THE DEVELOPMENT OF A VERTICAL TURBINE FOR DOMESTIC ELECTRICITY GENERATION

M. C. Percival, P. S. Leung, P. K. Datta
University of Northumbria, School of Engineering, Ellison Building, Ellison Place, Newcastle Upon Tyne,
Tyne and Wear, UK, NE1 8ST.
e-mail: michael.percival@unn.ac.uk
School of Engineering Tel: 0191 2274618
School of Engineering Fax: 0191 2273684

Keywords: Savonius; VAWT; Wind Turbine; S-rotor; Household Turbine.

Summary

This project produces an exploration of a Savonius rotor (S-rotor) wind turbine adapted for household/domestic electricity generation. The design process and justification of the new machine will be described. A prototype has been built and installed at a selected site. The operational experience of this site testing will also be summarised in the paper. The result so far is feasible.

This project produces an investigational exploration of a Savonius rotor wind turbine adapted for household electricity generation. The innovative technology turbine collects wind energy and converts it into electricity, which in turn produces a 12 volt output which is used to charge one heavy duty battery. As a result, the home is served simultaneously by the wind turbine and the utility. In this study, a small electricity generator has been specifically designed for household installation. The generator (alternator) is driven by a modified Savonius rotor. This type of rotor (which is of the vertical axis variety) is chosen instead of a horizontal axis machine due to its simplicity and reliability. The S-rotor has been designed using an analytical method and confirmed by natural wind testing. The design process and justification will be described in the paper. A prototype has been built and installed at a selected site. The operational experience of this site testing will be summarised in the paper. The result so far is feasible.

At present too few wind projects are being built in the UK, mainly because of planning permission objections. This problem will be eliminated with the development of the household turbine. The concept is to let homeowners generate their own clean power, thereby reducing Carbon Dioxide emissions. In addition, by putting the wind to work, the household electricity bill should be decreased. The Savonius turbine has been overlooked in the past for small household applications. However, this paper indicates that the design could be very useful for reducing fossil fuel energy consumption within the home. If this device became popular, the system would go some way to meeting the UK Government commitment to generating 10% of electricity from renewable sources by 2010, as set out in the Energy White Paper.

Objectives of the Project

- Evaluate the best blade offset by field testing using a small prototype model.
- Produce a turbine capable of generating 10% of the household's electricity.
- Build a fully functioning 100 Watt household turbine.
- Show that using the Savonius turbine for household generation is a viable option.

My Household Electricity Consumption

The electricity consumption was monitored in my household over the course of five months, and was then averaged out for a one month period. The calculations are shown below:

Average Monthly Electricity Consumption = 328.69 kWh/month
Average Yearly Energy Consumption = 328.69 x 12 = 3944.28 kWh/year or [3944.28/(24 x 365)] x 1000 = 450.26 W

For 10% of the electricity produced by the wind resource = 0.1 x 450.26 = 45.03 Watts. Therefore a 45.03 Watt machine is required. However, since the readings are from a 2 person household which is quite small, a good assumption would be to base the size of wind turbine on a more common size of family unit. Therefore a 4 person household would give: 2 x 45.03 = 90.06 Watts, so a 100 Watt turbine would be a more sensible size to construct. This figure is consequently adopted.

Small Scale Model Wind Turbine Testing

The model constructed is of the Vertical Axis Wind Turbine variety (VAWT), and is a 1/25 scale of the larger household turbine when rotor area is evaluated. This prototype was used to understand the fundamentals of turbine design, and to evaluate the best blade profile. It is based on the Savonius turbine design (shown below), and is a fully functioning, electricity producing scale model of the household turbine.

The Savonius generator relies solely on drag to produce a force that turns the turbine shaft. It consists of two simple scoops, where one side catches the moving air more than the other causing the turbine to spin. This design does not allow the turbine to spin faster than the oncoming wind.

This type of turbine is simple to build, and because it is vertical there is no need to have a mechanism to keep it turned into the wind.

The turbine frame stands ten inches (254 mm) tall, and produces power from a direct drive, single phase brushless permanent magnet alternator. The design is naturally self limiting for over speed protection. The turbine generates low levels of electricity (1.5 volts, 200 milliamps, 0.3 Watts – figures from Table 1) that are considered safe, and are of the same order of magnitude as produced by batteries used in small appliances.

