Calculations executed for the 3-bladed rotor of the VIRYA-0.98 windmill (λ_d = 3, 15° folded aluminium blades) meant to be coupled to a Nexus hub dynamo

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KD 615

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1 Introduction

The VIRYA-1.04 windmill is developed for manufacture in western as well as in developing countries. The VIRYA-1.04 has a 3-bladed rotor with cambered aluminium blades which are directly bolted to the front flange of a Shimano Nexus hub dynamo type DH-2R40 or another type with similar flange and shaft dimensions. The VIRYA-1.04 is described in a manual (ref. 1) which is available for free on my website.

The rotor blades of the VIRYA-1.04 have a 7.14 % cambered airfoil. Cambering requires a special press and for twisting of the blades, special tools for cambered blades are needed. These tools are relatively expensive if only one windmill is made. In this report KD 615 it is investigated if it might be possible to use rectangular blades with folded sides because now much simpler and cheaper tools are needed. The rotor diameter is chosen a little smaller (0.98 m) to make an efficient use of the chosen materials. This VIRYA-0.98 will be equipped with the same generator, head and safety system as the VIRYA-1.04. It is expected that the rated wind speed is 8 m/s for a 1.5 mm aluminium vane blade.

2 Description of the rotor of the VIRYA-0.98 windmill

The 3-bladed rotor of the VIRYA-0.98 windmill has a diameter D = 0.98 m and a design tip speed ratio λ_d = 3. Advantages of a 3-bladed rotor are that the gyroscopic moment is not fluctuating and that a 3-bladed rotor looks nicer than a 2-bladed or 4-bladed rotor.

The rotor has three blades which are made of rectangular aluminium sheets with size 156 * 312 * 1.5 mm. 64 blades can be made out of a standard sheet of 1.25 * 2.5 m with almost no waste material. All four corners of a blade are rounded with r = 5 mm. The blade has no camber but in stead of camber, both 39 mm sides are bent forwards over an angle of 15°. It is expected that the aerodynamic characteristics of this special airfoil are about the same as for a 7.14 % cambered airfoil. The chord c is a little smaller than the strip width because of the bent sides. Assume c = 0.154 m. A blade is twisted linear.

A blade is connected to the hub dynamo by an aluminium strip size 78 * 178 * 2 mm. 224 strips can be made out of a standard sheet of 1.25 * 2.5 m with almost no waste material. The overlap in between the blade and the connection strip is 20 mm. The inner side of the strip lies at 20 mm from the hart of the dynamo resulting in a rotor diameter of 980 mm. A blade is connected to the strip by two stainless steel M4 bolts and self locking nuts and four washers. The inner 30 mm of the strip is flat. The strip is twisted in between this flat side and the blade root to get the correct blade setting angle.

The hub dynamo has two identical flanges. For connection of the spokes, each flange has 18, 2.6 mm holes at a pitch angle of 20° and at a pitch circle diameter of 80 mm. The flange at the side of the electricity cable is called the back flange and the other flange is called the front flange. For use in a bicycle, the back flange side of the dynamo has to be mounted at the right side of the bicycle to realise the correct direction of rotation of the hub. The rotor is connected to the front flange and this means that the rotor must rotate left hand to realise the correct direction of rotation of the hub. The front flange has a collar with a diameter of 64 mm. A moon shaped excision is made in the strip for centring on the collar.

In the front flange, nine spoke holes at a pitch angle of 40° are modified into 4 mm holes. Each strip is connected to the front dynamo flange by three stainless steel bolts and self locking nuts M4 and six washers. The mass of all three blades together is about 0.8 kg which is very light for a rotor with a diameter of 0.94 m.

It is expected that it is not necessary to balance the rotor if the hole patterns in blade and strip are made accurately. It might be necessary to develop a drilling jig to realise this. The drawing of the rotor is given in appendix 1. The drawings of the generator, the head and the tower pipe are given in the manual of the VIRYA-1.04 with the original rotor with cambered blades (ref. 1).

