AN ORTHOGONAL SAVONIUS-TYPE WIND TURBINE: DESIGN AND EXPERIMENTS

by

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For the degree of Master of Science

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May, 2016
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(date) March 29, 2016

* We also certify that written approval has been obtained for any proprietary material contained therein.
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Last but not least, thank to my parents permanent love and support, which is the most precious strength throughout my life.
## List of Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamic</td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
</tr>
<tr>
<td>HCS</td>
<td>Hill Climb Searching</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PLA</td>
<td>Poly Lactic Acid</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>Perturb and Observe</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>VAWT</td>
<td>Vertical Axis Wind Turbine</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
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List of Symbols

A: swept area (rotor area)

As: aspect ratio

a: the distance between two adjacent blades (m)

Cp: coefficient of power

Cpmax: maximum coefficient of power

Ct: coefficient of torque

Cts: coefficient of static torque

D: rotor diameter (m)

H: height of rotor (m)

m: flux of air’s mass (kg)

R: rotor radius (m)

T: torque (N-m)

Ts: the static torque (N-m)

V: wind speed (m/s)

v: air volume (m$^3$)
Vtip: the tip speed (m/s)

\( \rho \): air density (kg/m\(^3\))

\( \omega \): angular velocity (rad/s)

\( \lambda \): the tip speed ratio
An Orthogonal Savonius-Type Wind Turbine: Design and Experiments

Abstract

by

YINGKANG DU

Finnish Engineer Sigurd Savonius introduced a vertical drag rotor in 1922 and named it Savonius turbine. It consists of two semi cylindrical blades in an “S” shape from the top view. Savonius turbines provide some advantages such as a simple and low-cost structure, self-starting capabilities and the ability to use wind speed from any direction. Savonius machines are widely used in many ways, including pumping and sailing. However, it has a poor power coefficient, typically in the range of 10% to 15%. In order to find new solutions to improve the aerodynamic efficiency, this project designs, manufactures and tests experimentally six Savonius prototypes. The prototypes combine different geometric characteristics. Coefficient of torque and coefficient of power for each prototype are measured. The experimental validation is conducted at the fully instrumented wind tunnel. The results give guidelines to improve the efficiency and reduce the cost of the Savonius wind turbines. Maximum power point tracking for Savonius turbine is also investigated.
Chapter 1

Introduction

1.1 Renewable Energy

All of society’s electrical energy sources can be separated into two main categories: renewable and nonrenewable. Nonrenewable sources include fossil fuels, such as oil and gas, which produce carbon pollution, while solar and wind energy common renewable energy sources, produce little pollution while producing electricity. From American Wind Energy Association (AWEA)’s 2014 U.S. wind industry Annual Market Report [1], “wind energy production avoided an estimated 125 million metric tons of carbon dioxide during 2014- more than 5.7 percent of U.S. power sector emissions” which is shown in Figure 1.1. We could tell that carbon dioxide production amount avoided by wind energy is great. Thus, in the long run, society’s development needs the application of wind energy, solar cells, and other renewable energy sources with minimal carbon footprints.
Wind energy is one of the fastest growing renewable sources and more and more countries already have relatively policy to support its development. The global installed wind capacity is 51,477 MW in 2014, while global cumulative installed wind capacity is 369,553 MW in 2014. [2] Wind energy plays an important role in nowadays energy market. According to Navigant Research in Figure 1.2, the wind energy was rapidly growing during last several decades, and it will still continually moderate growing in next five years with a slightly fluctuation. [3]
1.3 Basics of Wind Energy Conversion

1.3.1 Kinetic Energy

The kinetic energy (J) of air is calculated by [4]:

\[
E_{air} = \frac{1}{2} m V^2
\]  

(1.1)

m (kg) is the flux of air’s mass and V (m/s) is the air velocity.

To calculate the wind turbine’s kinetic energy of the air stream, we use the air density \( \rho \) (approximately 1.225 kg/m\(^3\)) and air volume \( \nu \) (m\(^3\)) to replace the m in (1.1); it could be defined as the following:

\[
E_{air} = \frac{1}{2} \rho \nu V^2
\]  

(1.2)
Power of the wind turbine (W) is kinetic energy per unit time which could be represented as:

\[ P = \frac{1}{2} \dot{m}V^2 \]  \hspace{1cm} (1.3)

From fluid mechanic theories, if \( A \) is the swept area of the wind across, the mass flow rate \( \dot{m} \) (kg/s) is shown as [5] the following:

\[ \dot{m} = \frac{dm}{dt} = \rho AV \]  \hspace{1cm} (1.4)

Therefore, the wind power is:

\[ P = \frac{1}{2} \rho AV^3 \]  \hspace{1cm} (1.5)

And according to \( P = FV \) [6], the thrust force (N) experienced by the rotor is:

\[ F = \frac{1}{2} \rho AV^2 \]  \hspace{1cm} (1.6)

Hence, since \( T = R \times F \) [6], the torque of rotor (N\cdot m) is:

\[ T = \frac{1}{2} \rho AV^2 R \]  \hspace{1cm} (1.7)

R is the rotor radius.

