Wind Tunnel Assessment of Small Direct Drive Wind Turbines with Permanent Magnets Synchronous Generators

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Abstract

Most of the small wind turbines for battery charging application are direct drive type with permanent magnets synchronous generators. A major problem in designing small direct drive wind turbines is the matching between the power curves of turbine and generator. The maximum power is extracted out from wind and fed into the load only if it is a match between the power curves of turbine rotor and generator. The assessment of the main components performances which contribute to the conversion process, namely turbine and generator, is made in wind tunnel. The experiments described below were carried out on wind turbines with carefully studied blade profile and permanent magnets synchronous generator, designed using a dedicated procedure. The paper describes the experimental layout and the results of the wind tunnel tests of two wind turbines, 250W and 1kW, designed for battery charging. The work has two objectives: measurement of the power curve of the turbine and the performances of the turbine-generator assembly with the load and the verification of the design method for maximum power delivered to the load.

Keywords

Wind turbine, synchronous generators, wind tunnel, power curve, electric energy

1. Scope of the work

Wind turbine design has two major components, turbine and generator. Those two components should be designed together for having the optimum overall performances of the wind system. In many cases, the mismatch between the turbine and generator can lead to poor results. In the previous work [1] it is the design method for maximum conversion efficiency of a turbine for delivering the maximum power to a load, battery, in the case of a stand alone wind system. The method gives the guidance for trimming the turbine to the load, by using the design method of the generator.

The experiments were carried in a wind tunnel on a 250W multi blade turbine and 1kW turbine, using two sets of blades with two synchronous generators. The 1kW wind turbine have been measured at selected angles of attack of the tip of the blades: 2^o, 5^o, 7^o, 10^o, 12^o, 15^o and 20^o. The smallest wind turbine tested, 250W, is multi-blade type, which has the angle of the tip of the blades fixed, at 7^o.

2. Experimental layout

The experiments were carried out in the Subsonic Wind Tunnel of I.N.C.A.S[1] - a close circuit wind tunnel, with maximum 160m/s wind speed in the smallest section, which has a cross-section of 2.5 x 2.0 m. The fan with 12 blades and 3.5 m diameter is driven by a 1200 kW variable speed DC motor driving. The wind tunnel used is normally designed for testing mock ups of airplanes and other specific aerodynamic measurements.
In the widest section of the wind tunnel, the airspeed is 1/10 of the airspeed in the main chamber, see Fig. 1. Therefore, the airspeed in the section where the test has been carried out is adjustable from zero to 16m/s. These wind speeds are in the normal operating range of the wind turbine.
Before installing the turbines, the airspeed in the cross section was checked and the uniformity is below 5%, all over the section of the testing chamber. Thus, the wind turbine can be measured with sufficient accuracy.

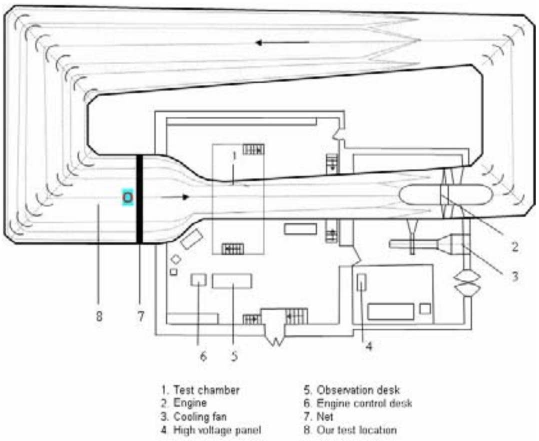

Fig. 1-Wind tunnel

The turbine and the generator are mounted on a metallic mast with the hub of the turbine in the centre of the cross

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[1] National Institute for Aerospace Research "Elie Carafoli"-Bucharest

section of the wind tunnel (Fig. 2). The section of the chamber in wind tunnel selected for tests is octagonal, where a 10m diameter rotor can be installed. Practically, for avoiding wall effect, the maximum wind turbine which is going to be tested is 6,2m.

