Calculations executed for the 2-bladed rotor of the VIRYA-5T windmill (λ_d = 6.5, galvanised steel tapered blades) meant for connection to the axial flux generator of Hefei Top Grand type TGET450-5KW-300R for grid connection or water pumping

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KD 758

It is allowed to copy this report for private use. It is allowed to use the rotor given in this report for a windmill. As manufacture of the blades requires an expensive blade press, making of the VIRYA-5T rotor is only advised for serial manufacture by a professional company. The rotor is not tested. Kragten Design accepts no responsibility for possible failures.

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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.

A larger rotor with 3 mm thick tapered stainless steel blades and a rotor diameter of 3.9 m is described in report KD 733 (ref. 3). This rotor is coupled to the VIRYA-4.2 PM-generator. It seems possible to use a similar construction for an even bigger rotor which is coupled to the axial flux generator of Hefei Top Grand type TGET450-5KW-300R. It appears that this is the case for a rotor diameter of 5 m and the windmill is therefore called the VIRYA-5T. The T is added because the rotor has tapered blades. The same generator is also used for the 3-bladed VIRYA-5B3 which is described in report KD 710 (ref. 4).

The VIRYA-5B3 has a 3-bladed rotor with wooden blades. It might be difficult to get the needed quality of wood and machining of wood might be not common for an average metal workshop. Wooden blades can also been damaged easily during transport. Therefore it is investigated if an alternative rotor with galvanised steel blades can be used. The VIRYA-5T has the same rotor diameter as the VIRYA-5B3. The VIRYA-5T has a somewhat higher thrust coefficient than the VIRYA-5B3 and the head geometry of the VIRYA-5B3 is therefore modified. The head geometry of the VIRYA-5T is checked in chapter 8. This head results in a rated wind speed of about 11 m/s.

The tower is the same as the 12 m high, 3-legs tower of the VIRYA-5B3 which is also used for the VIRYA-4.2 and the VIRYA-4.6B2 but it might also be possible to use the 8.6 m high tubular tower as described in report KD 582 (ref. 5). The 3-phase current coming out of the generator is rectified. The VIRYA-5T is primary meant for grid connection by an inverter but it might be possible to use if for water pumping (see chapter 7). It might also be possible to use the VIRYA-5T for 120 V battery charging (see KD 710 chapter 7).

2 Description of the rotor of the VIRYA-5T windmill

The 2-bladed rotor of the VIRYA-5T windmill has a diameter D = 5 m and a design tip speed ratio $\lambda_d = 6.5$. The design tip speed ratio is chosen somewhat higher than that of the rotor as described in report KD 616 because the blades are more slender. 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 5 / 1.8 = 2.7778. The original 1.8 m rotor had a sheet width at the blade tip of 75 mm, so the sheet width of a VIRYA-5T blade should be about 75 * 2.7778 = 208 mm. However, a smaller width of 180 mm is chosen because this matches better with the available standard sheet size.

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 2 from 2 mm up to 4 mm, the free blade length can also be increased by a factor 2 from 0.8 m up to 1.6 m.

It is decided to use 4 mm galvanised steel sheet size 1000 * 2000 mm for the blades. It is decided that there is an overlap of 500 mm = 0.5 m in between a blade and the connecting strip. This means that the free blade length is 1.5 m. This seems acceptable.

A sheet size 1000 * 2000 mm is cut into two sheets size 500 * 2000 mm. Two blades are cut out of one sheet size 500 * 2000 mm. As the width is chosen 180 mm at the blade tip, 320 mm is left for the blade root. Cambering of tapered blades requires a special press. Development of this press is out of the scope of this report.

So the increase of the width from the blade tip to the blade root is 320 – 180 = 140 mm. This results in a taper angle of the blade of 4°. The taper angle of the blades of the original 1.8 m rotor is 4.74°. So the taper angle is 0.74° smaller which is acceptable.

The camber radius of the original blades is 150 mm. So the radius of the VIRYA-5T blades should be about 2.7778 * 150 = 417 mm. However, the sheet width at the tip was chosen a factor 180 / 208 = 0.865 smaller than according to scaling with a factor 2.7778. The camber radius is therefore also smaller. Finally it is chosen that the camber radius is 350 mm. The airfoil nose and the tailing edge of the blade have to be rounded with a radius of 1.5 mm to minimise drag. Rounding means that some of the zinc layer is removed so the edges are painted with zinc paint. Galvanized sheet may also give reflections of the sun and so the blade is covered with non reflective black epoxy paint.

The connecting strip has dimensions 150 * 12 * 2000 mm. The overlap in between blade and strip is 500 mm. The distance in between the heart of the strip and the tailing edge of the blade is chosen 145 mm (for a straight blade). The connecting strip is twisted 12° in between the hub and the blade root to realize the correct blade setting angle at the blade root.

A blade is connected to the strip by three bolts M16. The strip has a radius R = 348 mm at the back side over a length of 500 mm to prevent that the camber of the blade is flattened when the bolts are tightened. The generator has a collar with a diameter of 150 mm and ten 25 mm deep threaded holes M12 at a pitch circle of 130 mm (the threaded holes aren't specified on the drawing given at point 4 of the data sheet so this has still to be verified). The connecting strip is connected to the generator hub by ten bolts M12 * 40 and ten locking washers. The mass of the whole rotor is about 58 kg which seems acceptable for a steel rotor.