This thesis is mainly concentrate on investigate the performance of Savonius-type turbines. As for Savonius turbines, swept area \( A \) is the area of rotor diameter (D, in m) multiplied by its height (H, in m):
\[ A = HD \]  \hspace{1cm} (1.8)

Hence, from above equations, the wind power of Savonius turbine is:

\[ P = \frac{1}{2} \rho HDV^3 \]  \hspace{1cm} (1.9)

### 1.3.2 The Power Coefficient (\( C_p \))

However, not all of the power from the wind is transferred to electricity by wind turbine. There are different types of kinetic energy are transferred, such as rotor consuming. Thus, combine with the wind power (\( P \)) from equation (1.5), we define the power coefficient (\( C_p \)) to represent the efficiency of the energy transferred from wind as the following [4, 7]:

\[ C_p = \frac{P_m}{P} = \frac{2P_m}{\rho AV^3} \]  \hspace{1cm} (1.10)

\( C_p \) is a dimensionless ratio to measure the efficiency of wind turbine converts wind energy into electricity. \( P_m \) is the mechanical power at the shaft of the wind turbine, which is after passing through the rotor, and it could also be represented as:

\[ P_m = \frac{1}{2} \rho AV^3 C_p \]  \hspace{1cm} (1.11)

### 1.3.3 The Torque Coefficient (\( C_t \))

The torque coefficient is defined as the dimensionless ratio of the actual torque produced by rotor over the theoretical total torque (obtained from equation 1.7) of the wind, which is represented as [4, 7, 16]:

\[ C_t = \frac{T_m}{T} = \frac{4T_{\text{rotor}}}{\rho ADV^2} \]  \hspace{1cm} (1.12)
1.3.4 The Static Torque Coefficient (Cts)

The static torque is the maximum torque value when the rotor is blocked and cannot rotate. The static torque coefficient defines the self-starting capability of the turbine, which is a dimensionless ratio of the rotor static torque over the total torque of the wind [4, 7, 16]:

\[
Cts = \frac{T_s}{T} = \frac{4T_s}{\rho ADV^2}
\]  

(1.13)

1.3.5 Tip Speed Ratio (TSR)

Tip speed ratio is a dimensionless value which is defined as the rotor tip speed over the wind speed as following [7-8]:

\[
TSR = \lambda = \frac{V_{tip}}{V} = \frac{\omega R}{V}
\]  

(1.14)

Rotor tip speed: \(V_{tip} = \omega R\)

Angular velocity: \(\omega = 2\pi f\) (rad/s)

The type of wind turbine, the number of the blades, and the configuration of the blades all have effects on the rotor’s tip speed ratio value. In the Magdi Ragheb and Adam M. Ragheb’s *Wind turbines theory- the Betz equation and optimal rotor tip speed ratio*, it illustrates that [8]:

If a rotor rotates too slowly, it allows too much wind to pass through undisturbed, and thus does not extract as much as energy as it could, within the limits of the Betz Criterion, of course. On the other hand, if the rotor rotates too quickly, it appears to the wind as a large flat disc, which creates a large amount of drag.
1.3.6 The Betz Limit

The Betz limit is the maximum power coefficient of all kinds of wind turbines theoretically, which is 59.3% and calculated by Albert Betz. From the Figure 1.3, it is obviously that none of them is exceeding the Betz limit. Moreover, two and three blades wind turbine has the highest power coefficient, as while the Savonius turbine has a poor power coefficient. [9]

![Figure 1.3 Performance of main conventional wind turbines](image)

1.4 Wind Turbine Basic Concepts

To investigate the characteristics of wind turbine, we need to know about its structures firstly. The components of wind turbine are mainly as the following (Fig 1.4):

- Rotor: combination structure of hub and blades.
- Tower: support the turbine, and because wind speed is increasing with the height, the taller tower enables the wind turbines to capture more power.
- Generator: converts mechanical energy to electricity.
- Controller: adjust the turbine pointing into the wind and produce the proper torque to control the wind turbines. Pitch and yaw control are two main aspects.
- Anemometer: measure wind speed and transfer the data to control the wind turbine’s torque.

Figure 1.4 Wind turbine’s components

http://energy.gov/eere/wind/inside-wind-turbine-0
1.5 Classification of wind turbines

1.5.1 Basic Introduction

Wind turbines’ working process is collecting kinetic energy and converting it into electricity. The manufacturers in wind energy area around the world dedicated not only in improving the power output of wind turbines, but also to improve the reliability and efficiency of them over the years. Based on the axis of turbines’ rotation, we usually classify the wind turbines into two categories: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). As the name implies, the HAWT’s blades spin on the horizontal axis, while VAWTs spin on the vertical axis.

Horizontal axis wind turbines as the most common type of wind turbines in use represents most of people’s impression when talking about wind turbines. HAWT blades rotate perpendicular to the wind and its rotational axis parallel to the ground. HAWT with its high efficiency and low cut-in wind speed are widely used in commercial wind energy area. Moreover, HAWT’s variable pitch angle enables it to catch optimum energy, and its tall tower enables it to access the stronger wind in sites with wind shear. [10] However, HAWT also have some disadvantages, such as its tall tower brings more inconvenience when designing and installing the generator and gearbox over the tower, and cost more resources. And it also needs the yaw control to make the turbine adjusted to a good position to capture the wind. HAWTs could be classified into one, two, three and more blades according to the number of its blades. Three blades horizontal axis wind turbines are most common and widely in use.
Vertical axis wind turbines as a promising type of wind turbines, now plays more important role. Different from horizontal axis wind turbines, the vertical axis wind turbines’ rotational axis is vertical to the ground and it rotates perpendicular to the wind. Compared to HAWT, VAWT’s 360-degree rotating rotor determines that it does not have yaw control and the design is much easier. And the gearbox and generator could be installed in ground level instead of on the tall tower, which makes the installation and maintenance process in a simple and economic way. However, the great starting torque of vertical axis wind turbines is one of the disadvantages which influence its efficiency. And the ground level support makes it need more footprint than horizontal axis wind turbines in wind farm scale. Moreover, to control it in a properly way to make sure the system rotates in a reasonable rotating speed is also important. There are mainly two types of vertical axis wind turbines: Savonius, Darrieus; and H-type wind turbines are also classified as vertical axis wind turbines.