Figure 1: the model turbine (side view)

Figure 2: the model turbine (end view)

Uses for the model design

To provide a purpose for building this model, other than results obtained from natural wind testing, the device was considered for more practical purposes. The limiting factor is the power output of 0.3 Watts generated in a 10 m/s wind flow, which therefore makes this turbine only suitable for minor applications. These are listed below.

1. To power a radio.
2. To power a Light Emitting Diode (LED) torch/lamp.
3. To produce electricity to light a bicycle lamp.
4. To illuminate a lamp for a bus shelter/telephone box or other similar applications.

Results for the small scale model

The performance of 10 blade shapes (S/d = 0.6 to -0.3) employed by the Savonius rotor wind machine have been studied and tested within the environment at the chosen test site of Whitley Bay, located on the North East coast of England. A range of wind speeds (4 – 10 m/s) were studied in 1 m/s increments, and the findings were based on the maximum wind speed tested of 10 m/s – see the results in Table 1, below. The turbine was located at a height of 2.22 metres above ground level on the roof of a summer house (Figures 1-2), and the profiles were used to predict the most appropriate offset and obtain the maximum power available for each blade shape. From the results in Table 1, a graph (Figure 3) was created. Hence the blade with the maximum power rating was chosen for the build process of the household turbine.

The results of voltage and current (shown in Table 1) were obtained during the test process. The gap spacing was identified as critical, as was the blade size (d = 180 mm, h = 110 mm) and therefore both of these variables were kept a constant throughout the test procedure.

Measured Wind Speed 10 m/s				
S/d	**Voltage (V)**	**Current (mA)**	**Power (W)**	**% of Max power available**
0.6	1.38	172.5	**0.2381**	**79.37**
0.5	1.43	187.1	**0. 2675**	**89.17**
0.4	1.47	197.4	**0.2901**	**96.71**
0.3	1.49	199.3	**0.2969**	**98.97**
0.2	1.5	200	**0.3**	**100**
0.1	1.48	196.1	**0.2902**	**96.72**
0	1.42	187.3	**0.266**	**88.68**
-0.1	1.33	175.8	**0.2338**	**77.94**
-0.2	1.21	169.3	**0.2048**	**68.27**
-0.3	1.13	155.3	**0.1755**	**58.49**