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-5T 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 = 2.5 m, r_B = 2.1 m, r_C = 1.7 m, r_D = 1.3 m, r_E = 0.9 m and r_F = 0.5 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-5T 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 180 mm at the blade tip (at $r_A = 2.5$ m) and 320 mm at the blade root (at $r_F = 0.5$ m). So the difference is 140 mm. This means that the sheet width b increases 140 / 5 = 28 mm per station. This gives the following values: $b_A = 180$ mm, $b_B = 208$ mm, $b_C = 236$ mm, $b_D = 264$ mm, $b_E = 292$ mm and $b_F = 320$ mm. The camber radius was chosen 350 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 (ref. 6). 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	180	350	0.2571	178.0	0.1780	6.46
B	208	350	0.2971	205.0	0.2050	7.48
C	236	350	0.3371	231.6	0.2316	8.51
D	264	350	0.3771	257.8	0.2578	9.54
E	292	350	0.4171	283.6	0.2836	10.58
F	320	350	0.4571	309.0	0.3090	11.63

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 758) has its own formula numbering. Substitution of $\lambda_d = 6.5$ and R = 2.5 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 2.6 * r \qquad (-) \tag{1}$$

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

$$\beta = \phi - \alpha \qquad (°) \tag{2}$$

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

Substitution of B = 2 in formula (5.4) of KD 35 gives:

$$C_l = 12.566 * r\,(1 - \cos\phi) / c \qquad (-) \tag{4}$$

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

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

The blade is calculated for six stations A till F which have a distance of 0.5 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.

sta-tion	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	Camber C (%)	Camber used (%)	$R_e * 10^{-5}$	α_{th} (°)	β_{th} (°)	β_{real} (°)
A	2.5	6.5	5.8	0.1780	0.91	3.88	6.46	7.14	3.4	1.4	4.4	3.0
B	2.1	5.46	6.9	0.2050	0.94	3.76	7.48	7.14	3.4	1.7	5.2	5.2
C	1.7	4.42	8.5	0.2316	1.01	3.45	8.51	7.14 + 10	3.4	1.3	7.2	7.4
D	1.3	3.38	11.0	0.2578	1.16	2.96	9.54	10	3.4	1.5	9.5	9.6
E	0.9	2.34	15.4	0.2836	1.44	2.30	10.58	10	2.5	5.4	10.0	11.8
F	0.5	1.3	25.0	0.3090	1.91	1.51	11.63	12.5	1.7	-	-	14.0

table 2 Calculation of the blade geometry of the VIRYA-5T rotor

In table 2 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 6.46 % at station A to 11.63 % at station F. To find the theoretical angles of attack α_{th} we 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 angle 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.

No value of α_{th} is found for station F because the required C_l-value of 1.91 can’t be generated. In table 1 it can be seen that the theoretical blade angles β_{th} vary in between 4.4° at the blade tip and 10.0° at station E. 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 4.4°. 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. They are given on the 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-5T 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 = 3.0° gives real values of β for the sections B, C, D and E which are matching 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}. The angle for which the connecting strip has to be twisted right hand is 12° for β_A = 3°. A sketch of the whole rotor is given in figure 2.