1.5.2 Darrieus Wind Turbine

Georges Jean Mary Darrieus designed his first vertical axis turbine and got the patent in 1931 in the United States. [11] The traditional Darrieus wind turbine’s shape is called troposkein, which is consists of two or three curved airfoil blades; their blades are connected together at the top and bottom, and rotating around a vertical shaft. (Figure 1.5) Not only such form of Darrieus wind turbines, there are also some other variation such as the H-rotor design (also called giromill or H-bar design) with the straight blades. (Figure 1.6) Darrieus wind turbine is the lift force powered type wind turbine, the structure of its blades make the speed could reach a high level and even higher than the wind speed, and produce lots of electricity. The 360 degree of rotation ensures its high efficiency. The
rotor of Darrieus also has the high tip speed ratio. However, the Darrieus wind turbine also has the limitation of great starting torque, and may need a starting push to let it rotating. The ground level’s wind speed is not as high as horizontal axis wind turbines’ high level wind speed. Plus, guy wires are needed to ensure its stability, which is not practical in commercial and installing point of view.

Figure 1.5 Darrieus wind turbine construction

http://science.howstuffworks.com/environmental/green-science/wind-power2.htm
1.5.3 Savonius Wind Turbine

Another main type of VAWT is Savonius wind turbine as showed in Fig 1.7, it consists of two semi cylindrical blades, if we looks from the top view it is an “S” shape. The Savonius turbine was invented by Sigurd Johanners Savonius in 1922. The main force to drive the rotor of Savonius turbine is drag force, and when it operates, the concave surface is experiencing more drag force than the convex surface and pushing the rotor to rotate. Moreover, the drag force makes its speed cannot approach the estimated wind speed and the power efficiency is lower than the lift type turbines. The Savonius turbine’s structure is simple and low cost with high torque; meanwhile, it’s necessary to improve its low efficiency.
1.6 Thesis Outline

This thesis is mainly discussing Savonius turbine in order to develop a low-cost small scale Savonius turbine configuration with a high torque for low wind speed, we improve the parameters of the design and physically fabricate different prototypes and conduct experiments in an open wind tunnel. Chapter 1 introduces the wind energy and illustrates the importance of developing it; some basic knowledge of wind energy conversion is also introduced; and the detailed classification of wind turbine with their characteristics is illustrated. Chapter 2 gives a review of previous literatures, and detailed introduces the whole process of designing and fabricating prototypes, and explains the equipment and process of experiments. Chapter 3 and chapter 4 conclude the results of experiments and make a suggestion for further improvement of Savonius type turbine. Chapter 5, the concept and classification of MPPT is explained. According to the experiment results and equipment limitation, a TSR algorithm MPPT for the best performed prototype (Sav4) is designed and tested.
Chapter 2

Prototypes Design and Experimental Setup

2.1 Literature Review of Savonius Turbine

The shape, overlap ratio, aspect ratio, stage number and blades number etc., all have great influence on Savonius type turbine performance. Thus, there are various numerical and experimental studies from different perspectives to investigate the aerodynamics characteristics to try to improve the efficiency of Savonius type turbine. Some of the researchers only did the numerical studies to analysis the aerodynamics behaviors. Patel et al. [12] in their research using Computational Fluid Dynamic (CFD) simulation to investigate the different overlap ratio effects on Savonius type turbine’s performance at different angular speeds of rotor. The overlap ratio of 0, 0.1, and 0.2 are simulated in their study, and the overlap of 0.2 is found to give the maximum coefficient of torque and power. Jean-Luc menet and Nachida Bourabaa [9] discussed how to better choose the geometrical parameters (overlap ratio, chassis, Reynolds number, central shaft, etc.), and proposed the optimum values of these geometrical parameters by analysis the simulation results.

There are also some other researchers did various experiments to analysis the performance of Savounius turbine, some of them performed the experiments in wind
tunnel, and some of them combine their computational and experimental results to analyze. M.A. Kamoji et al. [13] compared the conventional Savonius turbine with 90 degree twisted Savonius turbine in different overlap ratios and aspect ratios in a range of Reynolds numbers in an open-jet wind tunnel, in order to decrease the negative coefficient of static torque. The experiment result shows that without shaft rotor gives better performance than with shaft rotor, and power coefficients are sensitively increasing with the increase of Reynolds numbers of helical Savonius turbine. Ghatage and Jyeshtharaj [14] studied blade shape and number’s influence on Savonius turbine performance experimentally. They found that twisted blades have more efficiency than conventional blades turbine, and two blades with 30 degree twist has the maximum power coefficient. Khandakar et al. [15] conducted their research experiments of a three-bladed Savonius turbine in a low-speed subsonic wind tunnel, and made verification between experimental results with their CFD simulation results. They designed and fabricated three models with different gap ratio (0, 0.12, and 0.26) and tested them at different Reynolds numbers. It can be concluded that overlap ratio of 0.12 behaves the best among three models and lower Reynolds number has a better performance. K.K. Sharma et al. [16] studied two-stage two-bladed Savonius rotor experimentally and conducted experiments in wind tunnel. They mainly investigate the relationship between torque and power coefficient with tip speed ratio and overlap ratio, and obtained 0.514 as the maximum power coefficient at overlap ratio of 9.37%. Three-stage rotor with 120 degree bucket phase shift between the adjacent stages type of rotor was designed by Tsutomu et al. [17] and guide vanes were added on the rotor. They also conducted experiments in wind tunnel and studied guide vanes effects on torque coefficients. The
artificial neural nets technique is applied by Sargolzaei and Kianifar to predict the power ratio and torque of wind turbines. [18] Their experimental results highly corresponds with their prediction from artificial neural nets technique method, and they found that the torque is increasing belong with the increase of wind speed. Moreover, among the seven prototypes manufactured by them, the maximum torque is at 60 degree while the minimum torque is at 120 degree. Savonius turbine could not only be studied individually, but also could be combined with other type of turbines, for instance, Gupta et al. [19] have a comparative study of a three-bucket Savonius rotor with a combined three-bucket Savonius-three-bladed Darrieus rotor. They got the maximum power coefficient of 51% without overlap by combined rotor, which is higher than the entire conventional rotor with any overlap ratios. Also, when the overlap ratio is increasing, the power coefficient of combined rotor will decrease.

