantota area the CF value is close to being viable and it can be concluded that this type of turbines are most appropriate for rural areas with strong winds which are available throughout the year.

5.5 Water pumping

During May to September the entire dry regions of Sri Lanka experience average wind speeds of 4 – 5 m/s. Most of the agricultural lands are in the dry zone and therefore it should be possible to use the proposed wind turbine for agricultural water pumping, as well as for domestic pumping in the entire costal ranges and especially in Hambantota, in the northern province and in the Mannar district.

In wind pumping applications the below listed pumps are widely used all over the world:

- Screw pump [16],
- Cup seal type reciprocating pump,
- Rope pump.
CHAPTER 6 : CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Wind turbine efficiency was calculated using the linear momentum theory equations and thereafter validated through experiments but there is a mismatch between theoretical and experimental results. Therefore it can be concluded that the simple mathematical models developed by using blade element and momentum theories are not accurate and we have to implement an empirical model for this turbine, which should also include various applicable losses and imperfections of the system.

According to the observations and data analysis it can be concluded that the Cp value of the 1 x 1 m (aspect ratio of 1) turbine rotor is 0.10 and the related optimum tip speed ratio is 0.35. Although it was possible to achieve satisfactory results with the available resources, far more accurate experiments could be done by proper wind tunnel testing. Therefore, a wind tunnel test is recommended for the proposed turbine model.

According to the research [15], wind tunnel tests of Savonius rotors show a turbine efficiency in the range of 9.2% to 13% for different aspect ratios. Since experimental results for the hereby proposed pitched-plate VAWT are within the range for Savonius rotors, it can be concluded that the experimental results in this study are justifiable.

For the domestic power generation this turbine is not highly recommended for Colombo or for similar urban low-wind districts, but according to the capacity factor comparison Hambantota and similar rural high-wind districts would be viable locations.

6.2 Future work

6.2.1 Semicircular type flat plate turbine

Further development and refinement of the flat pitched-plate turbine model can be proposed as future work to this research. One of the improvements is to form the blades in semicircular shapes using multiple flat strips. In this configuration we can consider one side of the rotor as a conventional Savonius rotor with semicircular shape and on the other side all the strips are edged to the wind as described in Figures 10 and 11 above.

Semicircle shapes have higher drag coefficient than flat plates, therefore it can be expected that this newly proposed configuration will have a better power coefficient.
6.2.2 Darrieus and flat plate combined model

Darrieus rotors have higher efficiencies than Savonius but due to low starting torque these turbines are not widely used in water pumping applications. Since flat plate type turbine has very high starting torque it will be advantageous to combine these two types of turbines and eliminate the drawbacks of each single type.

All other components (generator, pump, gearbox) of small-scale systems can be considered as common, therefore adding complexity to the turbine by blending different types of rotors should not increase considerably the total cost, which additionally is compensated by the increment of $C_p$. 

Figure 41: Drag coefficient of a flat plate and a semicircle shape (cup/bowl) [18]

Figure 42: Improved Savonius rotor with hinged flat plates
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http://www.aerospaceweb.org/question/airfoils/q0150b.shtml


ABBREVIATIONS

HAWT: Horizontal Axis Wind Turbine
VAWT: Vertical Axis Wind Turbine
MPPT: Maximum Power Point Tracking
RPM: Revolutions Per Minute
PDU: Protocol data unit
Cp: Coefficient of power
CRC: Cyclic redundancy check
ACK: Acknowledgement
NAK: Negative acknowledgement
GUI: Graphical user interface
COE: Cost Of Energy
APPENDICES

ANNEX I : Matlab script for mathematical model by momentum theory

U1=2;  % Wind speed
% blade dimensions : length = 1m width = R m
blade_length = 1;
R=.5;  % Radius of the blade
syms r;
lambda = .6;% tip speed ratio
D_air=1.16;

power1=0;
blade_div = 100;
f_trapz=0;
f_prev=0;
force_acting_point=.5;

%for n=1:1:100
lambda = .01 *75;

for u_var= 1:1:10
U1 = u_var*1;

omega = lambda * U1/(R);

T = D_air * U1 * blade_length*(U1 - r*omega)*r;
T_int = int(T, r,0,.5);

% calculation of skin drag force due to viscosity
mu=1 * power(10,-5) ;
Re = (D_air*U1*R)/mu;
Cdf= 0.074 * power(Re,-(1/5));
Dynamic_pressure = D_air * power(U1,2)/2;
Tw= Cdf * Dynamic_pressure;
Skin_Drag = Tw* R * blade_length * 2;  % skin drag for both side of one blade

