The VIRYA-0.45
a small wind turbine for practical tests by students in the class room

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KD 662

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1 Introduction

Already in 1997 I met a Dutch man who was writing a book meant for high school students and he wanted a chapter in this book about wind turbine tests which can be performed in the class room. He asked me if I could design such a test rig and a wind turbine which could power at least a 6 V bicycle lamp. At that time I was running a commercial company and I said that this might be possible but that my work should be paid. I did a lot of research which ended into a working test rig and wind turbine but finally it appeared that no money was available and therefore the whole idea was never published. Now I am retired and I need no longer income out of my activities so I have decided to make everything public. This was extra stimulated by a man from Israel who also wants to design a test rig for students and therefore this report KD 662 is written in English.

In 1998, I have written report KD 27 (ref. 1) in which the test rig and the wind turbine are described. However, this report is in Dutch and it isn't digital as it was written on a Brother typewriter. So the parts out of this report which are still relevant today are translated into English. A technical drawing format A1 with drawing number 9807-01 was made for the rotor and the test rig. A technical drawing format A2 with drawing number 9807-02 was made for the tools to twist the spokes to give the blades the correct blade angle. Because these drawings are big, it isn't possible to scan them with my personal scanner. But I have made a photo of them and these photos are given in appendix 1 and 2. If these photos are printed on A4 format, the drawings will be too small to read the measurements but they can be read on a computer screen if the drawing is scaled up. The text on the drawings is in Dutch but this seems to be no problem. I won't supply prints of the drawings on the original size as printing can only be done in Eindhoven. The costs for petrol and mailing are too high for a free design.

2 Description of the test rig

The idea was to use a room fan to produce a certain horizontal air flow. I have bought a free standing room fan of manufacture FSL model S40-B, 230 V, 50 Hz, 60 W. The fan has a diameter of 400 mm. The fan is protected by a wired cover with a diameter of 430 mm. This cover has a massive disk in the centre with a diameter of 130 mm so no air is coming from the centre of the rotor. I did some tests without the cover but the wind speed at the heart of the fan is almost zero and so the disk isn't really hindering the flow. The motor switch has four positions 0, 1, 2 and 3. The highest flow is gained for position 3. The height of the foot can be adjusted. The highest height of the centre of the fan is 1.15 m. The wind speed has been measured for position 3 (see chapter 3) and it is about 4.5 m/s at a distance of about 100 mm from the front side of the fan. It can be calculated that the kinetic power available in the air flow is only about 6 W for this wind speed. If the fan motor absorbs 60 W at position 3, it means that a lot of energy is lost in the electronics, the motor and the fan. It also means that the wind turbine rotor must be made as large as possible to extract the maximum power from the moving air flow.

For the rotor diameter of the wind turbine it was chosen that D = 0.45 m. The flow coming out of the fan is expanding around the rotor so it is expected that almost all air particle passing through the fan will also pass through the rotor. As the cover has a disk in the centre where there is no air flow, it is useless to make a rotor which has blades up to the centre of the hub. The idea is that every group of students has to make its own rotor and therefore the rotor should be as simple as possible. But the starting torque should be high enough to over power the friction in the generator and the gear box at a rather low wind speed. This means that the total blade area must be large with respect to the swept area of the rotor.

Several rotors have been made and tested. Only the final rotor will be described. The theory how to design a windmill rotor is given in public report KD 35 (ref. 2). However, the rotor for this test rig isn't designed according to the rotor theory as this would have resulted in a rotor which was rather difficult to manufacture.

When I was working at the Wind Energy Group of the University of Technology Eindhoven, we did some wind tunnel tests with a rotor with eight flat square blades and the measured characteristics of this rotor were rather good. So it was decided to use the flat square plate for the rotor blades as such blades can easily been manufactured by students. Aerodynamic characteristics of a flat square plate are given in public report KD 551 (ref. 3).