Table 1

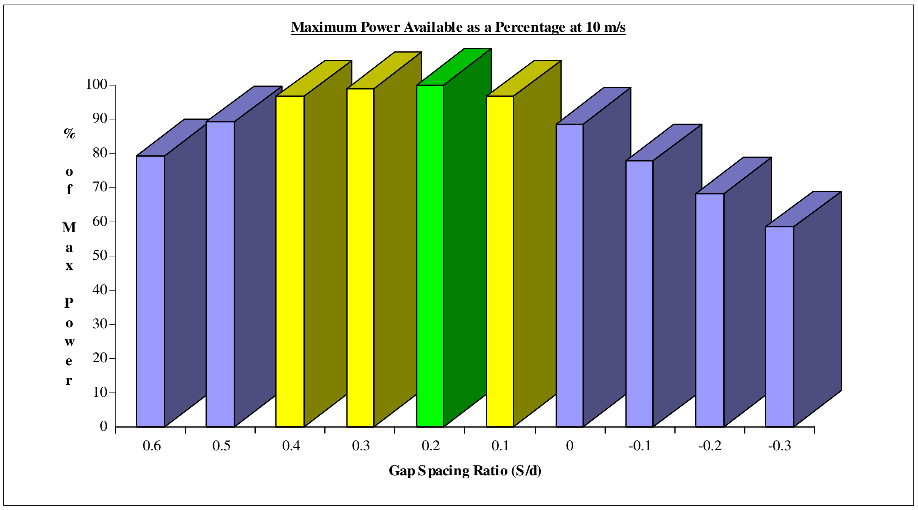

Figure 3

Conclusions from the small model tests

1. A maximum power of 0.3 Watts (100%) occurred when a blade of S/d = 0.2 was used, in a wind of speed 10 m/s. This can be viewed in Figure 3, directly above (green column).
2. The appropriate gap spacing ratio is S/d = 0.2.
3. The most suitable blade offset range was S/d = 0.1 – 0.4. Away from this region the power output from the machine was seen to drop off rapidly (shown in the blue columns in Figure 3).
4. These experimental results compare favourably with previous results conducted in this area whereby an optimum gap spacing was found to be: 0.15 [1] or 1/6 [2].
5. Self starting occurs in low wind speeds (4 m/s) and at all angles.
6. This value of 0.2 will be used in the full scale design of the household turbine.

Theory: Power Coefficient Analysis [3]

This hypothesis is reproduced to show the relationship between the power coefficient (C_p) and the wind speed, which expresses the basic theory of the Savonius wind machine. Principally the power that the rotor can extract from the wind P_w is less than the actual available from the wind power P_a. In order to calculate the performance of this wind machine, its configuration is essentially important.

Practically, when the turbine is placed in a wind tunnel with an inlet (1) and an outlet (2) the power that can be extracted from the wind is found by the following methodology:

- Find the average of wind speed through the rotor area V: $V_{ave} = \frac{(V_1 + V_2)}{2}$

  Where V_1 and V_2 are the inlet/outlet wind speeds in m/s

- Define the mass of the airflows passing through the S-rotor area, A per second in the stream tube by:

  $$m = \frac{\rho A(V_1 + V_2)}{2}$$

- According to the Kinetic Energy, $K_E = \frac{1}{2} mV^2$

- Therefore the power extracted, $P = \frac{1}{2} m(V_1^2 - V_2^2)$. Substituting the mass of air into this formula, the power that the rotor can extract from the wind is:

  $P_w = \frac{\rho}{4} (V_1^2 - V_2^2)(V_1 + V_2)A$, when the swept area A = h x (2d-S) = h x D (m^2)

- Similarly, if the S-rotor generates the electricity, the power that the rotor can extract from the wind is:
  $P_w = E \times I$ (Watts).

The available power, P_a from the wind is: $P_a = \frac{1}{2} mV_1^2$ when $m = \rho A V_1$, therefore:

$$P_a = \frac{1}{2}\rho A V_1^3$$

The power coefficient C_p is given by:

$$C_p = \frac{P_w}{P_a}$$

Therefore:

$$P_w = C_p \times P_a = C_p \frac{1}{2}\rho A V_1^3$$

which is the standard wind equation that is used in this documentation [3].

Block Diagram Representation of the Wind Turbine

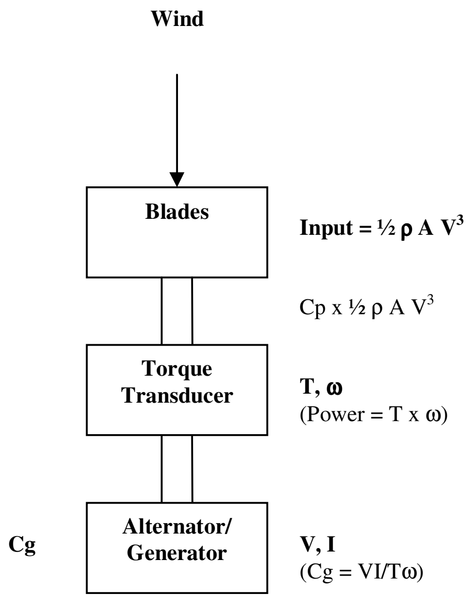

Figure 4

Following Figure 4 from top to bottom, it can be seen that:

The input from the wind = $\frac{1}{2} \rho A V^3$
Where $E = \frac{1}{2} \rho A V^3$

Then:

$T\omega = Cp \times E = Cp \times \frac{1}{2} \rho A V^3$
$VI = Cg \times T\omega = Cg \times Cp \times \frac{1}{2} \rho A V^3$

Where:

- Cg is the generator efficiency.
- Cp is the power coefficient.

A Guide to Rotor Dimensions plus Shaft Rotation Evaluation

All the preceding calculations are obtained from the following equations [3], and were placed in tabular form for clarity, contrast and ease of manipulation.

