Ideas about the 8-bladed rotor of the VIRYA-0.54 windmill (λ_d = 1.25, pentagonal aluminium blades) coupled to a Nexus hub dynamo for 12 V battery charging

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KD 702

The VIRYA-0.54 rotor has not yet been built and tested. No responsibility is accepted by Kragten Design by use of this rotor in combination with a hub dynamo.

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Contains page

1 Introduction

The VIRYA-1.04 and the VIRYA-0.98 wind turbines have 3-bladed aluminium rotors which are directly bolted to the front flange of a Shimano Nexus hub dynamo type DH-2R40. Both wind turbines make use of the same head and tower pipe and are provided with the hinged side vane safety system which turns the head out of the wind at high wind speeds. These wind turbines are described in a folder which is available for free on my website.

Although manufacture of the rotor and the head isn't very complicated, it might be too complicated for certain people in developing countries. So the idea came up to design a wind turbine which is even simpler because it has no head, no vane and no safety system. The same hub dynamo will be used as generator and after rectification of the current with a 1-phase bridge rectifier, it can be used for 12 V battery charging.

The tower is made of a long bamboo pole which is placed in a hole in the ground. The generator is connected to the top of the bamboo pole by a steel size about 5 * 25 * 500 mm with a 9.5 mm hole in the top and two hose clamps. The rotor is turned into the wind manually by turning the bamboo pole. As the rotor isn't turning into the wind, there is no gyroscopic moment and this reduces the maximum bending stress in the spokes of the blades.

As the wind turbine has no safety system, the rotor must be rather strong to resist the high rotor thrust which occurs at high wind speeds. However, the rotor isn't that strong that it can resist big storms. The whole wind turbine has to be laid down for wind speeds higher than 10 m/s (36 km/h)! To limit the rotor thrust at high wind speeds, the rotor diameter is chosen much smaller than for the VIRYA-1.04 or the VIRYA-0.98. It appeared that a rotor diameter of 0.54 m is a good choice and the wind turbine is therefore called the VIRYA-0.54. As the hub dynamo has a rather large peak on the sticking torque, the rotor must have a high starting coefficient to make that it starts at an acceptably low wind speed. So the total blade chord must be rather large which is realised by using an eight bladed rotor.

2 Description of the rotor of the VIRYA-0.54 windmill

The 8-bladed rotor of the VIRYA-0.54 windmill has a diameter D = 0.54 m and a design tip speed ratio λ_d = 1.25. The rotor is made from a 1.5 mm thick square aluminium sheet size 500 * 500 mm. The four corners are removed such that a regular octahedron is left. It appears that the maximum width measured over the corners of the octahedron is about 0.54 m resulting a the name VIRYA-0.54.

Eight kite shaped holes are made in this octahedron and a cut is made to the heart of each hole. This creates eight pentagon blades with each a 50 mm wide spoke. Each spoke is twisted 20° left hand and the rotor is therefore rotating left hand. Provisionally a twisting angle of 20° is chosen but this angle can be changed depending on the wanted optimum tip speed ratio and starting torque coefficient.

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 front flange has a collar with a diameter of about 65 mm. A 65 mm central hole is made in the rotor for centring on the collar. In the front flange, nine spoke holes at a pitch angle of 40° are modified into 4 mm holes. The same hole pattern is made in the rotor. The rotor is connected to the generator by nine stainless steel screws M4 * 10, nine self locking nuts M4 and eighteen washers. The mass of the whole rotor is about 0.79 kg which is acceptable for a rotor with a diameter of 0.54 m. The drawing of the generator is given in the manual of the VIRYA-1.04 (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 method is meant to design a rotor with the optimum aerodynamic geometry. The VIRYA-0.54 rotor has a geometry which is certainly not optimal but the method is used where possible. A blade is normally calculated for a number of stations. This rotor is calculated for only the centre of gravity c.o.g. of a blade which is lying about at r = 0.195 m. This is called station A. The chord at this radius is about 160 mm = 0.16 m. This report (KD 702) has its own formula numbering. Substitution of λ_d = 1.25 and R = 0.27 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 4.6296 * r$ (-) (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 = 8 and c = 0.16 m in formula (5.4) of KD 35 gives:

$C_l = 19.635\, r\, (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.16 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.53 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

So the blade is only calculated for station A corresponding to the c.o.g. The result of the calculations is given in table 1. The Reynolds value for this station is calculated for a wind speed of 5 m/s because this is a reasonable wind speed for a wind turbine which is used in regions with moderate wind speeds. The blade has a pentagon shape but it is assumed that the aerodynamic characteristics of a flat square sheet can be used. These characteristics are given in report KD 551 (ref. 3). The characteristics are given for a lowest Reynolds value of 2 * 10^5 but as the characteristics are not sensible for Reynolds it is assumed that the characteristics can also be used for lower Reynolds values. In figure 2 of KD 551 it can be read that α = 14.5° for C_l = 0.58.

sta-tion	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)
A	0.195	0.903	31.9	0.16	0.58	0.44	0.59	2	14.5	11.9	17.4	20

table 1 Calculation of the blade geometry of the VIRYA-0.54 rotor

The theoretical blade angle β_{th} = 17.4° but this is rather small and the starting torque coefficient of the rotor may be not large enough to get an acceptably low starting wind speed. So provisionally β_{lin} has increased up to 20° but this results in a decrease of α_{lin} up to 8.5° and a decrease of $C_{l\,lin}$ up to 0.44. If a prototype of the rotor is available, one can try different blade angles β and see how the starting torque coefficient and the optimum tip speed ratio varies.

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. As the rotor isn't designed according to the aerodynamic theory, the maximum power coefficient $C_{p\ max}$ will be rather low. Assume that $C_{p\ max} = 0.3$ for $\lambda_d = 1.25$ and for $\beta = 20°$. For the optimum torque coefficient $C_{q\ opt}$, it is valid that $C_{q\ opt} = C_{p\ max} / \lambda_d = 0.3 / 1.25 = 0.24$.

Substitution of $\lambda_{opt} = \lambda_d = 1.25$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 2$. However, formula 6.4 isn't correct for rotors with a very low value of λ_d and the real value of λ_{unl} is somewhat higher. Assume $\lambda_{unl} = 2.25$

The starting torque coefficient is calculated with formula 6.12 of KD 35 which is copied as formula 6.

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

The blade angle $\beta = 20°$. For a non rotating rotor, the angle $\phi = 90°$. The angle of attack α is therefore 90° - 20° = 70°. In figure 2 of KD 551 it can be read that $C_l = 0.39$ for $\alpha = 70°$. The average blade length k is about 140 mm = 0.14 m

Substitution of B = 8, R = 0.27 m, k = 0.14 m, $C_l = 0.39$ and c = 0.16 m in formula 6 gives that $C_{q\ start} = 0.17$. For the ratio in between the starting torque and the optimum torque we find that it is 0.17 / 0.24 = 0.71. This is rather high for a rotor with a design tip speed ratio of 1.25. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

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, $C_{q\ start} = 0.17$, $\rho = 1.2$ kg/m^3 and R = 0.27 m in formula 7 gives that $V_{start} = 3.6$ 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, $C_{q\ start} = 0.17$, $\rho = 1.2$ kg/m^3 and R = 0.27 m in formula 7 gives that $V_{start} = 2.9$ m/s. So this means that once the rotor is rotating a little, it will start at a wind speed of 2.9 m/s because of the fly wheel effect of the rotor. So the effective starting wind speed will be about 3.2 m/s which is higher than for the VIRYA-1.04 rotor for which V_{start} is about 2.6 m/s. The starting torque coefficient can be increased by increase of the blade angle β. In figure 2 of KD 551 it can be seen that the C_l-α curve is about a straight line for large angles α. So increase of the blade angle β results in about a linear increase of the starting torque coefficient.

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 flat 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-0.54 rotor are given in figure 1 and 2.