In front of the wind turbine is an anemometer for checking the wind speed readings made with Pitot tubes.

The images in Fig. 2 show the mast, the command room, and the close circuit TV set, for having the images of the turbine in the test chamber.

Fig. 2-Experimental setup

The tested wind turbines are direct drive type with permanent magnets synchronous generators.

In Fig. 3 is the schematic diagram of the data acquisition system with the position of the sensors and transducers. Between the turbine and sensors it is a compact torque and axial force transducer, see Fig.4. The permanent magnet generator has two roles in the experiments: as adjustable break for measuring the turbine characteristics and generator for measuring the performances of the whole wind turbine (see Fig. 4).

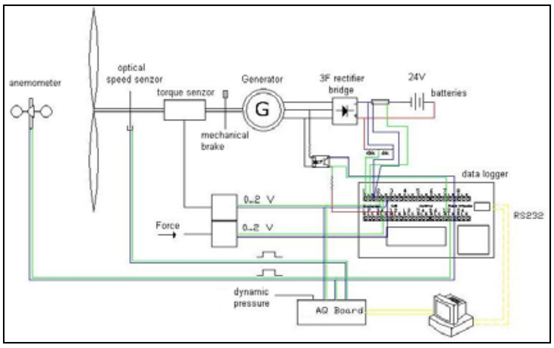

Fig. 3-Positioning the sensors and transducers

One data logger, Campbell 21X, records the experimental data averaged over 30 seconds: wind speed, torque, axial force, rotational speed, voltage and current at the output of the diode bridge of the generator.

The wind speed is measured by Pitot tubes in the main chamber and by an anemometer in the front of the wind turbine, for checking whether the presence of the turbine disturbs the airflow in the test chamber. The turning speed of the turbine is measured via an optical sensor and by measuring the frequency of the voltage at the output of the generator. Both measurements should coincide.

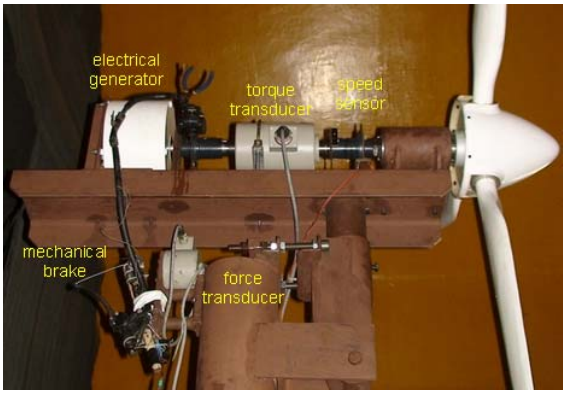

Fig. 4-Details of the experimental platform

The output power of the wind turbine is computed with the current and voltage on the DC side of the output circuit.

3. Measurement method

When measuring the power curve of the turbine, the generator acts as variable torque break. The torque is set by the load resistor at the output of the generator, see Fig.5.

The power curve of the turbine $P_t(n)$ is measured by setting a wind speed and the variable power at the shaft of the wind turbine is set by adjusting the value of the load/power resistor on the DC side of the circuit.

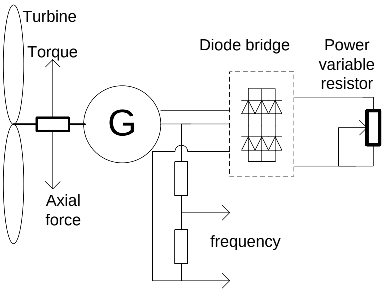

Fig. 5-Electrical layout for the measurement of power curve of the rotor

The shaft power of the turbine is:

$$P_t(n) = 2 \cdot \pi \cdot n \cdot M \qquad \text{eq. 1}$$

Where:

P_t -power at turbine shaft [W];
n-rotational speed[s^{-1}];
M-torque [Nm].