2.2 Savonius Turbine Design Configuration Consideration Elements

Different type of rotors determines different characteristics for a wind turbine. The performance of turbine is affected by the rotor configuration in various aspects, such as robustness, power efficiency, and speed and so on. There are several elements we mainly considerate when design the Savonius mechanical prototype [12, 20]: (1) overlap ratio; (2) aspect ratio; (3) number of rotor.

(1) Overlap ratio (G)

\[ \text{Overlap Ratio} = \frac{a}{D} \]  

\[ (2.1) \]

a: the distance between two adjacent blades
D: diameter of rotor

\[ \frac{H}{D} \] (2.2)

H is the rotor height, and d is the rotor diameter.

(3) Number of rotor and number of stage

Two blades of rotor are used in this research design. Only single stage turbine is carried out in this research.

Definitely, to improve the mechanical design of Savonius rotor is including but not limit to these above three elements. To further investigate the overall mechanical appearance design, the rotor’s separation gap (s) (showed as Figure 2.2), cross section’s shape of rotor (showed as Figure 2.3) based on aerodynamic blade designing [12], and stage numbers of rotors are also importance and worthy to discuss.
2.3 Savonius Turbine Design Configurations

Thus, based on the above three main elements and in order to improve the aerodynamic efficiency of vertical-axis Savonius turbine, we combine different geometric characteristics, six Savonius prototypes are designed, manufactured and tested experimentally in wind tunnel. Moreover, the SolidWorks2014 is used to design the rotor and the 3D printer (Ultimaker) is used to physically fabricate the model. The details and basic design configuration of these six prototypes are shown in the following and marked as the sequence of Sav1 to Sav6. All of these blades are of 2mm thickness, and the height of all rotors is 20cm. Each prototype is a two-blade structure with the blade
radius of 5.5 cm in different gap distances. Thus, rotor diameter of each prototype is the sum of two blade diameters and reduce the gap distance.

(1) Sav1

This prototype is the rotor with bar connection, and there is no gap distance (overlap ratio=0).

![Fabricated view of Sav1](image)

**Parameters (in cm):**

- Height (H): 20
- Rotor Diameter (D): 22.4

The front view and top view of the Sav1 rotor marked with coefficients values:
(2) Sav2

This prototype is two adjacent blades rotor with the distance of 2cm, and connected by the bar.

Parameters (in cm):

Height (H): 20

Rotor Diameter (D): 20.2
(3) Sav3

This prototype is two adjacent blades rotor with the distance of 4.3cm, and connected by the bar.

Coefficients (in cm):

Height (H): 20

Rotor Diameter (D): 18

(4) Sav4

This prototype is two adjacent blades with the distance of 2cm, and they are covered at the top and bottom by an end plate of 2mm thickness. The shape of end plates is ellipse, and the minor axis is 14cm, and the major axis is 22cm.

Parameters (in cm):

Height (H): 20

Rotor Diameter (D): 20.2

Figure 2.7 Fabricated view of Sav4
(5) Sav5

This prototype is two adjacent blades with the distance of 4.3cm, and they are covered at the top and bottom by an end plate of 2mm thickness. The shape of end plates is ellipse, and the minor axis is 14cm, and the major axis is 22cm.

Parameters (in cm):

- Height (H): 20
- Rotor Diameter (D): 18
This prototype has the same overlap ratio and end plates as Sav4 model, the only difference between them is the blade of Sav6 is twisted by 90 degree.

Parameters (in cm):

Height (H): 20

Rotor Diameter (D): 20.2
Table 2.1 Specifications of rotor configurations covered in this study

<table>
<thead>
<tr>
<th>Rotor name</th>
<th>Rotor Diameter (cm)</th>
<th>Overlap Ratio</th>
<th>Aspect Ratio</th>
<th>Rotor Area ($m^2$)</th>
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<tbody>
<tr>
<td>Sav1</td>
<td>22.4</td>
<td>0</td>
<td>0.89</td>
<td>0.0448</td>
</tr>
<tr>
<td>Sav2</td>
<td>20.2</td>
<td>0.1</td>
<td>0.99</td>
<td>0.0404</td>
</tr>
<tr>
<td>Sav3</td>
<td>18</td>
<td>0.24</td>
<td>1.11</td>
<td>0.036</td>
</tr>
<tr>
<td>Sav4</td>
<td>20.2</td>
<td>0.1</td>
<td>0.99</td>
<td>0.0404</td>
</tr>
<tr>
<td>Sav5</td>
<td>18</td>
<td>0.24</td>
<td>1.11</td>
<td>0.036</td>
</tr>
<tr>
<td>Sav6</td>
<td>20.2</td>
<td>0.1</td>
<td>0.99</td>
<td>0.0404</td>
</tr>
</tbody>
</table>

