Measurements performed on a Chinese axial flux generator of Hefei Top Grand model TGET165-0.15kW-500R for a 12 V battery load

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1 Introduction

The VIRYA-1.65 horizontal axis windmill is developed for manufacture in western countries as well as in developing countries. The VIRYA-1.65 has a 2-bladed stainless steel rotor and is meant for 12 V battery charging. It has an axial flux PM-generator of Chinese manufacture Hefei Top Grand model TGET165-0.15kW-500R. The design calculations of the VIRYA-1.65 rotor are given in report KD 593 (ref. 1). In chapter 6 of this report it is investigated, based on characteristics given by the manufacturer, if this generator can be used in combination with the VIRYA-1.65 rotor and safety system. It seems possible but certainty can only be gained if a generator is bought and measured for a 12 V battery load.

Information about the generator can be found on the website of Hefei Top Grand: www.china-topgrand.com where one can also find a dimensioned drawing. There are more Chinese suppliers of similar generators but Hefei Top Grand was chosen because they offer the generator for a reasonable price and because the contact person (Grace) gave quick answers to my questions in good English.

The generator is an axial flux generator with a rotating housing and a shaft which is clamped in the head frame of the windmill. The windmill rotor is bolted to the front housing by six M8 bolts. The generator supplies a 3-phase alternating current. For battery charging one needs a DC current and this is gained by an external 3-phase rectifier. Rectification of a 3-phase current is explained in report KD 340 (ref. 2).

The generator price off factory is US$ 150. The shipping costs by TNT are US$ 140 so totally US$ 290 or € 262.02. The transfer provision was € 21. TNT also has sent me an invoice for VAT and customs costs of € 43.16 so the total costs to get one generator at my office for testing are € 326.18. The generator is supplied without an oil seal on the shaft. This is not acceptable if the generator is used with the shaft horizontally because water will entre the bearings. So an oil seal has been ordered. The price of the oil seal including VAT and transport is € 7.25 which makes the total costs € 333.43. These costs are rather high but the price will go down a lot if larger quantities are ordered. The measurements were performed without the oil seal mounted.

2 Description of the test rig (see photo’s)

To build the test rig at minimum costs, some existing components were used and some components were bought second hand. To be able the check the matching with the rotor and to determine the efficiency, it is required to measure the mechanical power P_{mech} which is needed to drive the generator and to measure the electrical power P_{el} which is supplied by the generator. For the determination of the mechanical power one has to measure the torque Q and the rotational speed n. For the determination of the electrical power after the rectifier one has to measure the DC voltage U_{DC} and the DC current I_{DC}. This was done with a digital volt meter and a digital ampere meter with a maximum measuring range of 10 A.

The generator has to be measured for a range of rotational speeds and therefore it must be possible to vary the rotational speed of the driving motor. Variation of the rotational speed is easy for a DC motor and therefore a second hand permanent magnet DC motor was bought which can supply a mechanical power of 650 W at a rotational speed of 3000 rpm and at a DC voltage of 24 V. The nominal torque level is 2.07 Nm at 3000 rpm and it is expected that this torque can also be supplied at lower rotational speeds. However, a torque of about 2 Nm is too low to load the generator strong enough. Therefore a reducing chain transmission is made with gear wheels with 13 and 47 teeth and so with a gear ratio of 47 / 13 = 3.615. The slow shaft was created by using an existing asynchronous motor but this motor isn’t connected electrically. The DC motor and the asynchronous motor are bolted to the back side of a 6 mm steel plate which is clamped in a vice on a work bench. The gear wheels are new but come from old mopeds. The chain is also new and has 70 links. The steel sheet has slotted holes at the asynchronous motor to adjust the chain slack.

It appeared that both chain wheels have a small non concentricity and the chain slack therefore varies somewhat during rotation. This causes noise at high rotational speeds and a small fluctuation of the rotational speed, the torque, the voltage and the current. It was tried to read the average value as good as possible for the four corresponding meters. It would have been better to use a bigger motor which can supply the required torque for direct drive conditions but in this case the test rig would have been much more expensive as bigger permanent magnet DC motors were not available second hand.

The hub on the slow shaft has a flange at the front side with six 8.5 mm holes at a pitch circle of 65 mm and the generator is bolted to this flange by six bolts M8 * 16 mm. So the generator shaft is pointing forwards. The generator shaft has two 8.5 mm holes in the middle and a 450 mm long, M8 threaded rod is pushed through these holes and fixed with two M8 nuts. A nylon rope is connected to the threaded rod at a radius $r = 0.2$ m and a mass of 4.7 kg is connected to the end of the rope. The threaded rod itself is balanced by some nuts at the opposite side. The weight is put on an accurate balance which can be read for every 5 gram and for which the pointer makes five revolutions for 5 kg. The pointer of the balance is at $m_0 = 4.700$ kg if the test rig isn't running. If the test rig is running, a certain torque gives a pulling force F in the rope and the pointer of the balance moves backwards because of this force. The reduction of the measured mass is called Δm. It is valid that:

$$\Delta m = m_0 - m_{pointer} \quad \text{(kg)} \tag{1}$$

$$F = \Delta m * g \quad \text{(N)} \quad (g = 9.81 \text{ m/s}^2) \tag{2}$$

$$Q = F * r \quad \text{(Nm)} \quad (r = 0.2 \text{ m}) \tag{3}$$

$$P_{mech} = Q * \pi * n / 30 \quad \text{(W)} \tag{4}$$

$$P_{el} = U_{DC} * I_{DC} \quad \text{(W)} \tag{5}$$

$$R_{load} = U_{DC} / I_{DC} \quad (\Omega) \tag{6}$$

$$\eta_{DC} = 100 * P_{el} / P_{mech} \quad (\%) \tag{7}$$

For battery charging, one needs a 3-phase rectifier but some energy is dissipated in this rectifier. The voltage drop over the rectifier depends on the current. It is low for the very low current which flows through the digital volt meter if the open voltage is measured. However, as soon as a substantial current is flowing, it increases strongly. As the DC voltage and the DC current are measured, the energy loss in the rectifier is incorporated in the generator efficiency η_{DC}. So the AC power which is produced by the generator is larger than de DC power. The voltage drop over the rectifier is assumed to be 1.4 V for a rectifier with silicon diodes if a substantial current is flowing. So the power loss in the rectifier $P_{rectifier}$ is given by:

$$P_{rectifier} = 1.4 * I \quad \text{(W)} \tag{8}$$

So the electrical AC power P_{elAC} which is really produced by the generator is given by:

$$P_{elAC} = P_{el} + P_{rectifier} \quad \text{(W)} \tag{9}$$

The AC efficiency η_{AC} is then given by:

$$\eta_{AC} = 100 * (P_{el} + P_{rectifier}) / P_{mech} \quad (\%) \tag{10}$$

For variation of the motor speed one needs a variable DC voltage and the power supply must be able to supply a rather large DC current. This is done as follows. A variable transformer or Variac was available which can supply an AC voltage in between 0 and 230 V at a maximum current of 5 A. This equipment has an adjustable fuse which was adjusted at 5 A. The fuse can also be used as a start-stop button. As a maximum of 5 A is too low for large motor torques, the Variac is connected to a welding transformer which reduces a voltage of 230 V to about 45 V. The AC current coming out of the welding transformer is then rectified by a heavy rectifier with six separate diodes. For rectification of a 1-phase current only four diodes are used. The (fluctuating) DC voltage gained from the rectifier is then connected to the DC motor. Control of the motor speed is easy by turning the hand wheel of the Variac.

The DC motor voltage is measured by an old analogue volt meter. This voltage is only made visible to get a fast impression of the rotational speed but it isn't used in the calculations. The rotational speed of the generator is measured accurately by a laser rpm meter. The front flange of the generator is covered with black tape and a white reflecting spot is glued on this black area. The laser beam is pointing in the direction of the white spot and the rotational speed is directly given in rpm.

The generator wasn't loaded with a real 12 V battery but with an available battery charge controller. The charging voltage of a real 12 V battery depends on the charging state of the battery, on the size of the battery and on the charging current. Normally it varies in between 12 V and 14 V if the battery is not completely full. To protect a full battery against over charging, a battery charge controller has to be used which limits the maximum charging voltage up to maximal 14 V for a 12 V lead acid battery.

The battery charge controller consist of a dump load and a voltage controller. De dump load consist of two transistors and two 100 W resistors mounted on a heavy heat sink. The voltage controller contains an OpAmp and two potentiometers. One potentiometer is used to adjust the voltage at which the OpAmp start conducting. This potentiometer was adjusted at 13 V. The amplification factor can be adjusted with the other potentiometer. This potentiometer was adjusted such that the voltage was about 13.9 V for a current of 10 A. So with this adjustment, the measured voltages are close to what would have been measured for a real battery.

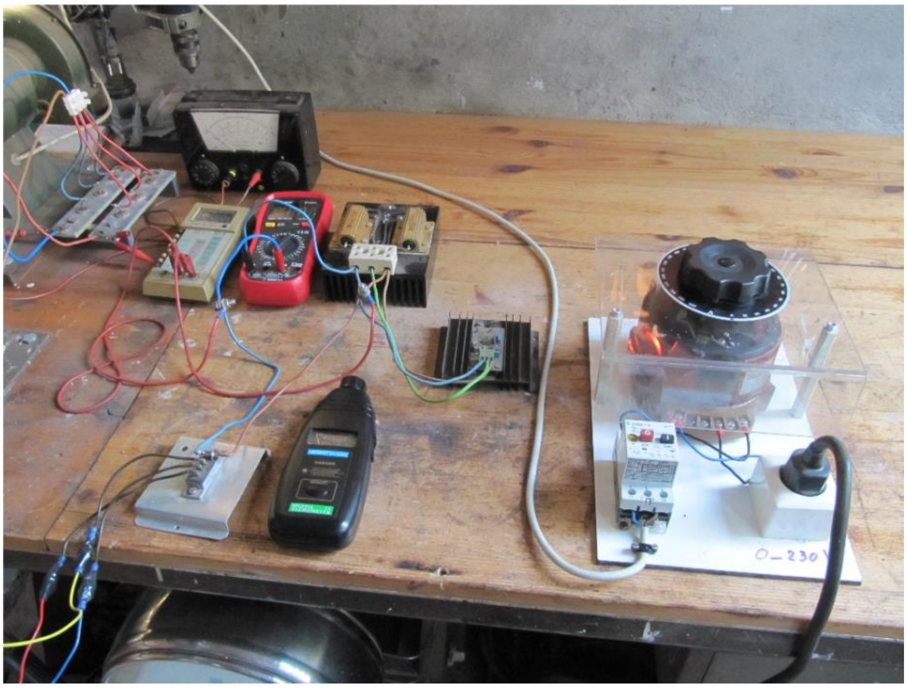

Photo 1

On photo 1 you see from back to front and from left to right: Analogue volt meter for motor voltage, rectifier with separate diodes for motor current, digital volt meter, digital ampere meter, dump load, voltage controller, 3-phase rectifier for generator current, laser rpm meter, Variac with adjustable fuse and black cable to welding transformer.