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 2). This report (KD 615) has its own formula numbering. Substitution of λ_d = 3 and R = 0.49 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 6.1224 * r$ (-) (1)

Formula's (5.2) and (5.3) of KD 35 stay the same so:

$\beta = \phi - \alpha$ (°) (2)

$\phi = 2/3 \arctan 1 / \lambda_{r\,d}$ (°) (3)

Substitution of B = 3 and c = 0.154 m in formula (5.4) of KD 35 gives:

$C_l = 54.400\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.154 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.514 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for five stations A till E which have a distance of 0.073 m. Station A corresponds to the blade tip. Station E corresponds to the end of the connecting strip. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root. First the theoretical values are determined for C_l, α and β and next β is linearised such that the twist is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

Although the blade has 15° bent sides, it is assumed that the aerodynamic characteristics for 7.14 % camber can be used. Aerodynamic characteristics for 7.14 % camber are given in report KD 398 (ref. 3). The Reynolds values for the stations are calculated for a wind speed of 5 m/s because this is a reasonable wind speed for a windmill which is designed for a rated wind speed of 9 m/s.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	0.49	3	12.3	0.154	0.61	0.65	1.58	1.7	0.0	0.3	12.3	12	0.058
B	0.417	2.553	14.3	0.154	0.70	0.67	1.36	1.2	1.0	0.8	13.3	13.5	0.041
C	0.344	2.106	16.9	0.154	0.81	0.84	1.14	1.2	1.7	1.9	15.2	15	0.034
D	0.271	1.659	20.7	0.154	0.95	1.11	0.92	1.2	2.7	4.2	18.0	16.5	0.032
E	0.198	1.212	26.4	0.154	1.12	1.37	0.71	1.2	4.2	8.4	22.2	18	0.070

table 1 Calculation of the blade geometry of the VIRYA-0.98 rotor

The theoretical blade angle β_{th} varies in between 12.3° and 22.2°. If a blade angle of 12° is taken at the blade tip and a blade angle of 18° is taken at the blade root, the linearised blade angles are lying close to the theoretical values for the most important outer part of the blade. The linearised lift coefficients near the blade root are higher than the theoretical values but even at station E, the blade is not stalling so it is expected that this is allowable. The strip is twisted 18° left hand in between the flat inner 30 mm and station E to get the correct blade angle at station E.

4 Determination of the C_p-λ and the C_q-λ curves

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the outer part of the blade is about 0.04. However, as the used airfoil is not a 7.14 % cambered sheet but a flat sheet with 15° bevelled edges, a higher value of 0.07 is chosen. Figure 4.7 of KD 35 (for B = 3) and λ_{opt} = 3 and C_d/C_l = 0.07 gives $C_{p\ th}$ = 0.38.
Substitution of $C_{p\ th}$ = 0.41, R = 0.49 m and blade length k = 0.312 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.33. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.33 / 3 = 0.11.
Substitution of $\lambda_{opt} = \lambda_d$ = 3 in formula 6.4 of KD 35 gives λ_{unl} = 4.8.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is copied as formula 6.

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (6)$$

The average blade angle β = 15° (for station C). For a non rotating rotor, the angle ϕ = 90°. The average angle of attack α is therefore 90° - 15° = 75°. The C_l-α curve for large angles α is given in figure 5 of report KD 398. For α = 75° it can be read that C_l = 0.5.
Substitution of B = 3, R = 0.49 m, k = 0.312 m, C_l = 0.5 and c = 0.154 m in formula 6 gives that $C_{q\ start}$ = 0.049. The real starting torque coefficient will be somewhat lower because we have used the average blade angle. Assume $C_{q\ start}$ = 0.045. For the ratio in between the starting torque and the optimum torque we find that it is 0.045 / 0.12 = 0.375. This is rather high for a rotor with a design tip speed ratio of 3.