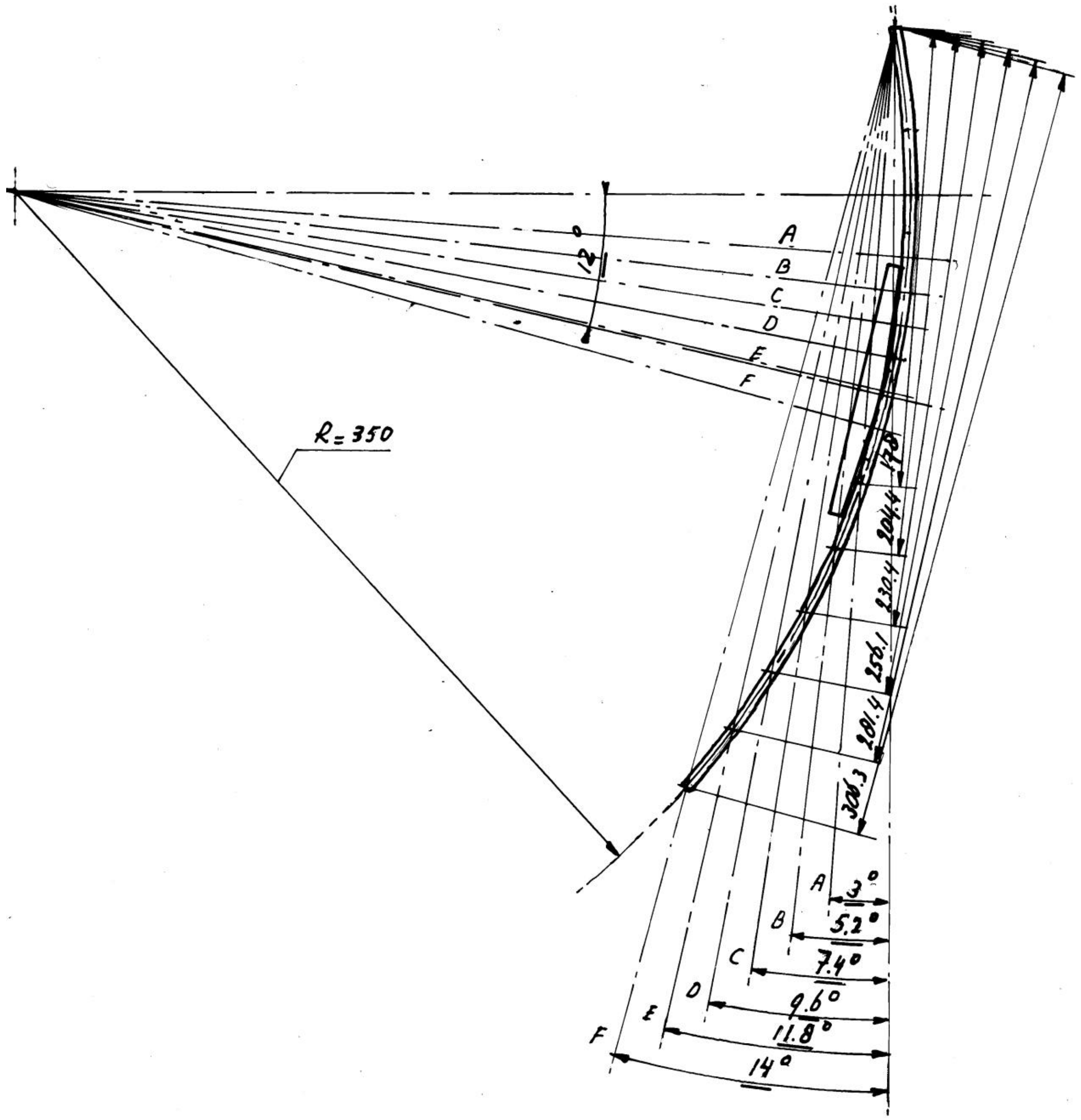

fig. 1 The right blade for six stations A, B, C, D, E and F

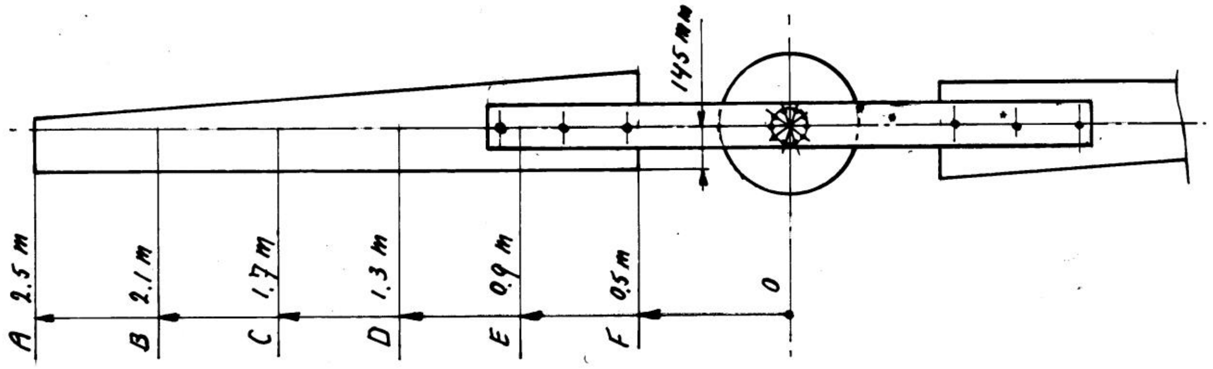

fig. 2 Front view of the VIRYA-5T rotor

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-5T chord at the blade tip is a factor 180 / 75 = 2.4 larger. But the design tip speed ratio is a factor 6.5 / 6 = 1.083 larger. This means that the Reynolds value is a factor 2.4 * 1.083 = 2.6 larger for a wind speed of 11 m/s. So the Reynolds value is the same for a wind speed of 11 / 2.6 = 4.23 m/s. This is even smaller 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-5T it is assumed that the C_p-λ curve has no unusual peak at higher tip speed ratios and that the maximum $C_p = 0.43$ for $\lambda_d = 6.5$. The VIRYA-5T rotor has chords which are relatively smaller than those of the 1.8 m original rotor but the blade angle at the tip is 3° instead of 2.1°. Therefore it is assumed that the starting torque coefficient is the same and so $C_{q\ start} = 0.005$. The estimated C_p-λ and C_q-λ curves are given in figure 3 and 4. The curves are made about congruent to the measured curves except for the unusual peak. But for moderate and high wind speeds, the peak will certainly exist. If the rotor is running in the peak area it will produce more power and it will make very little noise.

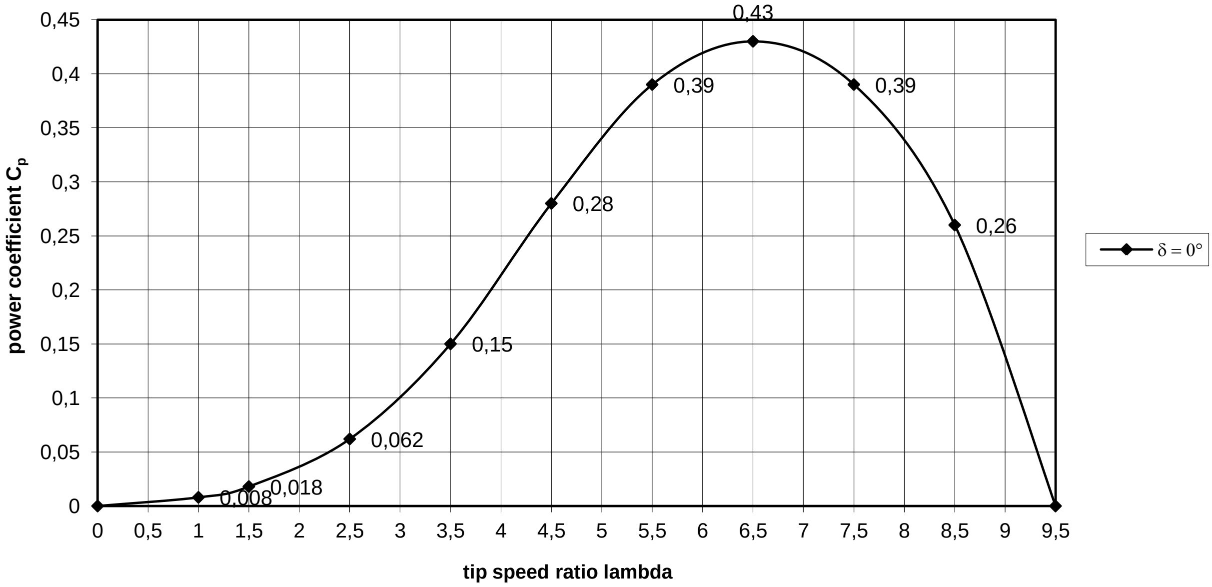

fig. 3 Estimated C_p-λ curve for the VIRYA-5T rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

