Experimental study and analysis of savonius wind turbine for output power calculation

Introduction

Savonius turbine is one of the simplest wind turbines. Aerodynamically, it is a drag-type device, consisting of two or three scoops. Looking down on the rotor from above, a two-scoop machine would look like an "S" shape in cross section. Because of the curvature, the scoops experience less drag when moving against the wind than when moving with the wind. The differential drag causes the savonius turbine to spin. Savonius turbines are used when less cost or reliability are much more important than efficiency.

In this work, different methods are used to measure the brake power of savonius wind turbine experimentally. Advantages and difficulties in each method are explained. Brake power is calculated for various wind speeds by two ways: testing the turbine in open atmosphere on the marsh land and testing it in the wind tunnel. For measuring brake power in open atmosphere, marsh land at National Institute of Wind Energy (NIWE), Chennai is chosen. To measure the performance of wind turbine in controlled atmosphere, it is tested in the wind tunnel present at the Applied Mechanics Department of IIT Madras. For power calculation of wind turbine in wind tunnel testing, concept of dynamometer is used. After finalizing the power output of turbine, appropriate alternator is selected to convert mechanical energy of turbine into electrical energy.

Testing of savonius wind turbine in open atmosphere at Pallikaranai

Initially, savonius turbine is tested in an open atmosphere on the marsh land at National Institute of Wind Engineering, Pallikaranai Chennai. Anemometer is used for measuring the wind speed. It is facilitated with storing of wind speed data per minute. Variation of RPM and starting torque, with wind speed are recorded. Starting torque is used for selecting the cut in speed of turbine. In Table 1, RPM variation with wind speed is given.

Starting torque of turbine is measured from the static condition. Tangential force on the rotor of turbine is measured and is multiplied by the radius of rotor, which gives the torque requirement for starting. Experimental setup to calculate starting torque is shown in picture 3 in appendix. The values of starting torque at various wind speed are given in table 2 below.

Relevant pictures of the experimental setup and equipment used to test Savonius wind turbine at Pallikaranai are included in appendix (Pictures 1-3). Advantages and disadvantages in this method are given below.

Advantages:

- No need of external power supply for testing.
- No need to design any experimental setup.

Disadvantages:

- Due to natural wind speed variation, it was really challenging to measure the RPM of wind turbine at various wind speeds.
- There was no external load applied on the turbine, which came out to be very difficult in exact power calculation.
- Wobbling of turbine was a big issue due to unavailability of fixed ground support.

Wind speed (m/s)	RPM (min^{-1})
2.5	33
3.8	57
4.0	60
2.0	34.5
1.6	46.5
2.3	51
3.5	48
3.8	60
2.5	21
3.6	25.5
4.3	45
4.7	70.5
2.8	33
2.7	38
3.2	46.5
4.4	38.5
2.7	42
4.2	72
3.9	62.25
2.9	41.25
3.4	42
3.5	57
5.1	81
4.2	82.5
5.3	111
5.3	108
4.5	90
5.4	111
5.7	99
5.8	87
4.5	69

Table 1: Variation of RPM with wind speed

Wind speed (m/s)	Starting torque (N.m)
3.4	1.7658
4.2	2.1582
5.0	3.9240
4.2	1.9620
5.6	4.905
3.4	1.962
4.4	2.1582
3.8	1.962
3.5	1.962
4.7	4.1202
4.5	2.943
5.1	5.886
5.2	5.4936
5.3	5.886
5.5	6.867
4.3	1.962
4.3	2.1582
4.1	1.962
5.7	7.6518
5.2	4.3164
5.0	3.7278
4.6	2.1582
5.2	4.7088
4.6	2.1582
3.6	1.7658
4.9	3.7278
5.5	4.3164
4.6	1.962
4.9	3.924
6.6	5.886
5.4	7.6518
5.0	3.5316
5.9	5.886
6.7	7.848
5.4	4.905
5.6	7.4556
5.9	4.7088
3.6	1.962
6.3	7.848
5.0	3.7278
6.0	4.1202
6.9	7.6518
6.7	4.905
5.2	3.924

