

**Calculations executed for the 2-bladed rotor of the VIRYA-3.9 windmill  
and the 3-bladed rotor of the VIRYA-3.9B3 windmill  
(both  $\lambda_d = 6$ , stainless steel tapered blades) driving the  
VIRYA-4.2 PM-generator for 26 V delta and 26 V star**

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Contains	page
1 Introduction	3
2 Description of the rotor of the VIRYA-3.9 windmill	4
3 Calculations of the rotor geometry	5
4 Determination of the $C_p$ - $\lambda$ and the $C_q$ - $\lambda$ curves	8
5 Determination of the P-n curves and the $P_{el}$ -V curve for 26 V delta and 26 V star	9
6 Checking of the starting behaviour	13
7 Use of a modified 115/200 V winding for 26 V star	14
8 Alternative 3-bladed VIRYA-3.9B3 rotor	16
9 References	19

## 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 2-bladed rotor with tapered blades and a rotor diameter of 2.92 m is described in report KD 656 (ref. 3). This rotor is coupled to the VIRYA-2.68 PM-generator. It seems possible to use a similar construction for an even bigger rotor which is coupled to the VIRYA-4.2 PM-generator. It appears that this is the case for a rotor diameter of 3.9 m and the windmill is therefore called the VIRYA-3.9.

The measurements of the VIRYA-4.2 generator are given in report KD 200 (ref. 4). The VIRYA-3.9 will be used for 24 V battery if the original 230/400 V winding of the generator is rectified in delta. The VIRYA generators are described in report KD 341 (ref. 5). The generator is based on an asynchronous 3-phase motor of manufacture ROTOR type 5RN112M04V (frame size 112 with lengthened stator iron) for which the short-circuit armature is replaced by an armature provided with permanent magnets. The drawing of the VIRYA-4.2 generator is not public.

The original VIRYA-4.2 has a 2-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 workshop. Wooden blades can also be damaged easily during transport. Therefore it is investigated if an alternative rotor with stainless steel blades can be used. The VIRYA-3.9 has a somewhat smaller rotor diameter than the original VIRYA-4.2 but it is assumed that the head geometry of the VIRYA-4.2 can be maintained. The effect of the slightly smaller rotor diameter of the VIRYA-3.9 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). So the head and the tower are the same as the head and tower of the VIRYA-4.2. This head results in a rated wind speed of about 11 m/s.

## 2 Description of the rotor of the VIRYA-3.9 windmill

The 2-bladed rotor of the VIRYA-3.9 windmill has a diameter  $D = 3.9$  m and a design tip speed ratio  $\lambda_d = 6$ . 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  $3.9 / 1.8 = 2.1667$ . The original 1.8 m rotor had a sheet width at the blade tip of 75 mm, so the sheet width of a VIRYA-3.9 blade should be about  $75 * 2.1667 = 162.5$  mm. However, a larger width of 180 mm is chosen because this matches better with the available sheet size and because this results in a somewhat lower lift coefficient.

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  $1500 * 3000$  mm for the blades. It is decided that there is an overlap of  $300 \text{ mm} = 0.3 \text{ m}$  in between a blade and the connecting strip. This means that the free blade length is 1.2 m. This seems acceptable.

A sheet size  $1500 * 3000$  mm is cut into six sheets size  $500 * 1500$  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 two tapered blades are made out of this cambered sheet by a rectangular grinder.

Assume that the groove made by the rectangular grinder has a width of 3 mm. This means that if the width at the blade tip is chosen 180 mm, the width at the blade root will be  $500 - 180 - 3 = 317$  mm. So the increase of the width from the blade tip up to the blade root is  $317 - 180 = 137$  mm. This results in a taper angle of the blade of  $5.2^\circ$ . The taper angle of the blades of the original 1.8 m rotor is  $4.74^\circ$ . So the taper angle is  $0.46^\circ$  larger which is acceptable.

The camber radius of the original blades is 150 mm. So the radius of the VIRYA-3.9 blades should be about  $2.1667 * 150 = 325$  mm. However, the sheet width was chosen larger than according to scaling with a factor 2.1667. The camber radius is therefore also chosen larger. The camber radius of the VIRYA-2.92 is 290 mm. These blades are made out of a rectangular sheet size  $375 * 1250$  mm. So the sheet used for the VIRYA-3.9 is a factor  $1500 / 1250 = 1.2$  larger. If this factor is also used for the camber radius, the camber radius should be  $1.2 * 290 = 348$  mm. Finally it is chosen that the camber radius = 350 mm. 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.

The connecting strip has dimensions  $100 * 10 * 1500$  mm. The overlap in between blade and strip is 300 mm. The distance in between the heart of the strip and the tailing edge of the blade is chosen 145 mm. The connecting strip is twisted  $13^\circ$  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 M12. The strip is bevelled  $5^\circ$  at the left and the right back side over a length of 300 mm to prevent that the camber of the blade is flattened when the bolts are tightened. The hub has an outer diameter of 80 mm. The connecting strip is connected to the hub by two bolts M12. The hub is connected to the tapered shaft of the generator by one central bolt M16.

### 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-3.9 rotor. These stations are called A, B, C, D, E and F and for the corresponding local radii  $r$  it is chosen that  $r_A = 1.95$  m,  $r_B = 1.65$  m,  $r_C = 1.35$  m,  $r_D = 1.05$  m,  $r_E = 0.75$  m and  $r_F = 0.45$  m. Station E corresponds to the end of the connecting strip. 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-3.9 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  $r_A = 1.95$  m) and 317 mm at the blade root (at  $r_F = 0.45$  m). So the difference is 137 mm. This means that the sheet width  $b$  increases  $137 / 5 = 27.4$  mm per station. This gives the following values:  $b_A = 180$  mm,  $b_B = 207.4$  mm,  $b_C = 234.8$  mm,  $b_D = 262.2$  mm,  $b_E = 289.6$  mm and  $b_F = 317$  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  $\alpha_c$  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  $\alpha_r$  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)	$\alpha_c$ (rad)	c (mm)	c (m)	C (%)
A	180	350	0.2571	178.0	0.178	6.46
B	207.4	350	0.2963	204.4	0.2044	7.46
C	234.8	350	0.3354	230.4	0.2304	8.46
D	262.2	350	0.3746	256.1	0.2561	9.48
E	289.6	350	0.4137	281.4	0.2814	10.49
F	317	350	0.4529	306.3	0.3063	11.52

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 733) has its own formula numbering. Substitution of  $\lambda_d = 6$  and  $R = 1.95$  m in formula (5.1) of KD 35 gives:

$$\lambda_{rd} = 3.0769 * r \quad (-) \quad (1)$$

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

$$\beta = \phi - \alpha \quad (^\circ) \quad (2)$$

$$\phi = 2/3 \arctan 1 / \lambda_{rd} \quad (^\circ) \quad (3)$$

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

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

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

$$Re_r = 3.335 * 10^5 * c * \sqrt{(\lambda_{rd}^2 + 4/9)} \quad (-) \quad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.3 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  $C_l$ ,  $\alpha$  and  $\beta$ . Next the real blade angle  $\beta_{real}$  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)	$\lambda_{rd}$ (-)	$\phi$ (°)	c (m)	$C_{lth}$ (-)	$Re_r * 10^{-5}$ V = 5 m/s	Camber C (%)	Camber used (%)	$Re * 10^{-5}$	$\alpha_{th}$ (°)	$\beta_{th}$ (°)	$\beta_{real}$ (°)
A	1.95	6	6.3	0.178	0.83	3.58	6.46	7.14	3.4	0.5	5.8	4
B	1.65	5.077	7.4	0.2044	0.85	3.49	7.46	7.14	3.4	0.7	6.7	6.2
C	1.35	4.154	9.0	0.2304	0.91	3.23	8.46	7.14 + 10	3.4	0.7	8.3	8.4
D	1.05	3.231	11.5	0.2561	1.03	2.82	9.48	10	2.5	0.8	10.7	10.6
E	0.75	2.308	15.6	0.2814	1.24	2.25	10.49	10	2.5	2.3	13.3	12.8
F	0.45	1.385	23.9	0.3063	1.58	1.57	11.52	12.5	1.7	6.7	17.2	15.0

table 2 Calculation of the blade geometry of the VIRYA-3.9 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 the to 11.52 % at station F. To find the theoretical angles of attack  $\alpha_{th}$  we need  $C_l$ - $\alpha$  curves for the six different cambers. However, only characteristics for 7.14 %, 10 % and 12.5 % are available. The  $C_l$ - $\alpha$  curve for 7.14 % camber was used for station A and B. The average angle of the  $C_l$ - $\alpha$  curves for 7.14 % and 10 % camber was used for station C. The  $C_l$ - $\alpha$  curve for 10 % camber was used for stations D and E. The  $C_l$ - $\alpha$  curve for 12.5 % camber was used for station F.