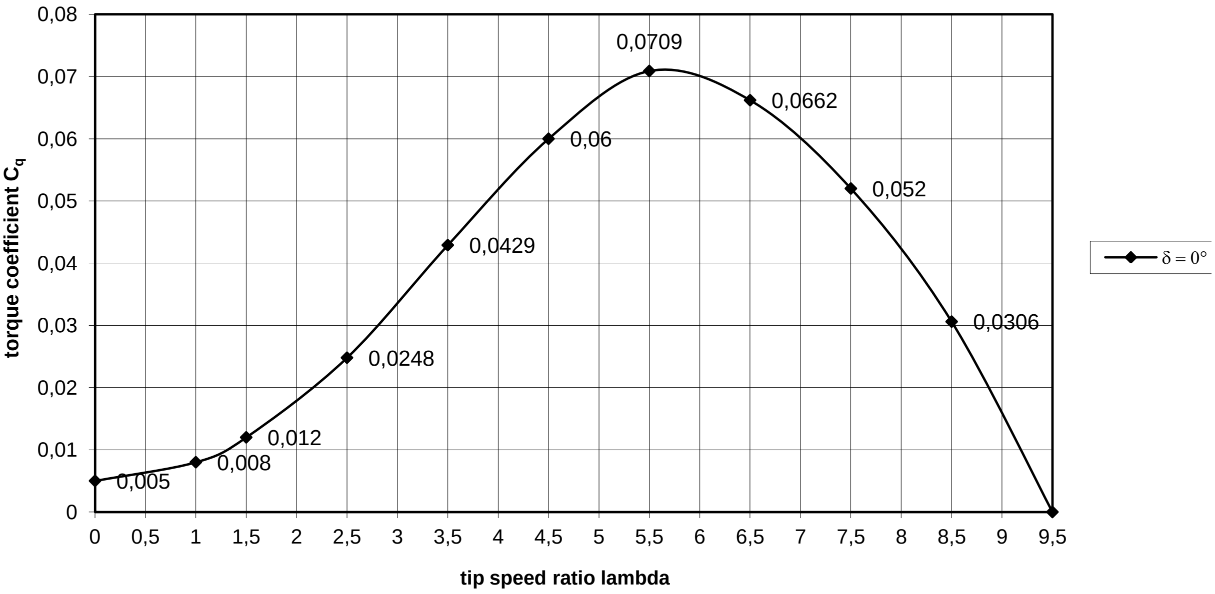

fig. 4 Estimated C_q-λ curve for the VIRYA-5T rotor for the wind direction perpendicular to the rotor (δ = 0°)

In figure 4 it can be seen that for the starting torque coefficient it is valid that $C_{qstart} = 0.005$. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

At point 11 of the specification of the generator it is mentioned that the starting torque is smaller than 0.3 Nm. This is very low and I doubt if this is correct if the generator has a seal on the shaft. The generator can be used without a seal for a vertical axis wind turbine but for a horizontal axis wind turbine, a seal is certainly necessary to prevent that water enters the bearings. Assume that the sticking torque with a seal is 2 Nm.

If the generator has no seal on the shaft and no outside chamber for mounting of an oil seal, it might be possible to use a V-ring of manufacture Forsheda type V-60A. This ring is clamped around the shaft and has an elastic lip which is pressed against the collar at the shaft side. But this is only possible if the collar surface is machined flat with a low roughness and if the lip isn't running over the threaded holes. Some grease has to be put on the lip at mounting.

Substitution of Q_s = 2 Nm, $C_{q\,start}$ = 0.005, ρ = 1.2 kg/m^3 and R = 2.5 m in formula 7 gives that V_{start} = 3.7 m/s. This is acceptable low for a 2-bladed rotor with a design tip speed ratio λ_d = 6.5 and a rated wind speed V_{rated} = 11 m/s.

5 Determination of the P-n curves and the optimum cubic line

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 12 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.

It is assumed that the δ-V curve is the same as the δ-V curve of the VIRYA-5B3 is given in figure 4 of KD 710. This curve is copied as figure 5.

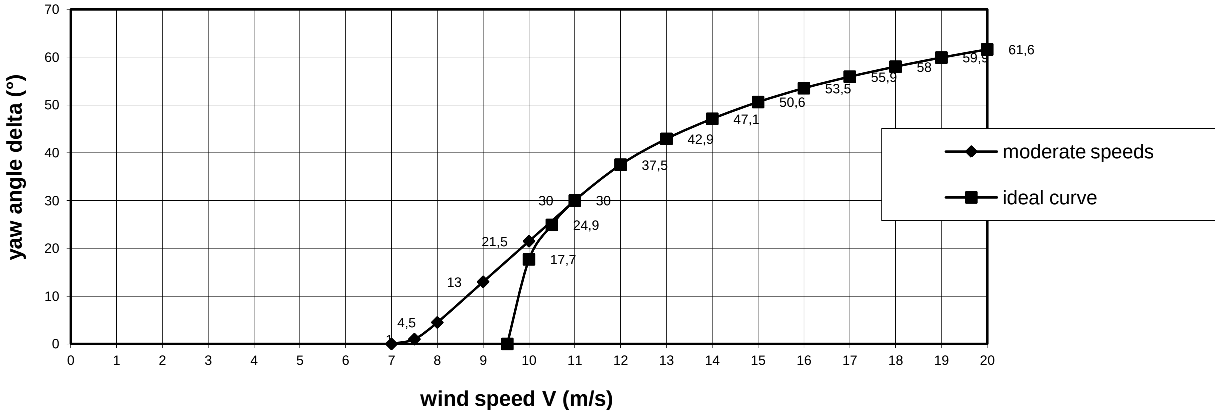

fig. 5 Estimated δ-V curve for a 12 mm meranti plywood vane blade

The head starts to turn away at a wind speed of about 7 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.

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 = 2.5 m in formula 7.1 of KD 35 gives:

$$n_\delta = 3.8197 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (7)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 2.5 m in formula 7.10 of KD 35 gives:

$$P_\delta = 11.781 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (8)$$

The P-n curves are determined for C_p values belonging to λ is 3.5, 4.5, 5.5, 6.5, 7.5, 8.5 and 9.5 (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 = 0°		V = 7 m/s δ = 0°		V = 8 m/s δ = 4.5°		V = 9 m/s δ = 13°		V = 10 m/s δ = 21.5°		V = 11 m/s δ = 30°	
λ (-)	C_p (-)	n (rpm)	P (W)	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)	n_δ (rpm)	P_δ (W)
3.5	0.15	40.1	48	53.5	113	66.8	221	80.2	382	93.6	606	106.6	896	117.2	1192	124.4	1423	127.4	1528
4.5	0.28	51.6	89	68.8	211	85.9	412	103.1	713	120.3	1131	137.1	1673	150.7	2225	159.9	2657	163.7	2852
5.5	0.39	63.0	124	84.0	294	105.0	574	126.1	992	147.1	1576	167.5	2331	184.2	3098	195.5	3701	200.1	3972
6.5	0.43	74.5	137	99.3	324	124.1	633	149.0	1094	173.8	1738	198.0	2570	217.7	3416	231.0	4080	236.5	4379
7.5	0.39	85.9	124	114.6	294	143.2	574	171.9	992	200.5	1576	228.5	2331	251.2	3098	266.5	3701	272.9	3972
8.5	0.26	97.4	83	129.9	196	162.3	383	194.8	662	227.3	1051	258.9	1554	284.7	2066	302.1	2467	309.3	2648
9.5	0	108.9	0	145.1	0	181.4	0	217.7	0	254.0	0	289.4	0	318.2	0	337.6	0	345.7	0

table 3 Calculated values of n and P as a function of λ and V for the VIRYA-5T 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.