The torque can be varied in a wide range since the rare earth permanent magnets synchronous generator has strong field and provides high torques at high output power for short periods of time. In the arrangement, the cooling of the generator is very efficient and the generator supports high currents.

For measurement of 1kW turbine, firstly the angle at the blade tip is set, and then the wind speed is set to a desired value. All the measurements of power curves have been measured at constant airspeed. At a given wind speed, the power resistor is varied from high values, meaning low braking power, to lower values, meaning increased braking power. The output frequency of the generator gives the rotational speed, computed by:

$$n = f / p \qquad \text{eq. 2}$$

Where:

f-voltage frequency[s^{-1}]
p-number of pole pairs of the generator.

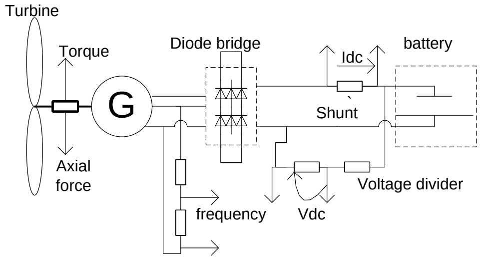

Fig. 6-Electrical layout for measurement of power curve of the wind turbine

For the measurements of output capabilities of the wind turbine, the electrical layout is in Fig. 6.
In the measurements of the power curve of the wind turbine, the load is a double diode bridge and a battery. The arrangement is quite similar to the normal operation of the stand-alone wind system in which the battery storage is the load.
The power curve of the wind turbine is *P(v)* and is computed via:

$$P(v) = Ib \cdot Ub \qquad \text{eq. 3}$$

Where:

P-power of the wind turbine [W];
v-wind speed [m/s];
Ib-battery current [A];
Ub-battery voltage [V].

Measurements of the power curves for the wind turbines have been carried out at selected angles of attack at the tip of the blades: 2°, 5°, 7°, 10°, 12°, 15° and 20°. The smallest wind turbine tested, 250W, is multi-blade type, and the angle of the blades is fixed, 7°. The angle of attack of the blades is set manually.

4. Results of the experiments

4.1. Measurements on 250W wind turbine

The first turbine tested is 8 blades, for low wind speeds, designed and fabricated by the authors. The generator is a 16 poles rare earth permanent magnets synchronous generator. The diameter of the turbine is 1,2 m and the blades twist is 20°, see Fig 7. The design method for maximizing the output power is, also, according to the method described in previous work [1].

The resulted mechanical power curve of the rotor is in Fig.8.
The maximum power of the rotor is at 200turn/min and 8,5m/s wind speed. The turbine is designed for low speed winds. In Fig.9 is the power curve of 250W wind turbine with battery load.

Fig 7.-250W wind turbine

In the figure:

Pe-electric power, at the output;
Pm-mechanical power of the rotor.

The rated power of the turbine, where is the maximum efficiency, is at 250W, even though the mechanical power of the rotor can be much higher at higher wind speeds. The turbine is operating well at low wind speeds, in locations where high wind speeds are very rare. The mechanical input power curve for the generator is the line which is across the maximum vales of the family of curves at various wind speeds. The design of the rare earth permanent synchronous generator used this curve for maximum power transfer.

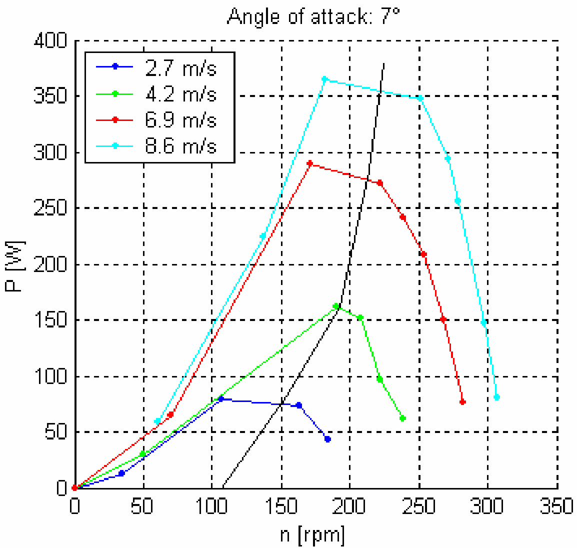

Fig. 8-Power curve of 250W rotor

4.2. Measurements on 1kW wind turbine

The second turbine is a 2,2m diameter turbine, a commercial one, that has been tested with the original generator and with a generator designed using the method for maximizing the power transfer from rotor to the load.