%skin_drag_torque= Skin_Drag .* R/2 .* (sin(theta1) + cos(theta1));
%skin_drag_power = (omega/(pi/2)) .*
(trapz(theta1,skin_drag_torque));
skin_drag_trapz=0;
skin_drag_torque_prev=0;
for l=0:1:50
theta2 = pi/100 * l;
skin_drag_torque= Skin_Drag .* R/2 .* (sin(theta2) + cos(theta2));
skin_drag_trapz = skin_drag_trapz + (skin_drag_torque + skin_drag_torque_prev)/2* (pi/100);
skin_drag_torque_prev = skin_drag_torque;
end
skin_drag_power = (skin_drag_trapz * (omega/(pi/2)))* 2; % skin
drag power due to 2 blades
%skin_drag_power=0;
power1 = T_int * omega;
turbine_power = power1-skin_drag_power ;
wind_power = .5 * R * blade_length *2 * D_air * power(U1,3);

% turbine efficiency calculation
eff(u_var) =turbine_power/wind_power;
power_out(u_var)=turbine_power;
lambda_n(u_var)=lambda;
U1_var(u_var)= U1;
end

plot(lambda_n,eff);
figure;
plot(U1_var,power_out);
ANNEX II : Main Controller Circuit

Main controller circuit layout

Figure 43: Main controller

RS485 communication interface

Figure 44: RS 485 interface
Power supply and signal conditioning unit

Figure 45: Power supply unit

Figure 46: Power supply and main controller PCB
ANNEX III : Anemometer and RPM interfacing

Figure 47: Anemometer interfacing unit

Figure 48: RPM and Anemometer

Figure 49: Hall Effect sensor for RPM measurement
### Error in RPM measurement

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timer resolution in control circuit</td>
<td>286.06</td>
<td>us</td>
</tr>
<tr>
<td>No of cycles per reading</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No of pulses per cycle</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No of pulses per reading</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Maximum error for one reading</td>
<td>286.06</td>
<td>us</td>
</tr>
<tr>
<td>Error in one pulse</td>
<td>286.06</td>
<td>us</td>
</tr>
<tr>
<td>Time for one cycle</td>
<td>1</td>
<td>s</td>
</tr>
<tr>
<td>RPM</td>
<td>60</td>
<td>rev/min</td>
</tr>
<tr>
<td>Error in RPM</td>
<td>0.01716851</td>
<td>rev/min</td>
</tr>
<tr>
<td>Error in Omega</td>
<td>0.00179788</td>
<td>Rad/s</td>
</tr>
</tbody>
</table>
Anemometer

Wind Transmitter - compact

Low power with Frequency Output

Ammonit Order No. P6140/20
Design and performance analysis of pitched-plate VAWT for domestic power generation.
MSc thesis, EKV947, August 2012
Accuracy of Anemometer reading

| Timer resolution in control circuit | 71.517 us |
| No of cycles per reading            | 5         |
| No of pulses per cycle              | 11        |
| No of pulses per reading            | 55        |
| Maximum error for one reading       | 71.517 us |
| error in one pulse                  | 1.300309091 us |

<table>
<thead>
<tr>
<th>wind speed (ms⁻¹)</th>
<th>pulse duration (s)</th>
<th>error per pulse (us)</th>
<th>Error in wind speed (ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07012</td>
<td>1.300309091</td>
<td>1.85444E⁻⁵</td>
</tr>
<tr>
<td>2</td>
<td>0.03506</td>
<td>1.300309091</td>
<td>7.4179E⁻⁵</td>
</tr>
<tr>
<td>3</td>
<td>0.023373333</td>
<td>1.300309091</td>
<td>0.000166906</td>
</tr>
<tr>
<td>4</td>
<td>0.01753</td>
<td>1.300309091</td>
<td>0.000296727</td>
</tr>
<tr>
<td>5</td>
<td>0.014024</td>
<td>1.300309091</td>
<td>0.000463644</td>
</tr>
<tr>
<td>6</td>
<td>0.011686667</td>
<td>1.300309091</td>
<td>0.00066766</td>
</tr>
<tr>
<td>7</td>
<td>0.010017143</td>
<td>1.300309091</td>
<td>0.000908777</td>
</tr>
<tr>
<td>8</td>
<td>0.008765</td>
<td>1.300309091</td>
<td>0.001186996</td>
</tr>
<tr>
<td>9</td>
<td>0.007791111</td>
<td>1.300309091</td>
<td>0.001502319</td>
</tr>
<tr>
<td>10</td>
<td>0.007012</td>
<td>1.300309091</td>
<td>0.001854749</td>
</tr>
</tbody>
</table>
ANNEX IV : Load cell interfacing

50Kg load cell was used to measure the torque of turbine shaft.

