Calculations executed for the 2-bladed rotor of the VIRYA-2.92 windmill (λ_d = 6, stainless steel tapered blades) driving the VIRYA-2.68 PM-generator for 24 V battery charging

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1 Introduction

Already in June 1978 I have performed measurements on a 2-bladed windmill rotor with tapered blades cut from a cylinder. The rotor and the measurements are described in the Dutch report R 343 D (ref. 1) of which the title can be translated as: “Report of wind tunnel measurements performed on a 2-bladed rotor with blades made out of a cylinder”. This report is no longer available but in November 2016 I have made an English translation of the parts out of report R 343 D about the rotor with 2 mm stainless steel blades and a design tip speed ratio $\lambda_d = 6$. This translation has report number KD 616 (ref. 2).

In 1978 I was working as a technical designer of water pumping windmills, pumps and test rigs at the Wind Energy Group of the University of Technology Eindhoven. This group was a member of CWD, Consultancy services Wind energy Developing countries. The measurements have been performed in the open wind tunnel of TNO Waddinxveen. TNO was a member of CWD during the first five years of CWD. This wind tunnel is later moved to the University of Delft and I have measured several other rotors in this wind tunnel. The wind tunnel is blowing air into the open space and the wake therefore can expand around the rotor which also happens in real wind. So there is no tunnel blockage as it is the case for closed wind tunnels. The measurements are therefore very accurate. The wind tunnel has a diameter of 2.2 m and the maximum rotor diameter of a rotor which can be measured is 1.8 m. All measured rotors as described in R 343 D have a diameter of 1.8 m.

It was rather difficult and expensive to manufacture the measured rotor. In chapter 5 of KD 616, a slightly larger rotor with a diameter of 2.02 m is described which also makes use of 2 mm stainless steel for the blades but for which the blades are connected to the generator hub by a simple twisted and cambered connecting strip. It seems possible to use a similar construction for a bigger rotor with tapered blades made out of 3 mm stainless steel sheet. The geometry of this bigger rotor is chosen such that the rotor matches well with the VIRYA-2.68 PM-generator and that there is an efficient use of material for the blades and for the connecting strip. It appears that this is the case for a rotor diameter of 2.92 m and the windmill is therefore called the VIRYA-2.92.

The measurements of the VIRYA-2.68 generator are given in report KD 78 (ref. 3). The VIRYA-2.92 will be used for 24 V battery charging and the generator with the original 230/400 V winding must rectified in delta for this use. The VIRYA-2.92 can also be used for 48 V battery charging if the winding is rectified in star but 48 V is a less current voltage. The VIRYA generators are described in report KD 341 (ref. 4). The generator is based on an asynchronous 3-phase motor of manufacture ROTOR type 5RN90L04V (frame size 90 with lengthened stator iron) for which the short-circuit armature is replaced by an armature provided with permanent magnets. The drawing of the VIRYA-2.68 generator is not public but an alternative generator using a housing frame size 100 is described in report KD 503 (ref. 5). This generator will have about the same characteristics as the VIRYA-2.68 generator.

The VIRYA-2.68 also has a 2-bladed rotor with cambered stainless steel blades but these blades have a constant chord which makes them easier to manufacture than tapered blades. However, the maximum C_p for a rotor with tapered blades is higher and the blades are producing less noise because the angle of attack is lying very close to the angle for which the drag lift ratio is minimal. Other advantages of tapered blades are that the rotor is stronger and that it looks better. So if one has the technical skills to manufacture tapered blades, the VIRYA-2.92 might be a good option.

The head and the tower are the same as the head and tower of the VIRYA-3 and the VIRYA-3B3 windmills with wooden blades. This head results in a rated wind speed of about 11 m/s. The effect of the slightly lower rotor diameter of the VIRYA-2.92 on the rotor thrust is compensated because rotors with cambered steel blades have a slightly larger thrust coefficient (about 0.75 in stead of 0.7).

2 Description of the rotor of the VIRYA-2.92 windmill

The 2-bladed rotor of the VIRYA-2.92 windmill has a diameter D = 2.92 m and a design tip speed ratio λ_d = 6. Advantages of a 2-bladed rotor are that no welded spoke assembly is required and that the rotor can be balanced and transported easily even if it is mounted.

The rotor has tapered blades which are made out of a cylinder. The camber is therefore small at the blade tip and large at the blade root. In the first instance, the blade geometry is chosen such that the blade is scaled as good as possible to the blades of the 1.8 m rotor which was tested in the wind tunnel. The scale factor is 2.92 / 1.8 = 1.6222. The original 1.8 m rotor had a sheet width at the blade tip of 75 mm, so the sheet width of a VIRYA-2.92 blade must be about 75 * 1.6222 = 122 mm.

The free blade length of the original 1.8 m rotor was 0.8 m for 2 mm stainless steel sheet. As freely supported cambered steel blades are sensible to flutter at high wind speeds, the free blade length should have a certain ratio with the sheet thickness. So if the sheet thickness is increased by a factor 1.5 from 2 mm up to 3 mm, the free blade length can also be increased by a factor 1.5 from 0.8 m up to 1.2 m.

It is decided to use 3 mm stainless steel sheet size 1250 * 2500 mm for the blades. So the blade length becomes 1.25 m. It is decided that there is an overlap of 40 mm = 0.04 m in between a blade and the connecting strip. This means that the free blade length is 1.21 m. This seems acceptable.

In the first instance, a sheet size 1250 * 2500 mm is cut into seven sheets size 357 * 1250 mm. Cambering of tapered blades is difficult as it requires a complicated press. Cambering of a rectangular sheet is easier and it can be done with a hydraulic blade press similar to the blade press which is used for constant chord blades. So the rectangular sheet is cambered with the correct radius. The radius of the original blades is 150 mm. So the radius of the VIRYA-2.92 blades must be about 1.6222 * 150 = 243.3 mm. Assume a camber radius of 250 mm is chosen. One sheet has to be divided in two tapered blades but as the sheet is already cambered, this can’t be done with a bench shears. So the sheet is ground into two tapered blades by a rectangular grinder. Assume this grinder makes a 2 mm wide groove. Assume the sheet width at the blade tip is chosen 125 mm. So the sheet width at the blade root will be 357 – 125 – 2 = 230 mm. The taper angle of the blade for this geometry is 4.80°. The taper angle of the blades of the original 1.8 m rotor is 4.74° so almost the same.

However, provisional rotor calculations executed for a blade with these dimensions have shown that the required lift coefficients are rather high for a design tip speed ratio of 6. Lower lift coefficients can be obtained if the chords are chosen larger so if a standard sheet size 1250 * 2500 mm is not cut into seven strips but into six strips. For six strips, the strip size becomes 416.7 * 2500 mm. This sheet is ground into two identical tapered sheets. Assume that the width of the grinding groove is 1.7 mm. Assume that the width at the blade tip is chosen 145 mm. So the width at the blade root is 416.7 – 145 – 1.7 = 270 mm. The camber radius is now chosen 290 mm. The taper angle of the blade for this geometry is now 5.71°, so about 1° larger than for the blades of the original 1.8 m rotor. The airfoil nose and the tailing edge of the blade have to be rounded with a radius of at least 1 mm to minimise drag.

For the connecting strip, it is decided to use stainless steel strip in stead of stainless steel sheet. The widest standard strip size is 150 mm for a strip thickness of 6 mm. The dimensions of the connecting strip are chosen 150 * 6 * 500 mm, so 12 connecting strips can be made from a standard 6 m strip. Both ends of the connecting strip are cambered with the same radius as used for the blades. The overlap in between a blade and the connecting strip is 40 mm resulting in a rotor diameter of 2 * 1250 + 500 – 2 * 40 = 2920 mm = 2.92 m. A blade is connected to the connecting strip by three bolts M10. Both ends of the connecting strip are twisted such that the correct blade angle at the blade tip is realised.