The rotor has four square aluminium blades size 150 * 150 * 1 mm. The corners are rounded with a radius r = 10 mm. Two opposite blades are connected to each other by an aluminium spoke size 40 * 300 * 2 mm. A blade is connected to a spoke by two screws M4 * 10, two self locking nuts M4 and four washers for M4. The two spokes make an angle of 90° with each other and are connected to the generator hub by four screws M4 * 10. Every side of a spoke is twisted 15° right hand so the blade angle β is 15° for a rotor which is rotating right hand. The starting torque for this blade angle is large enough to make the rotor start even at switch position 1 and the rotational speed is high enough to get a sufficient high voltage out of the generator. However, one of the tests for the students might be to find the optimum blade angle by try and error so if this test is a part of the course, it should not be told to them that 15° is the optimum blade angle.

The idea was that the wind turbine should produce some electrical power, so a generator is needed. A permanent magnet generator needs no energy to build the magnetic field and the efficiency is therefore rather high. However, I could find no direct drive generator in 1998 which generates a sufficiently high voltage at the rotational speeds which were realised by the chosen rotor. Therefore a permanent magnet DC motor with build in gear box was chosen. The manufacture was Premotec type 9904 120 52602. The nominal voltage is 12 V DC and it has a reducing planetary gear box with a gear ratio 1 : 9. I have checked on Google if this motor is still available and this appears to be the case. However, the same motor is manufactured by different companies all using the same motor number. I found Premotec supplied by for instance Distrelec, Airpax supplied by for instance Farnell and Philips supplied by for instance RS-Components. The cheapest motor is supplied by RS-Components and the price including VAT (but excluding mailing costs) is about € 44. On the website of Farnell, there is a datasheet in which it can be seen that this geared motor can be supplied for three different voltages and that the gear box can have a very large number of gear ratios. Every combination has its own motor number. The motor number 9904 120 52602 belongs to the 12 V version with a gear ratio 1 : 9.

The gear box has a shaft with a diameter of 4 mm and a flat side. The rotor hub has an inside diameter of 4 mm and is clamped to the flat side of the shaft by a screw M3. I don’t know what kind of bearings are used on the gear box shaft but some oil is needed in between the hub and the front collar of the gear box to prevent that this collar wears too fast by the rotor thrust.

A permanent magnet DC motor can be used as generator and now the gear box is accelerating the rotational speed. But the speed required to generate a loaded voltage of 12 V is rather high and therefore it is chosen to power a 6 V, 0.6 W bicycle lamp. The available power in the wind is only low and a lot of power is lost in the gear box and in the motor. Therefore the electrical power which can be produced at low rotational speeds is only very low. The motor has two contacts on top and two wires of different colours have to be soldered to these contacts to guide the generated current to the load.

One of the tests for the students can be to optimise the generated electrical power by using different resistors as load. So one measures the DC voltage U and the DC current I and looks for the resistance for which the power, which is the product I * U, is maximal. I haven’t performed these measurements. The available power in the wind can be changed by changing the distance in between the rotor and the fan. The minimum distance is about 100 mm.

The heart of the rotor has to be positioned at the same height as the heart of the fan. Therefore the generator has to be mounted at a column which is placed on a table. The column must be rather heavy to prevent that it topples.

The column has a steel foot size 200 * 200 * 10 mm, a steel pillar size ϕ 25 * 297 mm and a 90° bent bracket made from steel strip size 40 * 3 mm. The bracket has four tapered 3.5 mm holes in the vertical part. The gear box is connected to the bracket by four tapered screws M3 * 10 and four nuts M3. The original 2.7 mm holes in the flange of the gear box have to be enlarged up to 3 mm. The pillar has M8 internal thread at both sides. The bracket is connected to the pillar by a bolt M8 * 20. The foot is connected to the pillar by a tapered screw M8 * 20. The distance in between the heart of the rotor shaft and the foot of the column is 340 mm.