In table 1 it can be seen that the theoretical blade angles  $\beta_{th}$  vary in between  $5.8^\circ$  at the blade tip and  $17.2^\circ$  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  $2.1^\circ$ , so much smaller than  $5.8^\circ$ . A problem with a rotor made out of a cylinder is that only the blade angle at the blade tip  $\beta_A$  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  $\beta_A$ . 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-3.9 blade for different values of  $\beta_A$ . The composite drawing for the right blade seen from the right side is given as figure 1. It was found that  $\beta_A = 4^\circ$  gives real values of  $\beta$  for the sections B, C, D, E and F which are matching best with the calculated values of  $\beta_{th}$  in table 2.

The values for  $\beta$  found from the composite drawing are given in table 2 as  $\beta_{\text{real}}$ . The angle for which the connecting strip has to be twisted right hand is  $13^\circ$  for  $\beta_A = 4^\circ$ . A sketch of the whole rotor is given in figure 2.

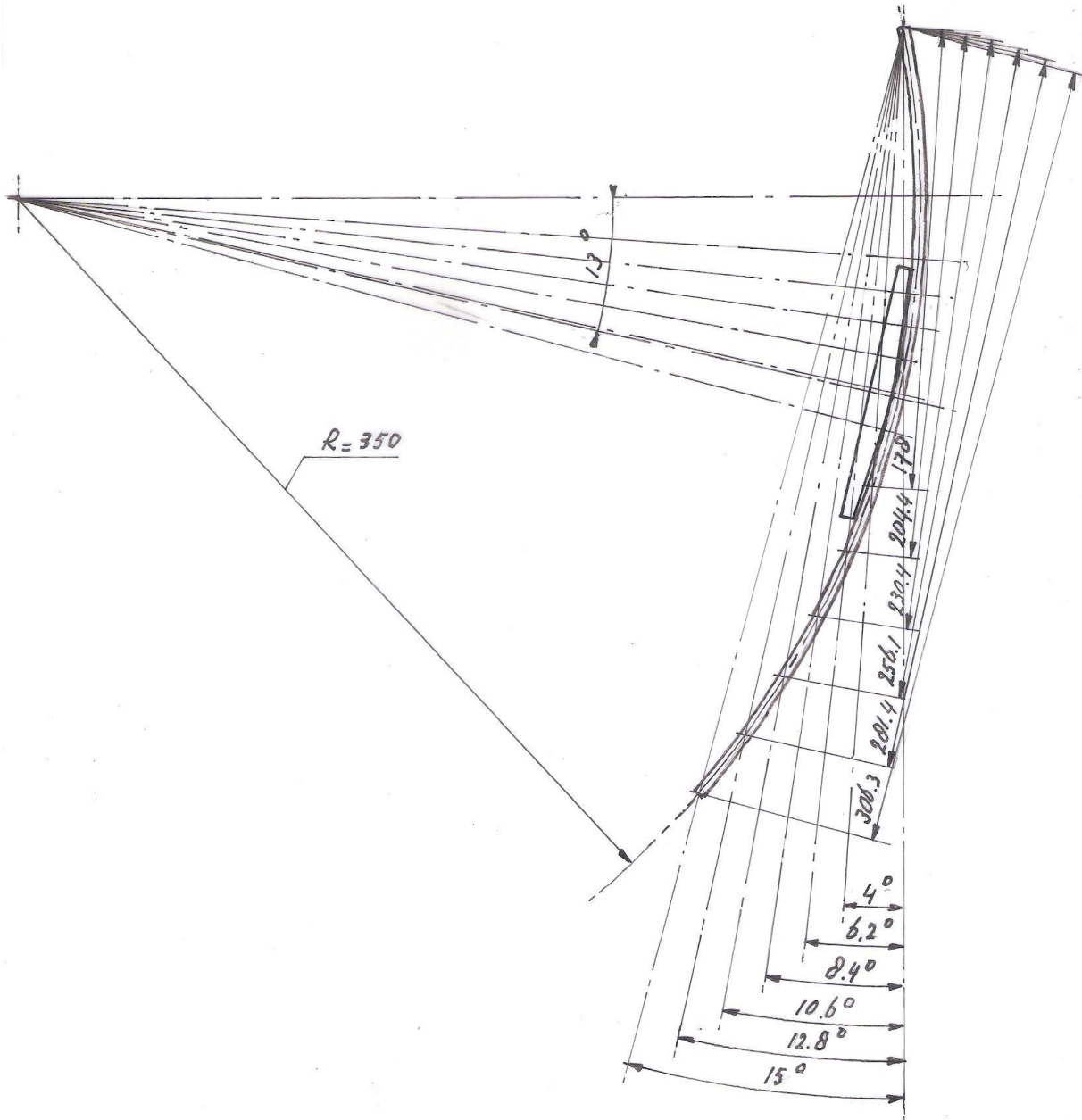


fig. 1 The right blade for six stations A, B, C, D, E and F

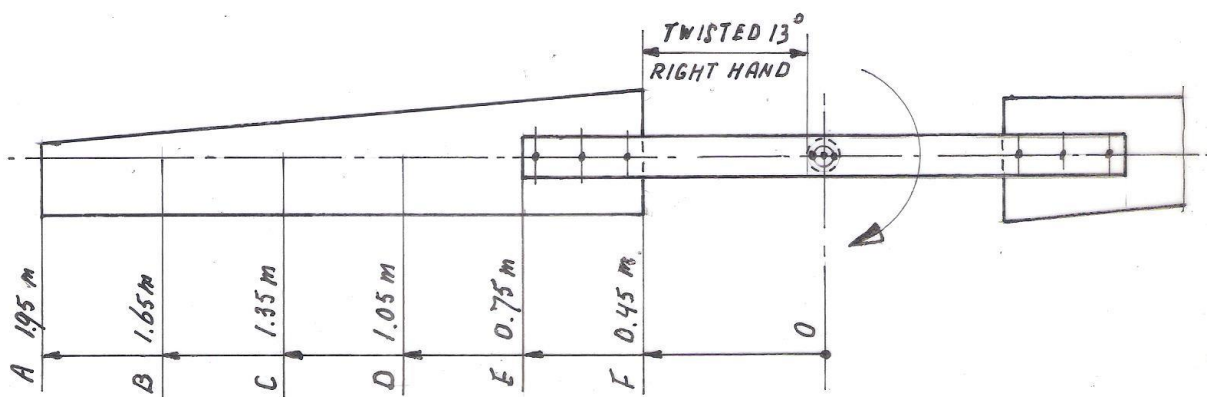


fig. 2 Front view of the VIRYA-3.9 rotor

#### 4 Determination of the $C_p$ - $\lambda$ and the $C_q$ - $\lambda$ curves

The determination of the  $C_p$ - $\lambda$  and  $C_q$ - $\lambda$  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-3.9 is a factor 2.167 larger than the tested rotor. However, the chord at the blade tip is relatively a factor  $180 / 162.5 = 1.108$  larger. This means that the Reynolds value is a factor  $2.167 * 1.108 = 2.4$  larger for a wind speed of 11 m/s. So the Reynolds value is the same for a wind speed of  $11 / 2.4 = 4.6$  m/s. This is even smaller than the value of 5 m/s which was used for the rotor calculations.

The measured  $C_p$ - $\lambda$  and  $C_q$ - $\lambda$  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  $C_p$ - $\lambda$  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  $C_p$ - $\lambda$  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  $C_l$ - $\alpha$  curve of a 10 % cambered airfoil as measured by Volkers.