Table 2: Variation of starting torque with wind speed

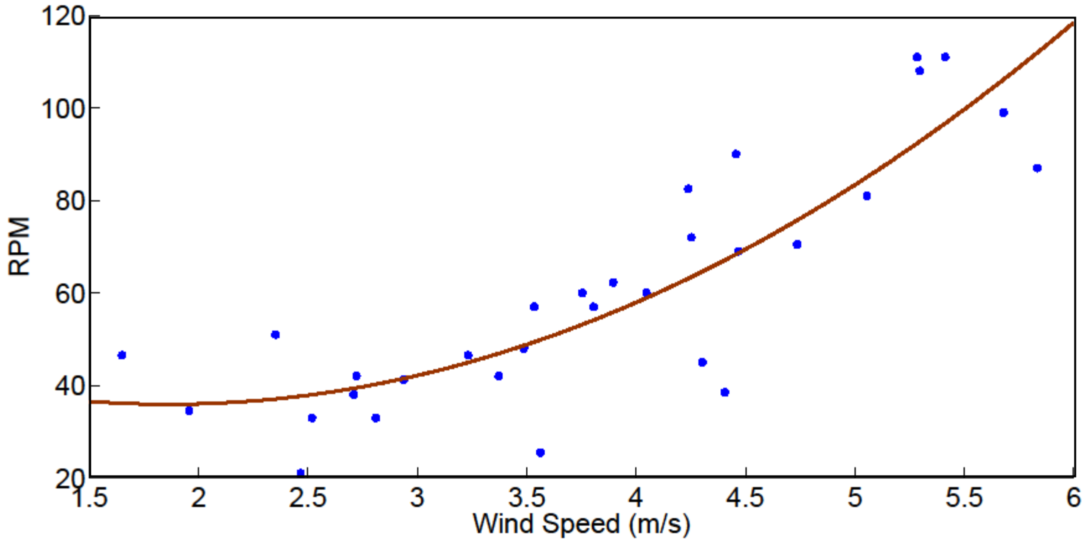


Figure 1: Variation of RPM with wind speed

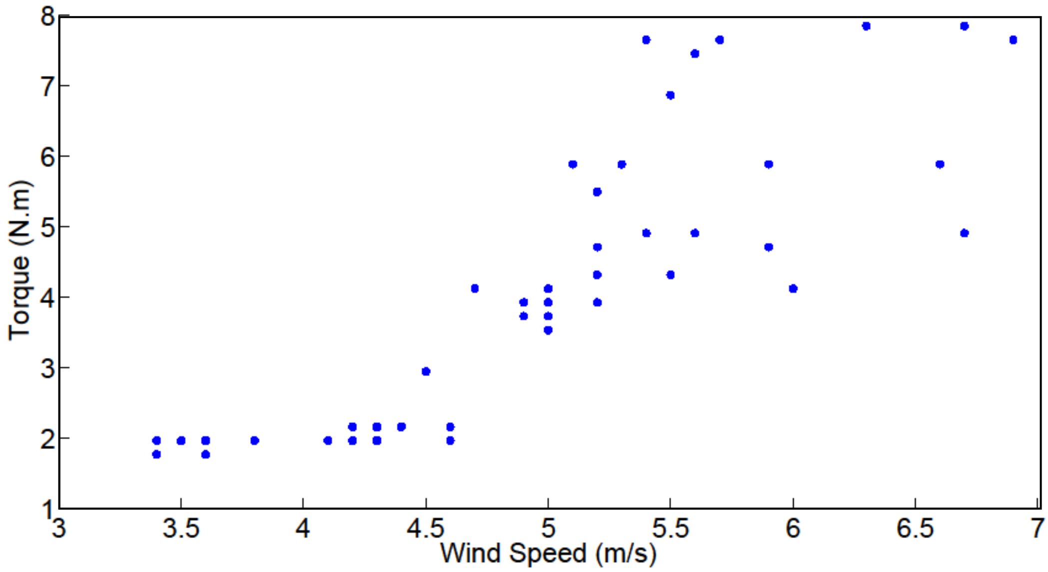


Figure 2: Variation of starting torque with wind speed

In figure 1, variation of RPM with wind speed is plotted. From the experimental data, a curve of best-fit is finalized. Best fit curve came out to be a second degree curve. From figure 2, it can be seen that minimum value of starting torque is 1.8 N.m at wind speed around 3.5 m/s whereas it can be as high as 8 N.m at wind speed around 6.8 m/s. To overcome the inertia of alternator, starting torque value should be considered, which will decide the cut-in speed of savonius turbine. Also to safeguard the alternator, maximum value of RPM should be restricted. This can be done by automatic braking of turbine rotor at the higher wind speeds.

Testing of savonius wind turbine in wind tunnel

Wind tunnel is used in aerodynamic research to study the effects of air moving past solid objects. In this case, it is used for the performance evaluation of savonius turbine. Wind tunnel at the Department of Applied Mechanics, IIT Madras consists of a tubular passage with the object under test mounted in the middle. Air is made to move past the object by a powerful fan. In this case the test object is savonius turbine. This wind turbine is instrumented with suitable means to measure the power generated and starting torque requirement. Wind tunnel specifications are as following:

Wind tunnel specifications
Subsonic open return wind tunnel
Testing section: 1 m diameter
Delivery volume: 15 m^3/sec
Fan speed: 0 – 750 RPM
Fan type: axial flow fan
Power requirement: 120 kW
Year of construction: 1965

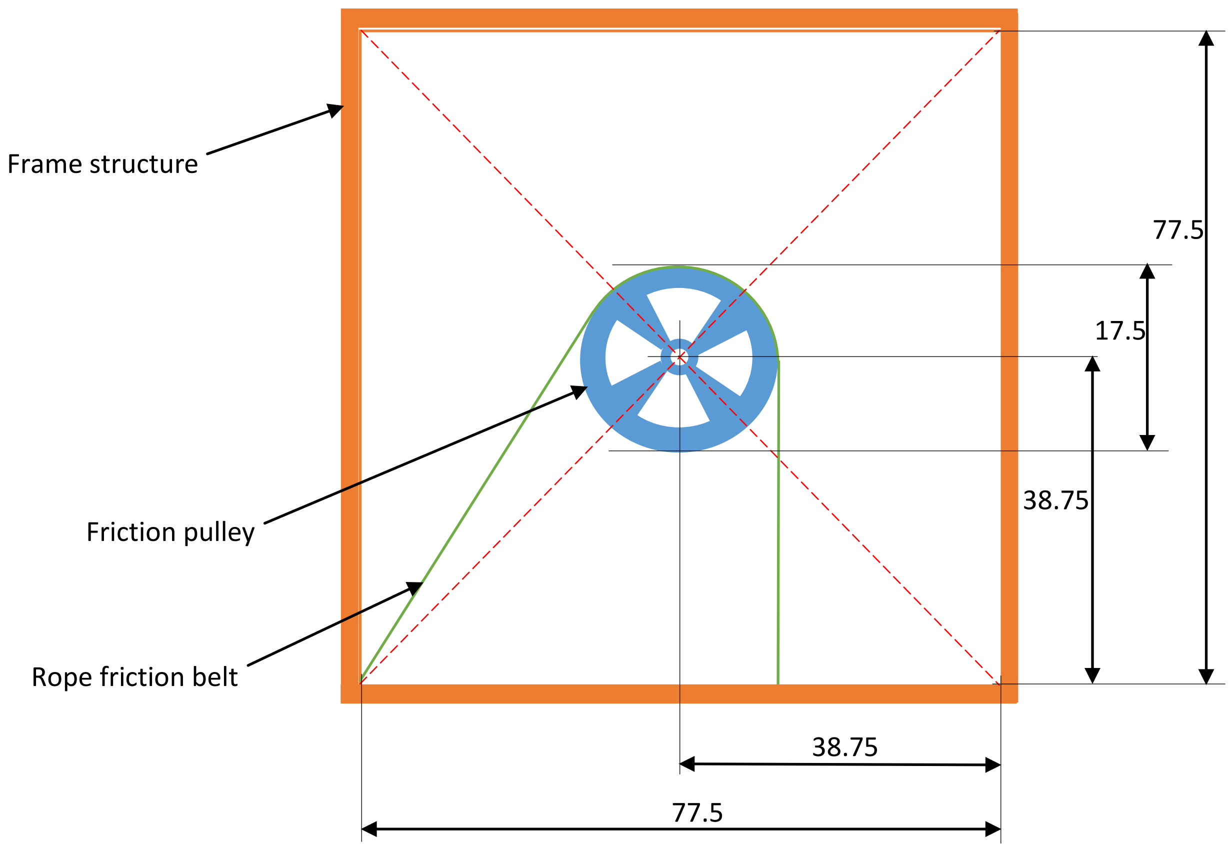
To calculate the power output of wind turbine, rope friction dynamometer concept is used. Dynamometer is a device coupled to the rotating shaft, used for the calculation of output torque of the system. Torque is multiplied by RPM, eventually to get the horsepower of system. In experimental setup, nylon rope is wrapped around the pulley which is attached to the main shaft of turbine. One end of the rope is fixed to spring balance and the other to dead weight. Essential measurements are taken by measuring a force transferred to the nylon rope through friction. Friction is increased by tightening the rope until the frequency of rotating shaft reduces and limit of turbine is reached.

A pulley is keyed to the rotating shaft of the turbine. A nylon rope is wrapped around the pulley with a contact angle 144 degrees (see figure 3). Initially, tension in the rope is applied for stopping the turbine from exceeding maximum RPM. Tension in rope is increased further by adding extra weights to one side of the rope. Tension in both the sides of rope is measured. From spring balance, tension on one side is obtained and the attached dead weight gives the same on the other side. Frictional torque equals difference in the tension multiplied by the radius of pulley. RPM of turbine is measured by the video inspection. Frictional power is multiplication of friction torque and rotational velocity of turbine. When PRM of turbine remains constant, frictional power equals the power output of turbine. This is the principle of friction belt dynamometer, which is used to obtain the power output of savonius turbine.

In the experiment, high tension side (T_1) is dead weight and low tension side (T_2) is having spring balance. Readings for a particular wind speed are taken more than once to avoid experimental errors. Set up of experiment is shown in figures 3 and 4. Several readings have been taken at different wind speeds, shown in table 3 below.