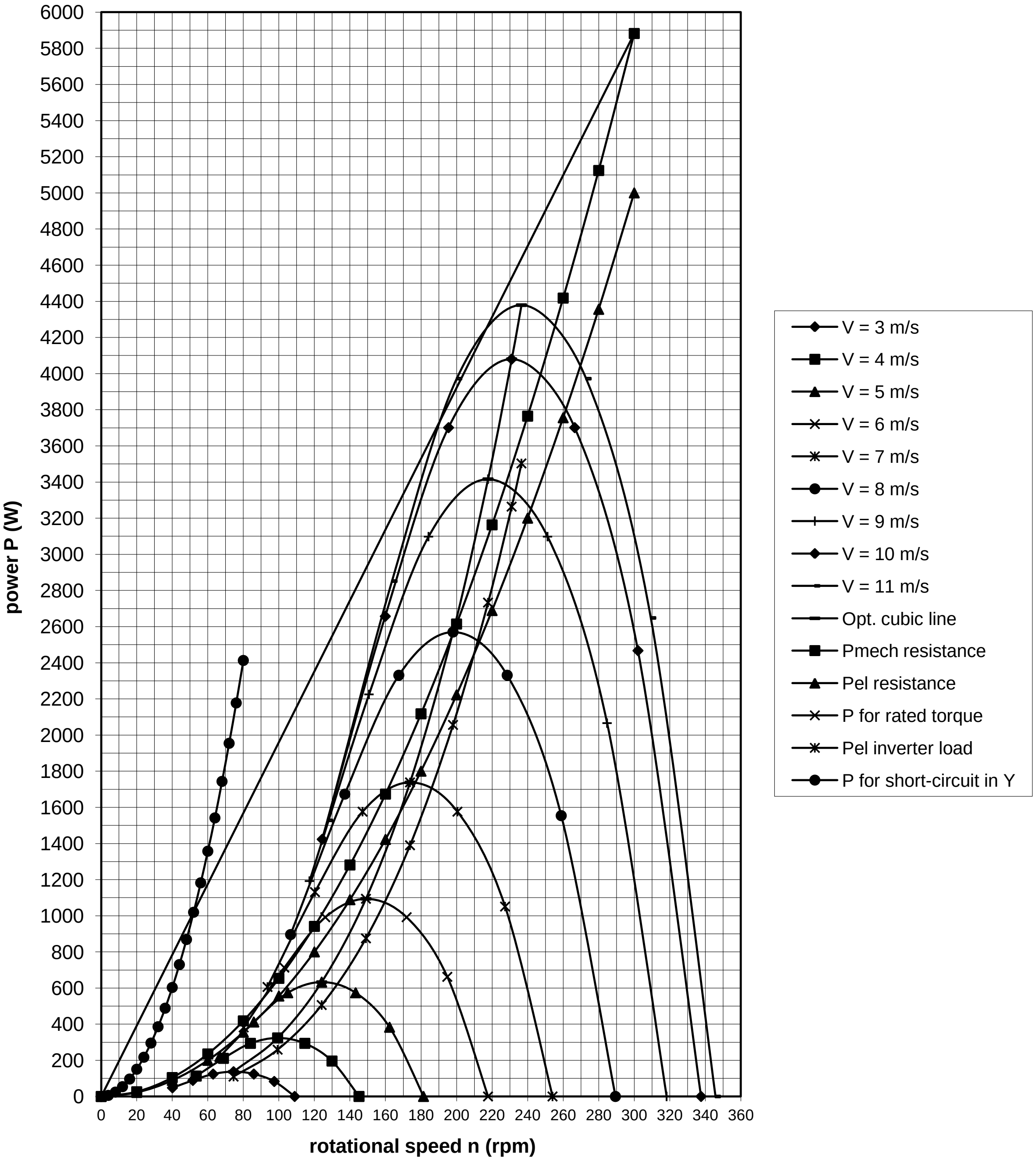

fig. 6 P-n curves of the VIRYA-5T rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the generator with a resistance load such that P_{el} = 5000 W at n = 300 rpm, P-n curve for the rated torque, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

6 Determination of the generator characteristics

The P_{mech}-n and P_{el}-n curves for a resistance load chosen by the manufacturer and for an inverter load such that the optimum cubic line is followed are determined in chapter 6 of KD 710. The P-n curves for the rated torque and for short-circuit in star are also determined in chapter 6 of KD 710. These curves are copied in figure 6. In figure 6 it can be seen that the P_{mech}-n curve for a resistance load is intersecting with the optimum cubic line at a wind speed of about 8 m/s. If the inverter is adjusted such that the optimum cubic line is followed, this means that the inverter load is lower for wind speeds below 8 m/s and somewhat higher for wind speeds above 8 m/s.

But the optimum cubic line is, even for V = 11 m/s, the optimum cubic line is lying lower than the curve for the nominal torque which means that the generator is strong enough for the VIRYA-5T. The P_{el}-n curve for an inverter load such that the optimum cubic line is followed is drawn for a total efficiency of generator plus inverter of 0.8. The working point for a certain wind speed for a correct inverter load is the point of intersection of the optimum cubic line with the P-n curve of the rotor for that wind speed. The electrical power is found by going downwards from the working point until the P_{el}-n curve is intersected. The P_{el}-V curve found this way is given in figure 7. The curve is the same as the curve of the VIRYA-5B3 because both wind turbines have the same rotor diameter, the same maximum C_p and the same δ-V curve.