The cambered part of the connecting strip has a length of 40 mm but the camber transfers fluently to the flat central part of the blade. It is assumed that this transfer part has an effective length of about 60 mm so the central 300 mm of the connecting strip isn't cambered. This makes the connecting strip rather flexible and this neutralizes the vibrations due to the gyroscopic moment which are inherent for 2-bladed rotors.

The hub is made out of a piece of round bar of 70 mm with a tapered hole in the middle for connection to the generator shaft. The alternative generator frame size 100 needs a 28 mm cylindrical hole with a key groove. The connecting strip is bolted to the hub by four bolts M10. One central bolt M10 is used for connection of the hub against the tapered generator shaft. The rotor is balanced by grinding so much from the heaviest blade tip till it is just in balance. After balancing blades and strip are marked.

3 Calculation of the rotor geometry

The original 1.8 m rotor was calculated but the calculations are lost as they are not mentioned in report R 343 D. However, the result of the calculation is given in a table which is mentioned on the manufacturing drawing of the rotor. A reduced copy of this drawing is given in figure 1 of KD 616 (ref. 2). The rotor calculations were made for only four stations. Six stations will be chosen for the VIRYA-2.92 rotor. These stations are called A, B, C, D, E and F and for the corresponding local radii r it is chosen that r_A = 1.46 m, r_B = 1.21 m, r_C = 0.96 m, r_D = 0.71 m, r_E = 0.46 m and r_F = 0.21 m. Station F corresponds to the blade root. The direction of numbering is just opposite that of the original 1.8 m rotor but the chosen direction is the same as for all other VIRYA rotors.

A problem with making of the rotor calculations for the VIRYA-2.92 rotor is that the camber is different for each station. The chord c and the camber C of each station can be calculated using the formulas given in chapter 5 of report KD 398 (ref. 6) but for the rotor calculations one needs aerodynamic characteristics for different camber. In KD 398 these characteristics are given only for 7.14 %, 10 % and 12.5 % camber.

The sheet width b can be calculated easily for the six chosen stations as the flat sheet is tapered linear. However, the chord c is smaller than the sheet width b and how much smaller depends on the camber. The sheet width was chosen 145 mm at the blade tip (at r_A = 1.46 m) and 270 mm at the blade root (at r_F = 0.21 m). So the difference is 125 mm. This means that the sheet width b increases 125 / 5 = 25 mm per station. This gives the following values: b_A = 145 mm, b_B = 170 mm, b_C = 195 mm, b_D = 220 mm, b_E = 245 mm and b_F = 270 mm. The camber radius was chosen 290 mm. The formulas which give the relation in between the strip width b, the chord c, the camber radius r_c, the airfoil thickness a, the half camber angle α_c and the camber C are given in chapter 5 of report KD 398. Figure 8 of KD 398 gives the geometry of a cambered plate. The calculations can be made on a pocket calculator if it is put in the modulus "rad". The strip width b and the bending radius r_c is known. We want to calculate the chord c and the camber C. First we have to calculate the half camber angle α_r which is given by formula 1 of KD 398. Next c is calculated with formula 5 of KD 398. Next C is calculated with formula 6 of KD 398. The result of the calculations is given in table 1.

Station	b (mm)	r_c (mm)	α_c (rad)	c (mm)	c (m)	C (%)
A	145	290	0.2500	143.5	0.1435	6.28
B	170	290	0.2931	167.6	0.1676	7.38
C	195	290	0.3362	191.3	0.1913	8.49
D	220	290	0.3793	214.8	0.2148	9.60
E	245	290	0.4224	237.8	0.2378	10.72
F	270	290	0.4655	260.3	0.2603	11.85

table 1 Calculated values of the chord c and the camber C for different stations

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 7). This report (KD 656) has its own formula numbering. Substitution of λ_d = 6 and R = 1.46 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 4.1096 * r$ (-) (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 = 2 in formula (5.4) of KD 35 gives:

$C_l = 12.566 * r (1 - \cos\phi) / c$ (-) (4)

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

$R_{e\,r} = 3.335 * 10^5 * c * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.25 m of one to another. The blade has a chord which increases at decreasing radius and the calculations therefore correspond with the example as given in chapter 5.4.1 of KD 35. This means that the lift coefficient should be about constant and about equal to the optimum lift coefficient for the whole blade. First the theoretical values are determined for C_l, α and β. Next the real blade angle β_{real} is determined for the chosen blade taper using figure 1. The result of the calculations is given in table 2. The aerodynamic characteristics of cambered airfoils are given in report KD 398 (ref. 6). 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 with V_{rated} = 11 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	Camber C (%)	$R_e * 10^{-5}$	α_{th} (°)	β_{th} (°)	β_{real} (°)
A	1.46	6	6.3	0.1435	0.77	2.89	6.28	2.5	0.3	6.0	4.5
B	1.21	4.973	7.6	0.1676	0.79	2.80	7.38	2.5	0.5	7.1	7.0
C	0.96	3.945	9.5	0.1913	0.86	2.55	8.49	2.5	0.5	9.0	9.5
D	0.71	2.918	12.6	0.2148	1.00	2.14	9.60	2.5	0.6	12.0	12.0
E	0.46	1.89	18.6	0.2378	1.27	1.59	10.72	1.7	3.6	15.2	14.5
F	0.21	0.863	32.8	0.2603	1.62	0.95	11.85	1.2	8.1	24.7	17.0

table 2 Calculation of the blade geometry of the VIRYA-2.92 rotor

In table 1 it can be seen that the theoretical lift coefficient C_{lth} is not constant but increasing at decreasing values of r. But the increase is less than for a constant chord blade.

The camber is increasing from 6.28 % at station A the to 11.85 % at station F. To find the theoretical angels of attack α_{th} we really need C_l-α curves for the six different cambers. However, only characteristics for 7.14 %, 10 % and 12.5 % are available. The C_l-α curve for 7.14 % camber was used for station A and B. The average of the C_l-α curves for 7.14 % and 10 % camber was used for station C. The C_l-α curve for 10 % camber was used for stations D and E. The C_l-α curve for 12.5 % camber was used for station F.

In table 1 it can be seen that the theoretical blade angles β_{th} vary in between 6° at the blade tip and 24.7° at station F. In the table at figure 1 of report KD 616 it can be seen that the blade angle at the blade tip is only 2.1°, so much smaller than 6°. A problem with a rotor made out of a cylinder is that only the blade angle at the blade tip β_A can be adjusted at a certain value. The blade angles at other stations depend on the taper of the blade and are difficult to calculate for a certain value of β_A but they were found using a composite drawing of the cross sections of the 1.8 m rotor which is given at the right side in figure 1 of KD 616. A similar composite drawing was made for the six stations of a VIRYA-2.92 blade for different values of β_A. The composite drawing for the right blade seen from the right side is given as figure 1. It was found that β_A = 4.5° gives that real values of β for the sections B, C, D and E which match best with the calculated values of β_{th} in table 2. The values for β found from the composite drawing are given in table 2 as β_{real}. For station F, β_{real} is much smaller than β_{th} which means that the real angle of attack α_{real} is much bigger than α_{th}. This means that the airfoil is stalling at station F but this is acceptable as station F contributes only very little to the generated power.

The angle for which the connecting strip has to be twisted to get the correct blade angle at the blade tip is a bit larger than β_A. This is because the sheet width at the blade tip is 145 mm but the width of the connecting strip is 150 mm. The angle for which the connecting strip has to be twisted right hand is 5° for β_A = 4.5°. A sketch of the rotor is given in figure 2.