Load cell is fixed to the frame and connected to brake pads, brake pads are controlled by external motor and force acting on brake pads is directly transferred to the load cell. Data acquisition system is collecting force on load cell at 1 s intervals and then calculates the torque (reading x distance to the brake pad from the shaft). These data are stored in the database.

\[ y = 3.6575x - 6.5258 \]

\( \text{Load(Kg)} \) Vs voltage(V)

\[ y = 3.6575x - 6.5258 \]

**Figure 50: Load Cell interfacing circuit**

**Load Cell Calibration**

During the calibration load cell interfacing unit output voltage was measured at different loads. Then load cell equation for the setup was obtained and this equation was used in the data acquisition program to convert actual voltage into the load.

<table>
<thead>
<tr>
<th>Load Kg</th>
<th>Voltage v</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>2.26</td>
</tr>
<tr>
<td>3</td>
<td>2.55</td>
</tr>
<tr>
<td>4</td>
<td>2.95</td>
</tr>
<tr>
<td>5</td>
<td>3.15</td>
</tr>
<tr>
<td>6</td>
<td>3.45</td>
</tr>
<tr>
<td>7</td>
<td>3.77</td>
</tr>
<tr>
<td>8</td>
<td>3.95</td>
</tr>
<tr>
<td>9</td>
<td>4.2</td>
</tr>
<tr>
<td>10</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Figure 51: Load cell calibration chart and data**
### Torque reading resolution

<table>
<thead>
<tr>
<th>Equation</th>
<th>( y = 3.657x - 6.525 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog to Digital Resolution</td>
<td>10 bit</td>
</tr>
<tr>
<td>Voltage resolution</td>
<td>0.004883 ( v )</td>
</tr>
<tr>
<td>Relative load resolution</td>
<td>0.017856 ( Kg )</td>
</tr>
<tr>
<td>Torque measurement</td>
<td>0.033283 ( Nm )</td>
</tr>
</tbody>
</table>
ANNEX V : RS485 communication system datasheets

The MAX232 is a dual driver/receiver that includes a capacitive voltage generator to supply EIA-232 voltage levels from a single 5-V power. Each receiver converts EIA-232 input levels to 5-V TTL/CMOS levels. These receivers have a threshold of 1.3 V and a typical hysteresis of 0.5 V, and it accepts ±30-V inputs. Each driver converts TTL/CMOS input levels into EIA-232 levels. The driver, receiver, and voltage-generator functions are available in the Texas Instruments §ASIC™ library.
Design and performance analysis of pitched-plate VAWT for domestic power generation.
MSc thesis, EKV947, August 2012

Fail-Safe, High-Speed (10Mbps), Slew-Rate-Limited RS-485/RS-422 Transceivers

The MAX3080-MAX3089 high-speed transceivers for RS-485/RS-422 communication contain one driver and one receiver. These devices feature fail-safe circuits, which guarantee a logic-high receiver output when the receiver inputs are open or shorted. This means that the receiver output will be a logic high if all transmitters on a terminated bus are disabled (high impedance). The MAX3080/MAX3081/MAX3082 feature reduced slew-rate drivers that minimize EMI and reduce reflections caused by improperly terminated cables, allowing error-free data transmission up to 115kbaud. The MAX3083/MAX3084/MAX3085 offer higher driver output slew-rate limits, allowing transmit speeds up to 500kbaud. The MAX3085/MAX3087/MAX3089’s driver slew rates are not limited, making transmit speeds up to 10Mbps possible. The MAX3089’s slew rate is selectable between 115kbaud, 500kbaud, and 10Mbps by driving a selector pin with a single three-state driver.

These transceivers typically draw 375μA of supply current when unloaded, or when fully loaded with the drivers enabled.

All devices have a 180kΩ input receiver input impedance that allows up to 256 transceivers on the bus. The MAX3080/MAX3085/MAX3089 are intended for half-duplex communications, while the MAX3080/MAX3081/MAX3082/MAX3084/MAX3085/MAX3087 are intended for full-duplex communications. The MAX3087 is selectable between half-duplex and full-duplex operation. It also features independently programmable receiver and transmitter output phase via separate pins.