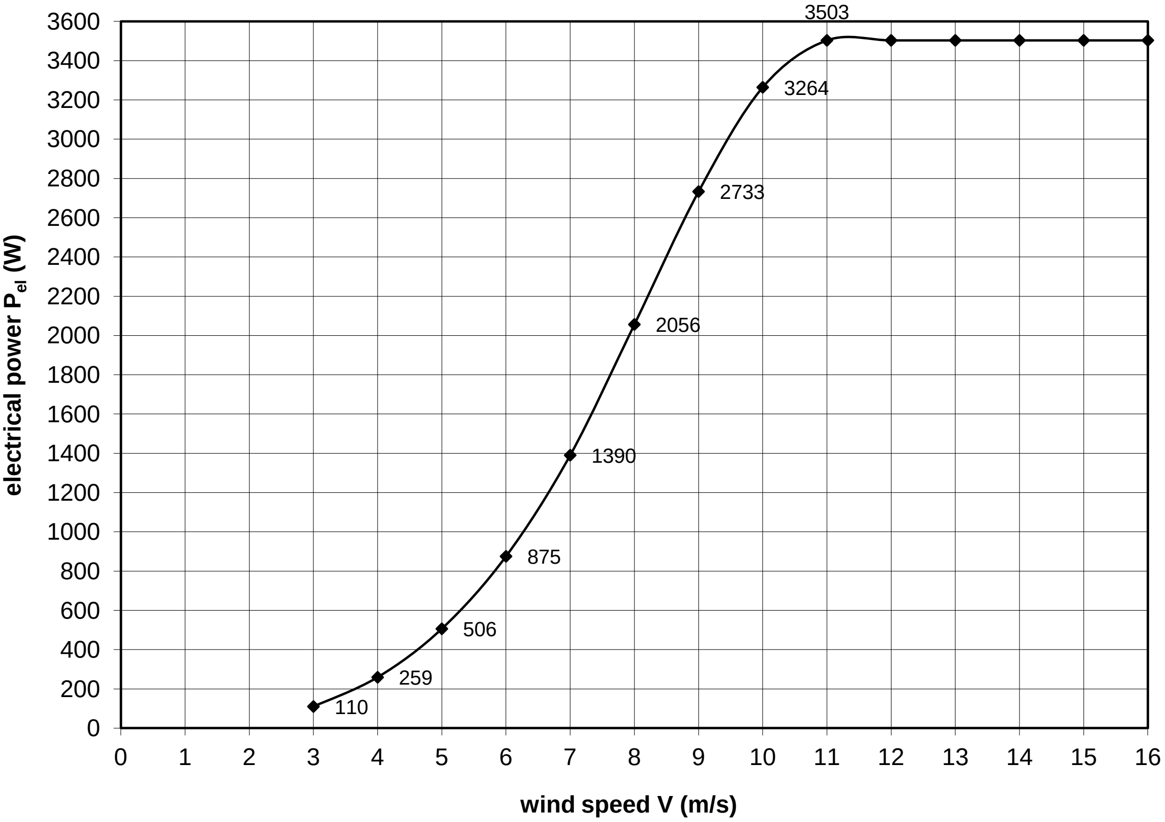

fig. 7 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for wind speeds higher than 3 m/s

The maximum electrical power is about 3.5 kW which is very good for a wind turbine with a rotor diameter of 5 m and a rated wind speed of 11 m/s. The P_{mech}-n, the P_{el}-n curves as given in figure 6 and the P_{el}-V as given in figure 7 are estimated and not measured. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the chosen generator of Hefei Top Grand, it is necessary to buy one and to test it at a large test rig with which it is possible to also measure the torque Q. One should also select and buy an inverter and measure the real electrical output for grid connection.

7 Use of the VIRYA-5T for water pumping

The PM-generator of Hefei Top Grand type TGET450-5KW-300R has a 3-phase winding. The three phase wires are coming out of the hollow generator shaft. In the specification it is mentioned that the nominal voltage is 220 VAC at n = 300 rpm. This voltage is the voltage in between two of the three phase wires. The three phases are connected in star and the star point is hidden somewhere inside the generator housing. The voltage in between the star point and one of the phases is a factor √3 lower than the voltage in between the phases. So the nominal phase voltage of the generator is 220 / √3 = 127 V at n = 300 rpm.

This generator can be ordered directly at the manufacturer but also at Alibaba. If TGET450-5KW-300R is typed at the website of Alibaba, many photos are given if one scrolls downwards. One of the photos shows the armature construction and in this photo it can be seen that 20 trapezium shaped magnets are used. So the armature has 20 poles. This means that the frequency of the generated voltage in one phase is 50 Hz if the armature rotates at 300 rpm. As 300 rpm is the nominal rotational speed, the frequency is 50 Hz at a loaded nominal voltage of 220 VAC in between two of the three phases.

There are two ways to use the VIRYA-5T for water pumping. One way is to use a pump with a DC pump motor with a high voltage range. The generator winding is rectified with a 3-phase rectifier and the rectified current is directly used by the motor. So no battery is used. If the pump is a centrifugal pump, the starting torque of the pump is very low and so it is expected that the connection in between the rectifier and the pump motor can be permanent.

The second way is to directly use the 3-phase current coming out of the generator. It is assumed that a one step centrifugal pump is used for low head water pumping. Such a pump is normally connected to a 3-phase asynchronous motor which is connected in star. The 3-phase grid in Europe has a frequency of 50 Hz and is connected in star. The nominal voltage in between the star point and one of the phases is 230 VAC. The voltage in between two of the three phases is a factor √3 higher and so about 400 VAC. So this is much higher than the nominal voltage in between the phases of the generator if it runs at 300 rpm. So if the pump motor is connected in star, the voltage generated by the generator is much too low. However, if the pump motor winding is connected in delta, the voltage over the motor coils is a factor √3 higher if the frequency is 50 Hz. It depends on the pump motor, if it is possible to connect it in star or in delta. It must have a terminal box with six terminals and three brass strips. If the three brass strips are connected in parallel, the motor winding is connected in delta.

In figure 6 it can be seen that the rotational speed of the rotor is much lower than 300 rpm at normal wind speeds. If the generator is loaded such that the optimum cubic line is followed, the maximum rotational speed is about 237 rpm for V = 11 m/s. The rotational speed for a wind speed of 6 m/s is about 150 rpm if the optimum cubic line is followed and the generator frequency for this rotational speed is 25 Hz.

Next assume that the frequency f = 25 Hz. This means that the pump motor will run at half the rotational speed as the rotational speed for which it is designed. The nominal water head of a centrifugal pump increases quadratic to the rotational speed. So assume that the VIRYA-5T is used for low head water pumping with a head of 1 m. This means that one has to take a standard pump which is designed for a nominal head of 4 m at a frequency of 50 Hz. This pump will have a nominal head of 1 m if the pump motor runs at half its nominal rotational speed. An advantage of using the pump motor at a low frequency and voltage, is that the maximum frequency and voltage of the generator at high wind speeds will never be too high. The electrical power of the generator at a frequency of 25 Hz, belonging to a wind speed of 6 m/s, is about 875 W (see figure 7).