For the VIRYA-3.9 it is assumed that the  $C_p$ - $\lambda$  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-3.9 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  $4^\circ$  in stead of  $2.1^\circ$  it is assumed that the starting torque coefficient is 0.0075 in stead of 0.005. The estimated  $C_p$ - $\lambda$  and  $C_q$ - $\lambda$  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 certainly exist. If the rotor is running in the peak area it will produce more power and it will make very little noise.

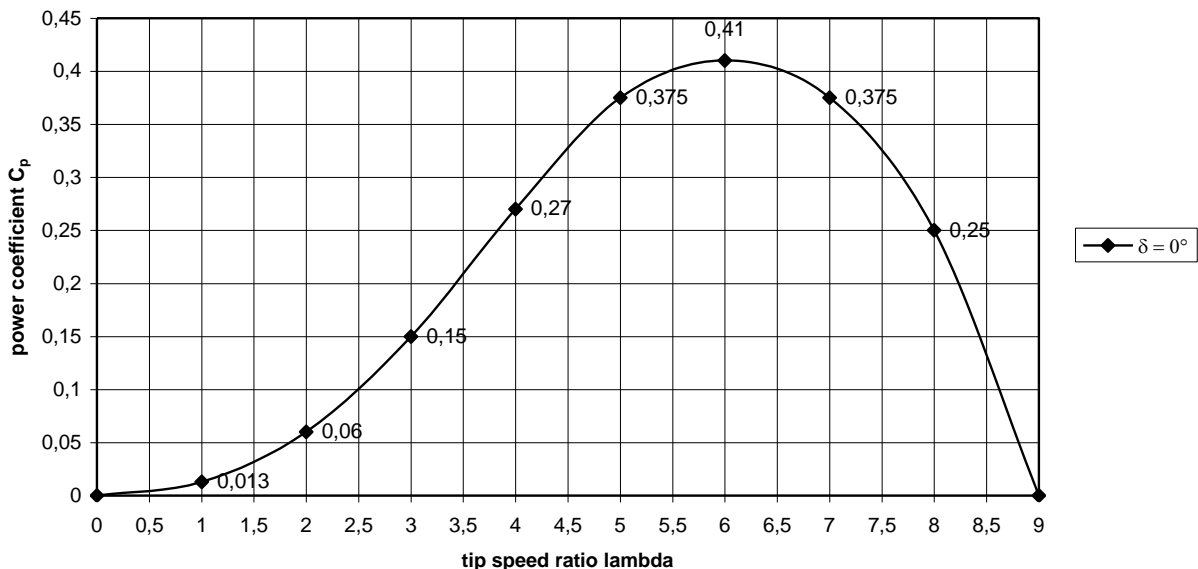


fig. 3 Estimated  $C_p$ - $\lambda$  curve for the VIRYA-3.9 rotor for the wind direction perpendicular to the rotor ( $\delta = 0^\circ$ )



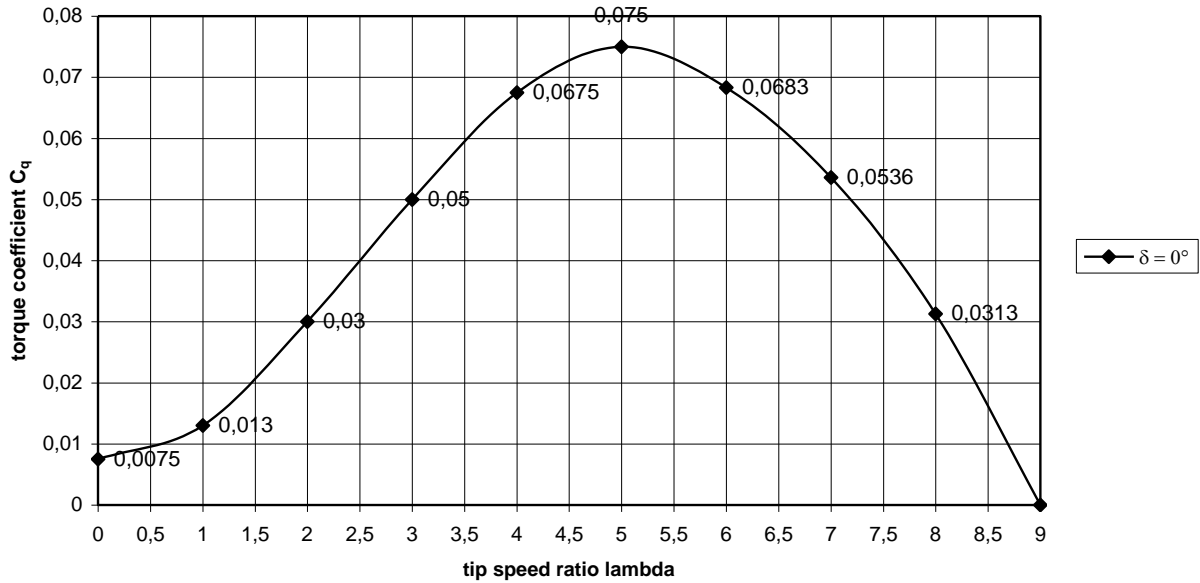


fig. 4 Estimated  $C_q$ - $\lambda$  curve for the VIRYA-3.9 rotor for the wind direction perpendicular to the rotor ( $\delta = 0^\circ$ )

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

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

For the VIRYA-4.2 generator, a sticking torque  $Q_s$  has been measured of about 0.9 Nm if the shaft is not rotating. Substitution of  $Q_s = 0.9$  Nm,  $C_{q\text{start}} = 0.0075$ ,  $\rho = 1.2$  kg/m<sup>3</sup> and  $R = 1.95$  m in formula 6 gives that  $V_{\text{start}} = 2.9$  m/s. This is acceptable low for a 2-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. This will be checked in chapter 6.

## 5 Determination of the P-n curves and the $P_{el}$ -V curve for 26 V delta and 26 V star

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a  $C_p$ - $\lambda$  curve of the rotor and a  $\delta$ -V curve of the safety system together with the formulas for the power P and the rotational speed n. The  $C_p$ - $\lambda$  curve is given in figure 3. The  $\delta$ -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<sup>3</sup>. This vane blade gives a rated wind speed  $V_{\text{rated}}$  of about 11 m/s. In report KD 223 (ref. 8) a method is given to check the estimated  $\delta$ -V curve and the estimated  $\delta$ -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  $\delta$ -V curve of the VIRYA-3.3D will be about the same as for the VIRYA-3.9. 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.

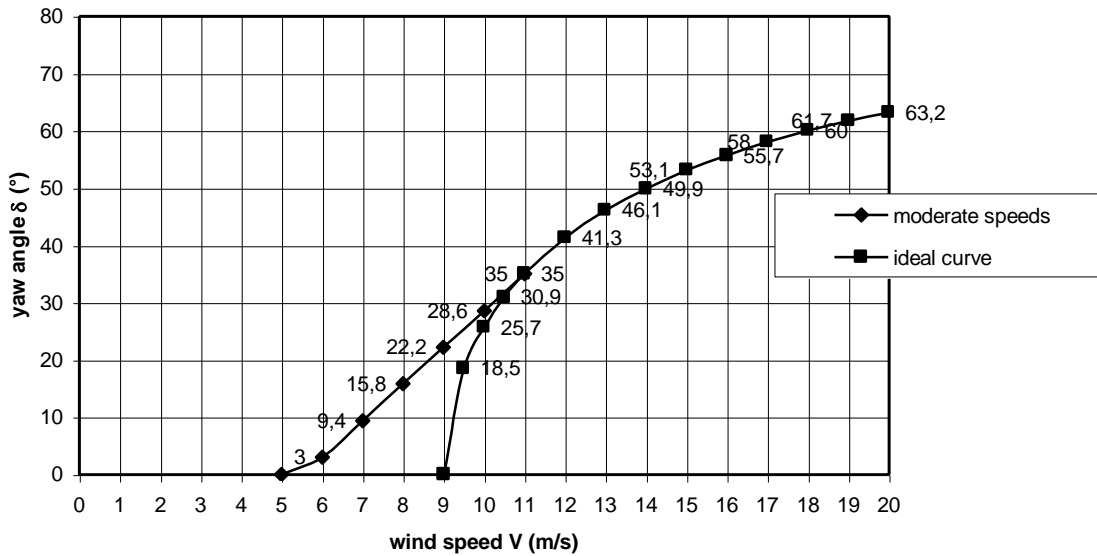


fig. 5 Estimated  $\delta$ -V curve for a 9 mm plywood vane blade

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  $\delta$  and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 1.95 m in formula 7.1 of KD 35 gives:

$$n_{\delta} = 4.8971 * \lambda * \cos\delta * V \quad (\text{rpm}) \quad (7)$$

Substitution of  $\rho = 1.2 \text{ kg / m}^3$  and R = 1.95 m in formula 7.10 of KD 35 gives:

$$P_{\delta} = 7.1675 * C_p * \cos^3\delta * V^3 \quad (\text{W}) \quad (8)$$

The P-n curves are determined for  $C_p$  values belonging to  $\lambda$  is 3, 4, 5, 6, 7, 8 and 9 (see figure 3). For a certain wind speed, for instance  $V = 3 \text{ m/s}$ , related values of  $C_p$  and  $\lambda$  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 $\delta = 0^\circ$		V = 4 m/s $\delta = 0^\circ$		V = 5 m/s $\delta = 0^\circ$		V = 6 m/s $\delta = 3^\circ$		V = 7 m/s $\delta = 9.4^\circ$		V = 8 m/s $\delta = 15.8^\circ$		V = 9 m/s $\delta = 22.2^\circ$		V = 10 m/s $\delta = 28.6^\circ$		V = 11 m/s $\delta = 35^\circ$	
$\lambda$ (-)	$C_p$ (-)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)	$n_{\delta}$ (rpm)	$P_{\delta}$ (W)
3	0.15	44.1	29	58.8	69	73.5	134	88.0	231	101.5	354	113.1	490	122.4	622	129.0	728	132.4	787
4	0.27	58.8	52	78.4	124	97.9	242	117.4	416	135.3	637	150.8	883	163.2	1120	172.0	1310	176.5	1416
5	0.375	73.5	73	97.9	172	122.4	336	146.7	578	169.1	885	188.5	1226	204.0	1555	215.0	1819	220.6	1966
6	0.41	88.1	79	117.5	188	146.9	367	176.1	632	202.9	968	226.2	1340	244.8	1700	258.0	1989	264.8	2150
7	0.375	102.8	73	137.1	172	171.4	336	205.4	578	236.7	885	263.9	1226	285.6	1555	301.0	1819	308.9	1966
8	0.25	117.5	48	156.7	115	195.9	224	234.7	385	270.6	590	301.6	817	326.5	1037	344.0	1213	353.0	1311
9	0	132.2	0	176.3	0	220.4	0	264.1	0	304.4	0	339.3	0	367.3	0	387.0	0	397.1	0

table 3 Calculated values of n and P as a function of  $\lambda$  and V for the VIRYA-3.9 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-4.2 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 measurements were performed for the original 230/400 V winding. The measured  $P_{\text{mech}}$ - $n$  and the  $P_{\text{el}}$ - $n$  curves for  $U = 26$  V delta are also plotted in figure 6. The generator has not been measured for 26 V star but the characteristics for 26 V star are estimated in chapter 5 of report KD 200 (ref. 4). The estimated  $P_{\text{mech}}$ - $n$  and the  $P_{\text{el}}$ - $n$  curves for  $U = 26$  V star 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  $P_{\text{mech}}$ - $n$  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  $P_{\text{el}}$  for that wind speed is found by going down vertically from the working point up to the point of intersection with the  $P_{\text{el}}$ - $n$  curve. The values of  $P_{\text{el}}$  found this way for all wind speeds, are plotted in the  $P_{\text{el}}$ - $V$  curves (see figure 7) for 26 V delta and for 26 V star.

The matching of rotor and generator for 26 V delta is rather good because the  $P_{\text{mech}}$ - $n$  curve of the generator is lying only somewhat to the right from the optimum cubic line for wind speeds higher than 4 m/s. The real tip speed ratio for wind speeds around 7 m/s is about 6.5. This is just the tip speed ratio for which the original 1.8 m rotor had a peak in the  $C_p$ - $\lambda$  curve and for which the rotor was very silent. It is expected that this is also the case for the VIRYA-3.9 rotor and this rotor in combination with the VIRYA-4.2 generator for 26 V delta will therefore be much more silent than rotors with steel blades with a high tip speed ratio and a constant chord.

The matching of rotor and generator for 26 V star is also rather good because the  $P_{\text{mech}}$ - $n$  curve of the generator is lying only somewhat to the left from the optimum cubic line for wind speeds in between 3 m/s and 7 m/s. However, for high wind speeds, the load isn't strong enough and for  $V = 11$  m/s, the  $P_{\text{mech}}$ - $n$  curve for 26 V star is lying even more to the right than the  $P_{\text{mech}}$ - $n$  curve for 26 V delta.

In the  $P_{\text{el}}$ - $V$  curve for 26 V delta it can be seen that the maximum power is 910 W at a wind speed of 11 m/s. The supply of power starts at a wind speed of 3.2 m/s ( $V_{\text{cut in}} = 3.2$  m/s). In chapter 4 it was calculated that  $V_{\text{start}} = 2.9$  m/s so there is no hysteresis in the  $P_{\text{el}}$ - $V$  curve for 26 V delta.

In the  $P_{\text{el}}$ - $V$  curve for 26 V star it can be seen that the maximum power is 670 W at a wind speed of 11 m/s which is a lot lower than for 26 V delta. This is because the generator efficiency is a lot lower at high currents for 26 V star than for 26 V delta. The supply of power starts at a wind speed of 2.4 m/s ( $V_{\text{cut in}} = 2.4$  m/s). In chapter 4 it was calculated that  $V_{\text{start}} = 2.9$  m/s so there is hysteresis in the  $P_{\text{el}}$ - $V$  curve for 26 V star for  $2.4 \text{ m/s} < V < 2.9 \text{ m/s}$ .

If both  $P_{\text{el}}$ - $V$  curves are compared it can be seen that the curve for 26 V star is better for wind speeds below 5 m/s but that the curve for 26 V delta is much better above 5 m/s. So 26 V star is only advised for regions with low wind speeds.

As at high wind speeds, the electrical power for 26 V star is much lower than for 26 V delta, it means that more heat is generated in the winding for 26 V star. So it must be investigated if the generator isn't becoming too hot at high wind speeds for 26 V star. If it appears that the generator becomes too hot at high wind speeds, the maximum power can be reduced by taking a lighter vane blade.

The  $P$ - $n$  curve for short-circuit in delta is lying just above the  $P$ - $n$  curve of the rotor for  $V = 9$  m/s. So the rotor will only slow down to almost stand still if short-circuit in delta is made and if the wind speed is less than 9 m/s.