Photo 2

On photo 2 you see the steel sheet in the vice with at the left side the DC motor with small chain wheel and on the right side the asynchronous motor with the big chain wheel. At the slow shaft the generator is mounted with the threaded rod lever connected to the shaft. On the floor at the left side you see the welding transformer and on the right side the balance with a 4.7 kg mass on it connected to the lever at r = 0.2 m by a nylon rope.

3 Description of the measurements

The generator was measured for ten different rotational speeds connected to the battery charge controller. For lower rotational speeds, the voltage was lower than 13 V and so no current was supplied. The measured values are given in table 1.

n (rpm)	$m_{pointer}$ (kg)	F (N)	Q (Nm)	P_{mech} (W)	U_{DC} (V)	I_{DC} (A)	P_{el} (W)	R_{load} (Ω)	η_{DC} (%)	$P_{rectifier}$ (W)	P_{elAC} (W)	η_{AC} (%)
0	4.700											
85	4.687	0.128	0.026	0.23	2.90	0	0		0	0	0	0
135	4.680	0.196	0.039	0.55	5.30	0	0		0	0	0	0
206	4.672	0.275	0.055	1.19	8.30	0	0		0	0	0	0
261	4.668	0.314	0.063	1.72	10.50	0	0		0	0	0	0
321	4.660	0.392	0.078	2.62	13.03	0.01	0.13	1303	5.0	0.01	0.14	5.3
361	4.390	3.041	0.608	22.98	13.18	1.29	15.71	10.22	68.4	1.81	17.52	76.2
406	3.970	7.161	1.432	60.88	13.30	3.25	43.23	4.09	71.0	4.55	47.78	78.5
471	3.320	13.538	2.708	133.57	13.50	6.26	84.51	2.16	63.3	8.76	93.27	69.8
512	2.975	16.922	3.384	181.44	13.64	7.92	108.03	1.72	59.5	11.09	119.12	65.7
563	2.540	21.190	4.238	249.86	13.86	10.00	138.60	1.39	55.5	14.00	152.60	61.1

table 1 Measurements performed on axial flux PM-generator model TGET165-0.15kW-500R

Measured are: n, $m_{pointer}$, U_{DC} and I_{DC}. Using formulas 1 – 10 and r = 0.2 m, F, Q, P_{mech}, P_{el}, R_{load}, η_{DC}, $P_{rectifier}$, P_{elAC} and η_{AC} are calculated. The calculated values are also given in table 1.

The Q-n curve is given in figure 1.
The U_{DC}-n curve is given in figure 2.
The I_{DC}-n curve is given in figure 3.
The R_{load}-n curve is given in figure 4.
The P_{mech}-n and the P_{el}-n curves are given in figure 5.
The P_{elAC}-n curve is given in figure 6.
The η_{DC} and the η_{AC} curves are given in figure 7.