The maximum rotational speed of the rotor is somewhat higher than 400 rpm. The rotor blades are rather light and the corners are rounded but one should never try to stop a rotating rotor by his hands! I think that the rotor will cut no fingers but your hand will certainly be wounded. It is absolutely forbidden to use the rotor outside the class room in real wind because then the rotational speed can become much higher and then the rotor becomes dangerous. The gear box bearings will probably be not strong enough to absorb the much higher rotor thrust at high wind speeds. Even inside the class room, the rotor should not rotate for a long time because this may result in to much wear of the gear box bearings.

3 Determination of the wind speed and the rotational speed of the rotor

The wind speed can be measured with a cup anemometer which can be hold in the hand but I didn't have such one available in 1998. So I made something myself which measures the force acting on a thin disk. The drag force F_d (in N) acting on a certain body is given by:

$$F_d = C_d * ½\rho V^2 * A \qquad \text{(N)} \qquad (1)$$

In this formula C_d is the drag coefficient which is about 1.15 for a thin disk. ρ is the air density which is about 1.2 kg/m^3 for air with a temperature of 20° C at sea level. V is the wind speed (m/s). A is the area of the body perpendicular to the wind direction. For a disk with a diameter d, the area $A = \pi/4 * d^2$. So formula 1 can be written as:

$$V = \sqrt{8 * F_d / (\pi * C_d * \rho * d^2)} \qquad \text{(m/s)} \qquad (2)$$

The diameter of the disk is chosen the same as the width of the ring shape flow coming out of the fan. This width is (400 – 130) / 2 = 135 mm. So d = 135 mm = 0.135 m. Substitution of $C_d = 1.15$, $\rho = 1.2$ kg/m^3 and d = 0.135 in formula 2 gives:

$$V = 10.06 * \sqrt{F_d} \qquad \text{m/s} \qquad (3)$$

To measure F_d, one can use a letter balance. However, a letter balance which works with weights, can only be used to measure a vertical force. So one has to make a construction which transfers the horizontal force acting on the disk to a vertical force acting on the letter balance. There are also letter balances working with a spring and these can be used if they can be adjusted to zero for a horizontal position of the balance axis. A letter balance normally gives the weight G in gram. The weight G in gram can be transferred to a force F in N by the formula:

$$F = 9.81 * G / 1000 \qquad \text{(N)} \qquad (4)$$

I have measured that the wind speed V at a distance of 100 mm from the fan is about 4.5 m/s for the switch in position 3. The power in the wind P_w is derived in chapter 2 of KD 35 and is given by:

$$P_w = ½\rho V^3 * A \qquad \text{(W)} \qquad (5)$$

For the area A of a fan with a diameter of 400 mm but with a cover with a massive disk with a diameter of 130 mm it can be calculated that $A = \pi/4\ (0.4^2 - 0.13^2) = 0.112\ m^2$. Substitution of $\rho = 1.2\ kg/m^3$, $V = 4.5$ m/s and $A = 0.112\ m^2$ in formula 5 gives that P = 6.1 W. So if the fan motor absorbs 60 W at switch position 3, only about 10 % of this power is transformed to kinetic power of the produced air flow!

The rotational speed n (rpm) of the rotor can simply be measured by counting the number of revolutions in a minute. One can look at the screw in the hub and count how many times this screw is passing. The unloaded rotational speed has been measured this way for switch position 1 and 2. The rotational speed for switch position 3 was too high for counting but I have also measured the open voltage and as the open voltage is about proportional to the rotational speed, the rotational speed for switch position 3 can be calculated from the rotational speed at switch position 1 and 2. The average is taken from the result if switch position 1 or 2 is chosen. I found the following result given in table 1 for a rotor with a blade angel of 15° positioned at 100 mm from the fan.