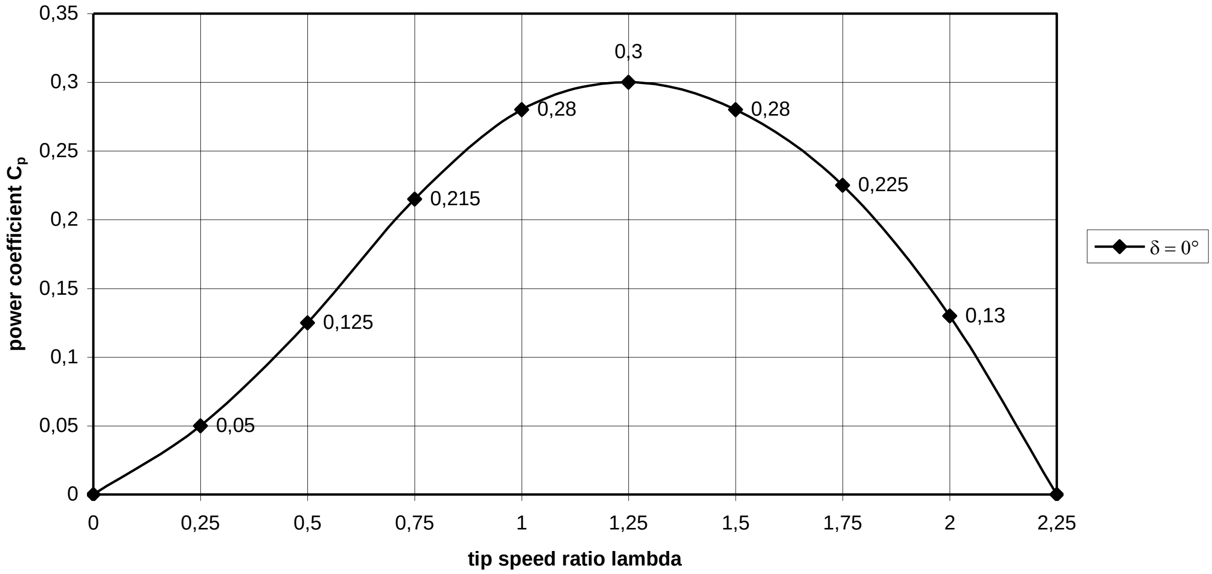

fig. 1 Estimated C_p-λ curve for the VIRYA-0.54 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