The required motor power increases proportional to the product of head and flow. The nominal head at a frequency of 50 Hz is a factor 4 higher than at a frequency of 25 Hz. The flow at a frequency of 50 Hz is a factor 2 higher than at a frequency of 25 Hz. So the required motor power at a frequency of 50 Hz is a factor 4 * 2 = 8 higher than at a frequency of 25 Hz.

So the pump motor must have a nominal electric power which is about a factor 8 higher at f = 50 Hz than at f = 25 Hz and so about 8 * 875 = 7000 W. If the pump motor has an efficiency of 79 %, the nominal mechanical power of the pump motor must be about 5500 W = 5,5 kW. One should be alert that this motor has a 230/400V winding and no 400/690 V winding! It might also be possible to take a 4 kW pump motor with a 230/400 V winding. This combination of wind turbine and pump is designed for a wind speed of 6 m/s which is realistic for a good wind regime. It will start pumping when the pump can supply the static water head. This will be the case at a wind speed of about 5 m/s. So I think that this seems a realistic option because a standard 1-step centrifugal pump for a head of 4 m with a 3-phase asynchronous motor is not an expensive pump. Specification of the pump output is out of the scope of this report. It would be good to test the output for a prototype of the VIRYA-5T. It can also be tested by using only a motor driven PM-generator and a pump.

8 Checking of the head geometry (see figure 8)

The head of the VIRYA-4.2 has been taken as starting point for the head of the VIRYA-5T as the VIRYA-4.2 head has been tested for some years and it has functioned well. The VIRYA-4.2 head is given on drawing 0401-03/A. The head of the VIRYA-4.6B2 is also derived from the head of the VIRYA-4.2 but the VIRYA-4.6B2 has a larger vane blade. The VIRYA-4.6B2 head is given on drawing 0501-03/A. The head of the VIRYA-5T has a larger vane blade than used for the VIRYA-4.6B2.

The head pipe of the VIRYA-4.2 and the VIRYA-4.6B2 is build up from a 2 m long 3” gas pipe and a 1.2 m long 2” gas pipe. The length of the 3” pipe is taken the same but the length of the 2” gas pipe is increased from 1.2 m up to 1.5 m for the VIRYA-5T head.

The head pin item 01/03 of the VIRYA-4.2 head has a diameter of 40 mm. The head pin of the VIRYA-4.6B2 has a diameter of 45 mm. The head pin of the VIRYA-5T will also have a diameter of 45 mm. So the same head bearing housing as used for the VIRYA-4.6B2 can also be used for the VIRYA-5T.

The VIRYA-4.2 and the VIRYA-4.6B2 head have a generator bracket to which a generator can be bolted which is made from an asynchronous motor. The VIRYA-5T makes use of a generator of Hefei Top Grand type TGET450-5KW-300R. The whole generator housing is rotating around the shaft. The shaft has a diameter of 59 mm and a length of 150 mm. Only the shaft diameter is specified by the manufacturer and so the shaft length has still to be verified. The VIRYA-5T head must have two generator brackets in which the shaft can be clamped. This must be done such that the rotor shaft has a tilt angle of 5° and that the eccentricity e is correct. The VIRYA-4.2 has an eccentricity which is 10 % of the rotor diameter, so e = 0.42 m. For the VIRYA-5T it is chosen that the eccentricity is 9 % of the rotor diameter. So the head geometry must be such that e = 0.45 m.

The VIRYA-4.2 has a 9 mm thick meranti plywood vane blade with a height and width of 1000 mm. For the VIRYA-5T, the height and width are increased to 1220 mm and so it is possible to make two vane blades out of a standard sheet size 4’ * 8’ = 1.22 * 2.44 m. However, it might be that a 9 mm meranti vane blade of this size becomes too flexible which may result in flutter of the vane blade at high wind speeds. This can be solved by using 12 mm okoume plywood which has a lower density than meranti plywood resulting in about the same vane weight and therefore in about the same rated wind speed. A composite drawing of the VIRYA-5T head is given in figure 8.

Now it can be checked if the rotor is about perpendicular to the wind for low wind speeds for the chosen vane geometry. For very low wind speeds, the vane blade is in the almost vertical position and the balance of moments around the tower axis is then given by formula 49 or 50 of KD 223 (ref. 8). Formula 50 is copied as formula 9.

$$C_n = \pi R^2 * C_t * e / \{h * w * (R_v + i_1)\} \qquad (-) \qquad (9)$$

C_n is the normal coefficient of a square plate. The C_n-α curve of a square plate is given in figure 6 of KD 223 (ref. 7). If the rotor is perpendicular to the wind, the angle α in between the wind direction and the vane blade is 30°. In figure 6 of KD 223, it can be read that $C_n = 1.38$ for $\alpha = 30°$. R is the rotor radius which is 2.5 m for the VIRYA-5T. C_t is the thrust coefficient which is about 0.75 for a rotor with a cambered plate airfoil. e is the eccentricity (m). It is chosen that e = 0.45 m. h is the height of the vane blade and w is the width. h = 1.22 m and w = 1.22 m. R_v is the distance in between the heart of the tower and the leading edge of the vane blade measured in parallel to the vane axis. R_v was measured from figure 8 and it was found that $R_v = 2.97$ m. i_1 is the distance in between the normal force N acting on the vane blade and the leading edge. i_1 depends on the angle of attack α but is about 0.37 * w for $\alpha = 30°$ (see figure 7 of report KD 223). So $i_1 = 0.45$ m for w = 1.22 m and $R_v + i_1 = 3.42$ m. Substitution of all these values in formula 9 gives that $C_n = 1.30$.

In figure 6 of KD 223 it can be seen that $C_n = 1.30$ belongs about to $\alpha = 28.5°$. This angle is 1.5° smaller than the angle $\alpha = 30°$ for which the rotor is perpendicular to the wind. This means that the rotor makes a negative yaw angle $\delta = -1.5°$ with the wind direction for very low wind speeds. This is correct because in this case the rotor will be about perpendicular to the wind for a wind speed of about 6 m/s.