Wind Speed (m/s)	Turbine RPM (sec^{-1})	Tension (T_1) (kg)	Tension (T_2) (kg)	Torque (N.m)	Power (Watt)
3.4 – 3.7	55	1.8	1.0	0.6867	3.955
	71	1.19	0.4	0.6781	5.042
	47.5	2.19	1.2	0.8498	4.2182
	82	0.612	0	0.5253	4.5108
	29	2.612	1.6	0.8687	2.6381
	63	1.612	0.8	0.697	4.5983
4.3 – 4.6	53.5	4.19	2.2	1.7082	9.5702
	68	3.612	2.1	1.2979	9.2423
	44	4.612	2.8	1.5554	7.1668
	84	2.612	1.2	1.212	10.6613
	74	3.19	1.9	1.1073	8.5808
	94	2.19	1.1	0.9356	9.2097
4.9 – 5.1	75.5	5.19	3.2	1.7082	13.5056
	90.5	4.19	2.35	1.5971	14.9683
	67.5	5.69	3.9	1.5365	10.8609
	51.5	6.69	4.25	2.0944	11.2952
	0	6.89	4.0	2.4807	0
	59	5.89	3.8	1.794	11.0842
	106	3.19	1.95	1.0644	11.8152
5.6 – 5.8	103.5	6.19	3.8	2.0515	22.2352
	85	7.19	4.5	2.309	20.5529
	71.5	8.19	5.4	2.3949	17.9317
	37.5	9.19	5.45	3.2103	12.6068
	0	9.39	5.5	3.3391	0
	40	8.69	5.4	2.8241	11.8296
	76	7.69	5.7	1.7082	13.5951
	91.5	6.69	4.1	2.2232	21.3024
6.3 – 6.6	52	10.19	5.9	3.6824	20.0522
	76	10.69	6.9	3.2532	25.8912
	90	8.19	4.8	2.9099	27.4252
	103	7.19	4	2.7382	29.5346
	117	6.19	3.45	2.3519	28.8156
	0	10.69	5.9	4.1116	0
6.8 – 7.0	101.5	9.19	6	2.7382	29.1045
	77.5	10.19	6.1	3.5108	28.4929
	61.5	10.69	6.3	3.7683	24.2689
	85.5	11.19	7.5	3.1674	28.3594
	103	8.19	5.0	2.7382	29.5346
	0	12.19	7.1	4.3691	0
7.2 – 7.5	77	12.19	7.6	3.9399	31.7691
	84	11.19	6.7	3.8541	33.9024
	92	10.19	5.95	3.6395	35.0637
	105.5	9.19	5.1	3.5108	38.7871
	35	12.69	7.4	4.5408	16.6429
	0	13.09	7.5	4.7983	0

Table 3: Variation of RPM and Torque with wind speed



(Note: All dimensions are in cm)

Figure 3: Experimental set-up (top view)

Wind turbine specifications
Savonius two stage vertical axis wind turbine
Turbine height: 141.5 cm
Turbine rotor diameter: 77 cm

Friction torque (T) = $(T_1 - T_2) \times$ Radius of pulley

Rotational velocity $(\omega) = 2 \times \text{pi} \times \text{RPM} / 60$

Frictional power $(P_F) = T \times \omega$

Power output of turbine (P_O) = Frictional power (P_F)

Theoretical power of turbine $= {}^{1}/_{2} \rho\, A\, V^2 \eta$

ρ = air density 1.225 $\mathrm{kg/m^3}$

A = height of rotor × dia. of rotor

V = wind speed (m/s)