To Calculate the Area (A)

As a starting point to generate some values a standard Power Coefficient (Cp) versus Tip Speed Ratio (X) diagram [4] for a Savonius rotor was used (Figure 14). From the diagram it can be determined that at X = 0.95 a power of 24.5% is gained. This value is used for the preceding power calculations below.

$P = Cp \frac{1}{2} \rho A V^3$ – standard wind equation (derived from power coefficient analysis)

$V = 10$ m/s (assuming this is the wind speed);
$\rho = 1.225$ kg/m^3 density of air at sea level and 15°C;
$Cp = 0.245$ (24.5% from the standard Power Coefficient/Tip Speed Ratio diagram [4]);
Power (P) = 200, 100, and 50 Watts.

To Calculate the Shaft Rotation (ω)

The equation below is used whereby the radius value R (D/2) is manipulated to obtain ω. It is assumed that the value of X (tip speed ratio) is equal to 1, to eliminate X in the equation below.

$X = R\omega/V$

ω = rotational speed (rads/s);
R = radius of rotor (m);
V = average wind speed, assume 10 m/s.

$\therefore \omega = V/R$, R is varied between 0.2 and 0.55 metres, a reasonable range baring in mind the speed of rotation.

To Calculate the height (h)

The equation below is used to calculate h:

Area (A) = height (h) x diameter (D)

			A = 1.333 metres 200 Watts (20 %)	**A = 0.666 metres** 100 Watts (10%)	**A = 0.333 metres** 50 Watts (5%)
		ω (rpm)	**h** (metres)	**h** (metres)	**h** (metres)
D = 0.4 m	R = 0.2 m	477.5	3.33	1.67	0.83
D = 0.5 m	R = 0.25 m	382	2.67	1.33	0.67
D = 0.6 m	R = 0.3 m	318.3	2.22	1.11	0.56
D = 0.7 m	R = 0.35 m	272.2	1.9	0.95	0.48
D = 0.8 m	R = 0.4 m	238.8	1.67	0.83	0.42
D = 0.9 m	R = 0.45 m	212.2	1.48	0.74	0.37
D = 1.0 m	R = 0.5 m	191	1.33	0.67	0.333
D = 1.1 m	R = 0.55 m	173.6	1.21	0.61	0.303

Table 2

From these results (Table 2) the following values have been obtained: D; ω; h. Furthermore the value of the Area A can be gained, since A = D x h. A generator and rotor can now be selected to fit in with the requirements of the wind turbine. The selection process is used to pin point: power rating (Watts) and generator speed (rpm).

From the above calculations it is deemed that the blade of dimensions: 0.8 x 0.83 metres (100 Watts) is the most appropriate for the development process. This assumption is based on a few key issues, namely:

1. A need to generate 100 Watts (10%) of the household energy by the wind resource available.
2. The overall structure will be of a more square shape, which should be more pleasing to the eye.
3. High possibility of buying an off the shelf blade (drum).
4. A fast enough shaft rotation, so that purchasing gears will not be a problem.

The Household Turbine

This section gives details of how the 100 Watt household wind generator was constructed for 12 volt battery charging using a Savonius rotor – this can be seen pictorially below (Figures 5 and 6). The 100 Watt figure was previously manipulated to show that this size turbine would produce 10% of the household's electricity, a figure set out in the energy white paper.

The rotor (Figure 7) is constructed from one 210 litre tighthead plastic blue polydrum (d = 0.54 m x h = 0.917 m), which drives a car alternator. The 12 volt output is used to charge one heavy duty battery. The drum size purchased was as close dimensionally to the values produced in the previous table (Table 2), so as to keep the power rating and calculations uniform.