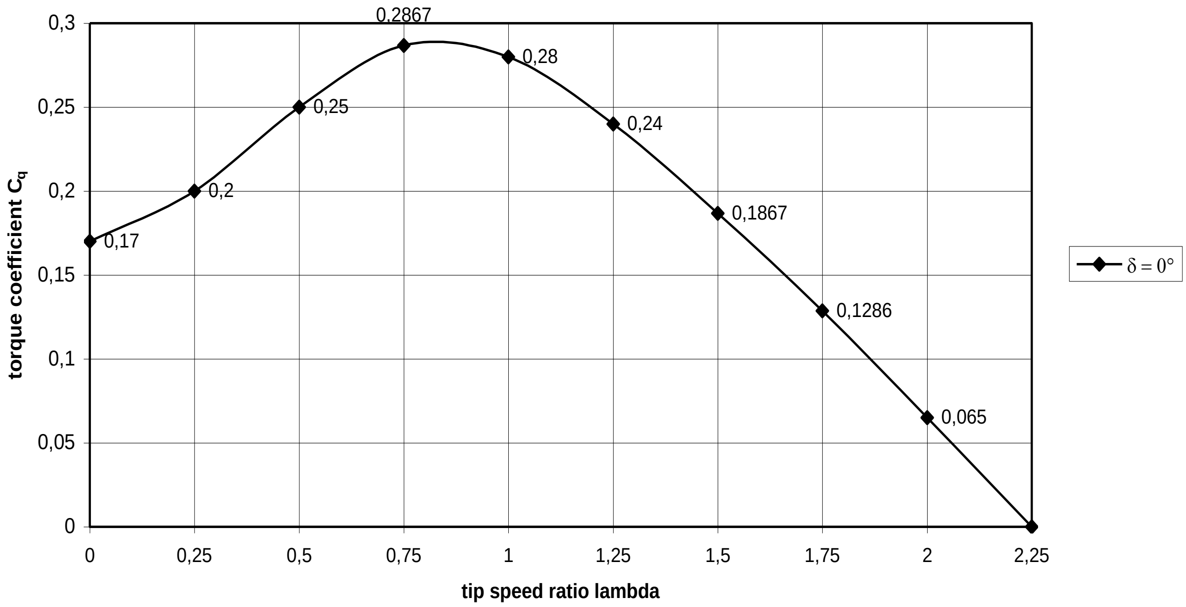

fig. 2 Estimated C_q-λ curve for the VIRYA-0.54 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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 VIRYA-0.54 has no safety system and so it is assumed that the rotor is perpendicular to the wind. It is assumed that the wind turbine is laid down for wind speeds higher than about 10 m/s (36 km/hour) and so the P-n curves are determined for wind speeds up to 10 m/s.

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-0.54 has no gearing so i = 1). The P-n curves are determined for C_p values belonging to λ is 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2 and 2.25 (see figure 1). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 10 m/s. As the rotor is perpendicular to the wind, the formulas for P and n are used which are given in chapter 4 of KD 35.

Substitution of R = 0.27 m in formula 4.8 of KD 35 gives:

$$n = 35.368 * \lambda * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 0.27 m in formula 4.1 of KD 35 gives:

$$P = 0.1374 * C_p * V^3 \qquad \text{(W)} \qquad (9)$$

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 = 3 m/s		V = 4 m/s		V = 5 m/s		V = 6 m/s		V = 7 m/s		V = 8 m/s		V = 9 m/s		V = 10 m/s	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.25	0.05	26.5	0.19	35.4	0.44	44.2	0.86	53.1	1.48	61.9	2.36	70.7	3.52	79.6	5.01	88.4	6.87
0.5	0.125	53.1	0.46	70.7	1.10	88.4	2.15	106.1	3.71	123.8	5.89	141.5	8.79	159.2	12.52	176.8	17.18
0.75	0.215	79.6	0.80	106.1	1.89	132.6	3.69	159.2	6.38	185.7	10.13	212.2	15.12	238.7	21.54	265.3	29.54
1	0.28	106.1	1.04	141.5	2.46	176.8	4.81	212.2	8.31	247.6	13.20	282.9	19.70	318.3	28.05	353.7	38.47
1.25	0.3	132.6	1.11	176.8	2.64	221.1	5.15	265.3	8.90	309.5	14.14	353.7	21.10	397.9	30.05	442.1	41.22
1.5	0.28	159.2	1.04	212.2	2.46	265.3	4.81	318.3	8.31	371.4	13.20	424.4	19.70	477.5	28.05	530.5	38.47
1.75	0.225	185.7	0.83	247.6	1.98	309.5	3.86	371.4	6.68	433.3	10.60	495.2	15.83	557.0	22.54	618.9	30.92
2	0.13	212.2	0.48	282.9	1.14	353.7	2.23	424.4	3.86	495.2	6.13	565.9	9.15	636.6	13.02	707.4	17.86
2.25	0	238.7	0	318.3	0	397.9	0	477.5	0	557.0	0	636.6	0	716.2	0	795.8	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-0.54 rotor

The calculated values for n and P are plotted in figure 3. The optimum cubic line which is going through the tops of the P_{mech}-n curves is also given in figure 3.

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 3.