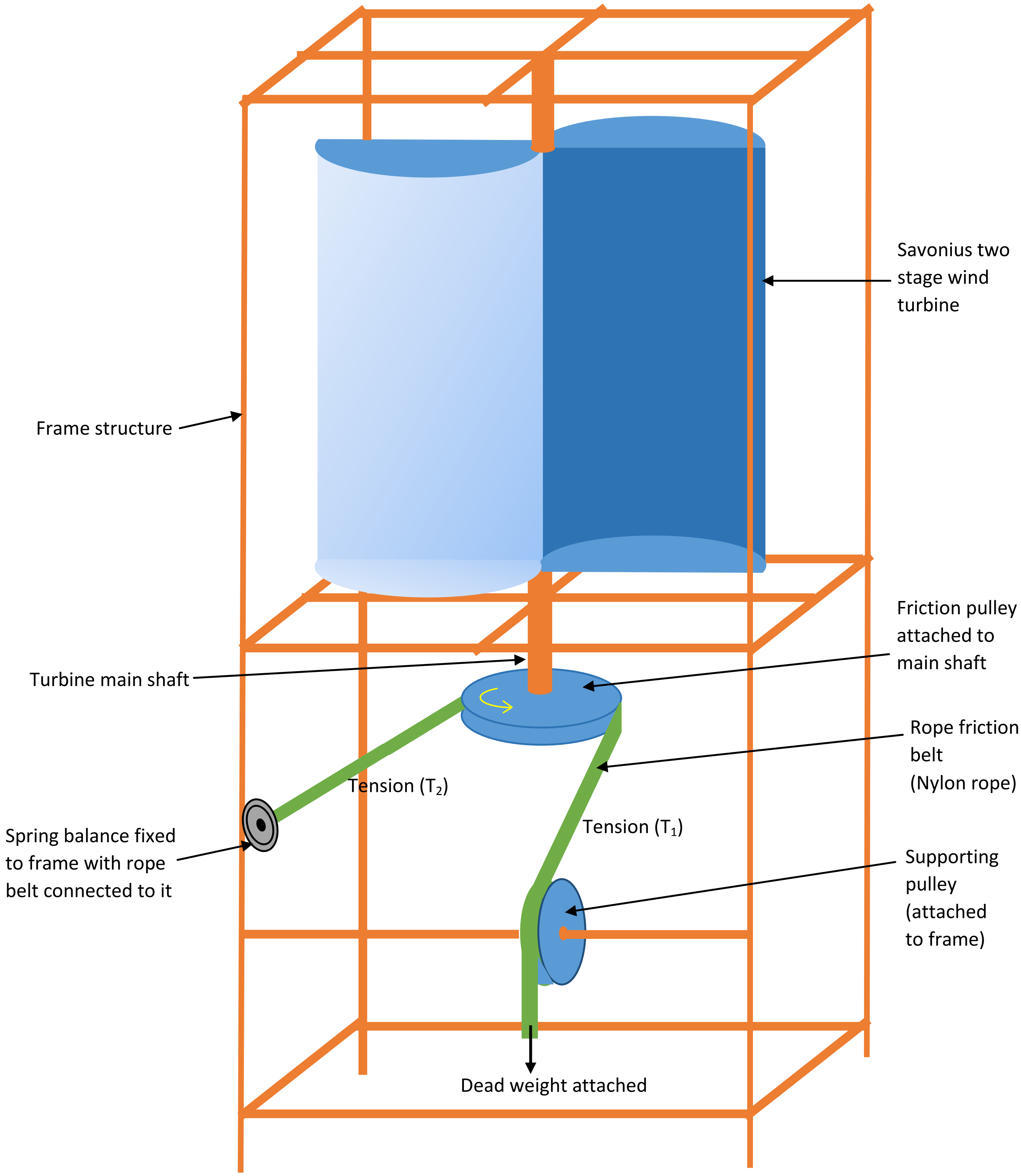


Figure 4: Experimental set-up for wind turbine testing in a wind tunnel

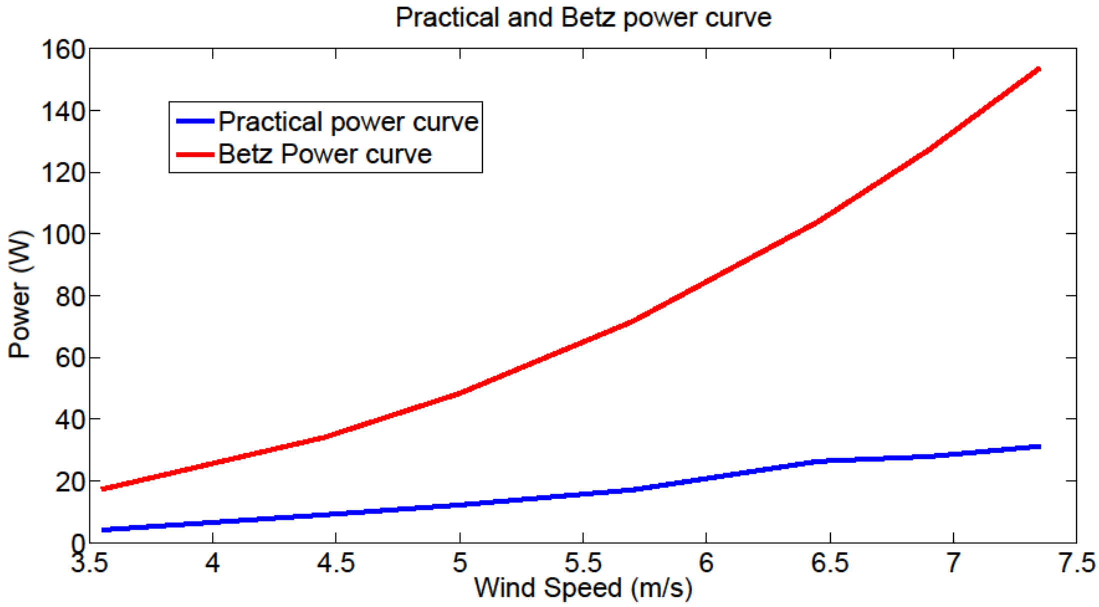


Figure 5: Variation of experimental and Betz power with wind speed

For clear understanding of the experimental setup and dynamometer concept, some pictures of actual setup are included in appendix (Pictures 4-6).

Power output of turbine is measured by two ways, Betz method (η = 59.3) and practical method. While calculating Betz power, efficiency of turbine assumed to be 59.3 (Betz limit). Power output by these two methods obtained and plotted with respect to wind speed. Red curve shows Betz power output and blue one shows practically measured power. Maximum power obtained is 31 watts at 7.3 m/s wind speed. Beyond this speed, there is uncontrolled wobbling of wind turbine, so it had to stop there. The difference between two curves in figure 5 is very much. This is because efficiency of wind turbine is assumed to be 59.3%, which is not possible practically. Practically wind turbines can achieve 20 to 70% of Betz limit. Actual efficiency of wind turbines lies in 11.86 to 41.51%.

Advantages and disadvantages of wind tunnel testing—

Advantages:

- Complete control over the wind speed.
- External load is imposed on the turbine so accurate calculation of output power of wind turbine is possible.
- Wobbling of wind turbine is fixed by tying it at the top portion and attaching its bottom portion to fixture.

Disadvantages:

- Huge amount of energy is consumed for running the wind tunnel.
- Need to design and construct setup for power calculation.

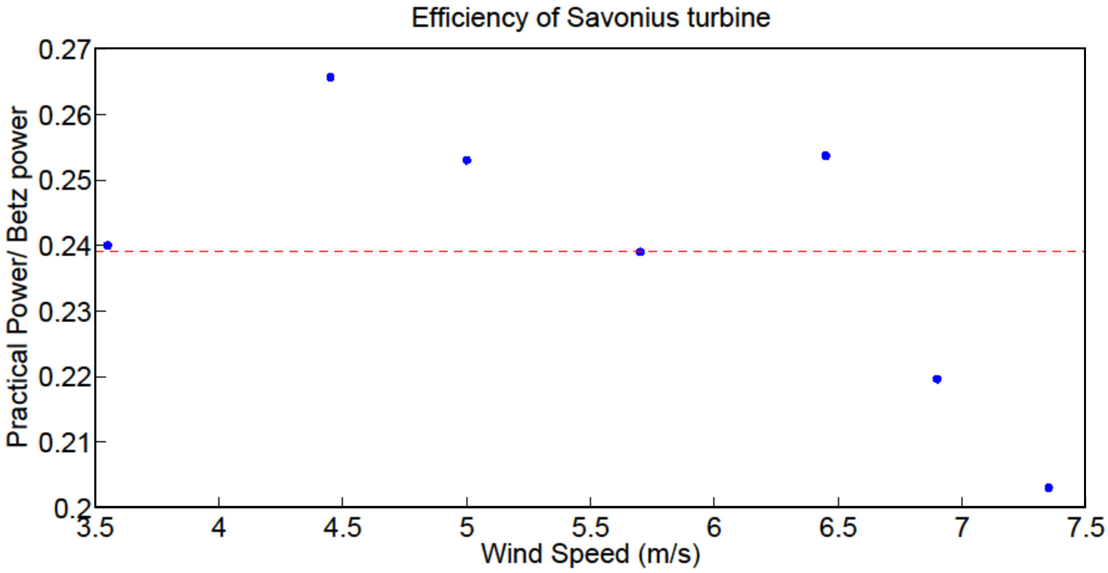


Figure 6: Variation of efficiency ratio with wind speed

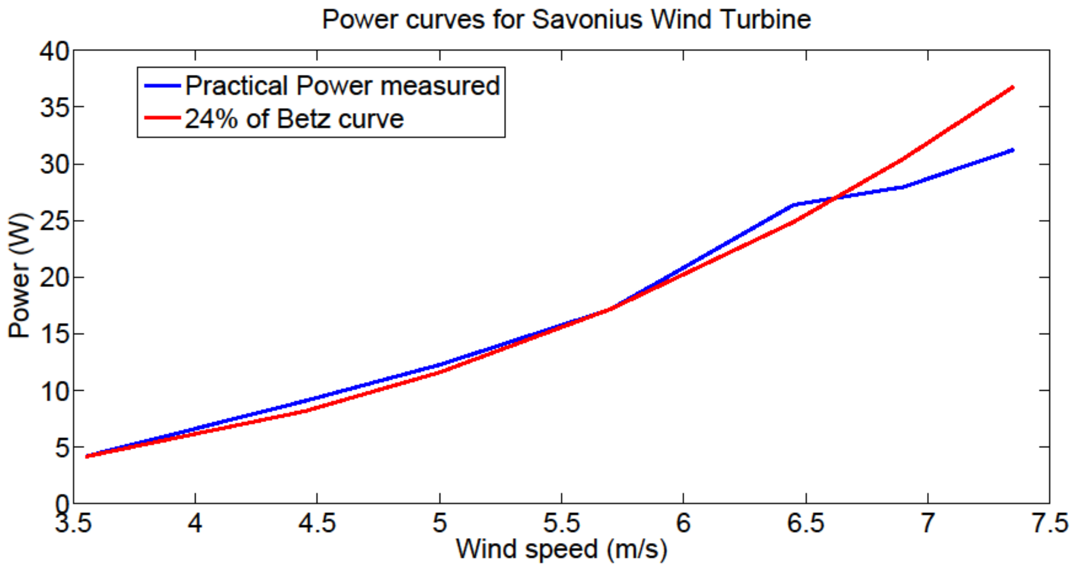


Figure 7: practical and theoretical and Betz power variation (η = 24% of Betz power) with wind speed