The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3}\right)} \qquad (m/s) \qquad (7)$$

The peak of the sticking torque Q_s of the Nexus hub dynamo has been measured and it was found that Q_s = 0.084 Nm. Substitution of Q_s = 0.084 Nm, $C_{q\ start}$ = 0.045, ρ = 1.2 kg/m^3 and R = 0.49 m in formula 7 gives that V_{start} = 2.9 m/s. The average sticking torque Q_{sa} at very low rotational speeds has also been measured and it was found that Q_{sa} = 0.054 Nm. Substitution of Q_{sa} = 0.054 Nm, $C_{q\ start}$ = 0.045, ρ = 1.2 kg/m^3 and R = 0.49 m in formula 7 gives that V_{start} = 2.3 m/s. So this means that once the rotor is rotating a little, it will start at a wind speed of 2.3 m/s because of the fly wheel effect of the rotor. So the effective starting wind speed will be about 2.4 m/s. This is a little lower than for the VIRYA-1.04 rotor for which V_{start} is about 2.6 m/s.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for λ = 0. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 4). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a 7.14 % cambered sheet airfoil is used. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-0.98 rotor are given in figure 1 and 2.

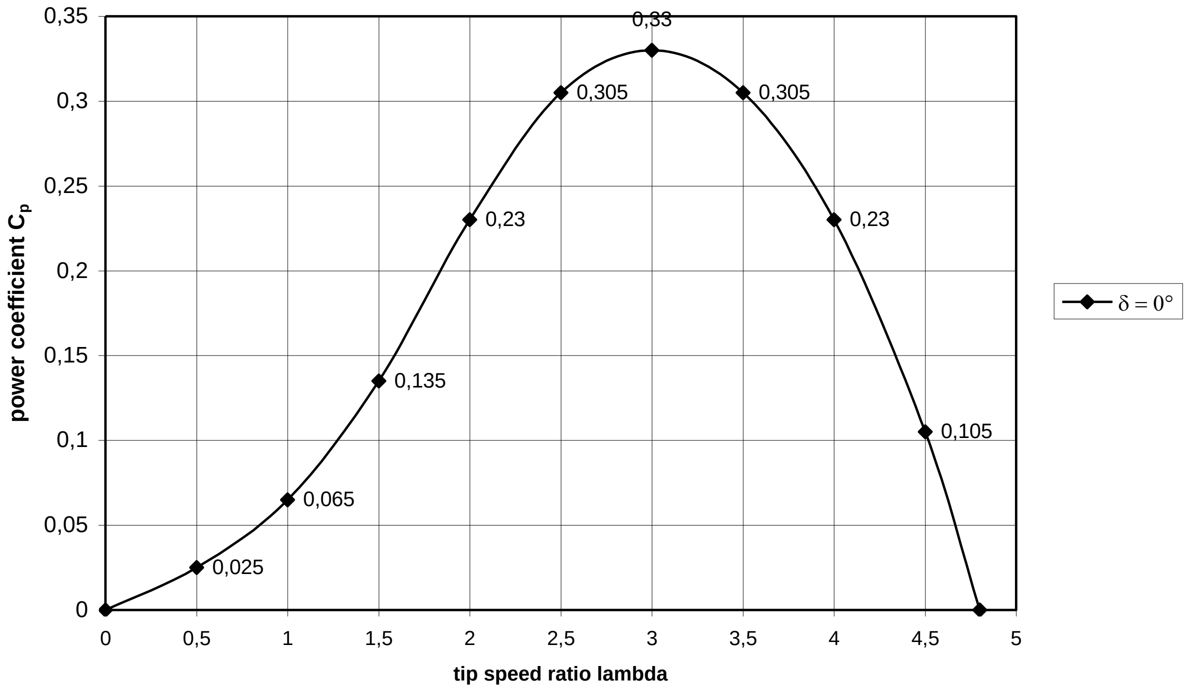

fig. 1 Estimated C_p-λ curve for the VIRYA-0.98 rotor for the wind direction perpendicular to the rotor (δ = 0°)