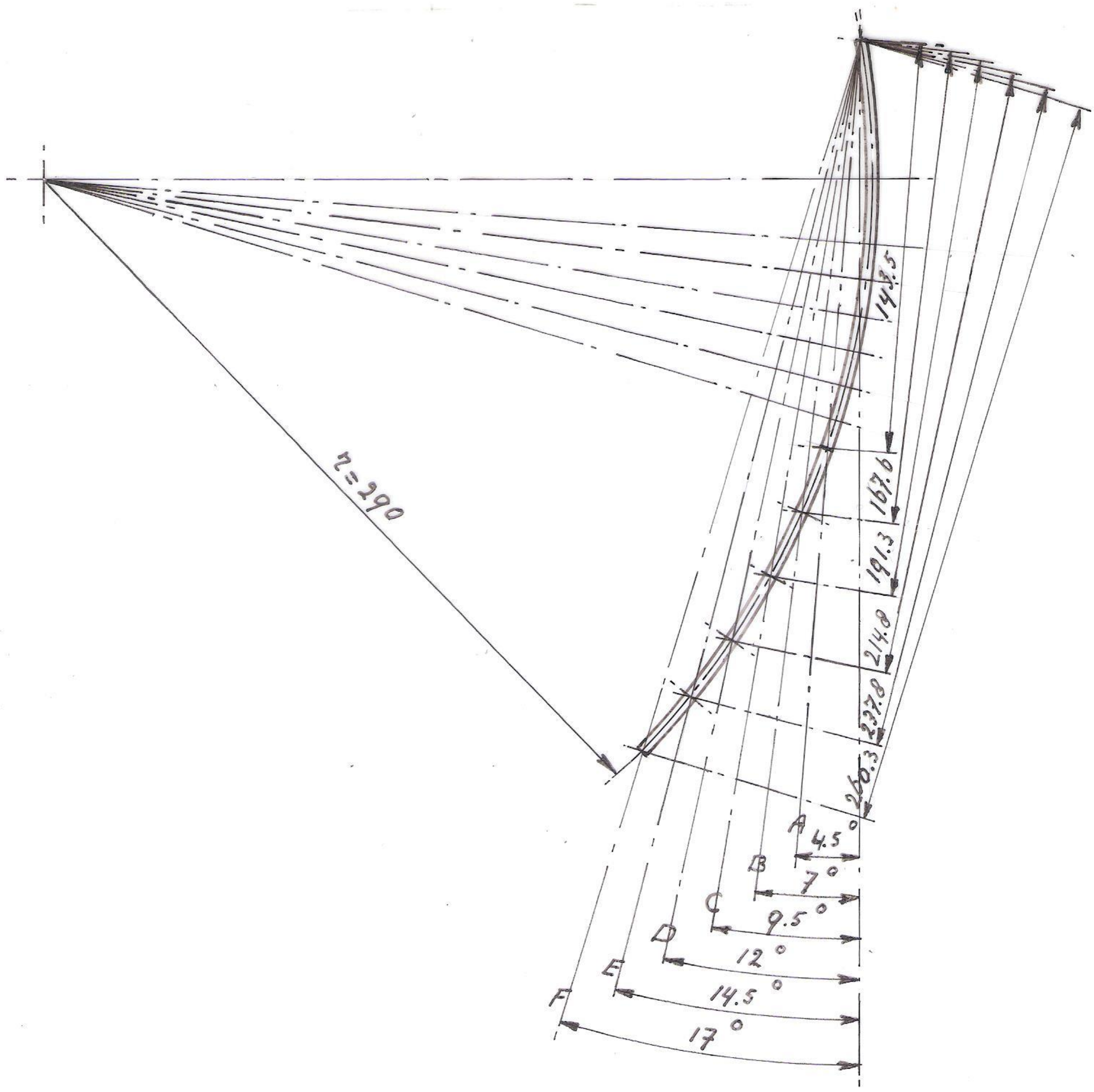

fig. 1 The right blade for six stations A, B, C, D, E and F

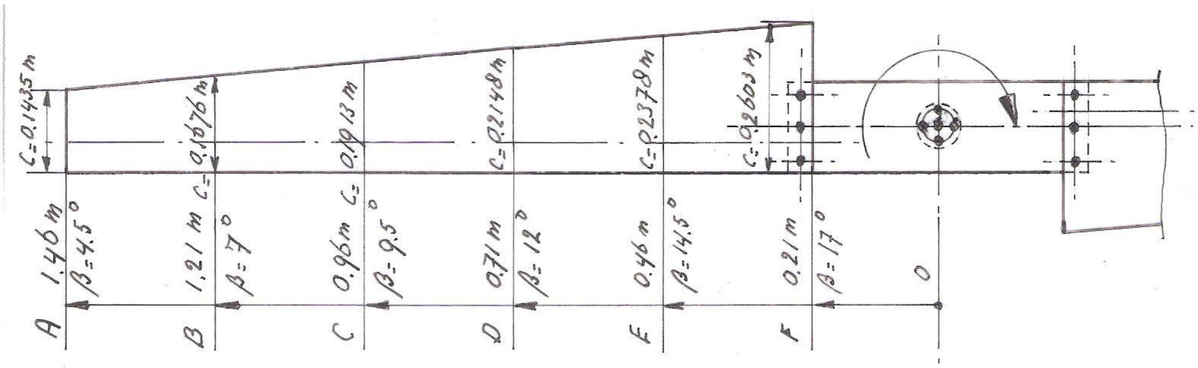

fig. 2 Front view of the VIRYA-2.92 rotor

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. However, the original 1.8 m diameter rotor has been measured in the wind tunnel and the measured characteristics should be more accurate than estimated ones. The wind tunnel measurements for the rotor with 2 mm stainless steel blade were only performed for a wind tunnel speed of 11 m/s which results in rather high Reynolds values. The VIRYA-2.92 is a factor 1.622 larger than the tested rotor. However, the chord is relatively about a factor 7/6 larger because six in stead of seven strips were cut from a standard sheet size 1.25 * 2.5 m. This means that the Reynolds value is about a factor 1.622 * 7/6 = 1.892 larger for a wind speed of 11 m/s. So the Reynolds value is the same for a wind speed of 11 / 1.892 = 5.8 m/s. But this is still larger than the value of 5 m/s which was used for the rotor calculations.

The measured C_p-λ and C_q-λ curves are given in figure 2 and 3 of KD 616. The C_p is about 0.41 for $\lambda = 6$. However, there is an unusual peak in the C_p-λ curve for $6.3 < \lambda < 7.5$. A similar rotor made out of 2 mm aluminium sheet has been measured for a tunnel speed of 5.5 m/s and then there is no unusual peak in the C_p-λ curve. So the peak must be caused by Reynolds effects and is explained in KD 616 as the result of the special shape of the C_l-α curve of a 10 % cambered airfoil as measured by Volkers.

For the VIRYA-2.92 it is assumed that the C_p-λ curve has no unusual peak at higher tip speed ratios and that the maximum $C_p = 0.41$ for $\lambda_d = 6$. As the VIRYA-2.92 rotor has chords which are relatively larger than those of the 1.8 m original rotor and as the blade angle at the tip is 4.5° in stead of 2.1° it is assumed that the starting torque coefficient is 0.0075 in stead of 0.005. The estimated C_p-λ and C_q-λ curves are given in figure 3 and 4. The curves are made about similar to the measured curves except for the unusual peak and the starting torque coefficient. But for high wind speeds, the peak will exist. If the rotor is running in the peak area it will produce more power and it will make very little noise.