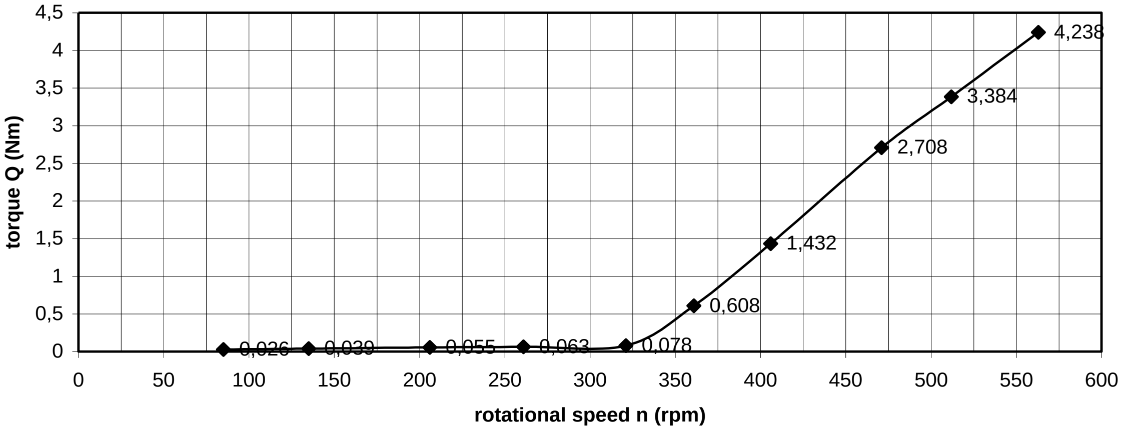

Fig. 1 Q-n curve

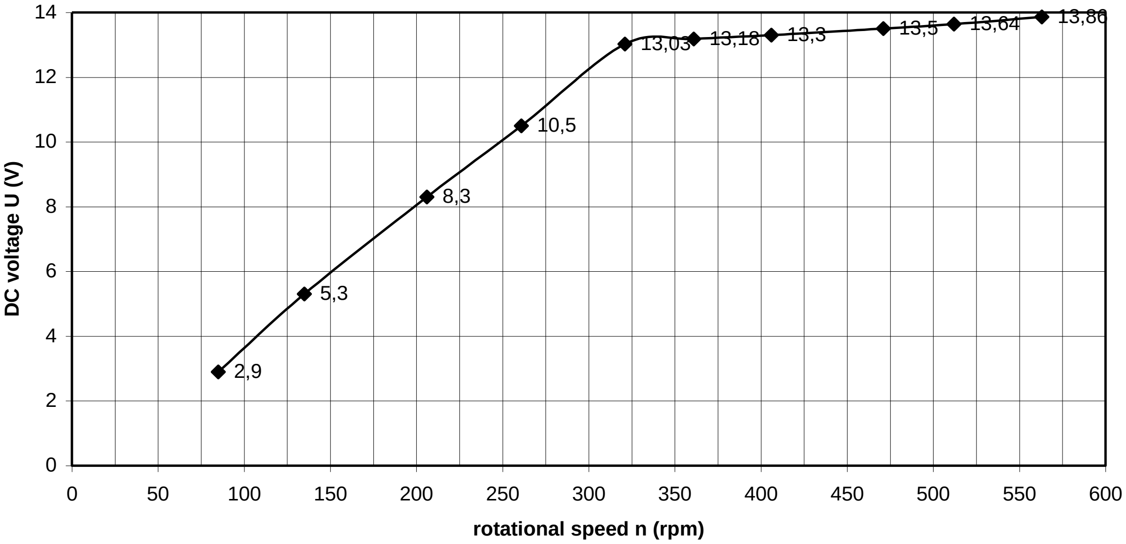

Fig. 2 U_{DC}-n curve

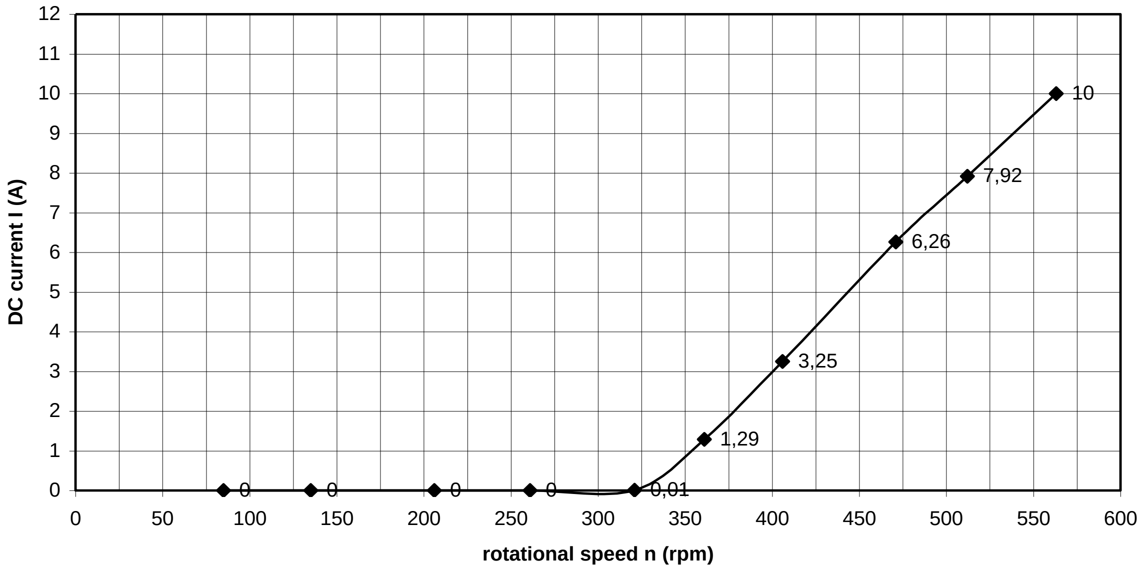

Fig. 3 I_{DC}-n curve

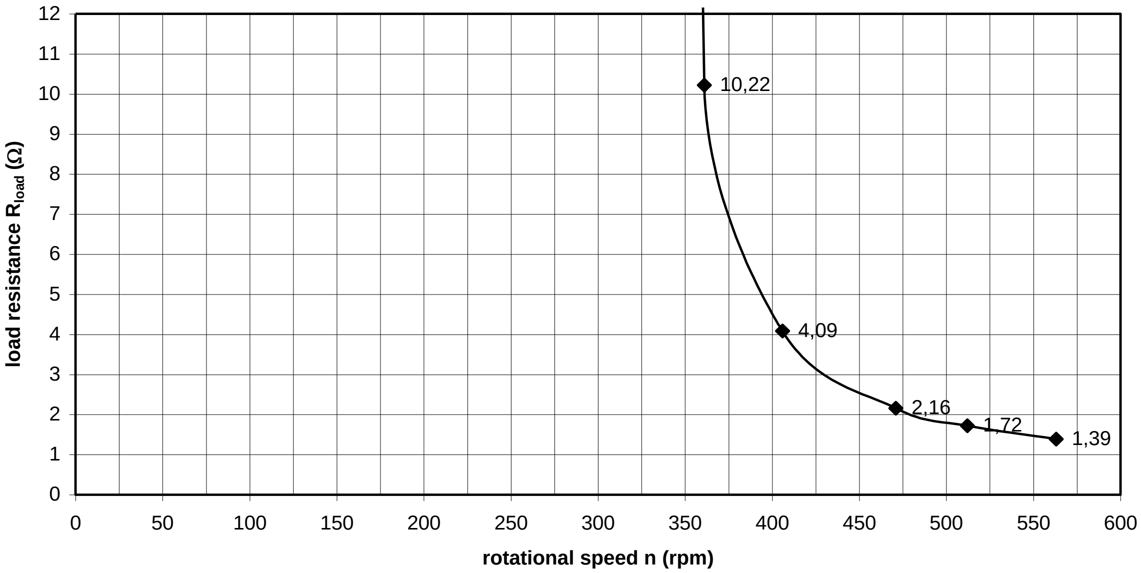

Fig. 4 R_{load}-n curve

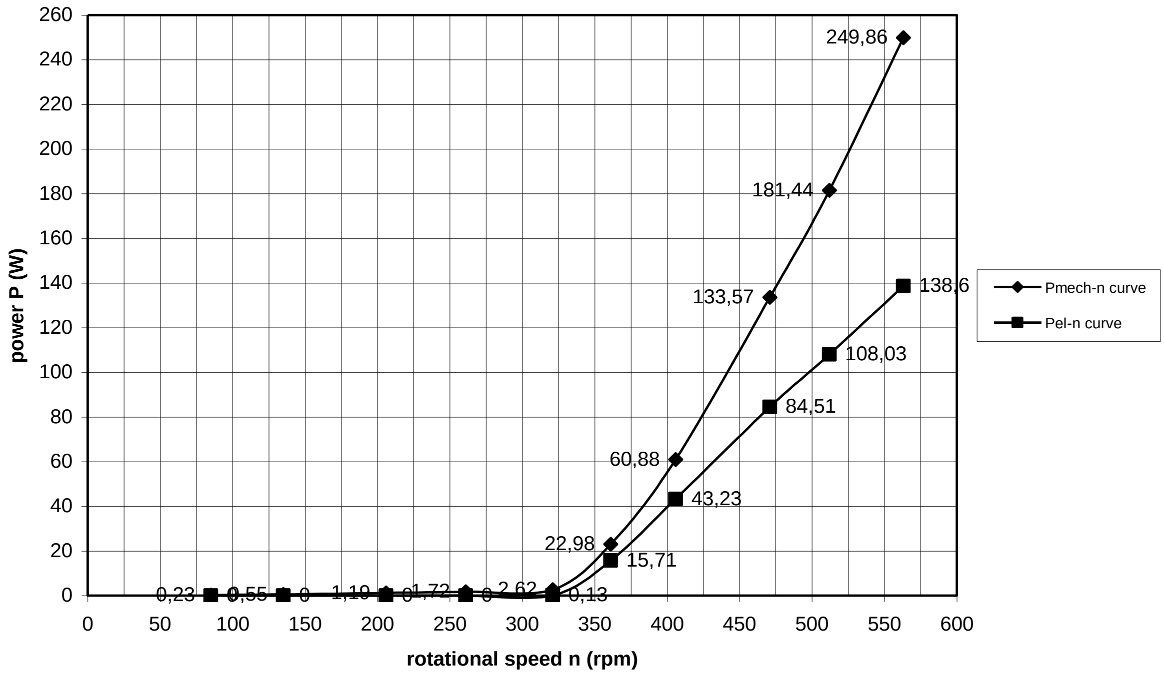

Fig. 5 P_{mech}-n and P_{el}-n curves

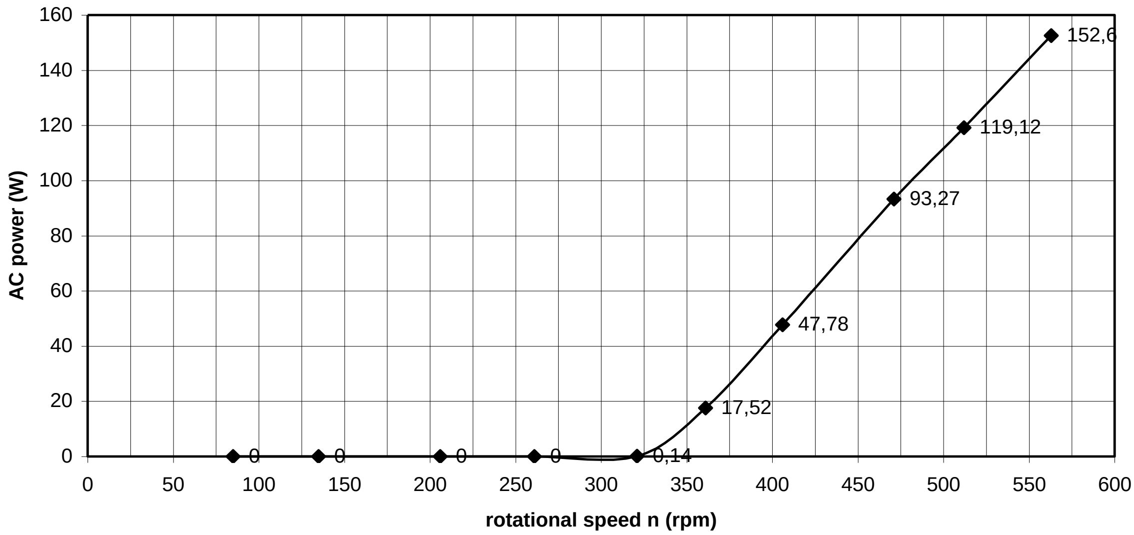

Fig. 6 P_{elAC}-n curve

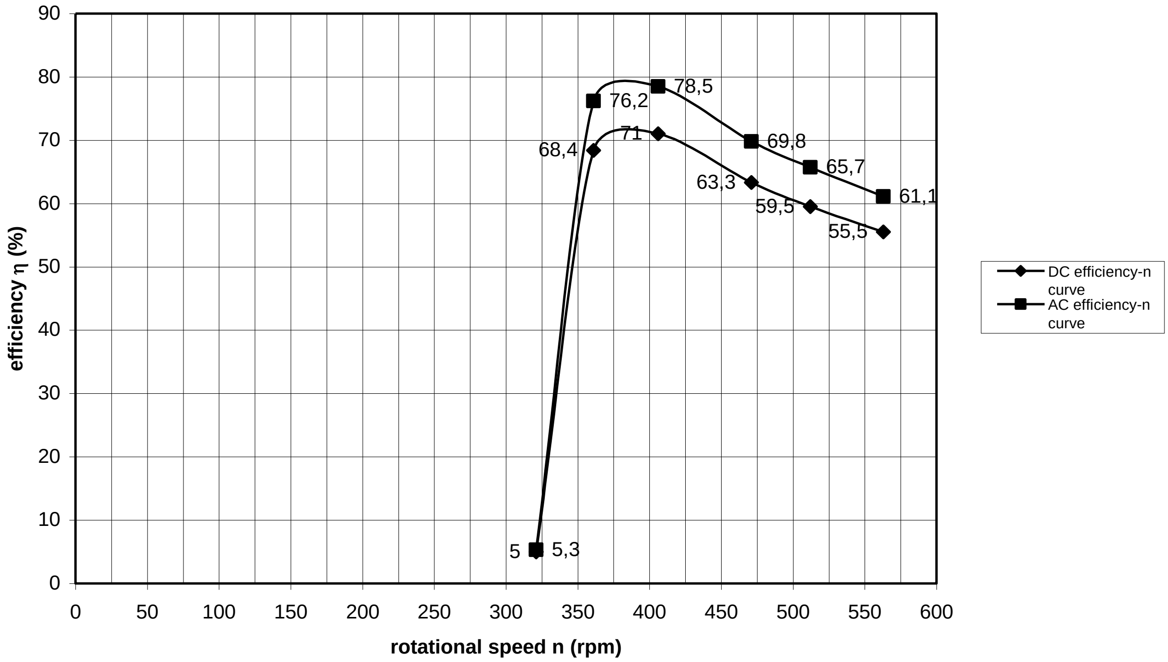

Fig. 7 η_{DC}-n and η_{AC}-n curves

4 Discussion of the results

In figure 2 it can be seen that the unloaded U_{DC}-n curve is about a straight line. It doesn't goes through the origin but it goes about through the point for n = 10 rpm on the x-axis. This must be caused by the voltage drop over the rectifier.

In figure 7 it can be seen that the maximum efficiency is gained about at n = 385 rpm. It is about 72 % for DC use and almost 80 % for AC use. This is rather high for a small generator. However, the efficiency decreases at larger powers because of the copper losses in the winding. In figure 4 it can be seen that R_{load} is about 5.7 Ω for n = 385 rpm. So R_{load} must be rather high to get a high efficiency. For a battery load, R_{load} becomes too low at high powers to get a high efficiency.