Figure 5: The Household Turbine

Figure 6: Turbine End View

Figure 7: Rotor and Frame

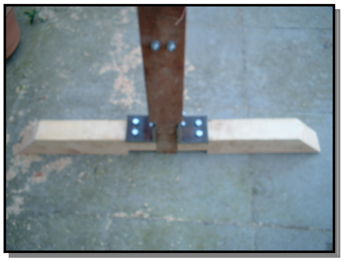

Figure 8: Feet

Figure 9: Gears

Figure 10: Car Alternator

Figure 11: Bearing

Figure 12: Transducer Display

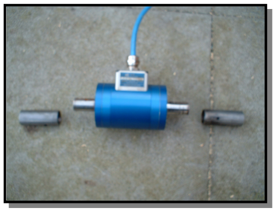

Figure 13: Transducer and Shaft Adapters

Rotor Construction (Figure 7)

The rotor blades are constructed from one 210 litre tighthead plastic polydrum bisected lengthwise. These troughs are mounted between two end plates made from MDF 0.99 metres long x 0.6 metres wide x 20 mm thick. The ends of the drum halves are simply bolted to the MDF pieces with M8 bolts, washers and locking nuts.

The main shaft through the centre of the rotor is a ½ inch (12.25 mm) diameter solid mild steel bar which is vertical in alignment. This shaft has an outer collar which is used as a rotor spacer between the bearings, which also adds extra strength. To secure the shaft to the end plates of the rotor, two collars are used. They are a close fit onto the shaft, and are bolted to the MDF with four M10 bolts and locking nuts. To support the rotor shaft three bearings (Figure 11) were used, one in each horizontal frame member.

A secondary output shaft is perpendicular to the vertical one, and is attached to the automobile alternator. This shaft is made up of two pieces: one solid shaft ½ inch (12.25 mm) diameter which is turned down at one end so that the worm wheel fits onto it; and a hollow tube which fits over the turned bar and the alternator. To support this shaft mechanism one bearing is placed at the left of the frame in the vertical frame member.

Gap spacing ratio (S/d)

The dimensions for mounting the drum halves are given below, where the optimum gap spacing from the small model testing was S/d = 0.2, which has been proven experimentally. Therefore:

$S/d = 0.2$, and we know that $d = 0.54$ metres, $h = 0.917$ metres

$\therefore \mathbf{S} = 0.2 \times 0.54 = \mathbf{0.108\ m}$
$\therefore \mathbf{D} = (0.54 + 0.54 - 0.108) = \mathbf{0.972\ m}$, and $\mathbf{R} = 0.972/2 = \mathbf{0.486\ m}$

Since $A = D \times h$, we have: $\mathbf{A} = 0.972 \times 0.917 = \mathbf{0.891\ m^2}$

These values are used in the calculations as produced in the results section (Table 3).

Frame Construction (Figure 7)

The frame consists of seven pieces of 4 inch (101.6 mm) by 3 inch (76.2 mm) wood. The joints are securely attached with M10 bolts, and angle bar 10 mm thick to make it as stiff as possible. The lower cross member is 0.6 metres above the ground, and the turbine height is 2.3 metres.

The Generator (Figure 10)

A car alternator is used as the generator for this wind turbine. The most suitable car alternator was found to be the Lucas 17ACR. It is a 36 amp alternator and starts to charge at 900 rpm. It is most important to match the size of generator as closely as possible to the rotor.

The alternator is connected to the left hand side of the main frame by two M10 bolts, locking nuts and washers.

To keep the voltage drop to a minimum the wiring from the alternator to the battery was rated at 30 amps, and a fuse of 10 amps was placed in the battery circuit near the positive battery terminal for protection.

Gearing (Figure 9)

The car alternator does not start to charge a 12 volt battery until 900 rpm is reached. This means that the rotor which spins at 238.8 rpm (from previous calculations, Table 2) will require gearing up by 900/238.8 = 4:1.

However, the rotor is constructed from a plastic drum (d = 0.54 m x h = 0.917 m) which is dimensionally different to the one from the calculations, and has an offset of 0.2. Therefore if X = 1:

$\boldsymbol{\omega} = \mathbf{V/R} = 10/0.486 = 20.58$ rads/s which is equivalent to $(20.58 \times 9.55) = \mathbf{196.5\ rpm}$

This means that the rotor which spins at 196.5 rpm will require gearing up by 900/196.5 = 4.6 = 5:1 for the car alternator. This is the gear ratio chosen for the project.