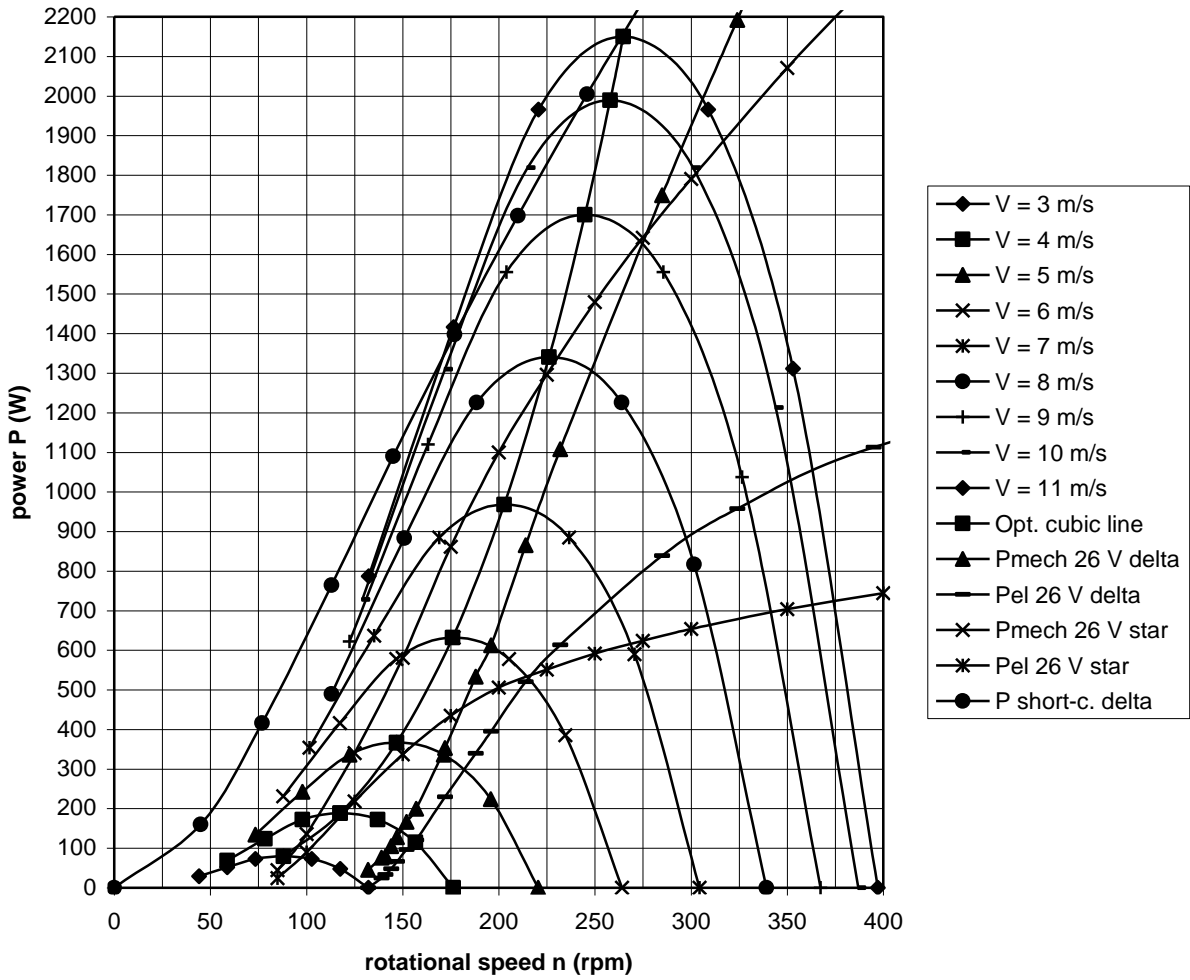


fig. 6 P-n curves of the VIRYA-3.9 rotor and the generator for 26 V delta and 26 V star

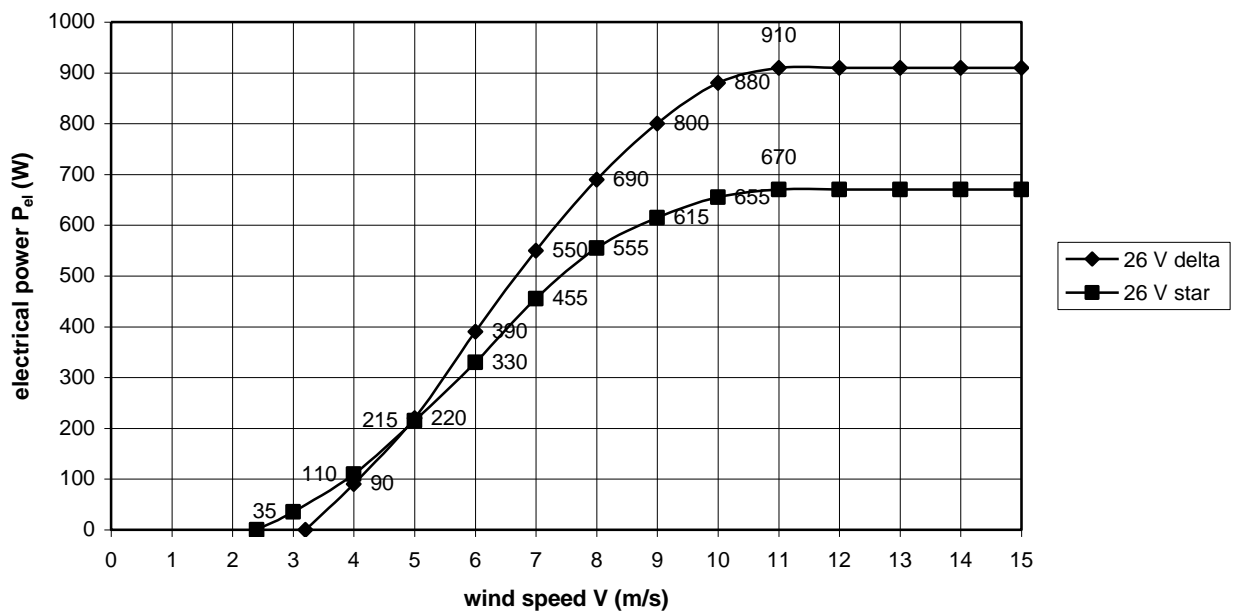


fig. 7  $P_{el}$ - $V$  curve of the VIRYA-3.9 windmill for 26 V delta and 26 V star

## 6 Checking of the starting behaviour

In chapter 4 it has been calculated that the starting wind speed is 2.9 m/s. At this wind speed the rotor is able to generate the unloaded sticking torque of 0.9 Nm of the generator if the shaft is not rotating. The unloaded sticking torque increases at increasing rotational speeds but how much depends on how the generator is rectified. The sticking torque for delta rectification rises faster than for star rectification because higher harmonic currents can circulate in the winding for delta rectification. The sticking torque has been measured for both situations and the result is given in figure 1 of report KD 200. This figure is copied as figure 8 for low rotational speeds.

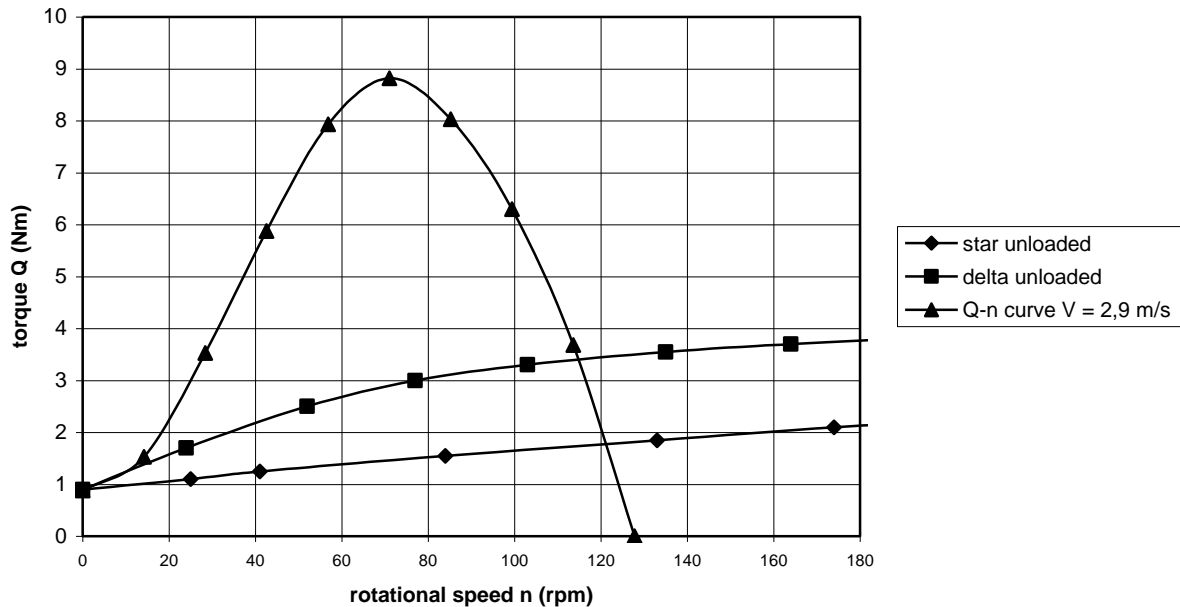


fig. 8 Unloaded sticking torque of the generator for rectification in delta and star and Q-n curves of the rotor for  $V = 2.9$  m/s