The manufacturer claims an efficiency of more than 85 %. This might be realistic for bigger generators and for a resistance load of the correct value but not for this very small generator.

The manufacturer claims a maximum power of 150 W at 500 rpm. In figure 4 it can be seen that a DC power of only about 100 W can be generated at 500 rpm if the load is a 12 V battery. In figure 6 it can be seen that the AC power is about 112 W at 500 rpm. In figure 4 it can be read that R_{load} is about 1.8 Ω for n = 500 rpm. It might be possible to generate more power if R_{load} is chosen larger. This results in a lower current but in a higher voltage and the final electrical power is higher if the increase in voltage is larger than the decrease in current. So the maximum AC power at n = 500 rpm may be larger than 112 W but 150 W seems much too optimistic.

I have performed some measurements with a resistance as load. I have many 100 W, 0.47 Ω resistors available from an old dump load. Four up to six these resistors were connected in series and resistances of 1.88 Ω, 2.35 Ω and 2.82 Ω were created this way. It was measured that P_{el} = 96.3 W for R_{load} = 1.88 Ω, that P_{el} = 83.6 W for R_{load} = 2.35 Ω and that P_{el} = 79. 6 W for R_{load} = 2.82 Ω. So just the opposite happens. The decrease of the current is larger than the increase of the voltage and the result is a decrease of the power. So the battery load gives about the maximum power at n = 500 rpm.

5 Checking of the matching of the generator with the VIRYA-1.65 rotor

The P-n curves and the optimum cubic line of the rotor for different wind speeds V are given in figure 4 of KD 593 (ref.1). This figure is copied as figure 8. For use of the generator in a horizontal axis windmill, an oil seal has to be mounted to prevent the entrance of water. This oil seal gives an increase of the sticking torque from 0.004 Nm up to 0.13 Nm. It is expected that the sticking torque is reduced to about 0.1 Nm when the oils seal has run in. This increase of the sticking torque can be neglected for the loaded measuring points. So the measured P_{mech}-n and P_{el}-n curves as given in figure 5 can be used and these curves (except for the unloaded points) are also copied in figure 8.