Since a high gear ratio (5:1) was required for the build process the most affordable and appropriate option was to use worm gears. In a worm gear, a threaded shaft engages the teeth on a gear.

Storage Battery

The type chosen was a Lead Acid Heavy Duty battery which is similar to a car battery but with heavy plates and special separators. Life is 8-10 years and efficiency is 70-75 per cent.

Results

Based on the results from the small wind turbine testing, one blade of S/d = 0.2 offset was selected for experimental testing of the household turbine, within the environment at a domestic property site at Whitley Bay, England. A range of wind speeds (5 – 9 m/s) were studied in 1 m/s increments, and the findings for the maximum wind speed of 9 m/s are shown in Table 3, below. This data is presented to the reader as it is seen as the most interesting, due to the power and rpm values measured. The set-up was used to predict the machine's power coefficient (Figure 14) and generator efficiency (Figure 15).

A 10 Nm torque transducer was connected between the rotor shaft and the car alternator, and a multi-meter was used to measure the output load (4 x 24W bulbs connected in parallel). The results, test variables, and calculations are shown below.

- V (volts) and I (amps) are measured using a multi-meter.
- *N*input (rpm), T (Nm), and P (Txω, in Watts) are measured using the torque transducer.
- Wind speed V, was measured using a digital anemometer.
- P is calculated from V x I.
- Cp is calculated from $C_p = (T\omega) / (½\, \rho\, A\, V^3)$.
- X (tip speed ratio) is calculated from X = Rω/V.
- ω is calculated from ω = 2π*N*/60.
- Cg is calculated from Cg = VI/Tω.
- *N*output = 5 x *N*input.
- $A = 0.891\ m^2$.
- R = 0.486 m.

Measured Wind Speed V = 9 m/s										
T (Nm)	**ω** (rads/s)	*N*input (rpm)	*N*output (rpm)	**V** (volts)	**I** (amps)	**P** **(T x ω)**	**P** **(V x I)**	**Cg**	**Cp**	**X**
4.39	20.37	194.50	972.5	22.04	3.89	89.51	85.74	0.958	0.225	1.1
4.50	20.00	190.96	954.8	20.78	4.15	89.91	86.24	0.959	0.226	1.08
4.49	18.89	180.35	901.75	16.88	3.99	84.74	67.35	0.795	0.213	1.02
4.30	17.59	167.98	839.9	16.34	3.29	75.59	53.76	0.711	0.19	0.95
5.69	15.37	146.76	733.8	17.76	3.15	87.53	55.94	0.639	0.22	0.83
5.65	14.07	134.38	671.9	16.6	3.24	79.57	53.78	0.676	0.2	0.76
6.54	12.78	122.00	610	13.38	3.09	83.55	41.34	0.495	0.21	0.69
7.04	10.74	102.55	512.75	12.8	2.21	75.59	28.29	0.374	0.19	0.58
7.44	9.63	91.94	459.7	12.27	2.9	71.61	35.58	0.497	0.18	0.52
8.06	5.93	56.58	282.9	12.28	1.99	47.74	24.44	0.512	0.12	0.32