In figure 6, ratio of experimental to theoretical power with respect to wind speed is plotted. Average of all the points is calculated and it is taken as the efficiency of savonius turbine. Efficiency (η) of savonius turbine is 23.92% of Betz limit. This means, the present savonius turbine can extract 23.92% of Betz energy. In figure 7, variation of practical and theoretical Betz power (taking $\eta = 23.92\%$) output is shown with wind speed. Power output of turbine varies from 4 to 31 watt for wind speed varying from 3.5 to 7.3 m/s.

Alternator

Whether constructing a wind turbine is economically viable at farm depends most strongly on the quality of wind resource. In generally, average annual wind speeds of at least 4.0 – 6.0 m/s (14.4 – 21.6 km/h) are needed for a small vertical axis wind turbines to produce enough electricity to be cost-effective.

Plan for this research process was to power an air-compressor and convert wind energy directly to compression energy. Compressed air could be stored in an airtight container to nullify the fluctuations, which would come from variable wind speed. Compressor would be coupled directly to the main shaft of turbine with appropriate power transmission system. But unfortunately, to power a compressor, power output from savonius turbine was not sufficient. So we decided to go conventional way of converting wind energy into electrical energy. We selected an alternator to convert energy in wind to electrical energy.

Alternator is an electric generator that converts mechanical energy into electrical energy. But there are some differences between generator and alternator. Alternators conserve energy by using only the energy that is needed. Generators use all the energy that is produced. Alternators produce voltage when needed and generators produce voltage at all times. Alternators generate a higher output.

There are mainly two types of alternators: Salient pole and smooth cylindrical. Salient pole alternators are used at low and medium speed applications, whereas smooth cylindrical alternators are used for very high speed applications. For savonius wind turbine application salient pole alternator are suitable.

DC-540 Low Wind Permanent Magnet Alternator

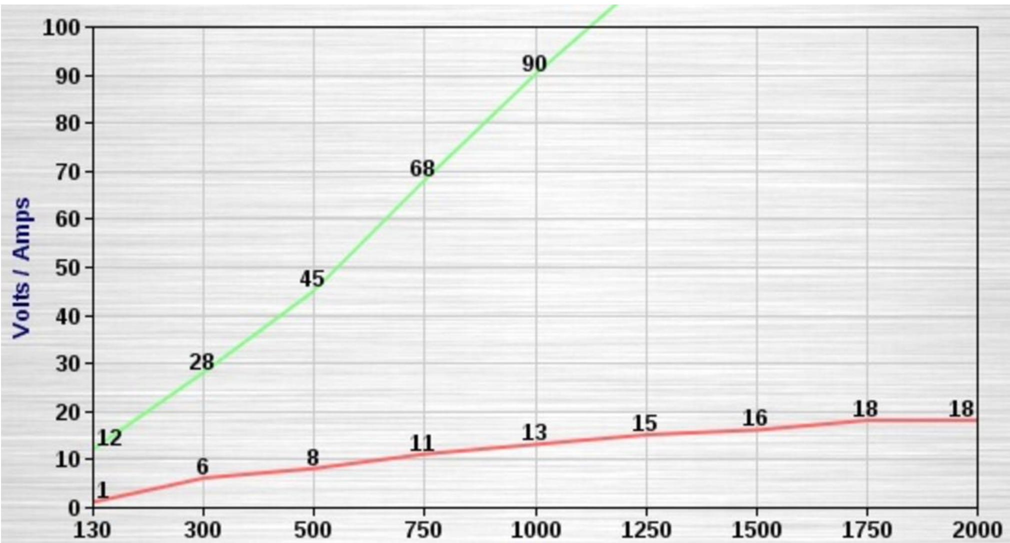


Figure 8: DC-540 Alternator specifications

Alternator specifications are shown in figure 8. Working range of alternator in detail is shown in table 4.

	Measured Data					Calculated Data	
Sr. No	ω [rpm]	$R_{setting}$ [Ω]	Voltage [V]	Current [A]	τ_{input} [N-m]	P_{output} watt	η
1	49	28.0	2.79	0.08	0.35	0.223	0.1247
	49	24.5	2.74	0.12	0.39	0.329	0.1637
	49	21.0	2.67	0.12	0.36	0.320	0.1723
	49	17.5	2.57	0.16	0.40	0.411	0.2009
	49	14.0	2.44	0.16	0.43	0.391	0.1754
	49	10.5	2.26	0.20	0.43	0.452	0.2030
	49	7.0	1.98	0.28	0.53	0.553	0.2022
	49	3.5	1.44	0.40	0.65	0.577	0.1720
	49	2.0	1.23	0.44	0.69	0.541	0.1531
	49	1.0	0.65	0.60	0.84	0.388	0.0902
2	117	28.0	8.15	0.28	0.59	2.282	0.3144
	117	24.5	8.00	0.32	0.62	2.560	0.3394
	117	21.0	7.80	0.36	0.67	2.808	0.3413
	117	17.5	7.54	0.40	0.71	3.016	0.3469
	117	16.0	7.46	0.44	0.73	3.282	0.3662
	117	15.0	7.30	0.48	0.77	3.504	0.3694
	117	14.0	7.18	0.52	0.75	3.734	0.4058
	117	12.5	7.06	0.52	0.82	3.671	0.3654
	117	11.5	6.86	0.56	0.86	3.842	0.3628
	117	10.5	6.67	0.60	0.88	4.002	0.3700
	117	9.0	6.49	0.68	0.92	4.413	0.3925
	117	8.0	6.14	0.76	0.99	4.666	0.3864
	117	7.0	5.87	0.80	1.08	4.696	0.3541
3	209	28.0	15.46	0.52	0.87	8.039	0.4246
	209	24.5	15.16	0.60	0.93	9.096	0.4450
	209	21.0	14.78	0.68	1.02	10.050	0.4500
	209	17.5	14.31	0.80	1.10	11.448	0.4751
	209	16.0	14.06	0.84	1.14	11.810	0.4721
	209	15.0	13.82	0.88	1.20	12.162	0.4636
	209	14.0	13.63	0.96	1.23	13.085	0.4849
	209	12.5	13.27	1.04	1.29	13.801	0.4887
	209	11.5	12.95	1.08	1.35	13.986	0.4741
	209	10.5	12.64	1.16	1.42	14.662	0.4720
4	275	28.0	20.62	0.72	1.08	14.846	0.4780
	275	24.5	20.19	0.80	1.14	16.152	0.4926
	275	21.0	19.67	0.92	1.25	18.096	0.5008
	275	17.5	19.00	1.04	1.38	19.760	0.4983
	275	16.0	18.71	1.12	1.40	20.955	0.5205
	275	15.0	18.40	1.20	1.54	22.080	0.4965
	275	14.0	18.05	1.24	1.49	22.382	0.5220
	275	12.5	17.70	1.36	1.65	24.072	0.5051
	275	11.5	17.20	1.48	1.69	25.456	0.5224
	275	10.5	17.71	1.56	1.85	27.628	0.5182
	275	9.0	16.07	1.72	1.96	27.640	0.4899
5	365	28.0	27.47	0.96	1.33	26.371	0.5170
	365	24.5	26.92	1.08	1.44	29.074	0.5266
	365	21.0	26.20	1.20	1.58	31.440	0.5202
	365	17.5	25.28	1.40	1.71	35.392	0.5420
	365	16.0	24.80	1.48	1.71	36.704	0.5602
	365	15.0	24.36	1.60	1.81	38.976	0.5631