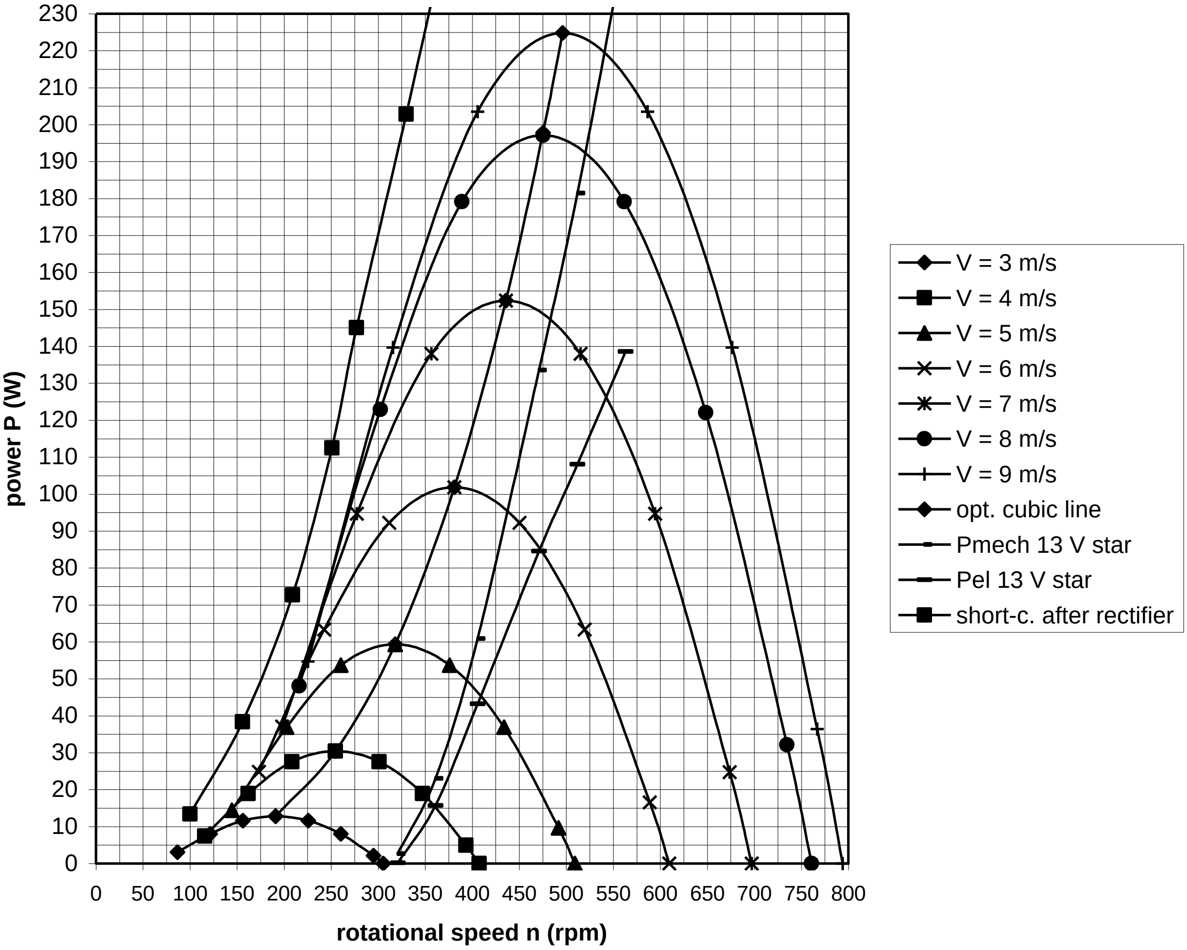

Fig. 8 P-n curves of the VIRYA-1.65 rotor and optimum cubic line, measured P_{mech}-n and P_{el}-n curves of the generator.

In figure 8 it can be seen that the matching is acceptable for wind speeds larger than 5 m/s because the P_{mech}-n curve of the generator is lying at only a small distance from the optimum cubic line. However, the matching is worse than for the estimated characteristics as given in figure 6 of KD 593.

The working point for a certain wind speed is lying at the point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for that wind speed. The corresponding electrical power is found by going down vertically until the P_{el}-n curve is crossed. The values of P_{el} found this way are given in the P_{el}-V curve of figure 9.

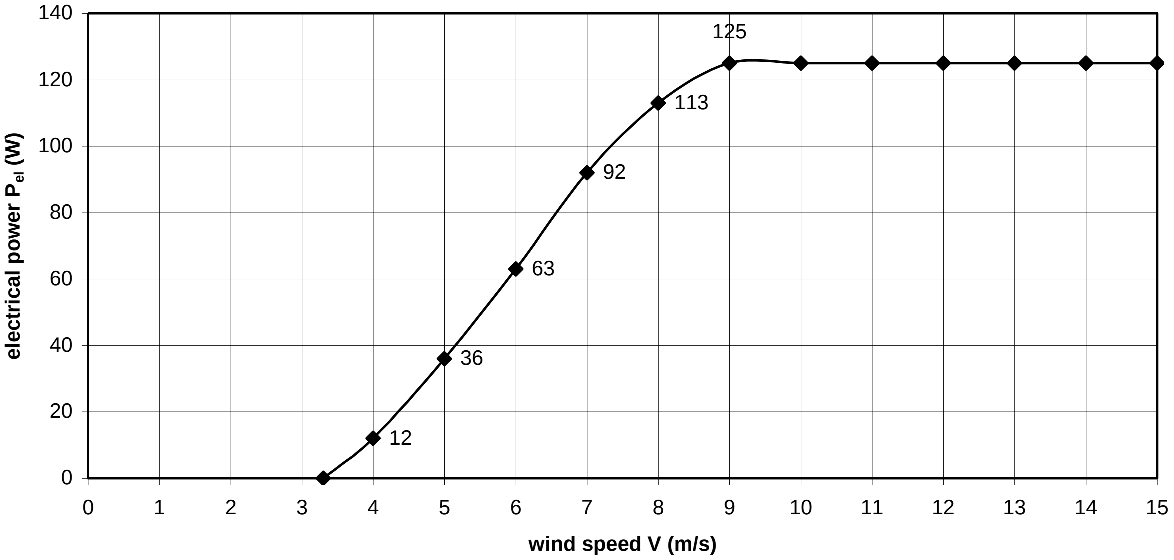

Fig. 9 P_{el}-V curve VIRYA-1.65 for 12 V battery charging

The P_{el}-V curve starts about at a wind speed of 3.3 m/s but if the open battery voltage is lower than 13 V, it will start at about 3 m/s which is acceptable. The maximum power is 125 W which isn't bad for a 12 V battery charging windmill with a rotor diameter of 1.65 m and a rated wind speed of 9 m/s. In figure 8 it can be read that the mechanical power is about 220 W for a wind speed of 9 m/s and a corresponding rotational speed of about 540 rpm. So the heat dissipation in the winding and the rectifier is 220 W – 125 W = 95 W. The current at 540 rpm is about 8.3 A (see figure 4). So the heat dissipation in the rectifier is 8.3 * 1.4 = 12 W. So the maximum heat dissipation in the winding of the generator is about 95 – 12 = 83 W. It has to be researched in practice if this is allowable.

The P_{el}-V curve is also worse than the estimated P_{el}-V curve as given in figure 7 of KD 593. But the characteristics seem to be good enough to really build and test the VIRYA-1.65 with this axial flux generator model TGET165-0.15kW-500R.