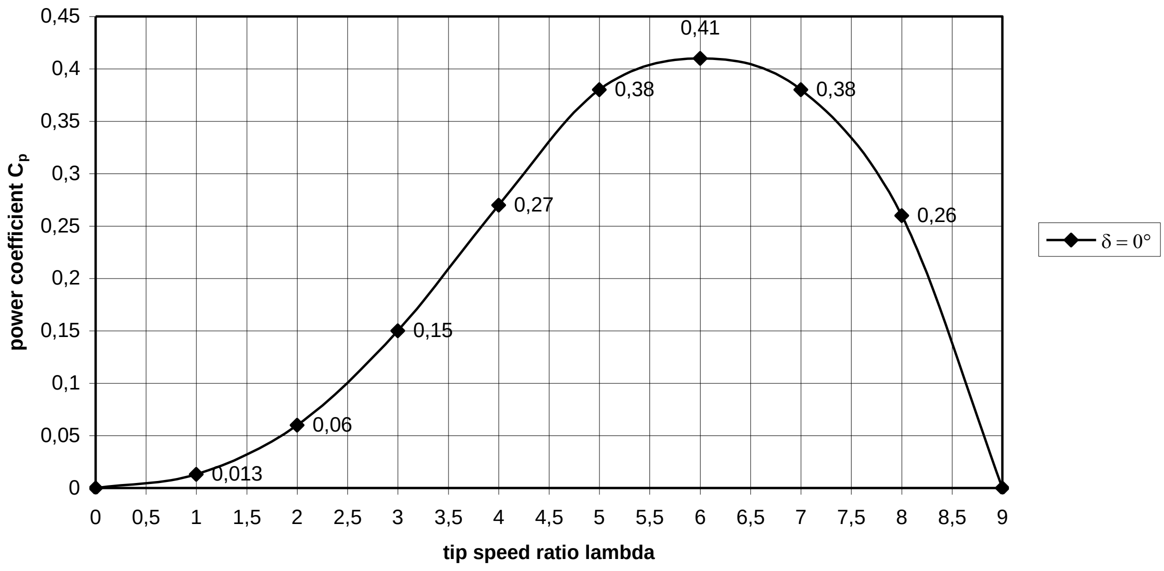

fig. 3 Estimated C_p-λ curve for the VIRYA-2.92 rotor for the wind direction perpendicular to the rotor (δ = 0°)

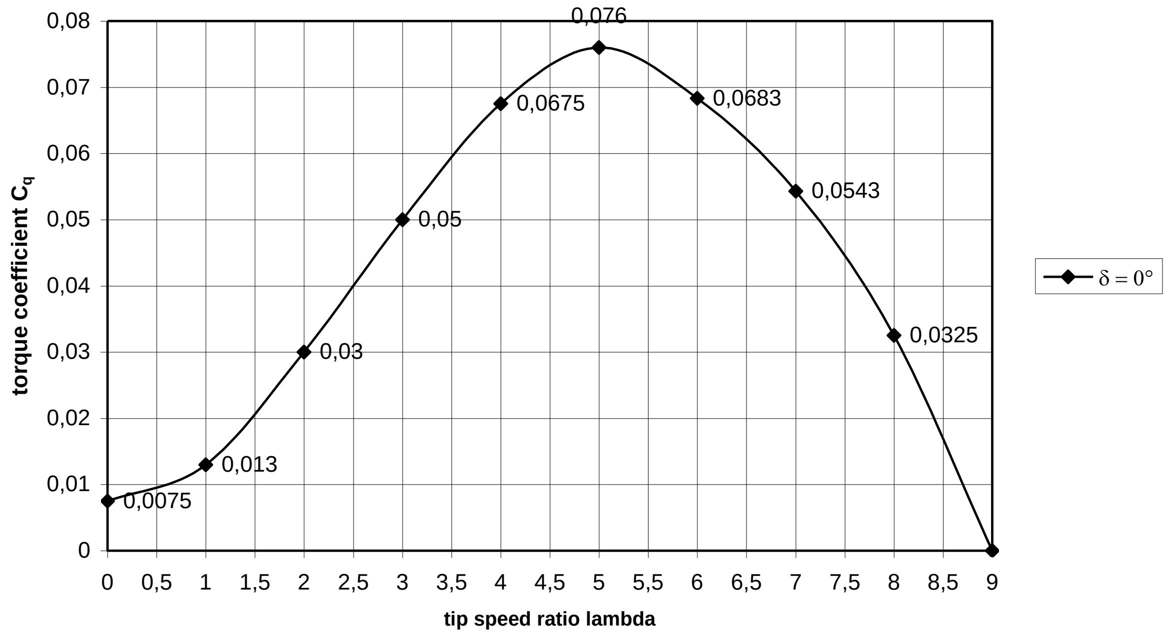

fig. 4 Estimated C_q-λ curve for the VIRYA-2.92 rotor for the wind direction perpendicular to the rotor (δ = 0°)

In figure 4 it can be seen that for the starting torque coefficient it is valid that C_{qstart} = 0.0075. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * \frac{1}{2}\rho * \pi R^3} \right)} \quad \text{(m/s)} \qquad (6)$$

For the generator, a sticking torque Q_s has been measured of about 0.4 Nm if the shaft is not rotating. Substitution of $Q_s = 0.4$ Nm, $C_{q\ start} = 0.0075$, $\rho = 1.2$ kg/m^3 and R = 1.46 m in formula 6 gives that $V_{start} = 3$ m/s. This is acceptable low for a 3-bladed rotor with a design tip speed ratio of 6. If the generator is used in delta for 24 V battery charging, the unloaded Q-n curve is rising faster than for star rectification because higher harmonic currents can circulate in the winding. However, the Q-n curve of the rotor is also rising rather fast and therefore the real starting wind speed will be about the same as the calculated value.

5 Determination of the P-n curves and the P_{el}-V curve for 24 V battery charging

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 a 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 3. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 9 mm meranti waterproof plywood with a density of about 0.6 *10^3 kg/m^3. This vane blade gives a rated wind speed V_{rated} of about 11 m/s. In report KD 223 (ref. 8) a method is given to check the estimated δ-V curve and the estimated δ-V curve of the VIRYA-3.3D windmill is checked as an example. This windmill also has a vane blade made of 9 mm plywood. So the δ-V curve of the VIRYA-3.3D will be about the same as for the VIRYA-2.92. The estimated and calculated curves appear to lie very close to each other so it is allowed to use the estimated curve. The estimated curve is given in figure 5.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 11 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 11 m/s will therefore also be valid for wind speeds higher than 11 m/s.

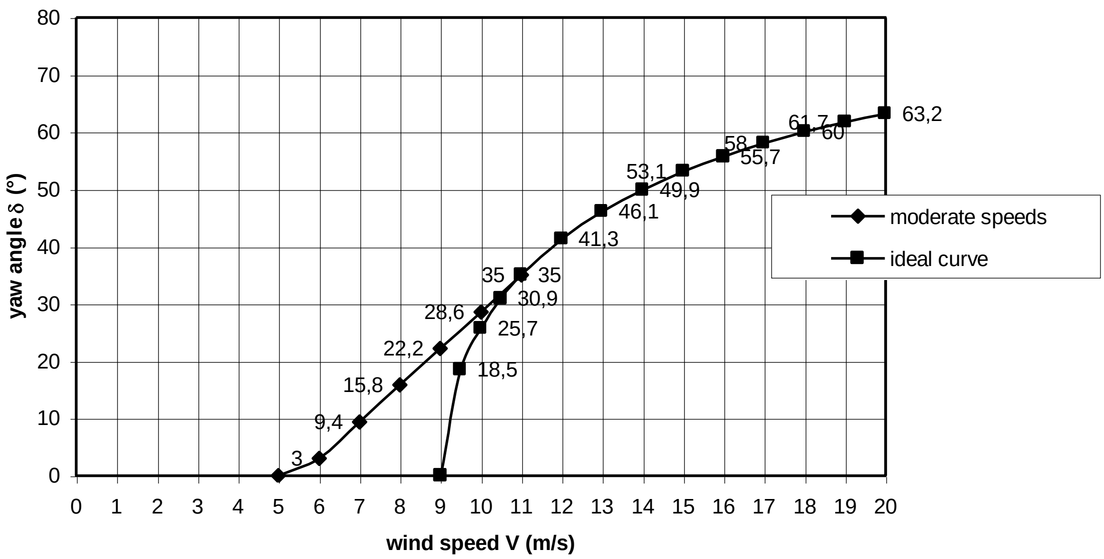

fig. 5 Estimated δ-V curve for a 9 mm plywood vane blade

The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10, and 11 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 = 1.46 m in formula 7.1 of KD 35 gives:

$n_\delta = 6.5406 * \lambda * \cos\delta * V$ (rpm) (7)

Substitution of $\rho = 1.2$ kg / m^3 and R = 1.46 m in formula 7.10 of KD 35 gives:

$P_\delta = 4.0180 * C_p * \cos^3\delta * V^3$ (W) (8)

The P-n curves are determined for C_p values belonging to λ is 3, 4, 5, 6, 7, 8 and 9 (see figure 3). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 7 and 8 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 5, is taken into account. The result of the calculations is given in table 3.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 3°		V = 7 m/s δ = 9.4°		V = 8 m/s δ = 15.8°		V = 9 m/s δ = 22.2°		V = 10 m/s δ = 28.6°		V = 11 m/s δ = 35°	
λ (-)	C_p (-)	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)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
3	0.15	58.9	16.3	78.5	38.6	98.1	75.3	117.6	129.6	135.5	198.5	151.0	274.9	163.5	348.7	172.3	407.9	176.8	440.9
4	0.27	78.5	29.3	104.6	69.4	130.8	135.6	156.8	233.4	180.7	357.3	201.4	494.8	218.0	627.7	229.7	734.2	235.7	793.7
5	0.38	98.1	41.2	130.8	97.7	163.5	190.9	195.9	328.4	225.8	502.9	251.7	696.4	272.5	883.4	287.1	1033	294.7	1117
6	0.41	117.7	44.5	157.0	105.4	196.2	205.9	235.1	354.4	271.0	542.6	302.1	751.4	327.0	953.2	344.6	1115	353.6	1205
7	0.38	137.4	41.2	183.1	97.7	228.9	190.9	274.3	328.4	316.2	502.9	352,4	696.4	381.5	883.4	402.0	1033	412.5	1117
8	0.26	157.0	28.2	209.3	66.9	261.6	130.6	313.5	224.7	361.4	344.1	402.8	476.5	436.0	604.5	459.4	707.0	471.5	764.3
9	0	176.6	0	235.5	0	294.3	0	352.7	0	406.5	0	453.1	0	490.5	0	516.8	0	530.4	0

table 3 Calculated values of n and P as a function of λ and V for the VIRYA-2.92 rotor

The calculated values for n and P are plotted in figure 6. The optimum cubic line which is going through the tops of the P-n curves is also given in figure 6.

The 4-pole generator of the VIRYA-2.68 windmill has been measured in delta for a constant voltage of 26 V which is the average charging voltage of a 24 V battery. The measured P_{mech}-n and the P_{el}-n curves for U = 26 V delta are also plotted in figure 6.

The generator has been measured for short-circuit in delta because the maximum torque level for short-circuit in delta is higher than for short-circuit in star. The P-n curve for short-circuit in delta is also plotted in figure 6.

The point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The electrical power P_{el} for that wind speed is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 7). The charging voltage at high powers will be somewhat higher than the average charging voltage of 26 V and therefore the generator efficiency will be somewhat higher too. This results in a somewhat higher electrical power. The P_{el}-V curve is corrected for this effect for high wind speeds.

The matching of rotor and generator is very good because the P_{mech}-n curve of the generator is lying close to the optimum cubic line for wind speeds higher than 4 m/s. In the P_{el}-V curve it can be seen that the maximum power is 450 W at a wind speed of 11 m/s. The supply of power starts already at a wind speed of 2.7 m/s ($V_{cut\ in}$ = 2.7 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. In chapter 4 it was calculated that V_{start} = 3 m/s so there is hysteresis in the P_{el}-V curve for $2.7 < V < 3$ m/s.

The P-n curve for short-circuit in delta is about touching the P-n curve of the rotor for V = 11 m/s and higher. This means that the rotor will slow down to almost stand still if short-circuit in delta is made and if the wind speed is less than 10 m/s.

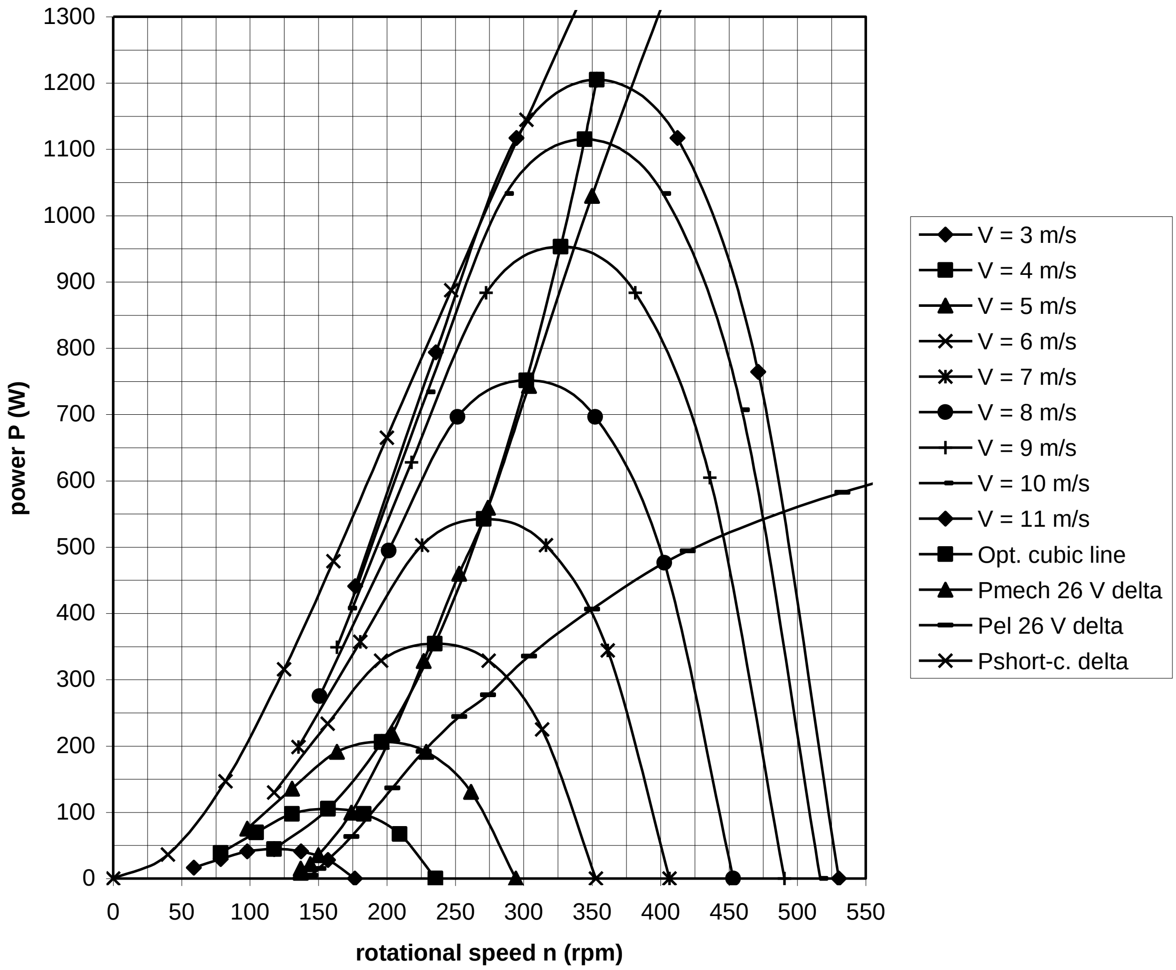

fig. 6 P-n curves of the VIRYA-2.92 rotor and the generator for 26 V delta (230/400 V winding)