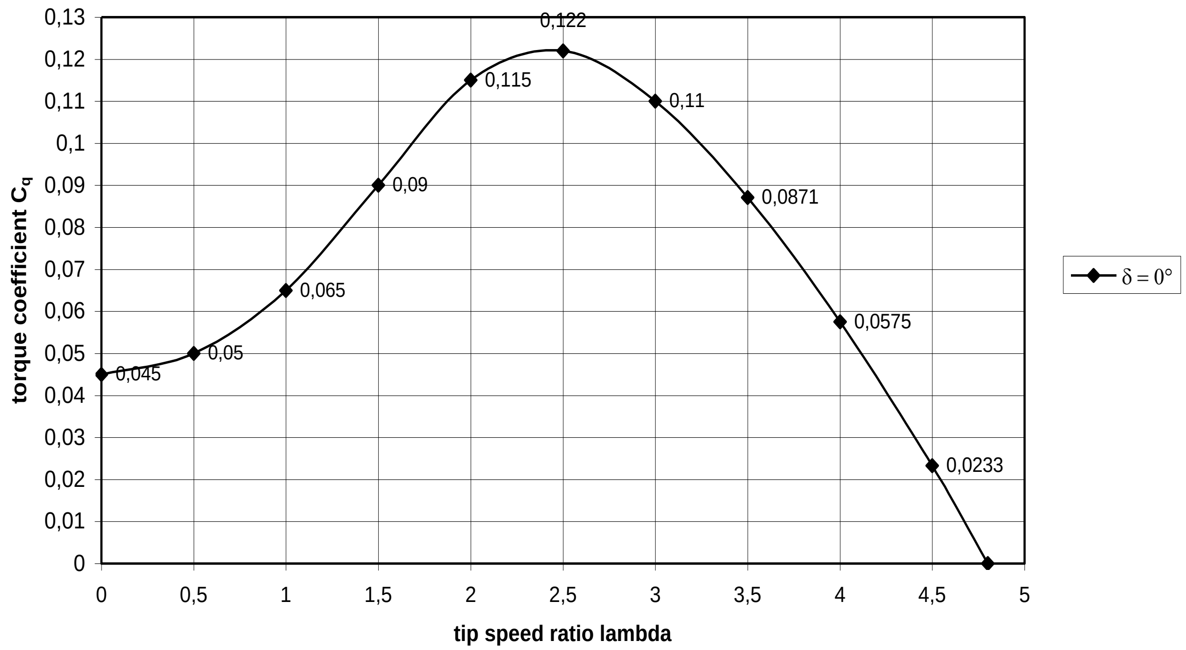

fig. 2 Estimated C_q-λ curve for the VIRYA-0.98 rotor for the wind direction perpendicular to the rotor (δ = 0°)

5 Determination of the P-n curves, the optimum cubic line and the P_{el}-V curve

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a C_p-λ curve of the rotor and the δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The C_p-λ curve is given in figure 1. The δ-V curve for a 1.5 mm aluminium is estimated on the basis of the proven δ-V curves of the VIRYA-1.8 and 2.2S windmills which have a 1 mm stainless steel vane blade and which have a rated wind speed of about 11 m/s. The estimated δ-V curve for a 1.5 mm aluminium vane blade is given in figure 3.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 8 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 8 m/s will therefore also be valid for wind speeds higher than 8 m/s.