	365	14.0	24.00	1.68	1.91	40.320	0.5512
	365	12.5	23.36	1.80	1.99	42.048	0.5526
	365	11.5	22.74	1.92	2.18	43.661	0.5233
	365	10.5	22.16	2.08	2.27	46.093	0.5309
6	490	28.0	36.98	1.28	1.70	47.334	0.5420
	490	24.5	36.22	1.44	1.81	52.157	0.5607
	490	23.0	35.68	1.48	1.85	52.806	0.5566
	490	22.0	35.33	1.56	1.90	55.115	0.5663
	490	21.0	34.97	1.64	1.92	57.351	0.5831
	490	19.5	34.55	1.72	1.98	59.426	0.5855
	490	18.5	34.09	1.80	2.02	61.362	0.5934
	490	17.5	33.89	1.88	2.16	63.713	0.5746
	490	16.0	33.22	2.00	2.24	66.440	0.5775
	490	15.0	32.54	2.12	2.38	68.985	0.5647
	490	14.0	32.10	2.24	2.45	71.904	0.5724
	490	12.5	31.20	2.40	2.61	74.880	0.5596
	490	11.5	30.26	2.56	2.74	77.466	0.5500
	490	10.5	29.54	2.76	2.88	81.530	0.5510
7	650	28.0	48.30	1.72	2.02	83.076	0.6050
	650	24.5	47.20	1.88	2.24	88.736	0.5813
	650	23.0	46.40	2.00	2.30	92.800	0.5920
	650	22.0	46.00	2.04	2.32	93.840	0.5934
	650	21.0	45.80	2.16	2.37	98.928	0.6133
	650	19.5	44.90	2.24	2.47	100.576	0.5989
	650	18.5	44.30	2.36	2.52	104.548	0.6102
	650	17.5	43.90	2.48	2.61	108.872	0.6127
	650	16.0	43.20	2.56	2.71	110.592	0.5995
	650	15.0	42.00	2.76	2.83	115.920	0.6027
	650	14.0	41.40	2.92	2.95	120.888	0.6021
	650	12.5	40.00	3.16	3.15	126.400	0.5894
	650	11.5	38.90	3.32	3.32	129.148	0.5720
8	870	28.0	64.10	2.24	2.60	143.584	0.6059
	870	26.5	62.90	2.32	2.61	145.928	0.6143
	870	25.5	62.40	2.40	2.65	149.760	0.6215
	870	24.5	62.60	2.52	2.72	157.752	0.6356
	870	23.0	61.20	2.60	2.79	159.120	0.6249
	870	22.0	60.60	2.72	2.89	164.832	0.6263
	870	21.0	60.50	2.84	2.98	171.820	0.6327
	870	19.5	59.00	2.96	3.05	174.640	0.6285
	870	18.5	58.20	3.08	3.16	179.256	0.6232
	870	17.5	57.80	3.24	3.33	187.272	0.6177
	870	16.0	56.00	3.44	3.42	192.640	0.6192
	870	15.0	55.20	3.60	3.53	198.720	0.6173
	870	14.0	54.30	3.80	3.68	206.340	0.6149
9	1160	31.5	84.20	2.64	2.91	222.288	0.6284
	1160	30.0	83.40	2.72	2.98	226.848	0.6274
	1160	29.0	82.60	2.80	3.03	231.280	0.6281
	1160	28.0	82.60	2.92	3.11	241.192	0.6383
	1160	26.5	81.40	3.00	3.16	244.200	0.6363
	1160	25.5	80.50	3.08	3.23	247.940	0.6321
	1160	24.5	80.30	3.20	3.34	256.960	0.6340
	1160	23.0	78.80	3.36	3.40	264.768	0.6410
	1160	22.0	77.80	3.48	3.49	270.744	0.6395
	1160	21.0	77.40	3.60	3.62	278.640	0.6339