It might be possible to use the generator as a brake by making short-circuit. The generator has been measured for short-circuit after the rectifier for rotational speeds in between 100 rpm and 400 rpm. The P_{mech}-n curve for short-circuit has been determined in the same way as it was done for battery charging and this curve is also given in figure 8. The curve is lying left from the P-n curve of the rotor for V = 9 m/s (and higher) which means that the rotor is slowed down to a very low rotational speed for every wind speed if short-circuit is made.

6 Testing experiences with the VIRYA-1.65 rotor

The VIRYA-1.65 rotor was built according to drawing 1503-01. The design calculations of this rotor are given in report KD 593 (ref. 1). This rotor has a 7.14 % cambered airfoil, a constant chord and no blade twist. This rotor and the Chinese axial flux generator were tested on the head of the VIRYA-1.8 windmill during the period September 2015 up to March 2017. The 2 m tower pipe of the VIRYA-1.8 was connected to the 12 m tower of the VIRYA-4.2 resulting in a total tower height of almost 14 m and this height gave a good wind regime for testing. As the rotor diameter of the VIRYA-1.65 is smaller than that of the VIRYA-1.8, the rotor thrust and so the moment which turns the rotor out of the wind, will also be smaller. This is compensated by taking a smaller aluminium vane blade size 2 * 375 * 375 mm in stead of the stainless steel vane blade size 1 * 416 * 416 mm of the VIRYA-1.8. A 2 mm aluminium vane blade is also lighter per area than a 1 mm stainless steel vane blade and the rated wind speed is therefore reduced from about 11 m/s up to about 9 m/s.

Some components were made to connect the generator shaft to the VIRYA-1.8 generator bracket. The windmill wasn’t loaded with a real 12 V battery but with a battery charge controller which was adjusted at a voltage of about 13 V. The windmill run almost all the time and wasn't stopped during heavy storms. But it has been checked if the rotor could be stopped at high wind speeds by making short-circuit and this appeared to be possible.

There were no problems with the windmill or with the generator during the testing period. However, the rotor was rather noisy at high wind speeds. In figure 8 it can be seen that the real tip speed ratio at high wind speeds is about 6 and this is rather high for a rotor with 7.14 % cambered steel blades. Finally it was decided that the noise production is unacceptable if people are living close to the windmill and that no licences of the VIRYA-1.65 will be sold.

The noise problem can probably be solved by using wooden blades with a Gö 711-10% airfoil. Report KD 669 (ref. 3) gives the design calculations for such a rotor, called the VIRYA-1.75W (W from wood). This rotor has a design tip speed ratio of 7, a constant chord and no blade twist. The rotor drawings are given on drawing 1802-01 and 1802-02 given in KD 669. This rotor has not yet be built. So it is not proven that this rotor is silently enough.

7 Testing experiences with the VIRYA-1.46 rotor

Another way to reduce the noise level for a steel rotor with a 7.14 % cambered airfoil might be to use a smaller rotor diameter and a lower design tip speed ratio. A prototype of the VIRYA-1.46 rotor was available. This rotor has three blades, a diameter of 1.46 m and a design tip speed ratio of 4.5. The design calculations of the VIRYA-1.46 rotor are given in report KD 476 (ref. 4). This rotor was originally designed for an Indian project and would be used in combination with a 22-pole PM-generator made from an asynchronous motor frame size 71. However, the Indian project was cancelled and the complete original VIRYA-1.46 has never been built. Only a prototype of the rotor was built by me in 2011 and I thought that this rotor could be used to continue the tests with the axial flux generator.

As the rotor diameter of the VIRYA-1.46 is smaller than that of the VIRYA-1.65, the head geometry of the VIRYA-1.65 isn’t optimal for the VIRYA-1.46 but this is accepted and the head wasn’t changed. The original hub plate of the VIRYA-1.46 is provided with three 6.5 mm holes at a pitch circle of 40 mm for three M6 bolts with which the hub plate is connected to the hub. The axial flux generator has six M8 threaded holes at a pitch circle of 65 mm. Only three of these holes were used and three 8 mm holes were drilled in the flat part of the existing hub plate of the VIRYA-1.46. The hub plate was connected to the generator by three bolts M8 * 20 mm.

The drawing number of the VIRYA-1.46 rotor is 1204-01. A blade is made out of a stainless steel strip size 1.5 * 125 * 625 mm. For the prototype of the rotor, 2 mm stainless steel has been used because the blades were made from longer existing blades from another prototype. The three blades are connected to each other by a stainless steel hub plate made from stainless steel sheet with a thickness of 2.5 mm. The blade angle at the tip is 8° and at the root is 17°, so a blade is twisted 9°. So there is a large difference in between this blades and the non-twisted blades of the 2-bladed VIRYA-1.65 rotor. Blade twist might also result in reduction of the noise level as the blade isn’t stalling at the blade root.

The VIRYA-1.46 rotor was mounted in August 2017 and has now (January 2018) run for about five months without problems. The noise production is substantially lower than for the 2-bladed VIRYA-1.65 rotor but also for this rotor, there is a rather large distance in between the P_{mech}-n curve of the generator for 13 V and the optimum cubic line of the rotor. So in practice the rotor runs at a higher tip speed ratio than 4.5. The cut-in wind speed is about 3.5 m/s which is rather high for a 12 V battery charger. The starting wind speed is about 2.5 m/s and the rotor is almost always running but it isn’t supplying any power to the batteries at low wind speeds. So this combination of the VIRYA-1.46 rotor and the axial flux generator of Hefei Top Grand is only an acceptable option for regions with rather high wind speeds.

8 References

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