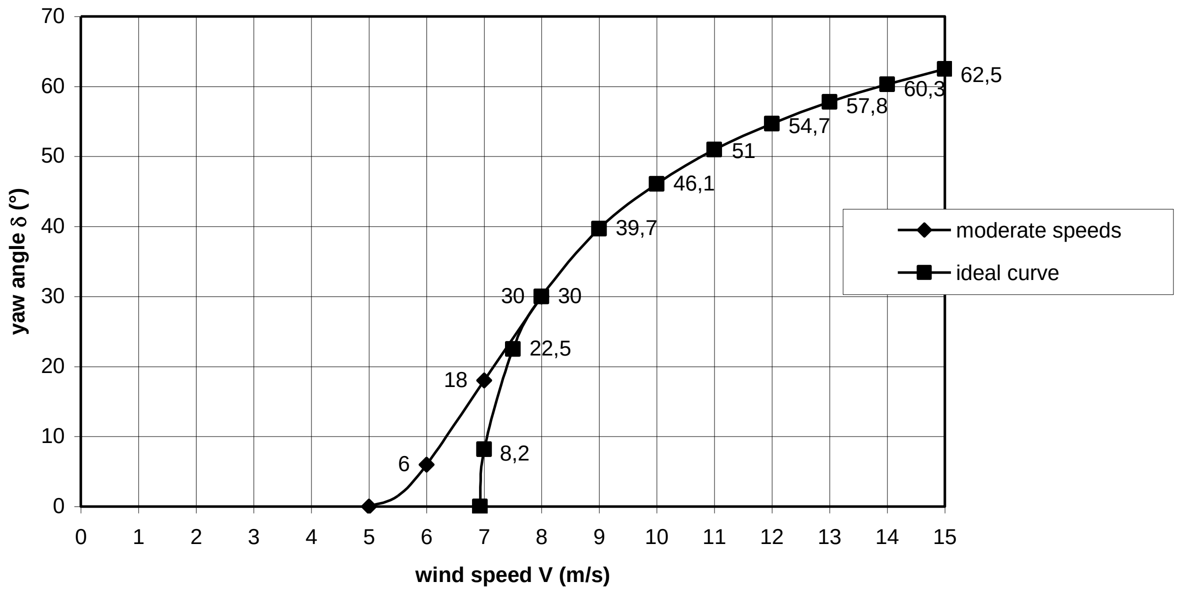

fig. 3 Estimated δ-V curve VIRYA-0.98 for a 1.5 mm aluminium vane blade

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator for a certain gear ratio i (the VIRYA-0.98 has no gearing so i = 1). Because the P-n curve for low values of λ appears to lie very close to each other, the P-n curves are not determined for very low values of λ. The P-n curves are determined for C_p values belonging to λ is 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 4.8 (see figure 1). The P-n curves are determined for wind the speeds 2, 3, 4, 5, 6, 7 and 8 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 0.49 m in formula 7.1 of KD 35 gives:

$n = 19.488 * \lambda * \cos\delta * V$ (rpm) (8)

Substitution of $\rho = 1.2 \text{ kg} / m^3$ and R = 0.49 m in formula 7.10 of KD 35 gives:

$P = 0.4526 * C_p * \cos^3\delta * V^3$ (W) (9)

For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed.

		V = 2 m/s δ = 0°		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 6°		V = 7 m/s δ = 18°		V = 8 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
1.5	0.135	58.5	0.49	87.7	1.65	116.9	3.91	146.2	7.64	174.4	12.98	194.6	18.03	202.5	20.32
2	0.23	78.0	0.83	116.9	2.81	155.9	6.66	194.9	13.01	232.6	22.12	259.5	30.72	270.0	34.62
2.5	0.305	97.4	1.10	146.2	3.73	194.9	8.83	243.6	17.26	290.7	29.33	324.3	40.73	337.5	45.91
3	0.33	116.9	1.19	175.4	4.03	233.9	9.56	292.3	18.67	348.9	31.73	389.2	44.07	405.1	49.67
3.5	0.305	136.4	1.10	204.6	3.73	272.8	8.83	341.0	17.26	407.0	29.33	454.1	40.73	472.6	45.91
4	0.23	155.9	0.83	233.9	2.81	311.8	6.66	389.8	13.01	465.1	22.12	519.0	30.72	540.1	34.62
4.5	0.105	175.4	0.38	263.1	1.28	350.8	3.04	438.5	5.94	523.3	10.10	583.8	14.02	607.6	15.80
4.8	0	187.1	0	280.6	0	374.2	0	467.7	0	558.2	0	622.7	0	648.1	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-0.98 rotor

The calculated values for n and P are plotted in figure 4. The optimum cubic line which is going through the tops of the P_{mech}-n curves is also given in figure 4.