The end of the 2” pipe is flattened up to 15 mm wide gap. In this gap a steel strip with dimensions 60 * 15 * 1198 mm is welded. This strip is 5 mm smaller but 3 mm thicker than the strip of the VIRYA-4.2 head. So it is stronger and stiffer. This strip makes a backwards angle of 15° with the 2” pipe. The vane blade is connected to this strip by three 3” stainless steel door hinges. In between the hinges, two sheets size 300 * 300 * 4 mm are bolted to the upper side of the strip. These sheets are bent such that they make a downwards angle of 3° with the horizon. These sheets function as an elastic stop for the vane blade and prevent that the angle in between the vane blade and the wind direction can become negative at very high wind gusts. This prevents flutter of the vane arm because the aerodynamic force on the vane blade can’t become negative for fast movements of the vane blade.

A stainless steel pin with a diameter of 45 mm is welded in the 3” pipe at a distance of 427 mm from the heart of the 45° bevelled side. This pin contains a central hole of 17 mm for the generator wires. All VIRYA windmills use a stainless steel pin which turns in INA Permaglide head bearings.

The distance of 427 mm is the same as for the VIRYA-4.2 head. A 6 mm thick sheet is welded to the 45° bevelled side. This thickness of 6 mm is also the same as for the sheet of the VIRYA-4.2 head. However, the other dimensions of the VIRYA-5T sheet are 150 * 150 mm. The shaft height of the VIRYA-4.2 is 112 mm. The eccentricity of the VIRYA-5T is 30 mm larger than for the VIRYA-4.2. This means that the shaft height of the VIRYA-5T must also be 30 mm larger. So this means that the clamping blocks must be that large that the shaft height is 112 + 30 = 142 mm = 0.142 m.

The generator bracket for the clamping blocks is welded such to the 3” pipe that the rotor shaft makes a tilting angle of 5° with the vertical. This angle makes that the distance in between the blade tip and the tower is large enough to prevent that the blades may touch the tower at high wind gusts. The original sheet of the VIRYA-4.2 also makes a 5° tilt angle. The two 25 mm thick clamping blocks are bolted to the sheet by four bolts M12. Figure 8 is drawn without this 5° tilting angle.

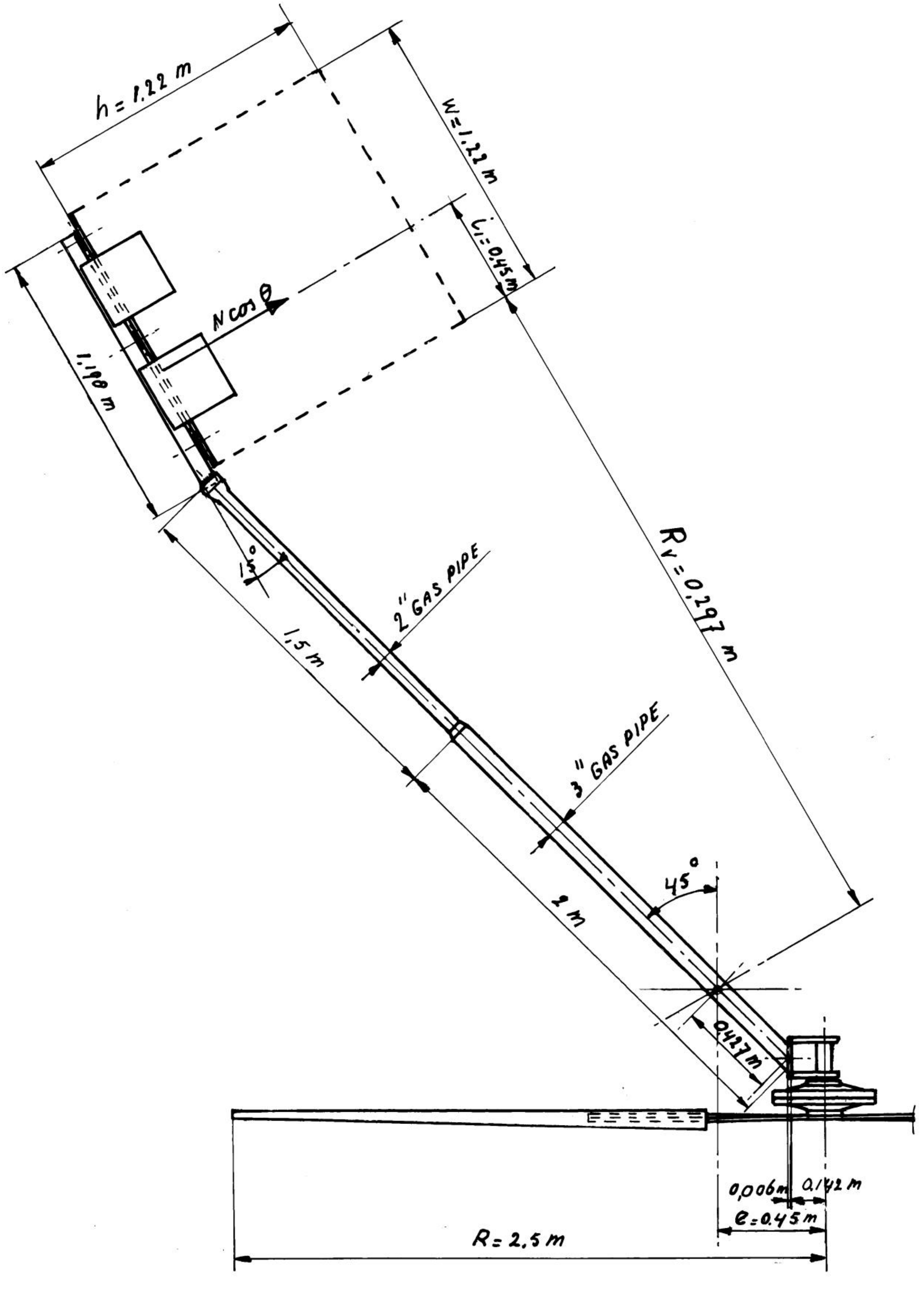

fig. 8 Top view head VIRYA-5T windmill

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