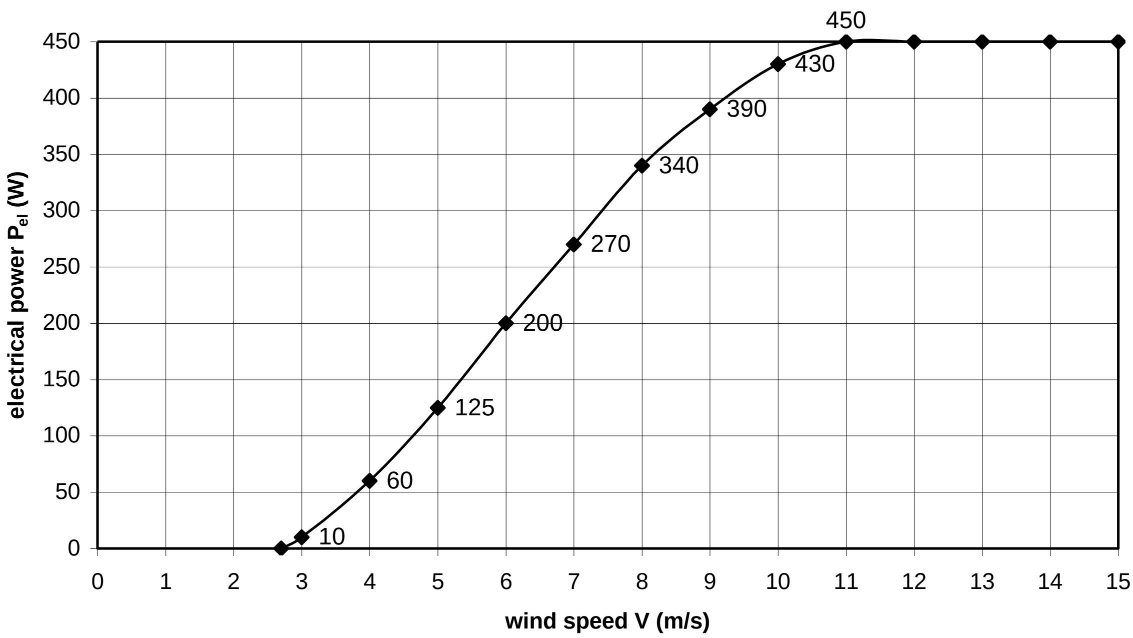

fig. 7 P_{el}-V curve of the VIRYA-2.92 windmill for 24 V battery charging and delta rectification

6 Alternative VIRYA-3.17 rotor with λ_d = 6.25

The idea came up to make the rotor bigger by using a 0.75 m long in stead of a 0.5 m long connecting strip and to use the same blades. So now eight connecting strips can be made from 6 m strip. As the strip is 0.25 m longer, the rotor diameter becomes 0.25 m larger too and so it becomes 3.17 m. So the windmill with this larger rotor is called the VIRYA-3.17.

Increase of the rotor diameter from 2.92 m up to 3.17 m means increase of the swept rotor area by a factor $(3.17 / 2.92)^2 = 1.18$. The rotor thrust will increase by the same factor. So the vane blade area has to be increased also by this factor to keep the rotor perpendicular to the wind at low wind speeds. If the same material size 150 * 6 mm is used for the connecting strip, the bending moment in this strip will increase but it is expected that the strip is still strong enough. As the connecting strip is longer, the rotor will become more flexible. So the distance in between the blade tip and the tower must be kept large enough to prevent that the blades can touch the tower at high wind gusts. The design tip speed ratio is increased from 6 up to 6.25 other wise the required lift coefficients would become too high.

Substitution of λ_d = 6.25 and R = 1.585 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 3.9432 * r \quad (-) \qquad (9)$$

Formula's (2), (3), (4) and (5) stay the same.

The blade is calculated for six stations A till F which have a distance of 0.25 m of one to another. The calculation method is the same as for the VIRYA-2.92 rotor. The result of the calculations is given in table 4.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	Camber C (%)	$R_e * 10^{-5}$	α_{th} (°)	β_{th} (°)	β_{real} (°)
A	1.585	6.25	6.1	0.1435	0.78	3.01	6.28	2.5	0.4	5.7	3.5
B	1.335	5.264	7.2	0.1676	0.78	2.97	7.38	2.5	0.4	6.8	6.0
C	1.085	4.278	8.8	0.1913	0.83	2.76	8.49	2.5	0.2	8.6	8.5
D	0.835	3.293	11.3	0.2148	0.94	2.41	9.60	2.5	0.2	11.1	11.0
E	0.585	2.307	15.6	0.2378	1.14	1.90	10.72	1.7	2.5	13.1	13.5
F	0.335	1.321	24.8	0.2603	1.49	1.28	11.85	1.2	7.4	17.4	16.0

table 4 Calculation of the blade geometry of the VIRYA-3.17 rotor

In table 1 it can be seen that the theoretical lift coefficient C_{lth} is not constant but increasing at decreasing values of r. But the increase is less than for a constant chord blade.

The camber is increasing from 6.28 % at station A the to 11.85 % at station F. The C_l-α curve for 7.14 % camber was used for station A and B. The average of the C_l-α curves for 7.14 % and 10 % camber was used for station C. The C_l-α curve for 10 % camber was used for stations D and E. The C_l-α curve for 12.5 % camber was used for station F.

In table 4 it can be seen that the theoretical blade angles β_{th} vary in between 5.7° at the blade tip and 17.4° at station F. A problem with a rotor made out of a cylinder is that only the blade angle at the blade tip β_A can be adjusted at a certain value. The blade angles at other stations depend on the taper of the blade and are difficult to calculate for a certain value of β_A but they were found using a composite drawing. The same composite drawing for the VIRYA-.292 rotor as given in figure 1, was used for the VIRYA-3.17 rotor but the whole picture was rotated left hand over 1°. It was found that β_A = 3.5° gives that real values of β for the sections B, C, D, E and F which match best with the calculated values of β_{th} in table 4. The values for β found from the composite drawing are given in table 4 as β_{real}.

For station F, β_{real} is now only somewhat smaller than β_{th} which means that the real angle of attack α_{real} is somewhat bigger than α_{th}. This means that the airfoil is not yet stalling at station F for the VIRYA-3.17 rotor. So the whole blade length is used effectively.

The angle for which the connecting strip has to be twisted to get the correct blade angle at the blade tip is a bit larger than β_A. This is because the sheet width at the blade tip is 145 mm but the width of the connecting strip is 150 mm. The angle for which the connecting strip has to be twisted right hand is 4° for β_A = 3.5°.

So the VIRYA-2.92 blades can also be used for the VIRYA-3.17 rotor. However, the 0.75 m connecting strip of the VIRYA-3.17 has to be twisted 4° right hand in stead of 5° for the 0.5 m long connecting strip of the VIRYA-2.92. So with only a little more material for the connecting strip, a rotor is gained which has a swept rotor area which is a factor 1.18 larger and so the mechanical power which can be generated for a certain wind speed will also be a factor 1.18 larger. The C_p-λ and C_q-λ curves for the VIRYA-3.17 are estimated in the same way as it was done for the VIRYA-2.92 rotor. It is assumed that C_{pmax} = 0.41 for λ_d = 6.25. As the blade angles are 1° smaller, it is assumed that C_{qstart} = 0.0065. The estimated C_p-λ and C_q-λ curves are given in figure 8 and 9.