Table 3

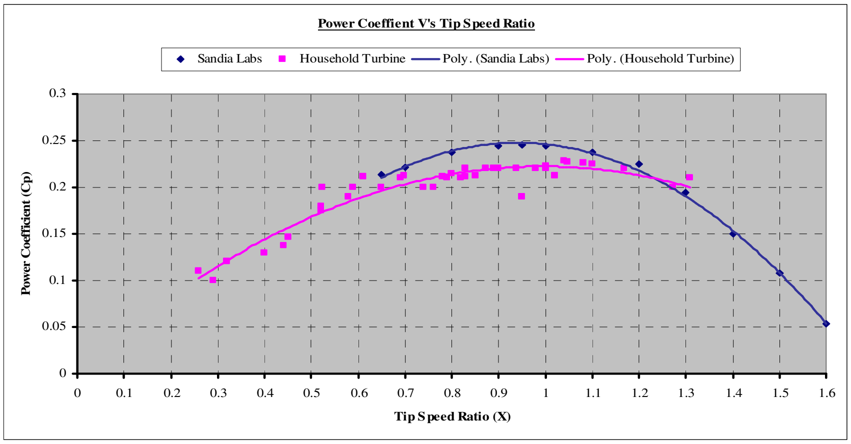

Figure 14: The full range of Power Coefficient, and Tip Speed Ratio data

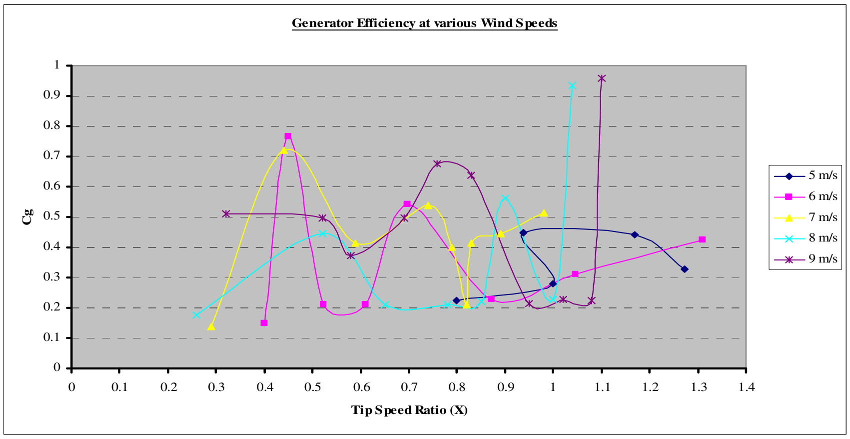

Figure 15: Generator Efficiency at various wind speeds

Conclusions

The performance of the wind generator depends upon the quality of construction and components used. The generator produced 89.91 Watts at 9 m/s wind speed (from the results in Table 3). This performance is satisfactory for fairly high wind areas. However, if a larger rotor was used a lower wind regime could produce similar results. Alternatively, a low speed alternator may be more suited to this purpose. The car alternator does not start to charge the battery until 900 rpm is reached: from the results this occurred in a wind speed of 9 m/s.

A generator efficiency of 0.959 (95.9 %) was obtained from the test results in a wind speed of 9 m/s (Table 3), and the average generator efficiency developed during the test was 0.404 which equates to 40.4 %**.** However, these values may not be wholly reliable since the plotted data shows that the generator efficiency seems to be highly unpredictable. This is in contrast to the power coefficient values that show a more consistent and predictable pattern.

Improvements to the Household Turbine

The first generation household turbine which has been manufactured appears to be rather large and heavy for the purpose of fixing it to the roof or chimney of a domestic property. However, this design would be suitable for commercial buildings. With some modifications to the frame, this type of windmill could feasibly be used with the home in mind. Many good features of this design were seen, namely: reliability; it is easy to manufacture; has no yaw mechanism; is of a low cost; and has self starting availability. Furthermore the build process has highlighted several improvements which are to be implemented by the author in the development of the next generation of household turbine. These enhancements are listed below.

1. Produce a more compact/lighter wind turbine for easy transportation.
2. Use a telescopic metal frame for reduced weight and size.
3. Use a permanent magnet generator or produce a custom made generator.
4. Improve the aesthetic appeal by using clear blades.
5. Connect the wind turbine directly to the mains within the home.
6. Use an inverter to adjust the 12 volt DC to mains supply (240 volt AC) thus opening up more household applications.
7. Increase the gear ratio so that the turbine has the potential to spin faster.
8. Add a braking mechanism to stop the rotor in gale force winds.

References

1. Blackwell BB, Sheldahl R, Feltz LV. Wind Tunnel Performance Data for Two and Three Bucket Savonius Rotor. *Journal of Energy* 1978; **2:**160-164.
2. Le Gourieres D. *Wind Power Plants Theory and Design*; Pergamon Press Ltd, 1982.
3. Manwell JF, McGowan JG, Rogers AL. *Wind energy explained: theory, design and application*; John Wiley and Sons Ltd: Chichester, 2002.
4. Moutsoglou A, Weng Y. Performance tests of a Benesh wind turbine rotor and a Savonius rotor. *Journal of Wind Engineering* 1995; **19**: 349-362.