Switch position	Open DC voltage U (V)	Rotational speed n (rpm)
1	5.5	200
2	9.2	320
3	11.6	413

Table 1 Open voltage U and unloaded rotational speed n as a function of the switch position

Even if no power is extracted from the generator, the rotor won’t turn really unloaded because some torque is needed for the friction of the generator brushes and the bearings and gears of the gear box.

4 Tests to be performed by the students

Some tests have already been described in chapter 2. The first test is to make the rotor and to find the optimum blade angle β. The second test is to find the maximum electrical output. Therefore one needs a certain range of resistors and one measures the DC current I and the DC voltage U for each resistor. The electrical power P_{el} is given by:

$P_{el} = U * I$ (W) (6)

U and I have to be measured accurately and simultaneously for every resistor so one needs two digital volt meters.

The third test might be to find a lamp which gives the most light for switch position 3. One can use incandescent lamps or LED’s.

The fourth test might be to build a device for measuring of the wind speed. However, the school may also buy a professional small cup anemometer but one should be sure that this one gives the correct wind speed at low wind speeds. Some devices give too low values at low wind speeds because of the friction of the cup anemometer bearings. If a good measuring devise is available, one can measure the wind speed at different distances from the fan and at different distances from the fan axis.

The fifth test might be to determine the optimum tip speed ratio of the rotor. It is assumed that the rotor turns at the optimum tip speed ratio if the generated electrical power is maximal. So the generator has to be loaded with the resistor for which the maximum power was found. I have not yet performed these measurements as the test rig was not ready when report KD 27 was written. The tip speed ratio lambda (λ in the Greek alphabet) is defined as:

$\lambda = V_{tip} / V$ (-) (7)

In this formula V_{tip} is the tip speed (m/s) and V is the undisturbed wind speed (m/s) so the wind speed which would be measured in the rotor plane if no rotor was placed. The tip speed ratio λ depends on the type of rotor and on the load. λ varies in between 0 if the rotor is slowed down to stand still and the unloaded lambda λ_{unl} if no load is attached. The relation in between the tip speed V_{tip} and the rotational speed n is given by:

$$V_{tip} = \pi * n * R / 30 \qquad (m/s) \qquad (8)$$

(7) + (8) gives:

$$\lambda = \pi * n * R / (30 * V) \qquad (-) \qquad (9)$$

The unloaded tip speed ratio λ_{unl} can be determined from the measurements of the wind speed at switch position 3 and the unloaded rotational speed at switch position 3. Substitution of $n = n_{unl} = 413$ rpm, R = 0.5 D = 0.5 * 0.45 = 0.225 m and V = 4.5 m/s in formula 9 gives that $\lambda_{unl} = 2.16$. This is rather low. However, this isn’t the real unloaded lambda because even with open clamps, the gear box shaft will need some torque to rotate because of the friction of the motor and the gear box. I expect that the real unloaded tip speed ratio is about 2.5 if the wind speed was measured correctly.

The students can measure the optimum rotational speed of the rotor n_{opt} for which the generated power was found to be maximal for switch position 3. If this rotational speed is substituted in formula 9, one finds the optimum tip speed ratio λ_{opt}. I expect that λ_{opt} is about 1.6 for $\lambda_{unl} = 2.5$.

Determination of the C_q-λ curve of the rotor (see KD 35 chapter 6.4) requires measuring of the rotor torque Q and this is expected to be too complicated for high school students.