The profile of the blades is very much like NACA 2215 modified, with an approximately 18^0 twisting angle of the blades.

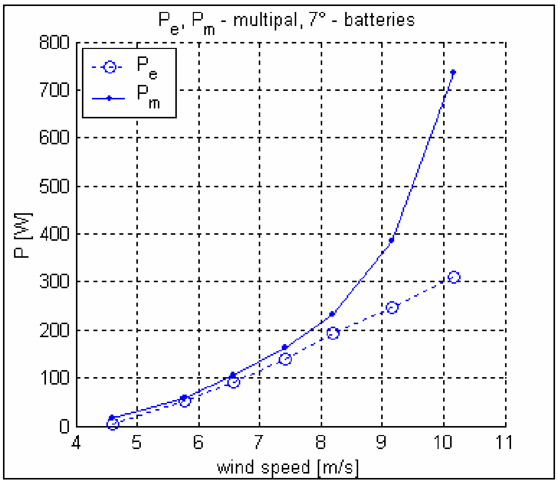

Fig. 9-Power curve of the 250W wind turbine

The commercial turbine selected for tests is designed also for battery charging applications. The rated voltage of the battery is 24V. For the tests, the battery capacity is 100Ah.

Fig.10-1kW wind turbine rotor on the testing platform

For better explaining the results, the mechanical characteristics are given separately, Fig.11 through 16. First, the power curve of the rotor is measured, at different blade tip angles. After determining the mechanical power curve of the rotor with the aid of the electrical layout in Fig 5., having the same blade tip angle, the electrical power is measured with the electrical layout in Fig. 6. The goal of the measurements of the mechanical power of the rotor is to determining the maximum power at a given airspeed, the value of the rotational speed and cut in speed which is the input mechanical characteristic of the permanent magnet electrical generator. Also, the cut in speed is a very important parameter for selecting the proper angle of attack.

At 5^{o} the turbine start to spin at 6m/s, but the mechanical power at the rotor shaft is 1400W.

The maximum power at 7^0 and 9,8m/s air speed is 1230W at 450 turn/min. The cut in speed is 4,5m/s.

At 10^{o} blade tip angle, the maximum power is 1000W at 430 turn/min and cut in speed 3,5 m/s.