All rotors and end plates with height of 20cm and thickness of 0.2cm

2.4 Materials and Printer

All of the Savonius turbines are printed by Poly Lactic Acid (PLA) material. This kind of material is organic and could be recycled, mainly made from cornstarch and sugarcane. Thus, it is easy and safe for us to use PLA. The prototypes printed by PLA
have a good quality of the smooth and shiny surface. All of the prototypes are fabricated by 3D printer in Control & Energy Systems Center lab.

2.5 Wind Tunnel

The experiments were conducted in the fully-instrumented wind tunnel at CWRU-Control and Energy Systems Center (Figure 2.14). This wind tunnel is low-speed and low-turbulence. The wind tunnel consists of three main parts: fan, test section and honey comb, and the fan and test section are connected by a diffuser section, while the test section and honey comb are connected by a contraction section. Diffuser section acts as a transition between fan section and test section, which allows air flow to be expanded and gradually varies. Contraction section’s structure not only behaves like a transition between the test section and honey comb, but also helps to reduce the turbulence and increases the air flow velocity in a smoothly way.
Figure 2.14 Wind Tunnel
2.6 Overview of Experiment Process

The general view of the experiments process is shown in Figure 2.15: there are two loops of our experiment. Loop 1 is marked as pink color, and this loop is to control wind speed in wind tunnel. A 480V electrical box is used to provide the power to drive the motor by control of variable frequency drive (VFD). The VFD is a drive which used to control the motor speed and torque by varying the input frequency and voltage. [21] The input frequency of VFD is between 15 Hz to 60 Hz, and the wind speed range is from 3m/s to approximately 20m/s in ideal situation. All of the experiments in this research are using 8m/s as the wind speed, the corresponding frequency input is 30 Hz. In our system, the Arduino (Mega 2560) is used as the input to VFD. For the loop 2
which is marked in figure 10 as black color, is the interface process between experimental objective (wind turbines) and control systems. In order to make the currents operates in the normal range, the circuits is used as a complex BJT to amplifier the current. The current sensor and voltage sensor are used in the loop to measure the electrical properties, and they are connected with microprocessor (NXT) directly. The computer as a center control part is runs under Matlab for the Supervisory Control and Data Acquisition (SCADA) system, and interfaces with microprocessor and Arduino.

The experiments are all operated under the wind speed of 8 m/s. Each prototype is fixed and located in the middle of wind tunnel’s test section, the specification of the test section area is 0.7m*0.8m*1.2m (height/width/length). Since current sensor and voltage sensor are equipped to measure the generator current (Ig, calibrated in A) and voltage (Vg, calibrated in volts), the electric power of generator output could be calculated by [22]

\[ P_e = V_g I_g \]  \hspace{1cm} (2.3)

Plus, the relationship between electric power and mechanical power is:

\[ P_e = \eta P_m \]  \hspace{1cm} (2.4)

\( \eta \) is the efficiency of generator and drive-train. Thus, combine with the equation of (1.11), the power coefficient is represented as:

\[ C_p = \frac{2P_m}{\rho A V^3} = \frac{2P_e}{\eta \rho A V^3} = \frac{2V_g I_g}{\eta \rho A V^3} \]  \hspace{1cm} (2.5)

Vg and Ig are measured by voltage and current sensors in real time. By regulating the variation of Vg from the largest to smallest value as the reference, the corresponding
current and rotor velocity is also varies according to the theory of generator machine.

From equation 1.14, the value of TSR varies with the variation of $V_g$, $I_g$ and $\omega$. Thus, the $C_p$-$\lambda$ curve could be plotted.

Moreover, combine (2.5) with equations (1.7) and (1.14), the mechanical torque could be obtained by:

$$T_m = \frac{P_m}{\omega}$$

(2.6)

Therefore, combine with the equation (1.12), the torque coefficient could be calculated. The results of power coefficient and torque coefficient are plotted and regulated by Matlab.
Chapter 3

Results and Discussion

3.1 Overview of Experiments Results for Six Prototypes

The following Table 3.1 shows the six prototypes optimal point’s value of power coefficient, which correlates with the Figure 3.1. By comparing the Cp-lambda curve of six rotors, it shows that the Sav4 performances best (with C_{pmax}=0.097 at TSR=0.78) while the Sav1 (with C_{pmax}=0.0235 at TSR=0.44) is worst. The rotors with end plates perform much better than with bar connection rotors. Curves for torque coefficients over \lambda correspond to the results of Cp-\lambda curves: the Sav4’s torque coefficient is the highest, while the Sav1’s value is the smallest. The Figure 3.1 matches well with Figure 3.2, which also indicate that the Sav4 has the highest efficiency.
Table 3.1 Maximum coefficient of power and the corresponding TSR for six prototypes