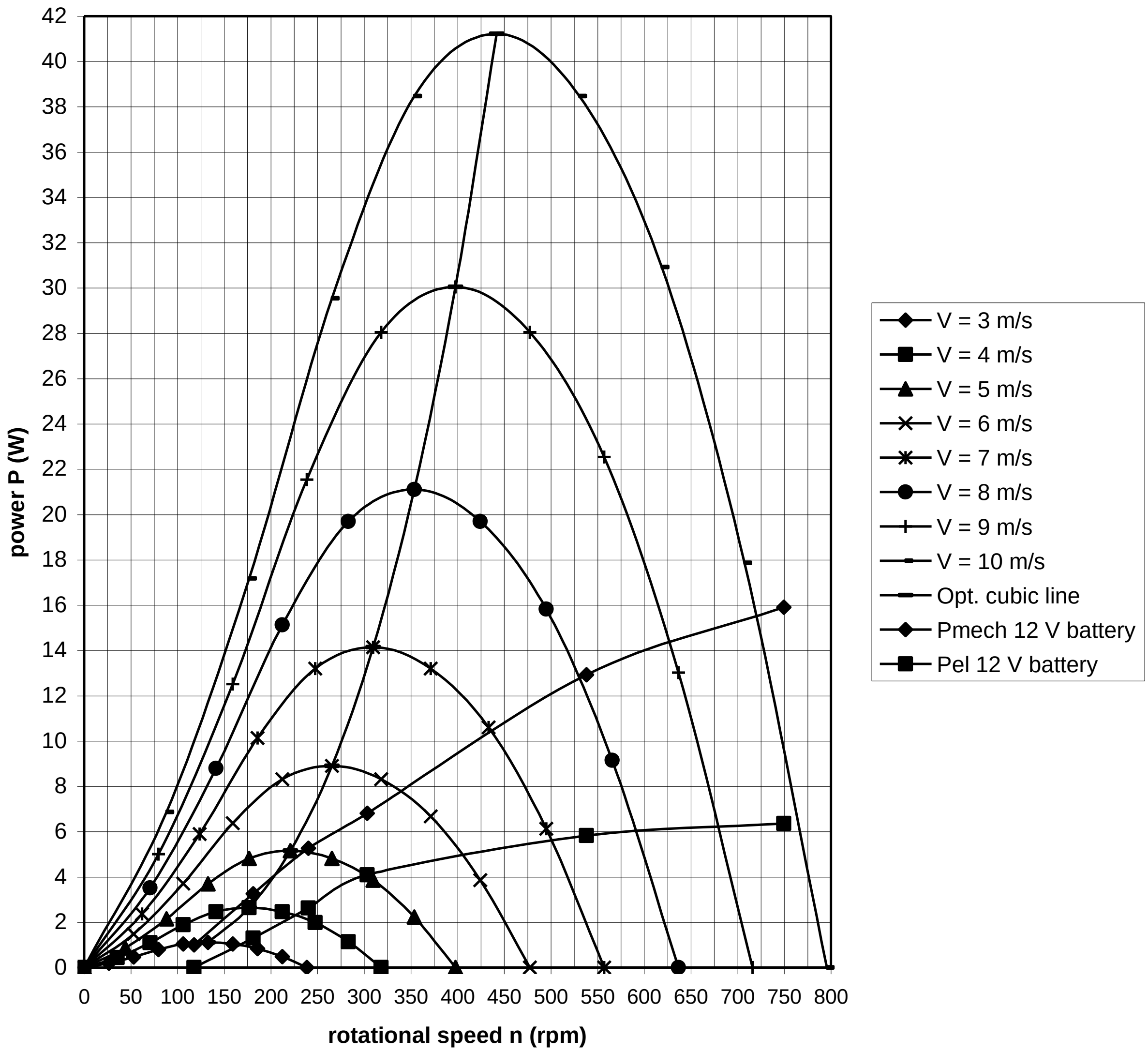

fig. 3 P-n curves and optimum cubic line of the VIRYA-0.54 rotor, measured P_{el}-n curves and estimated P_{mech}-n curves for a 12 V battery load

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 4.

In figure 3 it can be seen that the matching in between rotor and generator is only good for 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 10 m/s is about 725 rpm and the tip speed ratio is about 2. The rotor won’t be noisy at this tip speed ratio.

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-0.54 windmill on the roof of a house as the vibration will probably be felt and heard inside. It is certainly not allowed to use the VIRYA-0.54 for wind speeds higher than 10 m/s as then the rotational speed will become much too high. This is the disadvantage of using no safety system.