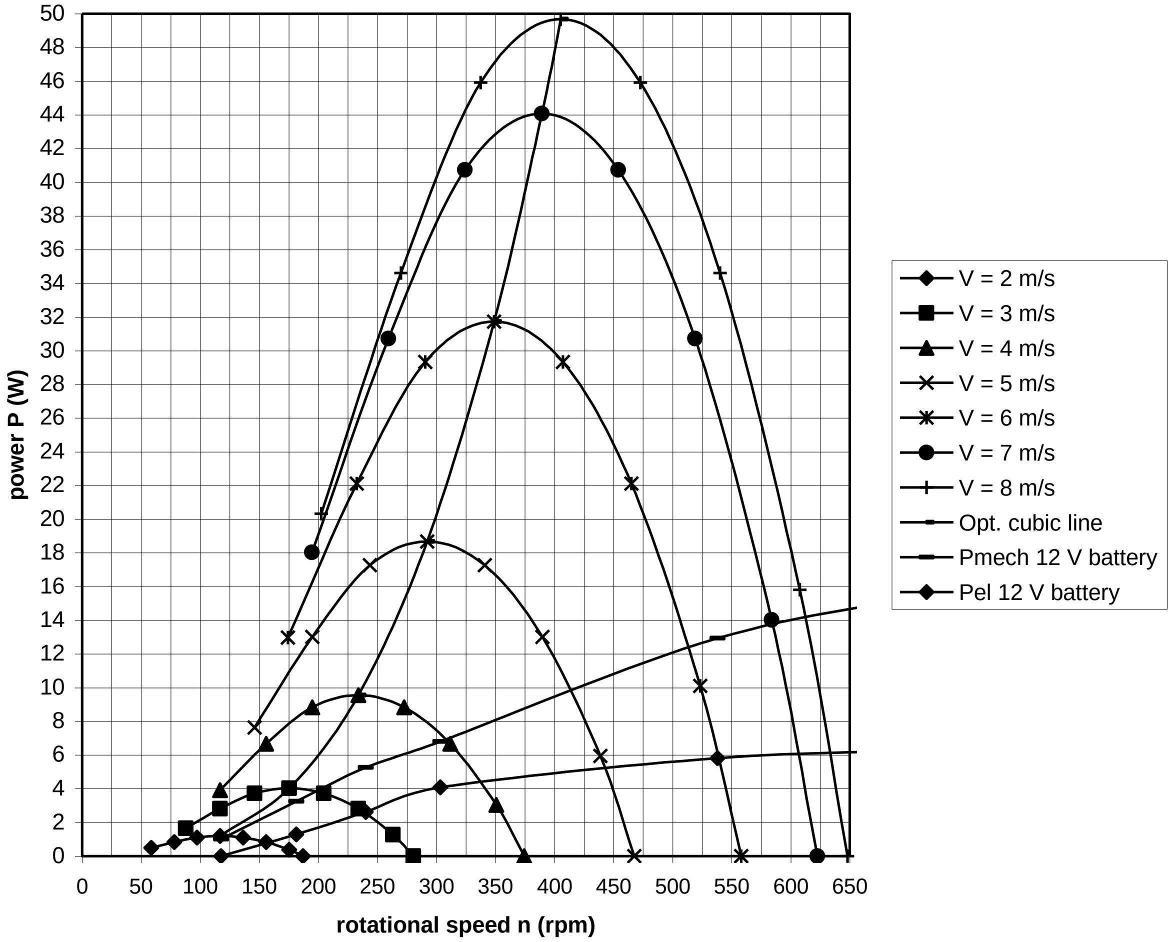

fig. 4 P-n curves and optimum cubic line of the VIRYA-0.98 rotor

The Nexus hub dynamo has been measured for an old 12 V car battery as load. The AC-current of the dynamo was rectified with a 1.5 A, 1-phase bridge rectifier. The dynamo was driven by a PM-DC motor which could run on variable speed. The dynamo was coupled to the motor hub by a flat belt. The rotational speed of the dynamo was measured by a laser rpm meter. The DC-voltage U was measured by a digital volt meter. The DC-current I was measured by an analogue volt meter. The electrical power P_{el} is the product of U * I.