The Q-n curve of the rotor for a certain wind speed can be determined in the same way as the P-n curve for a certain wind speed but one has to use the formula for Q in stead as the formula for P. The formula for Q for a rotor perpendicular to the wind is given by formula 4.3 of KD 35. Substitution of  $\rho = 1.2$  kg/m<sup>3</sup>,  $V = 2.9$  m/s and  $R = 1.95$  m in this formula gives:

$$Q = 117.54 * C_q \quad (\text{Nm}) \quad (10)$$

The rotational speed n is given by formula 8. Substitution of  $\delta = 0^\circ$  and  $V = 2.9$  m/s in formula 8 gives:

$$n = 14.202 * \lambda \quad (\text{rpm}) \quad (11)$$

The Q-n curve is now determined for values  $\lambda$  of 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 and the corresponding values of  $C_q$  (see figure 2). The Q-n curve found this way is also given in figure 8. In figure 8 it can be seen that the Q-n curve for  $V = 2.9$  m/s is rising faster than the unloaded sticking torque for rectification in star. However, at low rpm, it is rising with about the same rate as the unloading sticking torque for rectification in delta. This means that at  $V = 2.9$  m/s, there is no torque difference to accelerate the rotor. So the real starting wind speed will be a little higher than 2.9 m/s if the generator is rectified in delta. This is certainly acceptable and so use of the VIRYA-3.9 rotor in combination with the VIRYA-4.2 generator for 26 V delta is a realistic option.

## 7 Use of a modified 115/200 V winding for 26 V star

The generator has been measured for the original 230/400 V winding. It is possible to modify this winding into a 115/200 V winding by connecting the first and the second layer in parallel instead of in series. This results in halving of the voltage and in doubling of the current. The modification procedure is described in chapter 4 of report KD 341 (ref. 5).

The generator has been measured for 52 V star. This is the average charging voltage of a 48 V battery. The original VIRYA-4.2 was used for 48 V battery charging and so the measurements for 52 V star could be used. However, a battery voltage of 48 V is less common than 24 V and a special 55.2 V battery charge controller has to be used to limit the maximum charging voltage up to 2.3 V per cell. A 27.6 V, 200 W battery charge controller is described in a manual which is available on my website at the bottom of the list with KD-reports (ref. 9). The power which can be dissipated can be increased to 1200 W by connecting six dump load modules together in parallel.

So now it is assumed that the standard 230/400 V winding is modified into a 115/200 V winding. The measured characteristics for 52 V star can now be used for 26 V star. Figure 6 is now copied as figure 9 but the curves for the original winding for 26 V delta and 26 V star are replaced by the curves for the modified winding for 26 V star.

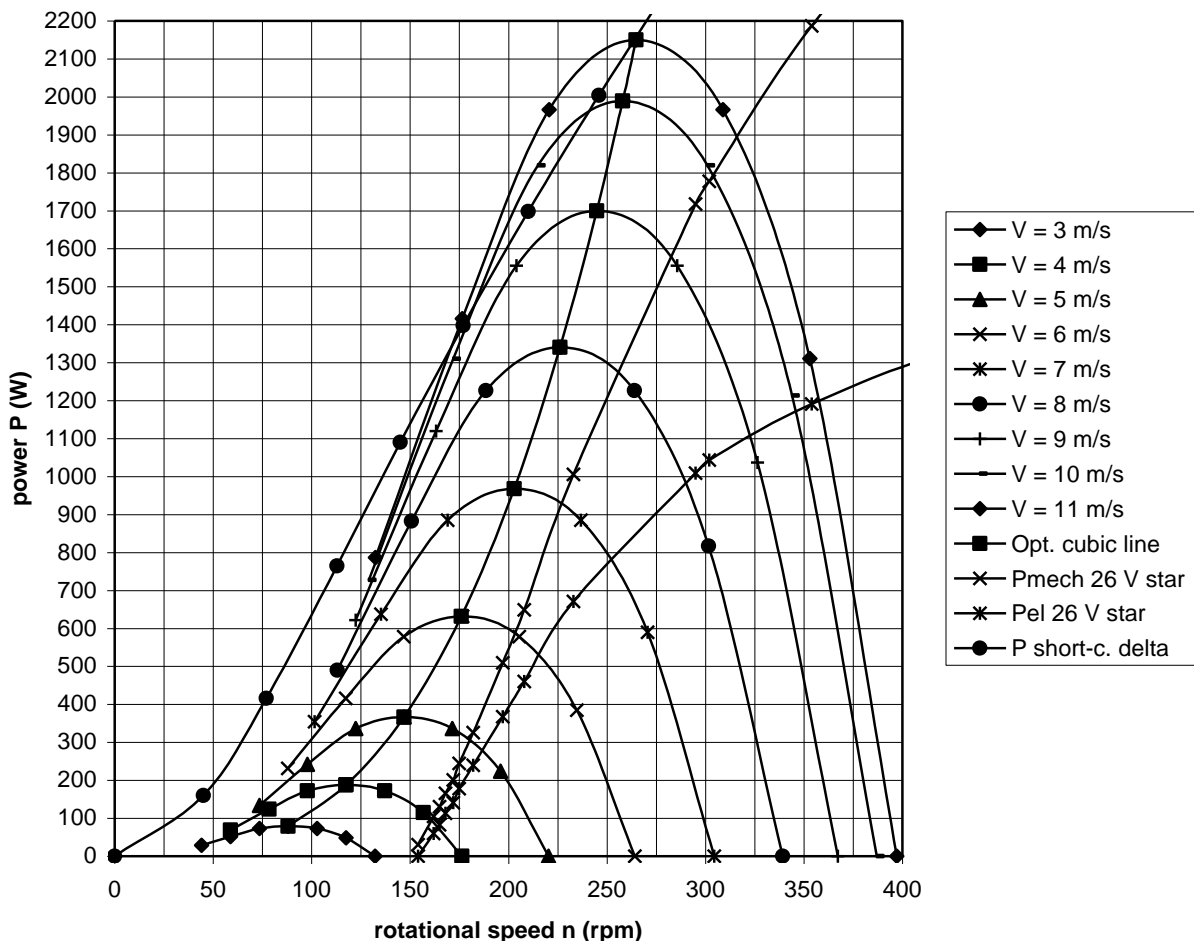


fig. 9 P-n curves of the VIRYA-3.9 rotor and the generator for 26 V star for the modified 115/200 V winding

Is figure 9 is compared with figure 6 it can be seen that the  $P_{\text{mech}}-n$  curve for the modified winding for 26 V star is lying somewhat more to the right than the  $P_{\text{mech}}-n$  curve for the original winding for 26 V delta. So the matching is less good but still acceptable.

The noise production will still be low because the rotor runs with a tip speed ratio for which the original 1.8 m rotor was very silent. The  $P_{el}$ - $V$  curve for the modified winding for 26 V star is derived in the same way as it was done for the original winding and is given in figure 10.