<table>
<thead>
<tr>
<th>Name of Rotor</th>
<th>Cpmax</th>
<th>Tip Speed Ratio (TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sav1</td>
<td>0.0235</td>
<td>0.44</td>
</tr>
<tr>
<td>Sav2</td>
<td>0.036</td>
<td>0.45</td>
</tr>
<tr>
<td>Sav3</td>
<td>0.033</td>
<td>0.39</td>
</tr>
<tr>
<td>Sav4</td>
<td>0.097</td>
<td>0.78</td>
</tr>
<tr>
<td>Sav5</td>
<td>0.094</td>
<td>0.83</td>
</tr>
<tr>
<td>Sav6</td>
<td>0.083</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 3.1 Six prototypes coefficient of power
3.2 Experiments Results for Six Prototypes Individually

The following Figures (3.3-3.8) are each turbine’s torque and power coefficients variation. It is obviously that all of curves have the trend that with the increasing of tip speed ratio (lambda) value, the power (torque) coefficient also increases till the maximum point and then with the increasing of lambda value, the power (torque) coefficient decreases. Because of the Savonius turbine’s characteristic, the experiment results of torque and power all have vibration around each corresponding point of TSR. The Cftool toolbox in Matlab is used to find the appropriate fitting curve of each model. Each of the torque coefficient curve and its corresponding power coefficient curve matches well.
The maximum torque coefficient is also belonging to Sav4, which is around 0.225. The minimum torque coefficient is Sav1’s, which is around 0.125. Torque coefficients of rotors with end plates are much higher than rotors with bar connection.
Figure 3.3 Performance of coefficient of torque and coefficient of power for Sav1
Figure 3.4 Performance of coefficient of torque and coefficient of power for Sav2
Figure 3.5 Performance of coefficient of torque and coefficient of power for Sav3
Figure 3.6 Performance of coefficient of torque and coefficient of power for Sav4
Figure 3.7 Performance of coefficient of torque and coefficient of power for Sav5
Figure 3.8 Performance of coefficient of torque and coefficient of power for Sav6
3.3 Discussion

3.3.1 Effects of Overlap Ratio

Figure 3.9 shows the power coefficient of bar connection type Savonius turbine (Sav1, Sav2 and Sav3), while the Figure 3.10 shows the power coefficient of end plate connection type Savonius turbine (Sav4 and Sav5) at different overlap ratio. For bar connection turbines, the maximum coefficient (Cpmax=0.036 at TSR=0.45) is at the overlap ratio of 0.1 among these three prototypes. The rotor without gap distance (overlap ratio=0) has the minimum power coefficient, which is a sharp decrease compared to the rotors with gap distance (overlap ratio=0.1 & overlap ratio=0.24). However, only less than 10% different value between the maximum power coefficients at overlap ratio of 0.1 and overlap ratio at 0.24.

Table 3.2 Maximum power coefficient value with the corresponding tip speed ratio of bar connection Savonius turbines (Sav1, Sav2 and Sav3)

<table>
<thead>
<tr>
<th>Overlap Ratio</th>
<th>Cpmax</th>
<th>Tip Speed Ratio (lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0235</td>
<td>0.44</td>
</tr>
<tr>
<td>0.1</td>
<td>0.036</td>
<td>0.45</td>
</tr>
<tr>
<td>0.24</td>
<td>0.033</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Figure 3.9 Comparison of power coefficient of bar connect type rotor (Sav1&Sav2&Sav3) at different overlap ratio

For the prototypes designed with end plates (Sav4 and Sav5), table 3.3 shows the detailed information of their maximum power coefficient and corresponding TSR value. It is easily to see that the maximum value of power coefficient is 0.097 at TSR=0.78 with the overlap ratio of 0.1. Similarly, the gap distance’s difference does not lead to a big difference between two power coefficient values: there is an only 3% difference between two coefficients of power. Moreover, the researcher thinks that although there is no big difference between them, the Sav4 rotor (at overlap ratio=0.1) is much better than Sav5 (at overlap ratio=0.24) not only because Sav4 has a larger Cp value. It is obviously that the Sav4 rotor experiences a steady process after approaching to the
maximum point of power coefficient, while the Sav5 rotor’s Cp-lambda curve is sharp decreasing after reaching the maximum point of power coefficient. Thus, if it is applied to the reality, the Sav4 has a larger region of high power coefficient value as well as the range of lambda, which means the range of wind speed is also larger which enables the turbine to gather more wind energy.

Table 3.3 Maximum power coefficient value with the corresponding tip speed ratio of end plates connection Savonius turbines (Sav4 and Sav5)

<table>
<thead>
<tr>
<th>Overlap Ratio</th>
<th>C_{p_{max}}</th>
<th>Tip Speed Ratio (lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.097</td>
<td>0.78</td>
</tr>
<tr>
<td>0.24</td>
<td>0.094</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Figure 3.10 Comparison of power coefficient of end plate connect type rotor (Sav4&Sav5) at different overlap ratio
3.3.2 Effects of turbine structure

Table 3.4 Maximum power coefficient value with the corresponding tip speed ratio of bar connection Savonius rotor (Sav2) and end plates connection Savonius rotor (Sav4) at overlap ratio=0.1, aspect ratio=0.99

<table>
<thead>
<tr>
<th>Name of Rotor</th>
<th>Cpmax</th>
<th>Tip Speed Ratio (TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sav2</td>
<td>0.036</td>
<td>0.45</td>
</tr>
<tr>
<td>Sav4</td>
<td>0.097</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Figure 3.11 Comparison of power coefficient between Sav2 and Sav4 at the same overlap ratio (0.1)
Table 3.5 Maximum power coefficient value with the corresponding tip speed ratio of bar connection Savonius rotor (Sav3) and end plates connection Savonius rotor (Sav5) at overlap ratio=0.24, aspect ratio= 1.11