The torque could not be measured and the P_{mech}-n curve is determined for an estimated efficiency curve which has a maximum of η = 0.6 for about n = 300 rpm. The estimated P_{mech}-n curve and the measured P_{el}-n curve for 12 V battery charging are also given in figure 4.

The working point for a certain wind speed is the point of intersection of the P_{mech}-n curve of the generator and the P-n curve of the rotor for that wind speed. The corresponding electrical power P_{el} is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve of the generator. This is done for all wind speeds and the values of P_{el} found this way are given in the P_{el}-V curve of figure 5.

In figure 4 it can be seen that the matching in between rotor and generator is only good for very low wind speeds. For high wind speeds, the working point is lying far to the right side of the optimum cubic line which means that the rotor is running almost unloaded and that the C_p is very low. The rotational speed for a wind speed of 8 m/s is about 600 rpm and the tip speed ratio is about 4.5.

The hub dynamo has 28 poles and so 28 preference positions in one revolution. The dynamo has been measured up to a maximum rotational speed of about 750 rpm. The dynamo makes noise caused by the preference positions. The noise at 750 rpm has a high frequency and is rather loud. Therefore it is not advised to mount the VIRYA-0.98 windmill on the roof of a house as the vibration will probably be felt and heard inside.

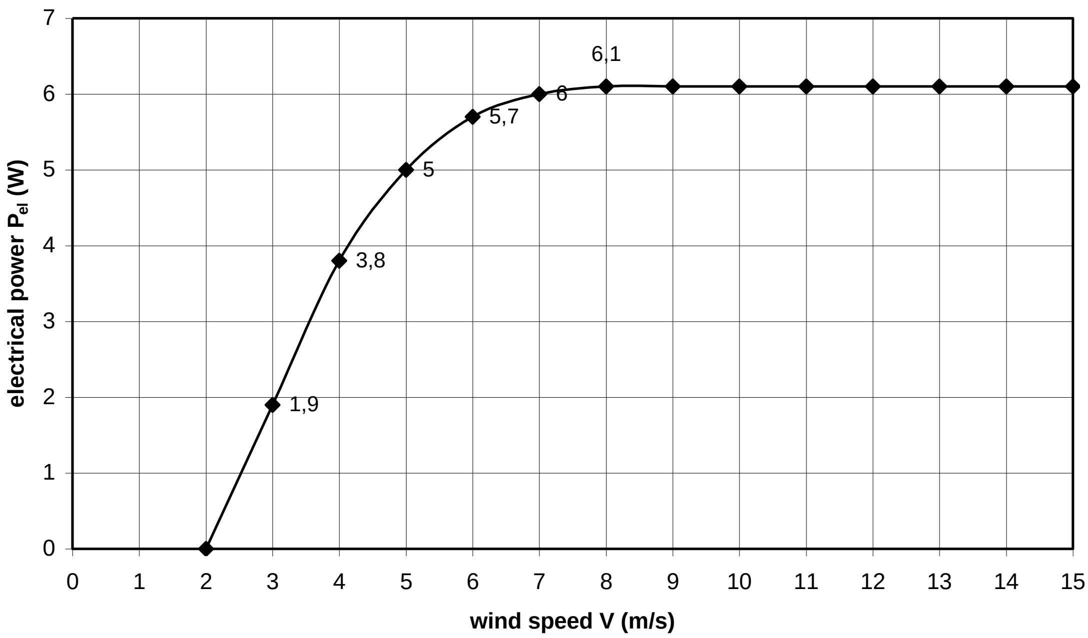

fig. 5 P_{el}-V curve of the VIRYA-0.98 windmill for 12 V battery charging

The wind speed where the generation of power starts is called the cut in wind speed $V_{cut\ in}$. In the P_{el}-V curve it can be seen that $V_{cut\ in}$ = 2 m/s. This is very low. In chapter 4 it was calculated that the effective starting wind speed is about 2.4 m/s. So there is hysteresis in the P_{el}-V curve for $2 < V < 2.4$ m/s.