Table 4: Working range of Alternator DC-540

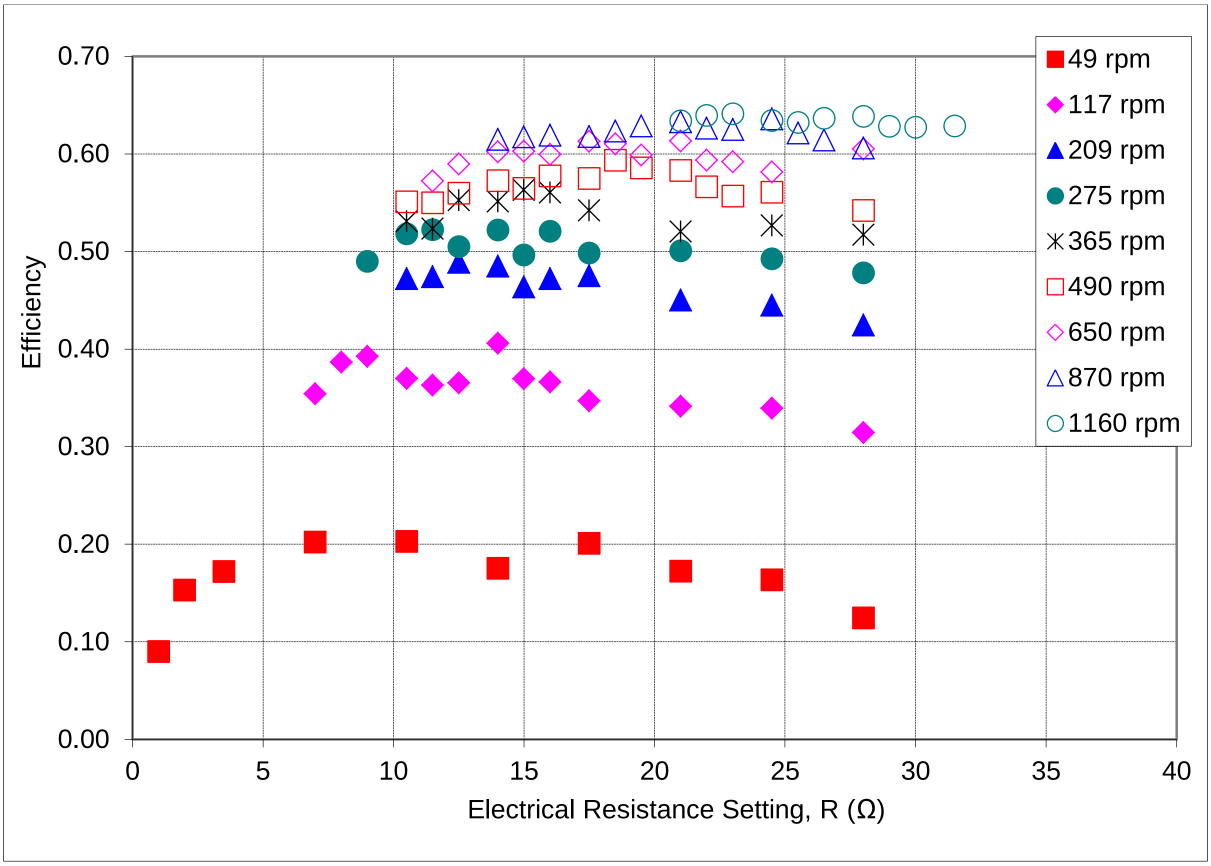


Figure 9: Variation of efficiency of DC-540 alternator

Efficiency variation of DC-540 alternator is shown in figure 9. Incorporating this efficiency, final power output from savonius turbine after connecting alternator is shown in table 5.

Wind speed (m/s)	Turbine RPM (min^{-1})	Alternator RPM (min^{-1})	Power output (watt)
3.4 – 3.7	58	0	0
4.3 – 4.6	69.58	117	3.01
4.9 – 5.1	75	117	4.41
5.6 – 5.8	72.14	117	4.70
6.3 – 6.6	87.60	209	11.81
6.8 – 7.0	85.80	209	13.09
7.2 – 7.5	78.70	275	14.85

Table 5: Final power output from the alternator DC-540

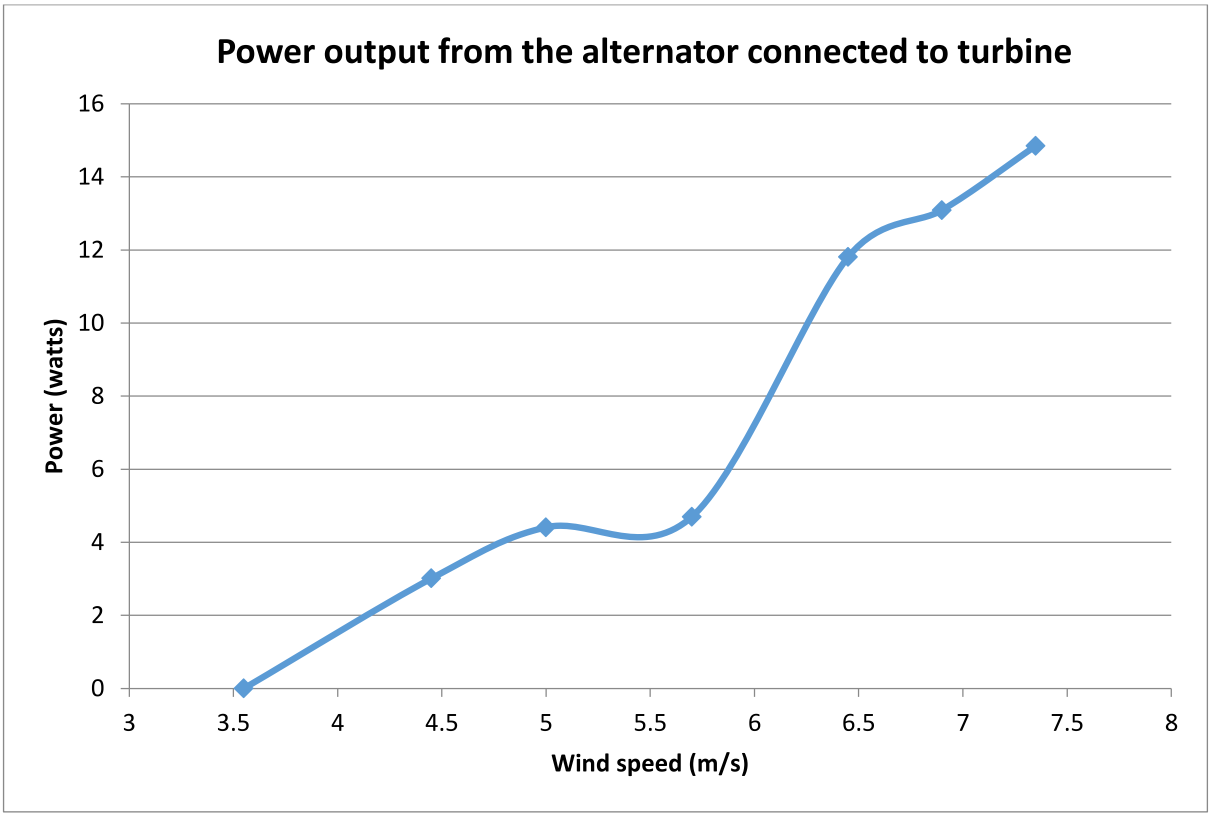


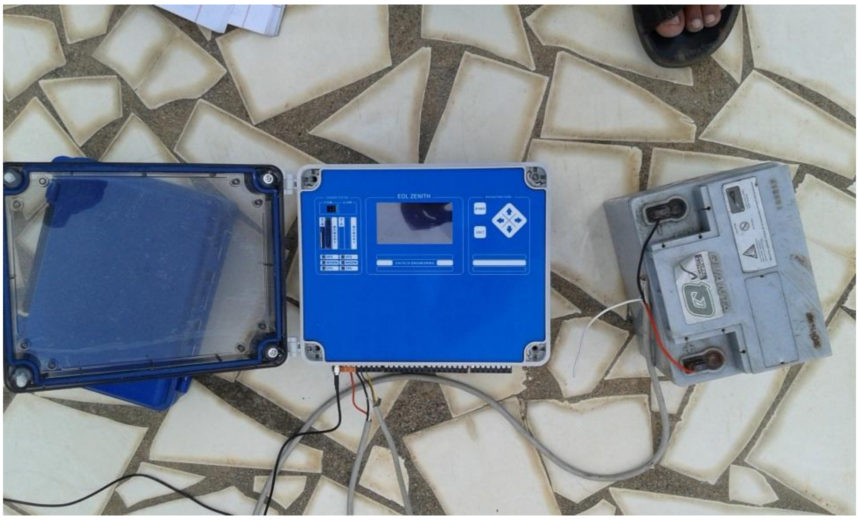
Figure 10: Final power output from the alternator DC-540 which is connected to savonius turbine

Power output after connecting alternator to wind turbine is as shown above. In this, efficiency variation of alternator is taken into consideration. From figure 9, it is clear that as the RPM of alternator increases, its efficiency increases and eventually increases the final power output. It is taken into consideration that as the RPM of turbine increases, gearbox changes alternator PRM to the next step.

In this problem there are three steps of alternator RPM involved: 117, 209 & 275. According to change in wind speed, gearbox should change the speed of alternator shaft in the above steps. From figure 10 and calculation of starting torque, cut in speed of savonius turbine is 4 m/s.