<table>
<thead>
<tr>
<th>Name of Rotor</th>
<th>C_pmax</th>
<th>Tip Speed Ratio (TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sav3</td>
<td>0.033</td>
<td>0.39</td>
</tr>
<tr>
<td>Sav5</td>
<td>0.094</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Figure 3.12 comparison of power coefficient between Sav3 and Sav5 at the same overlap ratio (0.24)
From the detailed information of power coefficient and its corresponding TSR in Table 3.4 and Table 3.5, combined with the Cp-lambda curve shown in Figure 3.11 and 3.12, it is apparent that the rotor with end plates has much higher power coefficient than the rotor with bar connection. The prototypes’ structure has a huge effect on the performance of Savonius turbine.

3.3.3 Comparison between conventional Savonius rotor with 90-degree twisted-blade design Savonius rotor

Compared to 90-degree twisted-blade design Savonius rotor (Sav6), the conventional rotor (Sav4) performs better at the same overlap ratio of 0.1 by the results from table 3.6 and Figure 3.13. However, both Sav4 and Sav6 have a steady operation area around the maximum point of Cp, there is no sharp drop of power coefficient after TSR reaching the optimal point. Thus, the overall efficiencies of these two prototypes are high in general.

<table>
<thead>
<tr>
<th>Name of Rotor</th>
<th>Cpmax</th>
<th>Tip Speed Ratio (TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sav4</td>
<td>0.097</td>
<td>0.78</td>
</tr>
<tr>
<td>Sav6</td>
<td>0.083</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 3.6 Maximum power coefficient value with the corresponding tip speed ratio of conventional Savonius rotor (Sav4) and 90-degree twisted-blade design Savonius rotor (Sav6) at overlap ratio=0.1, aspect ratio=0.99
Figure 3.13 comparison of power coefficient between Sav4 and Sav6 at the same overlap ratio (0.1)
Chapter 4

Maximum Power Point Tracking for
Savonius Turbine

4.1 Backgrounds

From Chapter 3 experimental results, each turbine has its own Cp-λ curve, which represents the behavior and performance of turbine. Since the high effective and low cost wind turbine is an important area for wind energy studies, Maximum Power Point Tracking (MPPT) algorithm is implemented. For this thesis, MPPT is investigated to further improve Savonius type turbine’s efficiency.

4.2 Classification of MPPT Methods

There are several main types of MPPT to be classified in generally [23-30]:

4.1.1 Optimum Torque Control

The optimum torque control is based on adjusting the torque of generator to the maximum value when wind speed varies. The wind turbine’s characteristic (Cpmax-λopt) is needed for this method. For the given optimum value, from equation (1.14), the optimum generator rotational speed could be calculated from:

$$\omega_{opt} = \frac{\lambda_{opt} V}{R}$$  \hspace{1cm} (4.1)
Combine with equation (1.77, 1.11), the power and torque under the optimum torque control are given as [22-25, 27]:

\[ P_m = K_{opt} \times \omega_{opt}^3 \]  

(4.2)

\[ T_m = K_{opt} \times \omega_{opt}^2 \]  

(4.3)

\[ K_{opt} = \frac{\rho A R^3 C_{pmax}}{2 \lambda_{opt}^3} \]  

(4.4)

This main disadvantage of this method is the Cp-\( \lambda \) curve is needed, which could be obtained by simulation or experiments.

4.1.2 Power Signal Feedback Control

Similarly as optimum torque control strategy, the power signal feedback control also needs to obtain the Cp-\( \lambda \) curve. It regulates the power and generator speed to ensure the system approach MPP. [26-27, 30]

4.1.3 Tip Speed Ratio (TSR) Control

For each given wind turbine, the optimum value of TSR is constant if the wind speed not varying. The optimum rotational speed is determined by equation of (4.1).

In order to keep the TSR in the optimum value to ensure the system capture the maximum power from wind, the wind speed is need to be measured and compared to the actual speed continually and accurately. [28-30] The advantage of this method is its high efficiency, however, the anemometer is essential for this method and it may not accurate enough and improves the cost.
4.1.4 Perturb and Observe (P&O) Control

For a given function, the P&O method is based on perturbing a control parameter in small step-size and observing the resulting changes in the objective function, until the slope becomes zero. [23, 28, 30] Since each $C_p$-$\lambda$ curve has one maximum point, thus if the operating point needs to be moved to right if it is observed in left side of the peak value, otherwise, it will be moved to left side if it is observed in the right side of the peak value by controller. This strategy is also called hill climb searching (HCS). However, it is not simple to determine an appropriate step size, especially for large scale wind turbines with rapid variation of wind speeds. The larger step size has a faster response, but is not accurate and will cause oscillations around the peak point. The smaller step size is more accurate and improves the efficiency of controller, but the operation process will be slower. Thus how to better balance the tradeoff between the efficiency and tracking speed is an important subject needs to be discussed. P&O strategy does not need variable mechanical sensors and essential knowledge of the wind turbine and generator’s characteristics, which is more like a mathematical solution to seeking maximum power point, so it is simple and low cost.
4.2 The MPPT Method Used in This Thesis

From the results from Chapter 3 in this thesis, the Sav4 is found as a best performance one among all prototypes, thus it is decided as the experiment objective in this chapter. Absolutely, this MPPT method could also be used for other prototypes as well. This research use tip speed ratio strategy to realize maximum power point tracking under the wind speed of 8m/s to investigate the Savonius type turbine MPPT for the following reasons:

- All of the experiments results in Chapter 3, plus the limitation of the wind tunnel and experiment equipment, the 8m/s is the best wind speed situation for our Savonius turbine prototypes to make them perform well. Moreover, based on the optimal TSR is maintaining in constant for each wind turbines if regardless the variation of wind speed, so we do not need to use sensor to measure wind speed and we could keep the TSR at its optimal value.