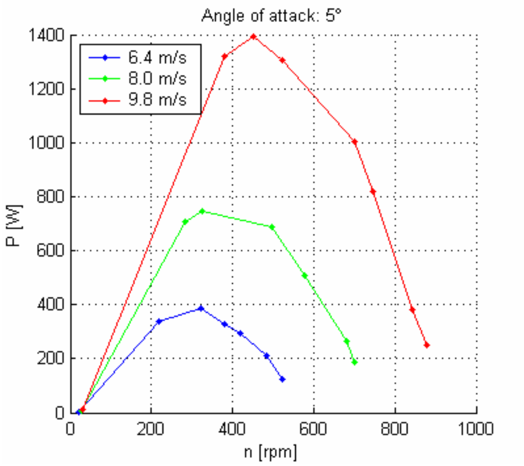

Fig.11- Mechanical power curve at 5^{o}

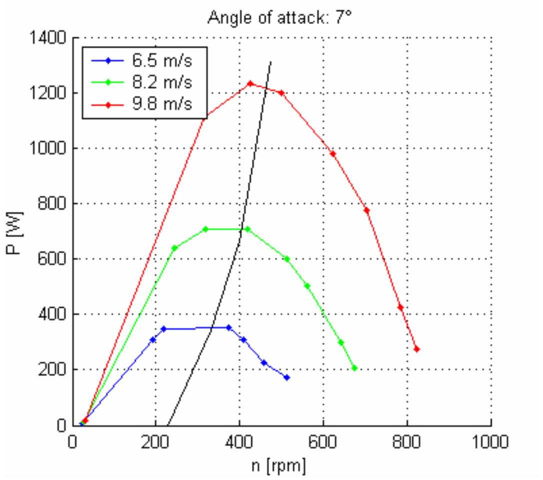

Fig..12- Mechanical power curve at 7^{o}

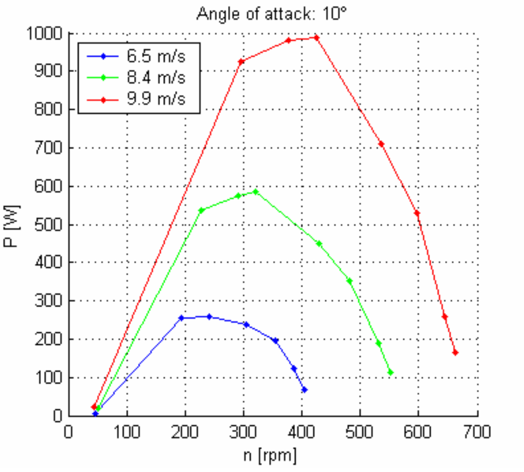

Fig.13-Mechanical power curve at 10^{o}

At 12^{o} angle, the maximum power at 10 m/s air speed, the maximum power is 900W, at 350 turns/min.

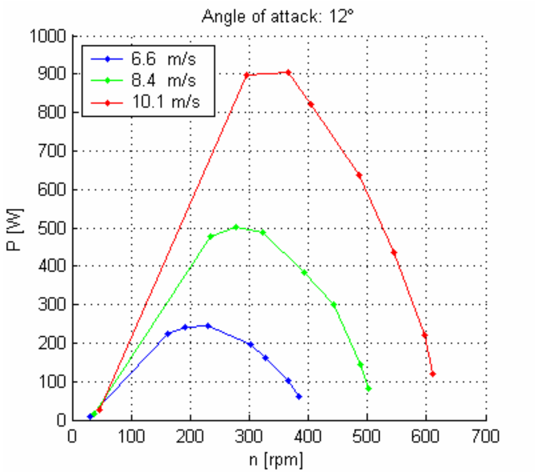

Fig.14-Mechanical power curve at 12°

Maximum power at 15° decreases at 700W and the corresponding turning speed at 330.

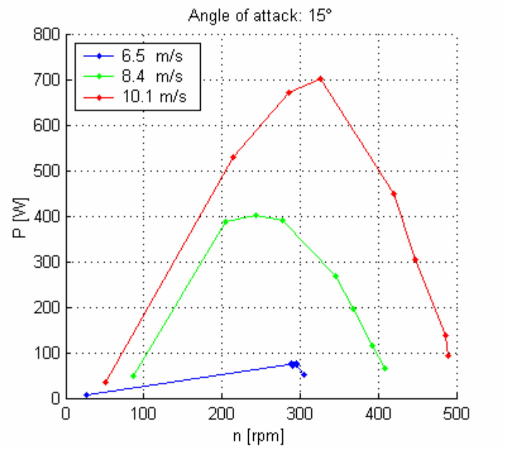

Fig.15-Mechanical power curve at 15°

At 20° blade tip angle, the power is very low, 475W. Therefore this angle cannot be considered for the wind turbine.