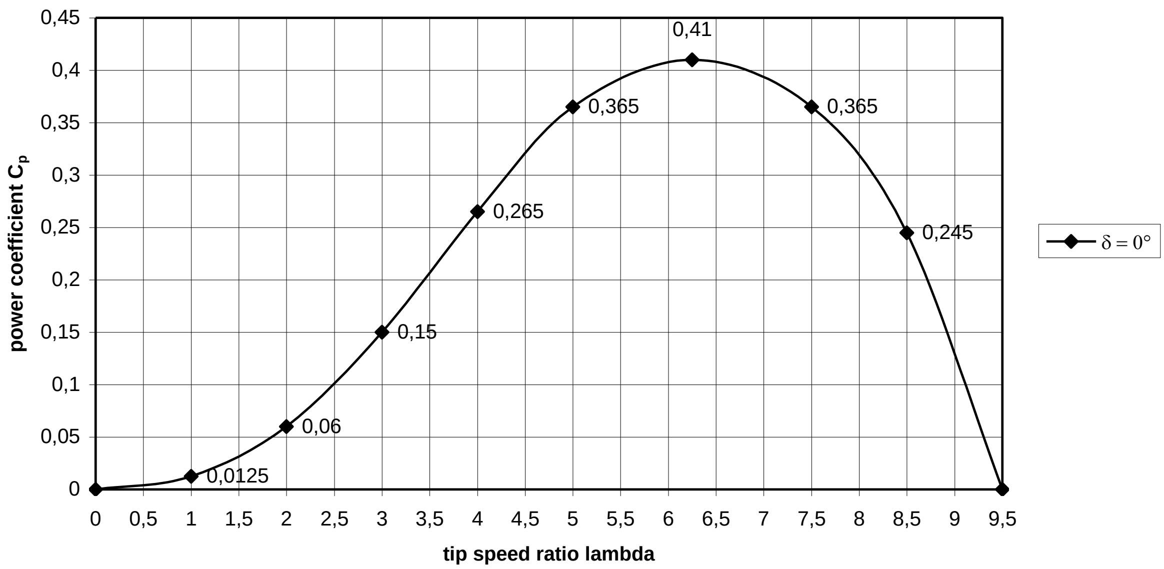

fig. 8 Estimated C_p-λ curve for the VIRYA-3.17 rotor for the wind direction perpendicular to the rotor (δ = 0°)

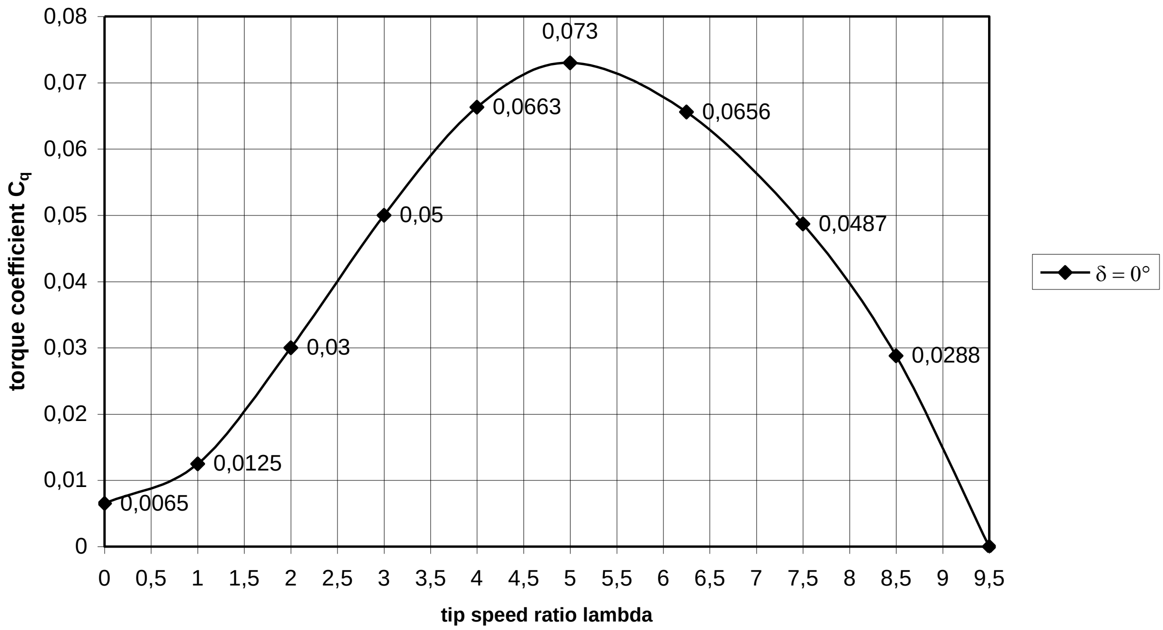

fig. 9 Estimated C_q-λ curve for the VIRYA-3.17 rotor for the wind direction perpendicular to the rotor (δ = 0°)

The P-n curves are determined in the same way as for the VIRYA-2.92 rotor. Substitution of R = 1.585 m in formula 7.1 of KD 35 gives:

$n_\delta = 6.0248 * \lambda * \cos\delta * V$ (rpm) (10)

Substitution of ρ = 1.2 kg / m^3 and R = 1.585 m in formula 7.10 of KD 35 gives:

$P_\delta = 4.7354 * C_p * \cos^3\delta * V^3$ (W) (11)

The P-n curves are determined for C_p values belonging to λ is 3, 4, 5, 6.25, 7.5, 8.5 and 9.5 (see figure 8). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 10 and 11 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 5, is taken into account. The result of the calculations is given in table 5.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 3°		V = 7 m/s δ = 9.4°		V = 8 m/s δ = 15.8°		V = 9 m/s δ = 22.2°		V = 10 m/s δ = 28.6°		V = 11 m/s δ = 35°	
λ (-)	C_p (-)	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)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
3	0.15	54.2	19.2	72.3	45.5	90.4	88.8	108.3	152.8	124.8	234.0	139.1	324.0	150.6	411.0	158.7	480.7	162.9	519.7
4	0.265	72.3	33.9	96.4	80.3	120.5	156.9	144.4	269.9	166.4	413.3	185.5	572.4	200.8	726.1	211.6	849.3	217.1	918.1
5	0.365	90.4	46.7	120.5	110.6	150.6	216.1	180.5	371.8	208.0	569.3	231.9	788.4	251.0	1000	264.5	1170	271.4	1265
6.25	0.41	113.0	52.4	150.6	124.3	188.3	242.7	225.6	417.6	260.0	639.5	289.9	885.6	313.8	1123	330.6	1314	339.3	1420
7.5	0.365	135.6	46.7	180.7	110.6	225.9	216.1	270.7	371.8	312.1	569.3	347.8	788.4	376.5	1000	396.7	1170	407.2	1265
8.5	0.245	153.6	31.3	204.8	74.3	256.1	145.0	306.8	249.6	353.7	382.1	394.2	529.2	426.7	671.3	449.6	785.2	461.4	848.8
9.5	0	171.7	0	228.9	0	286.2	0	342.9	0	395.3	0	440.6	0	476.9	0	502.5	0	515.7	0

table 5 Calculated values of n and P as a function of λ and V for the VIRYA-3.17 rotor

The calculated values for n and P are plotted in figure 10. The optimum cubic line which is going through the tops of the P-n curves is also given in figure 10.

The 4-pole generator of the VIRYA-2.68 windmill has been measured in delta for a constant voltage of 26 V which is the average charging voltage of a 24 V battery. The measured P_{mech}-n and the P_{el}-n curves for U = 26 V delta are also plotted in figure 10.

The generator has been measured for short-circuit in delta because the maximum torque level for short-circuit in delta is higher than for short-circuit in star. The P-n curve for short-circuit in delta is also plotted in figure 10.