Applications
- RS-422/RS-485 Communications
- Level Translators
- Transceivers for EMI-Sensitive Applications
- Industrial-Control Local Area Networks

Ordering Information

<table>
<thead>
<tr>
<th>PART</th>
<th>TEMP. RANGE</th>
<th>PIN-PACKAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX3080CPD</td>
<td>0°C to +70°C</td>
<td>14 SO</td>
</tr>
<tr>
<td>MAX3080CSD</td>
<td>0°C to +70°C</td>
<td>14 SO</td>
</tr>
<tr>
<td>MAX3080FD</td>
<td>-40°C to +85°C</td>
<td>14 SO</td>
</tr>
</tbody>
</table>

Selection Table

<table>
<thead>
<tr>
<th>Part</th>
<th>Half/Full Duplex</th>
<th>Data Rate (Mbps)</th>
<th>Slew Rate Limited</th>
<th>Low-Power Shutdown</th>
<th>Receiver Driver Enable</th>
<th>Quiescent Current (μA)</th>
<th>Transceivers On Bus</th>
<th>Pkg Count</th>
<th>Industry-Standard Pinout</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX3080</td>
<td>Full</td>
<td>0.15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>375</td>
<td>256</td>
<td>14</td>
<td>75190</td>
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<tr>
<td>MAX3081</td>
<td>Full</td>
<td>0.15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>375</td>
<td>256</td>
<td>8</td>
<td>75179</td>
</tr>
<tr>
<td>MAX3082</td>
<td>Half</td>
<td>0.15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>375</td>
<td>256</td>
<td>8</td>
<td>75176</td>
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<tr>
<td>MAX3083</td>
<td>Full</td>
<td>0.5</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>375</td>
<td>256</td>
<td>8</td>
<td>75179</td>
</tr>
<tr>
<td>MAX3084</td>
<td>Full</td>
<td>0.5</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>375</td>
<td>256</td>
<td>8</td>
<td>75176</td>
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<tr>
<td>MAX3085</td>
<td>Half</td>
<td>0.5</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<td>256</td>
<td>8</td>
<td>75179</td>
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<tr>
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<td>No</td>
<td>No</td>
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<td>256</td>
<td>8</td>
<td>75176</td>
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<tr>
<td>MAX3087</td>
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<td>0.5</td>
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<td>No</td>
<td>No</td>
<td>375</td>
<td>256</td>
<td>8</td>
<td>75179</td>
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<tr>
<td>MAX3088</td>
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<td>No</td>
<td>No</td>
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<td>8</td>
<td>75176</td>
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<tr>
<td>MAX3089</td>
<td>Selectable</td>
<td>Yes</td>
<td>Selectable</td>
<td>Yes</td>
<td>Selectable</td>
<td>375</td>
<td>256</td>
<td>14</td>
<td>75190*</td>
</tr>
</tbody>
</table>

*Pin compatible with 75190 with additional features implemented using pins 1, 6, 8, and 13.

For free samples & the latest literature: http://www.maxim-ic.com, or phone 1-800-998-8800.
For small orders, phone 1-800-835-8769.
ANNEX VI: Domestic wind power system

DC Generator

Ginlong Technologies GL-PMG-1000

World Leading Professional Wind Turbine Parts Supplier

<table>
<thead>
<tr>
<th>Electrical Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Output Power (W)</td>
</tr>
<tr>
<td>Rated Rotation Speed (RPM)</td>
</tr>
<tr>
<td>Rated DC Current at Rated Output (A)</td>
</tr>
<tr>
<td>Rated Torque at Rated Power</td>
</tr>
<tr>
<td>Phase Resistance (Ohm)</td>
</tr>
<tr>
<td>Output Wire Length (mm)</td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td>Generator configuration</td>
</tr>
<tr>
<td>Design lifetime</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Starting Torque (Nm)</td>
</tr>
<tr>
<td>Rotor Inertia (kg-m²)</td>
</tr>
<tr>
<td>Bearing Type</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft Material</td>
</tr>
<tr>
<td>Shaft Bearing</td>
</tr>
<tr>
<td>Outer Frame Material</td>
</tr>
<tr>
<td>(TT75 full heat treatment for increasing the performance of aluminum alloy to &gt;450°C at 120°C)</td>
</tr>
<tr>
<td>Fasteners (inner and outer)</td>
</tr>
<tr>
<td>Windings Temperature Rating</td>
</tr>
<tr>
<td>Magnet Material</td>
</tr>
<tr>
<td>Magnet Temperature Rating</td>
</tr>
<tr>
<td>Lamination Stack</td>
</tr>
</tbody>
</table>

GL-PMG-1000 PMG Power Curve

GL-PMG-1000 PMG Open Circuit Voltage

GL-PMG-1000 PMG Input Torque Curve