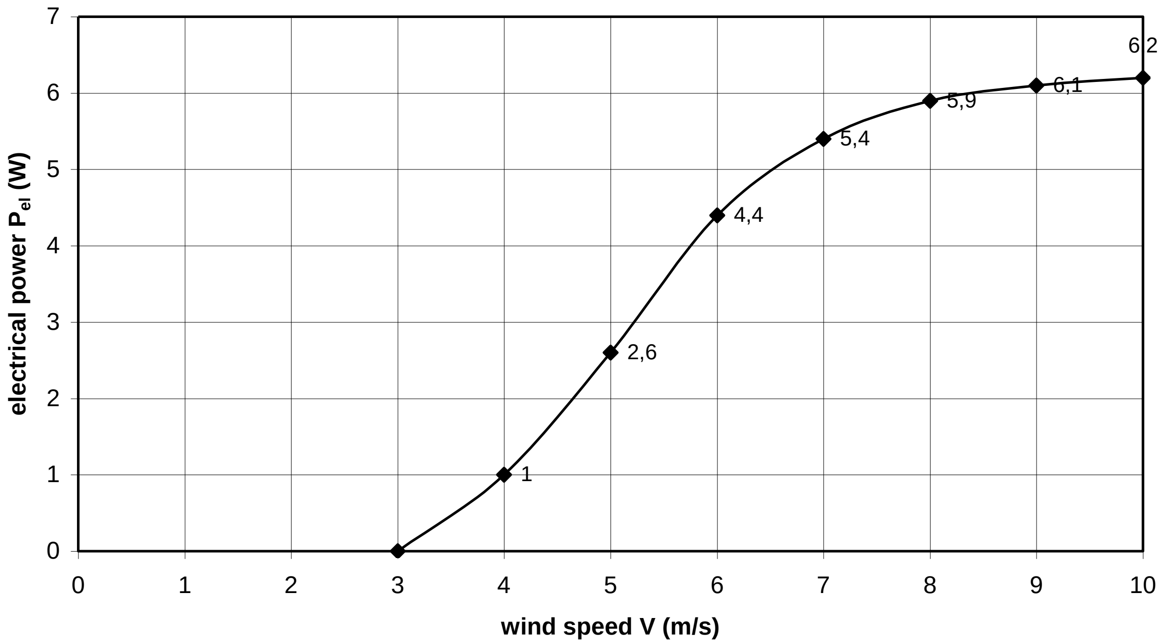

fig. 4 P_{el}-V curve of the VIRYA-0.54 windmill for 12 V battery charging

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 $V_{cut\ in}$ = 3 m/s. This is low enough for areas with moderate wind speeds. In chapter 4 it was calculated that the effective starting wind speed is about 3.2 m/s. So there is some hysteresis in the P_{el}-V curve for 3 < V < 3.2 m/s.

The maximum electrical power is about 6.2 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 6 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.

Although the rotor isn't designed according to the aerodynamic theory, it might still have acceptable characteristics. When I was working at the Wind Energy Group of the University of Technology Eindhoven, we have tested an 8-bladed rotor with square blades in the wind tunnel. This rotor was meant as wind servo but it had rather good characteristics if the rotor was perpendicular to the wind. It has been measured for a range of blade angles β and yaw angles δ. The measurements are given in report R-668-A (ref. 6). Recently I have made a summary of this report for the blade angle β = 30°. These summary is given in report KD 671 (ref. 7). The rotor had an optimum tip speed ratio of 2 for this blade angle. So it can be expected that the blade angle of the VIRYA-0.54 can be increased without getting a much lower optimum tip speed ratio.

6 References

1 Kragten A. Manual of electricity generating windmill VIRYA-1.04, February 2013, reviewed March 2014, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands, can be copied for free from my website.

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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.