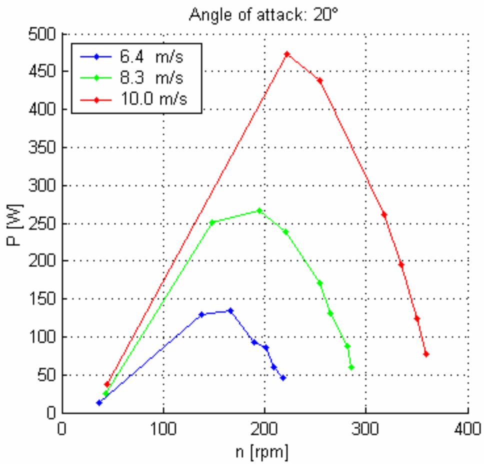

Fig.16- Mechanical power curve at 20°

There are very interesting conclusions:

1. The mechanical power of the rotor decreases with the increasing angle of attack, from 1400W at 5° to 700W at 15°;
2. The cut in speed decreases with the angle of attack, but not so much;
3. The rotational speed at maximum power decreases with the increasing angle of attack, from 440turns/min to 230turns/min.

Having those power curves, the conclusion is that the wind turbine should be adjusted to 7° angle of attack, for best performances: convenient cut in speed and high power output.

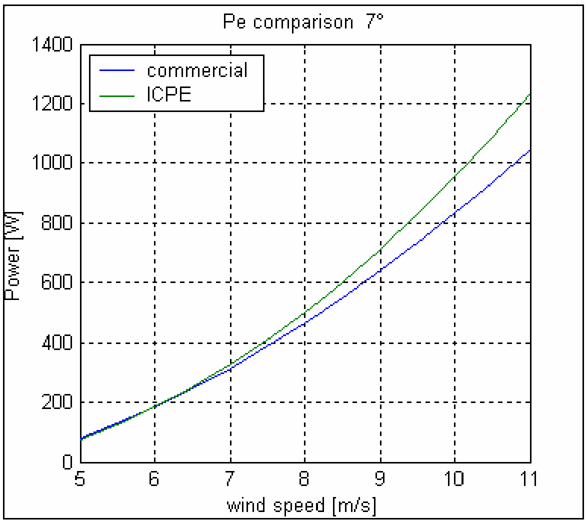

Fig.17-Comparison between generators

Based on the experiments, the wind turbine designer can have now the input for designing the generator for maximum power transfer for this turbine:

- Input power 1200W;
- The rated rotational speed 430 turns/min.
- The rotational speed when the generator starts injecting power in battery is 200-220(see Fig.12).

These data and the input mechanical power curve(solid black line) in Fig. 12 were used for designing and then manufacturing a rare earth permanent magnets synchronous generator, for maximum power transfer. This generator has been tested with the rotor of the commercial turbine.

5. Comparison between generators

One of the goals of the experiments is to validate the design method proposed for maximum power transfer, described in previous work [1] and a good design made for a commercial wind turbine.

In Fig.17 is the comparison of the measured output of the same rotor with two generators: the commercial and the generator designed by authors for the same rotor, for maximum power transfer with. The results of the measurement are in Fig.17, were green curve is for the design of the authors and blue curve for the commercial one.

The generator for the commercial turbine is a good design. The commercial wind turbine can deliver 820W at 10m/s wind speed. But using the method for maximizing the power transfer, the power can be increased to 980W, which means almost 20% extra power. The input mechanical power for designing the generator is the line drawn on Fig.12. This line is through the points of maximum of the power curves *Pt(n)*, with the parameter *v*, airspeed.

6. Conclusions

The proposed design procedure for maximizing power transfer from wind to the load gives the expected results. The power of a wind turbine can be increased by simply adjusting the geometry of the generator.

For designing a good wind turbine, the designer should compute first the family of mechanical power curves for the turbine, having a given blade profile, chord, twist angle and cut in wind speed. The angle of attack, at the tip of the blade should be selected for a convenient start torque at low wind speed. Then, the mechanical input power curve of the generator should be used for designing the generator.

The final test of the wind turbine should be in the wind tunnel. If it is necessary, for achieving the maximum power, the windings of the generator should be adjusted for having optimum power transfer.

The following tunnel test will be on multi-blade 2kW turbine and 7kW one with 6,2 m diameter.

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