The point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The electrical power P_{el} for that wind speed is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 11). The charging voltage at high powers will be somewhat higher than the average charging voltage of 26 V and therefore the generator efficiency will be somewhat higher too. This results in a somewhat higher electrical power. The P_{el}-V curve is corrected for this effect for high wind speeds.

The matching of rotor and generator is not as good as for the VIRYA-2.92 because the P_{mech}-n curve of the generator is lying to the right side of the optimum cubic line. But the matching is still acceptable. In the P_{el}-V curve it can be seen that the maximum power is 475 W at a wind speed of 11 m/s. The supply of power starts already at a wind speed of 2.7 m/s ($V_{cut\ in}$ = 2.7 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. The whole P_{el}-V curve is better than the one of the VIRYA-2.92.

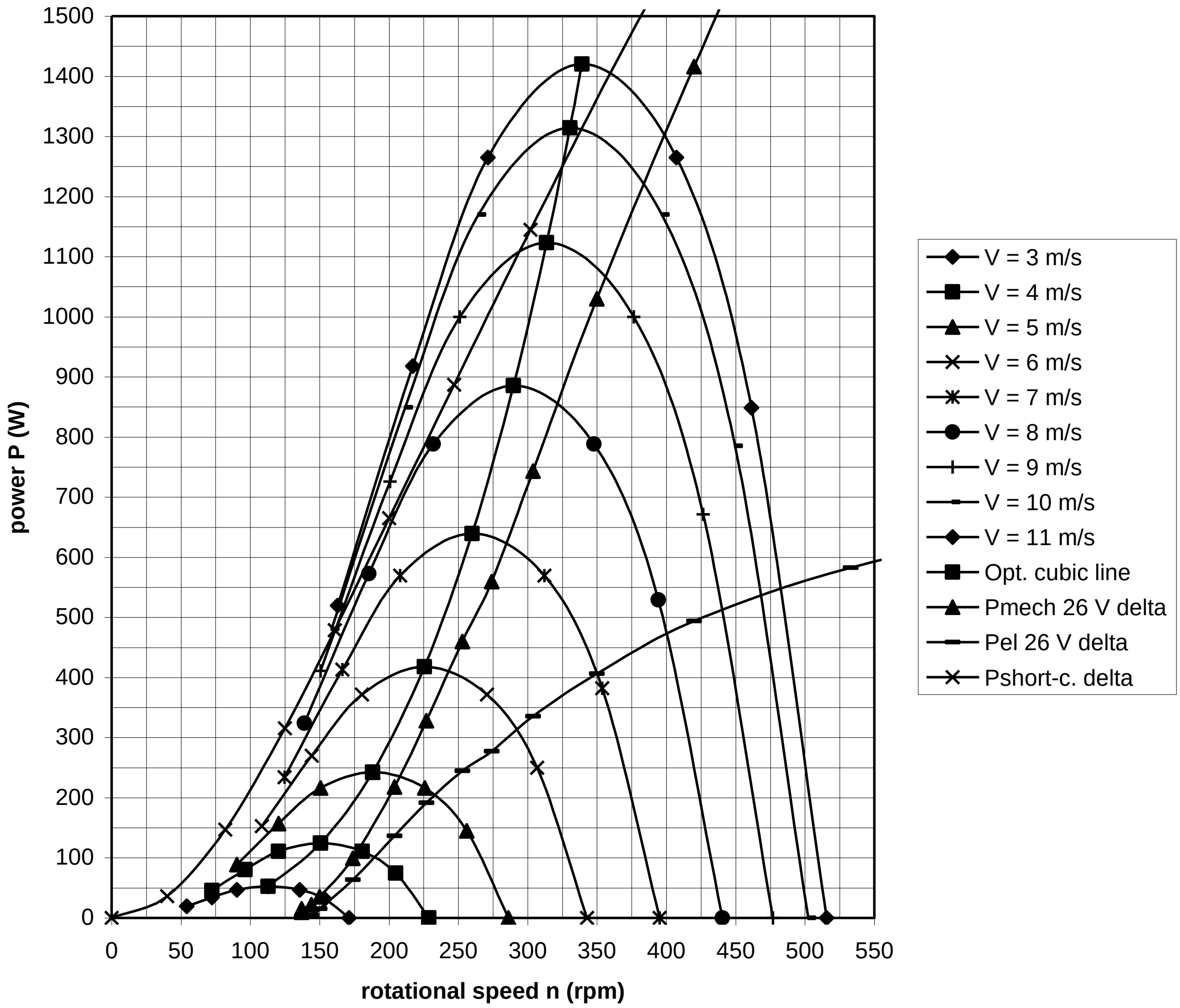

fig. 10 P-n curves of the VIRYA-3.17 rotor and the generator for 26 V delta (230/400 V winding)

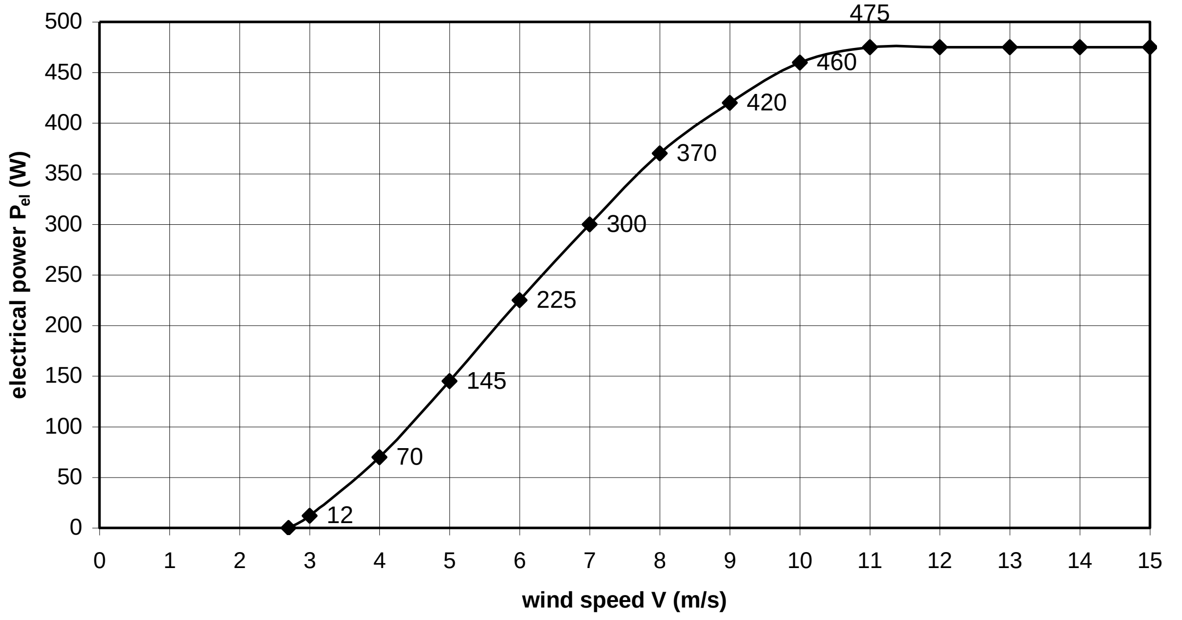

fig. 11 P_{el}-V curve of the VIRYA-3.17 windmill for 24 V battery charging and delta rectification

The P-n curve for short-circuit in delta is now about touching the P-n curve of the rotor for V = 8 m/s and higher. This means that the rotor will slow down to almost stand still if short-circuit in delta is made and if the wind speed is less than 8 m/s. This is rather low and the VIRYA-2.68 generator might be a bit too small for the VIRYA-3.17 rotor. It might be that the alternative generator with frame size 100 as described in report KD 503 (ref. 5) has a somewhat higher maximum torque level for short-circuit in delta and that this generator has therefore better characteristics to be used as a brake for the VIRYA-3.17 rotor.

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