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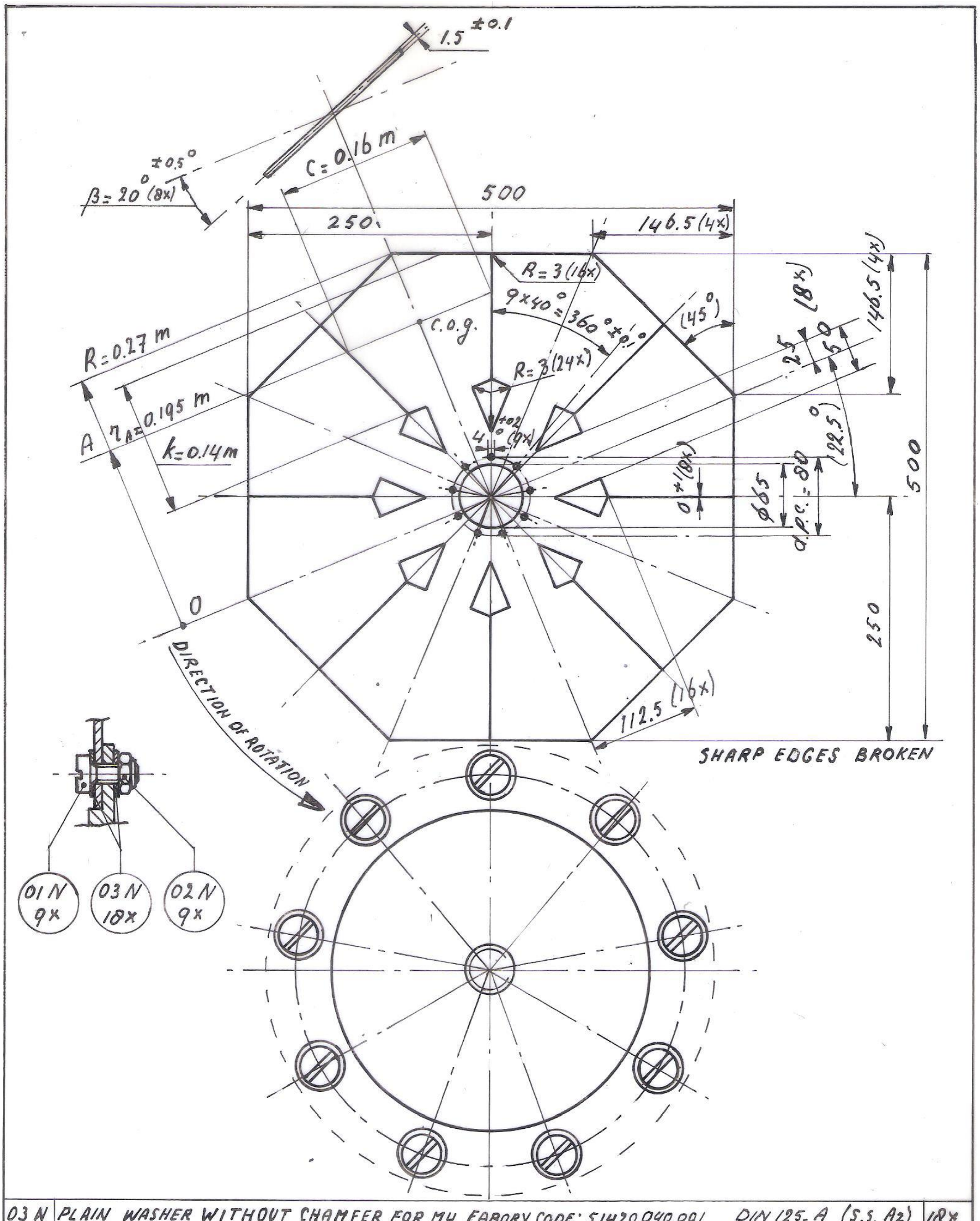
7 Kragten A. Translation of parts of report R-668-A, “Optimalisering van een windservo” (optimization of a wind servo) from Dutch into English. Ideas about the VIRYA-2B8, February 2019, free public report KD 671, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1 VIRYA-0.54 rotor, $\lambda_d = 1.25$, B = 8



03 N	PLAIN WASHER WITHOUT CHAMFER FOR M4 FABORY CODE: 51420 040.001 DIN 125-A (S.S. A2)	18x
02 N	HEXAGON NUT WITH PLASTIC INSERT M4 STAINLESS STEEL A2 FABORY CODE: 51730 040.001 DIN 985	9x
01 N	SLOTTED CHEESE HEAD SCREW M4x10 STAINLESS STEEL A2 FABORY CODE: 51121 040.010 DIN 84	9x

DRAWING NUMBER 2001-01	SUBJECT	VIRYA-0.54 ROTOR	TOLERANCE	±0.2
DRAWN BY: A.KRAGTEN	MATERIAL	ALUMINIUM HALF HARD ENAW-5754	SCALE	1:5 1:1
DATE: 14-8-2020			ROUGHNESS	6.3
AMERICAN PROJECTION	TREATMENT	—	MASS (KG)	0.79