The maximum electrical power is about 6.1 W. However, an old car battery was used and the charging voltage at maximum power was about 14.6 V. The charging voltage for a new battery will be lower and therefore it is expected that the real maximum power will be about 5.8 W. A more accurate P_{el}-V curve can be determined if a new battery is used and if the dynamo is measured more accurately on a test rig with which it is also possible to measure the torque Q. However, the given P_{el}-V curve gives a good idea about the possibilities of using a hub dynamo for a very small wind turbine which is used for 12 V battery charging.

The strips which connect the blades to the hub are stronger than the blades of the VIRYA-1.04 rotor. Although the thickness of the blade is only 1.5 mm, it is stronger than the strip because the moment of resistance is increased a lot by the 15° bent sides. The strength of the VIRYA-1.04 rotor has been calculated in report KD 518 (ref. 5) and it was found that the VIRYA-1.04 rotor is strong enough. So the VIRYA-0.98 rotor will also be strong enough and separate calculations of the strength of the rotor will not be made.

6 Manufacture of the parts

I have made a prototype of the rotor as specified on drawing 1605-01 in appendix 1. To minimise imbalance, it is important that the three blades item 01 and the three strips item 02 are identical as good as possible. The strips should be cut on a shearing machine with a stop to realise this. The hole pattern should be made as accurate as possible.

Blade item 01

First make the radius R = 5 mm at the corners and drill the two 4 mm holes. The holes in three blades can be drilled together if the blades are clamped together by a glue clamp during drilling. Start with a 2.5 mm drill and end with a 4 mm drill. Remove sharp edges all around. Draw lines at 39 mm from the sides, at 10 mm from the tip and at 20 mm from the root with a sharp pencil.

For bending the sides over 15°, one needs a simple tool. This tool can be made from 12 mm steel square bar. Saw two pieces with a length of 332 mm and drill a 6.5 mm hole at 6 mm from each end. These two strips are clamped around the blade with two M6 bolts and nuts such that one side coincides to the pencil line. The strips are clamped in a vice in about the middle. The blade is pushed backwards by two hands until the correct angle of 15° is gained. The strips are then removed and the same procedure is followed for the other side.

The blade has to be twisted 6° right hand. The same steel strips can be used for twisting but two wooden blocks are needed at the hollow side of the blade to prevent that the blade is flattened. The blade is clamped in a vice with the long side upwards and with the two holes at the side of the vice. Twist about 7° and then somewhat back until the correct angle of 6° is gained. One needs a tool to measure the angle.

Strip item 02

The five 4 mm holes are drilled when the strip is still flat. The hole pattern for the three holes at R = 40 mm must be made accurately otherwise the strip won't fit to the dynamo hub. Draw a line at 30 mm from the inner side and at 20 mm from the outer side with a pencil.

The strips item 02 have to be twisted 18° left hand. I have used an existing tool from another VIRYA windmill but one probably can also make a tool from 12 mm square bar. Saw two 500 mm long steel strips and make a 6.5 mm hole at 207 mm from each end. The two strip are clamped around the outer side of item 02 such that the inner side of a strip corresponds to the pencil line. The inner part of the strip is clamped in a vice such that the upper part of the vice corresponds to the other pencil line. The strip should be twisted about 20° and then twisted back until the correct angle of 18° is gained. Prevent that the strip is bent during twisting.

The blades were connected to the dynamo and a strip was connected to the shaft such that this strip could be hold in a hand. The rotor starts at walking speed. The rotor turns nicely at a bicycle speed of about 20 km/hour. As I have not built a complete VIRYA-1.04 windmill but only a VIRYA-1.04 rotor, the complete VIRYA-0.98 windmill could not be tested by me in real wind.

7 References

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5 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-1.04 windmill (λ_d = 3.5, 7.14 % cambered aluminium blades) meant to be coupled to a Nexus hub dynamo. January 2013, reviewed May 2013, free public report KD 518, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1 VIRYA-0.98 rotor, λ_d = 3, B = 3