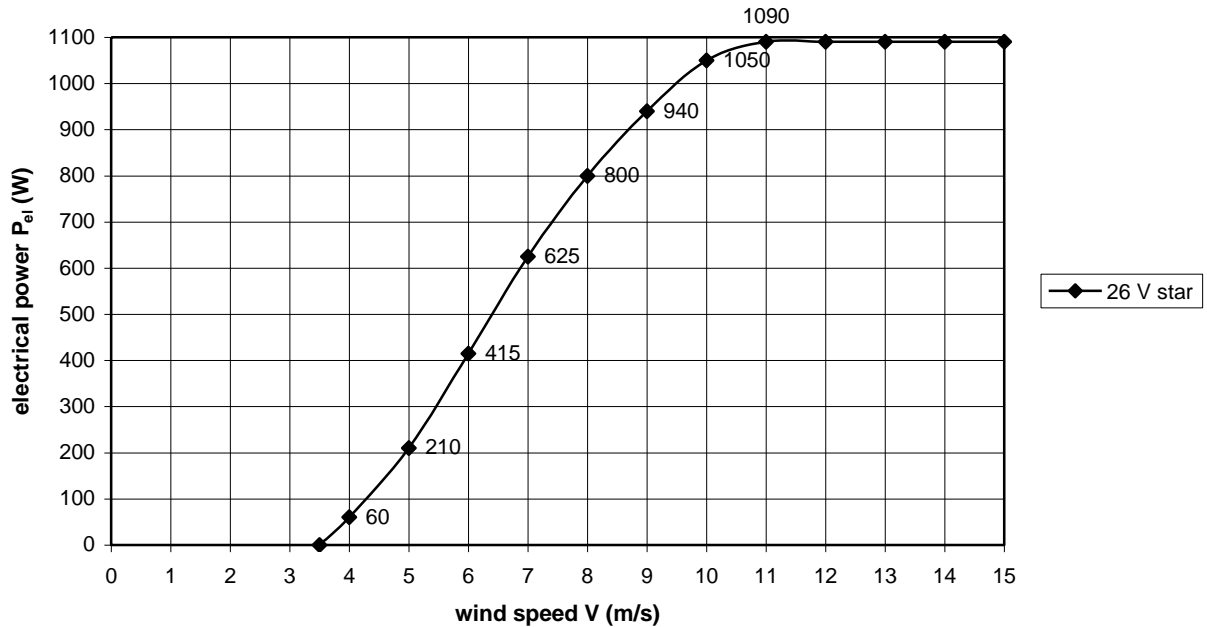


fig. 10  $P_{el}$ - $V$  curve of the VIRYA-3.9 windmill for 26 V star for the modified 115/200 V winding

If figure 10 is compared to the curve for 26 V delta in figure 7, it can be seen that the cut-in wind speed is increased from 3.3 m/s up to 3.5 m/s. However, the maximum electrical power is increased from 910 W up to 1090 W. So a battery charge controller which can dissipate a maximum power of 1200 W is certainly large enough.

If figure 10 is compared to the curve for 26 V star in figure 7, it can be seen that the cut-in wind speed is increased from 2.4 m/s up to 3.5 m/s. However, the maximum electrical power is increased from 670 W up to 1090 W.

So the much higher electrical power for the modified winding for 26 V star results in less heat dissipation in the winding and so in a lower generator temperature at high power.

It will be clear that it is also possible to use the original 230/400 V winding rectified in star for 48 V battery charging and that then the same  $P_{el}$ - $V$  curve is valid as given in figure 10.

### 8 Alternative 3-bladed VIRYA-3.9B3 rotor

The disadvantage of a 2-bladed rotor is that the gyroscopic moment in the rotor shaft is fluctuating. It is maximal for the blades in the vertical position and zero for the blades in the horizontal position. This fluctuation can be flattened by using an elastic element which connects both blades. The connecting strip of the 2-bladed VIRYA-3.9 is rather flexible but as the blades are rather heavy, it isn't sure if the fluctuation of the gyroscopic moment is flattened enough. Fluctuation of the gyroscopic moment results in vibration of the tower if the frequency of the fluctuation is the same as the natural frequency of the tower.

The gyroscopic moment in one blade is always fluctuating but the resulting moment of three blades on the rotor shaft is constant for a constant rotational speed of the rotor and a constant angular velocity of the head. So a 3-bladed rotor isn't giving vibration of the tower. It is possible to design a 3-bladed rotor with the same design tip speed ratio  $\lambda_d = 6$  as used for the 2-bladed VIRYA-3.9. The windmill with this rotor is called the VIRYA-3.9B3.

As the product of the number of blades  $B$  and the chord  $c$  must have a certain value for a certain lift coefficient, a certain design tip speed ratio and a certain rotor radius  $r$ , the chord of this 3-bladed rotor must be  $2/3$  of that of the 2-bladed rotor. The same stainless steel sheet size  $1500 * 3000 * 3$  mm is used. First this sheet is cut into nine sheets size  $333 * 1500$  mm. As  $9 * 333 = 2997$  mm, 3 mm is left and so this 3 mm must be cut from the last strip to make that all nine sheets have the same weight!

Two tapered blades are ground from one sheet after cambering. It is assumed that 3 mm is needed for the rectangular grinder. So the effective width is  $333 - 3 = 330$  mm. The blade width  $b$  at the tip is 180 mm for the 2-bladed rotor. So it is assumed that it is 120 mm for the 3-bladed rotor. So the strip width at the blade root is  $330 - 120 = 210$  mm. So the width increases from the blade tip to the blade root by  $210 - 120 = 90$  mm. The blade is calculated for six stations which have a distance of 300 mm with respect to each other so the width increases by  $90 / 5 = 18$  mm per station. The camber radius  $r_c$  should also be about  $2/3$  of the camber radius of the 2-bladed rotor. It is chosen that  $r_c = 230$  mm. The cord  $c$  and the camber  $C$  are calculated in the same way as it was done for the 2-bladed rotor and the result is given in table 4.

Station	b (mm)	$r_c$ (mm)	$\alpha_c$ (rad)	c (mm)	c (m)	C (%)
A	120	230	0.2609	118.7	0.1187	6.56
B	138	230	0.3000	135.9	0.1359	7.56
C	156	230	0.3391	153.0	0.153	8.56
D	174	230	0.3783	169.9	0.1699	9.57
E	192	230	0.4174	186.5	0.1865	10.59
F	210	230	0.4565	202.8	0.2028	11.61

table 4 Calculated values of the chord  $c$  and the camber  $C$  for different stations

This rotor has three 0.75 m long spokes made out of stainless steel strip size  $80 * 10$  mm which make an angle of  $120^\circ$  with each other. The three strips are welded together at the centre and clamped in between the hub and a clamping disk by means of three bolts M12. The rotor calculations are similar as for the 2-bladed rotor. Formula 1, 2, 3 and 5 are still valid. Substitution of  $B = 3$  in formula (5.4) of KD 35 gives:

$$C_1 = 8.378 * r (1 - \cos\phi) / c \quad (-) \quad (12)$$

The Reynolds values for the stations are calculated for a wind speed of 5 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values. The result of the calculations is given in table 5.



station	r (m)	$\lambda_{rd}$ (-)	$\phi$ (°)	c (m)	$C_{lth}$ (-)	$Re_r * 10^{-5}$ V = 5 m/s	Camber C (%)	Camber used (%)	$Re^* 10^{-5}$	$\alpha_{th}$ (°)	$\beta_{th}$ (°)	$\beta_{real}$ (°)
A	1.95	6	6.3	0.1187	0.83	2.39	6.56	7.14	2.5	0.8	5.5	3.5
B	1.65	5.077	7.4	0.1359	0.85	2.32	7.56	7.14	2.5	0.9	6.5	5.8
C	1.35	4.154	9.0	0.153	0.91	2.15	8.56	7.14 + 10	2.5	0.9	8.1	8.1
D	1.05	3.231	11.5	0.1699	1.03	1.87	9.57	10	1.7	1.9	9.6	10.4
E	0.75	2.308	15.6	0.1865	1.24	1.49	10.59	10	1.7	3.3	12.3	12.7
F	0.45	1.385	23.9	0.2028	1.59	1.04	11.61	12.5	1.2	7.9	16.0	15.0

table 5 Calculation of the blade geometry of the VIRYA-3.9B3 rotor

In table 5 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 6.56 % at station A the to 11.61 % at station F. To find the theoretical angles of attack  $\alpha_{th}$ , we need  $C_l$ - $\alpha$  curves for the six different cambers. However, only characteristics for 7.14 %, 10 % and 12.5 % are available in KD 398. The  $C_l$ - $\alpha$  curve for 7.14 % camber was used for station A and B. The average angle of the  $C_l$ - $\alpha$  curves for 7.14 % and 10 % camber was used for station C. The  $C_l$ - $\alpha$  curve for 10 % camber was used for stations D and E. The  $C_l$ - $\alpha$  curve for 12.5 % camber was used for station F.

In table 5 it can be seen that the theoretical blade angles  $\beta_{th}$  vary in between 5.5° at the blade tip and 16.0° 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 5.5°. A problem with a rotor made out of a cylinder is that only the blade angle at the blade tip  $\beta_A$  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  $\beta_A$ . 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-3.9B3 blade for different values of  $\beta_A$ . The composite drawing for the right blade seen from the right side is given as figure 11. It was found that  $\beta_A = 3.5^\circ$  gives real values of  $\beta$  for the sections B, C, D, E and F which are matching best with the calculated values of  $\beta_{th}$  in table 5. A drawing of the whole rotor is given in figure 12. The distance in between the heart of a spoke and the tailing edge of the blade is chosen 95 mm (in a flat plane). The spoke has to be twisted 12.5° right hand in between the hub and the blade root. A spoke has to be bevelled over the outer 300 mm at the left and right backside by an angle of 6° to prevent flattening of the blade when the bolts are tightened. A blade is connected to a spoke by three bolts M12 \* 45. The bolt head is at the backside. A heavy washer has to be mounted under the head of the outer bolt to prevent a too high stress in the blade at this point because of the rotor thrust.