Appendix

Picture 1: Experimental setup at NIWE, Pallikaranai Chennai



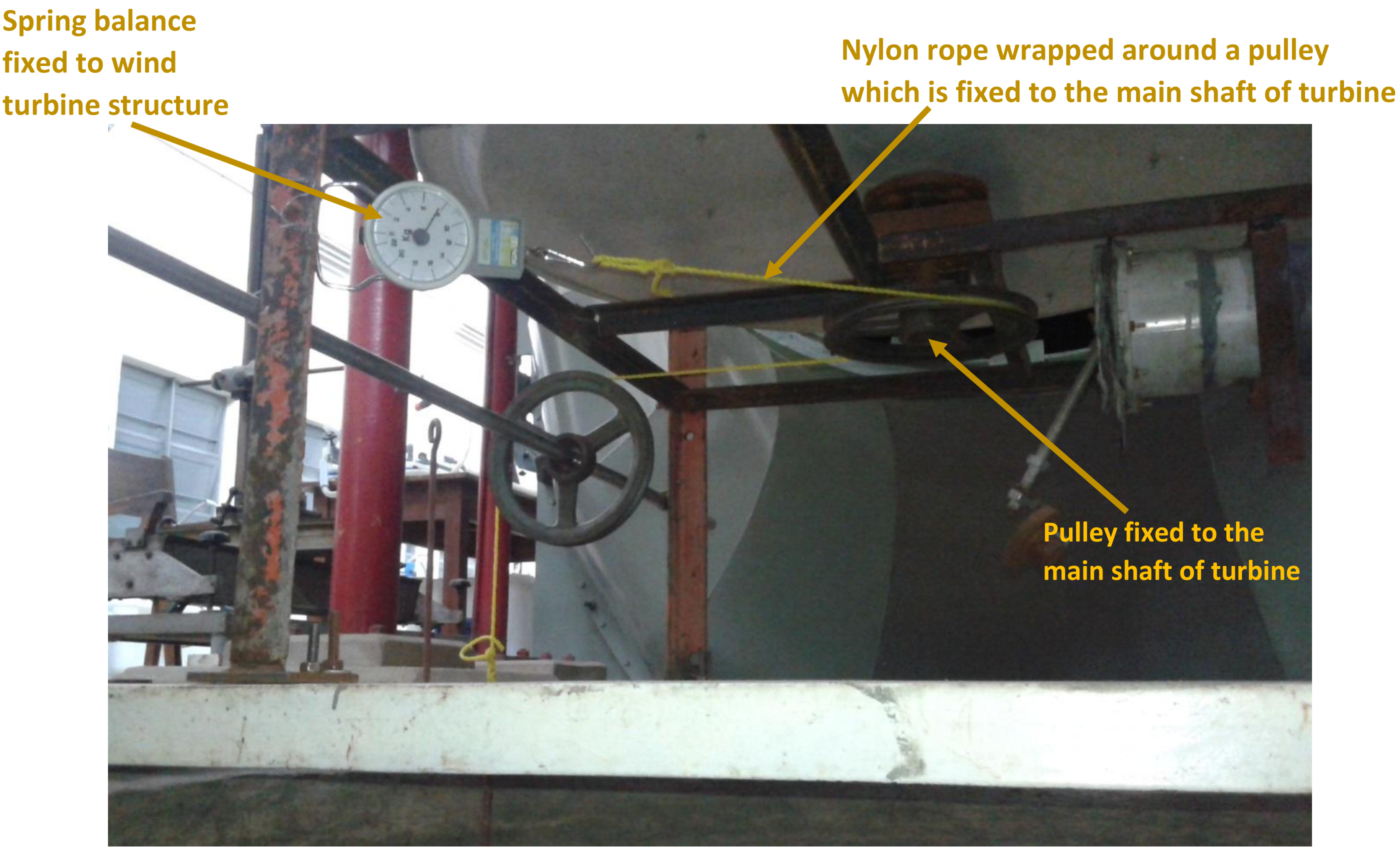
Picture 2(a): Anemometer storing device and battery

Picture 2(b): Anemometer sensor

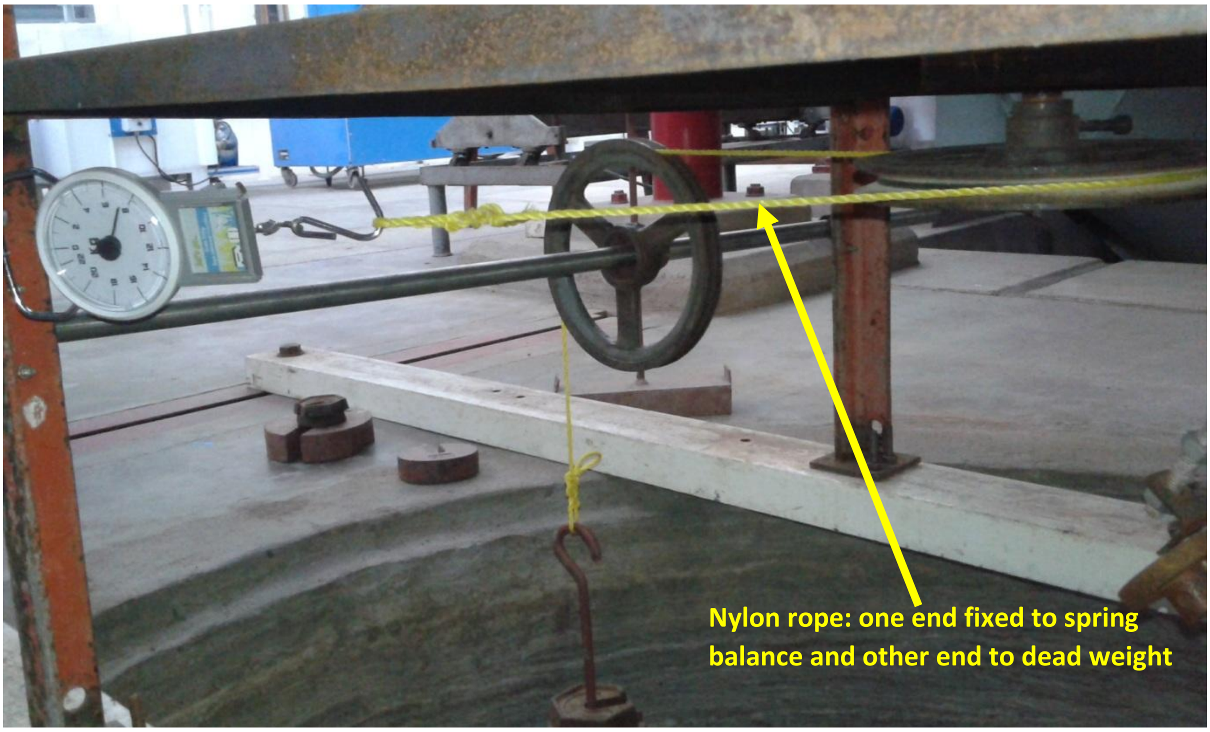
Picture 3: Experimental setup for measurement of starting torque

Picture 4: Wind tunnel and savonius turbine

Picture 5: Wind speed measurement by anemometer



Picture 6(a) Experimental setup for measurement of power output



Picture 6(b) Experimental setup for measurement of power output