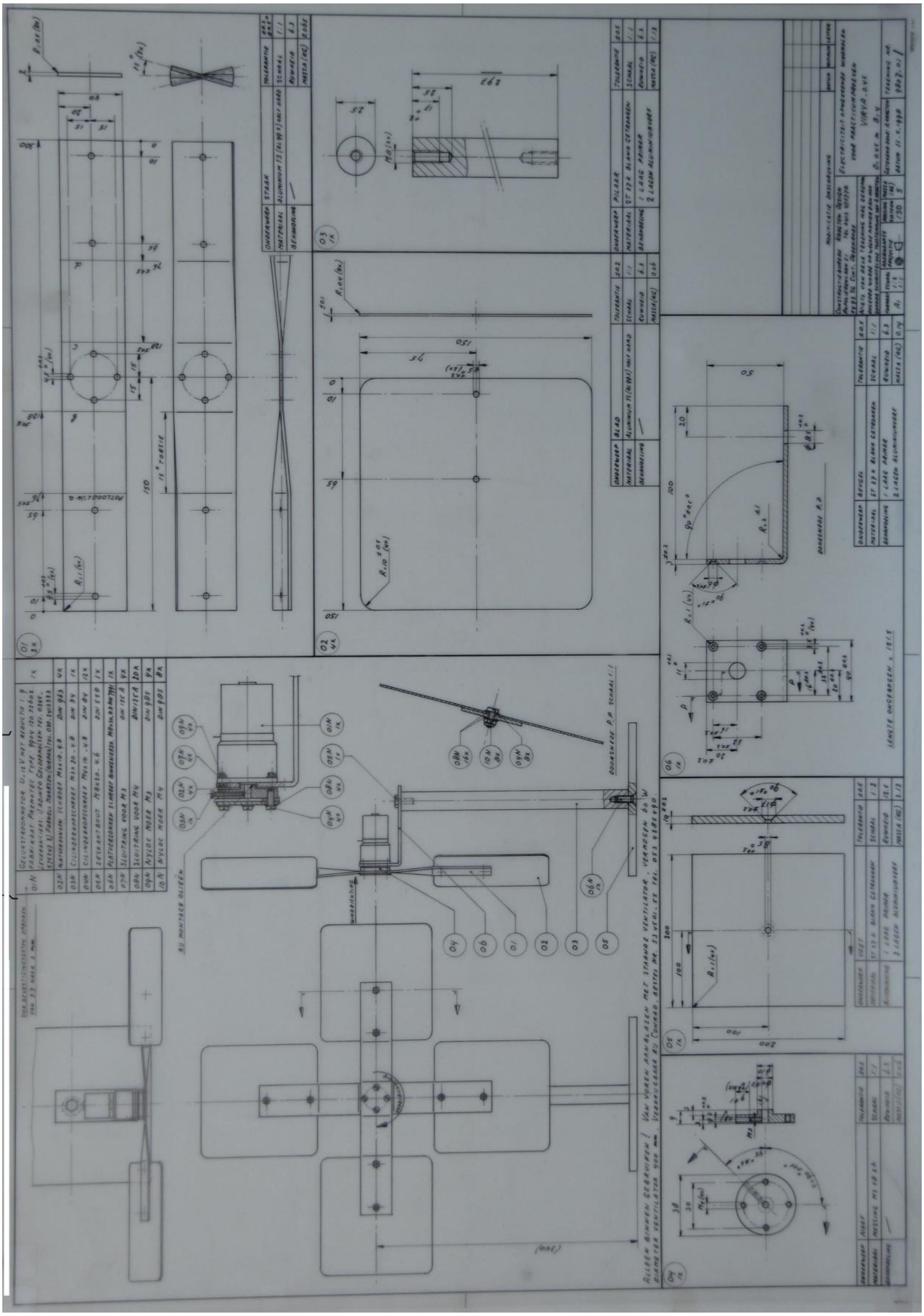
4 References

1 Kragten A. De VIRYA-0.45. Een windmolen voor practicumproeven met windenergie in de klas (in Dutch), May 1998, report KD 27, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, reviewed February 2017, free public rapport KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Aerodynamic characteristics of rectangular flat plates with aspect ratios 5 : 1, 2 : 1, 1 : 1, 1 : 2 and 1 : 5 for use as windmill vane blades, March 2014, reviewed April 2016, free public report KD 551, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1 Photo of drawing 9807-01



Appendix 12 Photo of drawing 9807-02