The mass of one blade is about 5.79 kg. The mass of one spoke is about 4.56 kg. The mass of the hub is about 1.95 kg. The mass of the clamping disk is about 0.39 kg. So the mass of the whole rotor is about 33.4 kg. This is acceptable for a stainless steel 3-bladed rotor with a diameter of 3.9 m.

It might be possible to use this rotor to drive a centrifugal pump through a vertical shaft in the centre of the tower and an accelerating transmission in the head but description of this option is out of the scope of this report.

The maximum  $C_p$  of a 3-bladed rotor is somewhat higher than for a 2-bladed rotor with the same design tip speed ratio because the tip losses for a 3-bladed rotor are less than for a 2-bladed rotor (see KD 35 figure 4.3). However, the Reynolds values of the 3-bladed rotor are lower resulting in a higher  $C_d/C_l$  ratio and this results in a lower maximum  $C_p$ . It is assumed that both effects compensate each other and so it is assumed that the  $C_p$ - $\lambda$  and  $C_q$ - $\lambda$  curves as given in chapter 4 for the VIRYA-3.9 are also valid for the VIRYA-3.9B3. So the P-n curves and the  $P_{cl}$ -V curves as given in chapter 5 and chapter 7 are also valid for the VIRYA-3.9B3. The starting behaviour as explained in chapter 6, will also be the same.

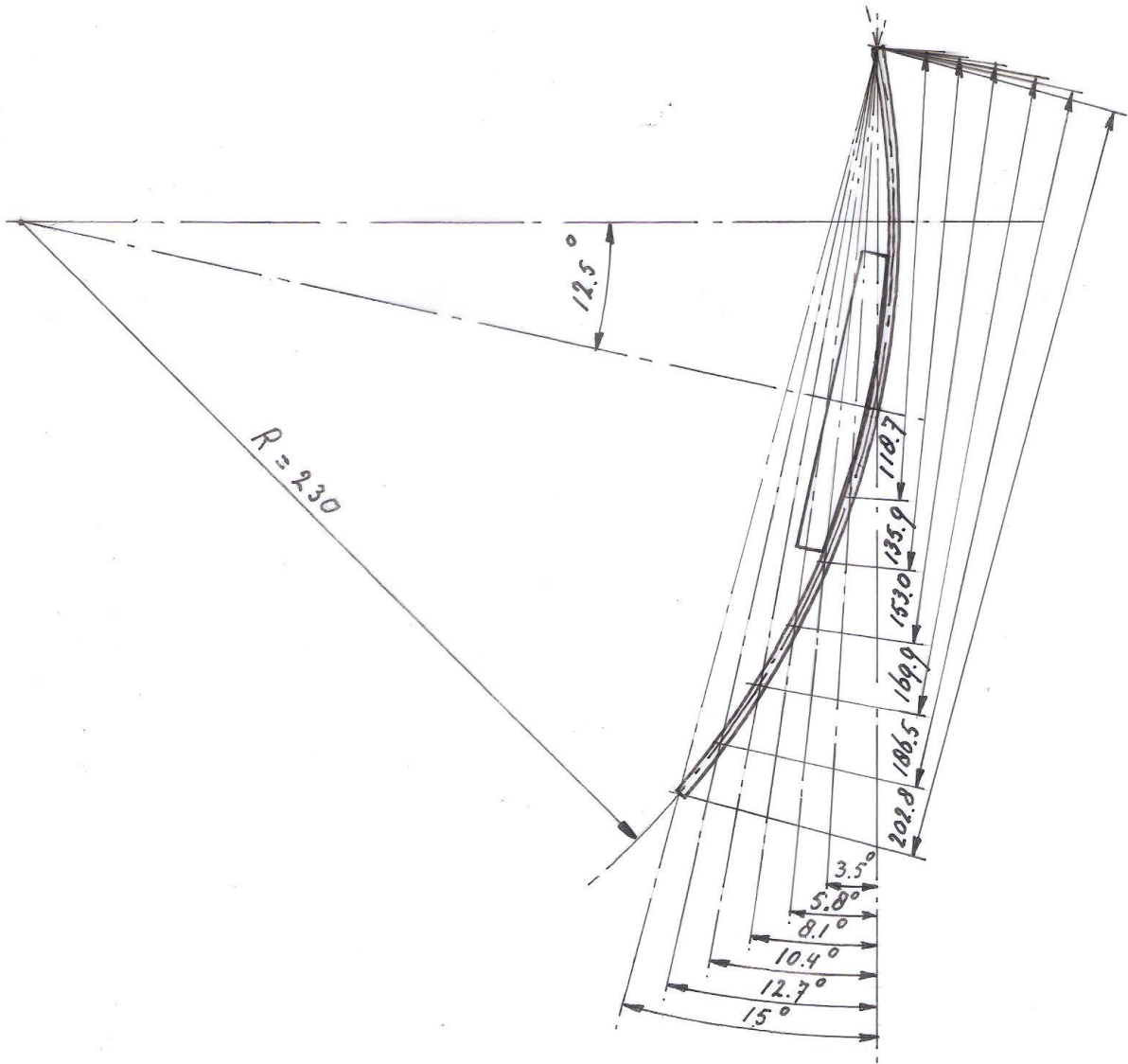


fig. 11 The right blade for six stations A, B, C, D, E and F

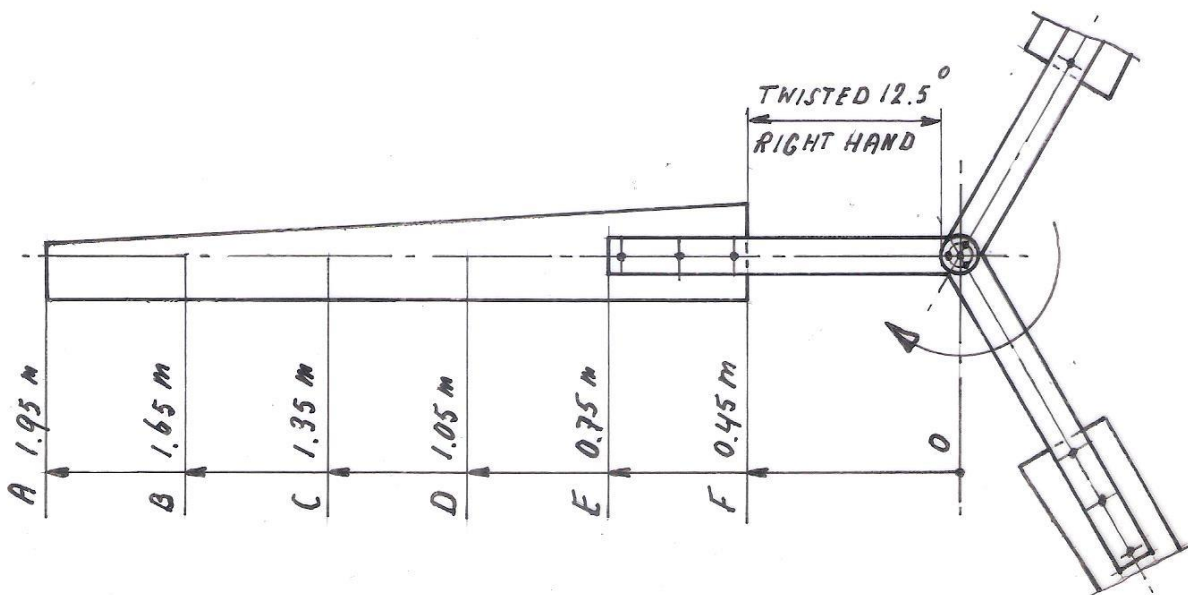


fig. 12 Front view of the VIRYA-3.9B3 rotor

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