- Optimal TSR is more directly than torque and power control for our experimental objectives by analyzing the results from Chapter 3.

- P&O control method is not the best proper method to use for our Savonius turbines, because the step size is complex to find. From six prototypes’ Cp- curve shown in Figure 3.3-3.8, it is easily to find that Cp value of Savonius type turbine is varies in a very small range, which is really complex to determine the step size and set its value for the controller. Thus, the P&O method is not suitable for Savonius type rotors.
Therefore, the TSR control method is used in our MPPT experiments for Sav4, and wind speed is set as 8m/s. From equation of (1.14), and based on wind velocity V is 8m/s as a constant, the experiment is maintaining the optimal TSR value by generator voltage control to ensure the wind turbine performances at the maximum power point. The TSR value is already get experimentally in Chapter 3.

4.3 Experiment Results

Figure 4.1 and Figure 4.2 shows the power coefficient and TSR value respectively. Figure 4.3-4.5 shows the rotor velocity, current and voltage value measured from sensor in real time. Figure 4.6 shows the Sav4 rotor’s Cp-λ curve under MPPT. These six figures give a clear overview of the MPPT performance for the process with a sudden disturbance in middle. The Savonius turbine is a drag type vertical axis wind turbine, and because of the vibration and its structure’s characteristic, at the Cp-lambda curve and torque-lambda curve, each point of lambda value, corresponds to a range of Cp and torque value. This makes it is complex to determine the optimal curve of power coefficient. Thus, the maximum power point for the Sav4 could be tracked is around 0.086, which less than the maximum power point is obtained from Chapter 3 experiment results.

The TSR is maintained at 0.77 to 0.78 which is around the optimal value we got in Part’s result. During the middle of experiment, a disturbance was gave to rotor and from Figure 4.1-4.5, it is apparent that there is a sharp drop of all values, and after a very short time recovery, all parameters back to the value which maintains the optimal value of rotor.
Figure 4.1  Power coefficient versus time
Figure 4.2 TSR versus time
Figure 4.3 $\omega$ value versus time
Figure 4.4 Ig versus time
Figure 4.5 Vg versus time
Figure 4.6 Cp versus lambda
Chapter 5

Conclusion

5.1 Savonius Turbine Design and Experiment Results Summary

In conclusion, this thesis investigates the Savonius type turbine’s characteristic experimentally, and the experimental results give us a clear overview of Savonius type turbine’s performance. Power and torque coefficient increases corresponding with the TSR increasing till the optimal value, and then will decrease as the TSR still increasing. Sav1 rotor without gap distance has the minimum power coefficient of 0.0235 at TSR=0.44 among all six prototypes. The Sav4 rotor with overlap ratio of 0.1 has the maximum power coefficient of 0.097 at TSR=0.78 compared with other rotors. The rotors with end plates show a much better performance than the rotors with bar connection, the structure of rotors has a big influence on the efficiency. For both bar connection and end plates connection structure rotors, overlap ratio of 0.1 gives the higher power coefficients than overlap ratio of 0.24, and with gap distance rotors contributes more coefficients than zero gap distance rotors. 90-degree twisted blade rotor (Sav6) performs much better than bar connection rotor (Sav2), however the efficiency of it is still less than end plate connection rotor (Sav4) when they all at overlap ratio of 0.1. Moreover, Sav4 costs less material than Sav6. Therefore, Sav4 has the highest efficiency and normal cost of material, which is the best among all six prototypes, and twisted blade
rotor does not have much advantage when compared with conventional rotors in this study.

5.2 Future Development of Savonius Turbine

It is obviously that the vertical axis wind turbines are promising and full of challenging in development. For this research, there are different types of two-bladed one-stage Savonius turbines at different overlap ratio and aspect ratio in this research work, and compared 90 degree twisted blade turbine’s performance with the conventional blade turbine. We could investigate further on the aerodynamics design of turbine, such as change blades numbers and stage numbers. Moreover, we could also analyze aerodynamic characteristics of twisted blades in order to find out the optimum design of twisted rotor.

However, except only discussed about Savonius turbines’ design and performance, for the further study, we could combine Darrieus-type and Savonius-type together since Darrieus is lift type and Savonius is drag type turbine. The Savonius part could give an initial rotational start force to Darrieus part, since Darrieus-type turbine cannot self-started. This kind of Darrieus-Savonius type wind turbine could be used varies from small scale to large scale and the cost is low.
5.3 Conclusion of MPPT

In this research part, the method for estimating TSR of Sav4 is presented by maintaining the TSR at optimal value according to the Cp- curve obtained from Chapter 3 results, and the wind speed in wind tunnel is 8 m/s. This method makes the TSR algorithm in a simple way according the equipment and results we already got. The results of MPPT show that although the Cp tracks the maximum value well, it still cannot reach the maximum point of power coefficient, which is mostly caused by the characteristics of Savonius-type turbine, the vibration range of Cp value during the experiments is wide and the limitation of wind tunnel conditions also contributes to a smaller value of maximum power coefficient.
References


