Calculations executed for the rotor of the VIRYA-10R windmill (λ_d = 7, Gö 711 airfoil) with a 2-bladed rotor made out of Roofmate, glass fibre and epoxy using the hinged side vane safety system and a generator type TGET770-H-10KW-100R for grid connection

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January 2025

KD 774

 A prototype of the VIRYA-10R windmill has not yet been built and tested. This should be done only by a professional company after making detailed drawings. Although the VIRYA-10R has been designed carefully, no responsibility is accepted by Kragten Design for the proper functioning.

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Contains page

1 Introduction

Already in 1977 I have designed and built a very light 2-bladed windmill rotor with a diameter D = 3.2 m, a design tip speed ratio λ_d = 8 and a NACA 4412 airfoil which was manufactured from the isolation material Roofmate covered with glass fibre and epoxy. A photo of this rotor is given in appendix 1. This rotor was damaged in a strong storm because the windmill for which it was used, was not provided with a safety system which limits the thrust and because the rotor was not strong enough. However, the manufacturing procedure was rather simple and a large rotor can be manufactured with the used procedure at a rather low price. So it is investigated how a rather large rotor looks like if it is manufactured from Roofmate material.

Roofmate is standard supplied in sheets with a length of 1250 mm and a width of 600 mm. It can be supplied in a large range of thicknesses. There is some tolerance on the length and so the sections out of which the rotor is built up can be a little shorter or longer than 1250 mm but this effect is neglected for the rotor calculations.

A rotor is made of eight 1250 mm long sections resulting in a rotor diameter of 10 m. The windmill is called the VIRYA-10R. The R (of Roofmate) is added to distinguish it from the VIRYA-10 with three wooden blades.

It might be difficult in some countries to obtain wood of good quality and therefore this alternative rotor made out of Roofmate, glass fibre and epoxy is designed. An adjacent advantage is that this rotor is very light. The VIRYA-10R rotor is mounted to the same axial flux generator type TGET770-H-10KW-100R as used for the VIRYA-10 which is described in report KD 715 (ref. 1). However, the VIRYA-10 is provided with the pendulum safety system with a torsion spring and the VIRYA-10R is provided with the hinged side vane safety system. The VIRYA-10R makes use of a tubular tower with a height of about 18 m.

2 Description of the rotor of the VIRYA-10R windmill

A blade is made of three 1250 mm long segments which are glued together by epoxy. Two rotor blades are glued to a central part which is also made from Roofmate and which has a length of 2 * 1250 = 2500 mm and a thickness of 120 mm. So the rotor diameter D = 8 * 1250 = 10000 mm = 10 m and the rotor radius R = 5 m. The whole rotor is covered with some layers of glass fibre imbedded in epoxy to make the rotor strong and stiff enough. The required number of layers has still to be determined. The original rotor with D = 3.2 m had only one layer.

A blade segment is made of a 1250 mm long part of Roofmate by connecting a jig with the required airfoil to both sides of the sheet. The blade segment is cut from the sheet by moving a hot wire simultaneously along both jigs. This procedure allows a small blade twist in between both sides of the blade segment.

The 2-bladed rotor of the VIRYA-10R windmill has a design tip speed ratio λ_d = 7. This is lower than the λ_d = 8 of the 3.2 m rotor made in 1977 and the chords are therefore relatively larger resulting in a stronger rotor. The most important advantages of a 2-bladed rotor above a 3-bladed rotor are that the connection of the blades to the hub is simple and that balancing of the rotor is rather simple too.

The rotor has blades with a linearised chord and blade angle and is provided with a Gö 711 airfoil. The geometry and characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 2). The maximum thickness is 14.85 % of the chord. A disadvantage of this airfoil is that it has only been measured for a rather high Reynolds value Re = 4 * 10^5 but as the used chords are rather large, this is no problem.

The rather large thickness also makes that the rotor is relatively stronger and stiffer than the original rotor. The lower side of the Gö 711 airfoil is flat over 97.5 % of the chord which simplifies manufacture. The central part has a rectangular cross section in the middle with rounded edges but long transition parts to realise a fluent transition to the airfoil geometry.

The chord c is 0.42 m at the blade tip and 0.6 m at the blade root. The increase of the chord and so also of the blade thickness, results in a strong increase of the blade strength at the root. A square 3 mm thick stainless steel sheet with sizes of 500 mm is glued by epoxy to both sides of the central part to guide the forces acting on the rotor to the generator. There are four M12 bolts at a pitch of 450 mm at the corners of the sheets. The rotor is connected to the generator by eight M16 bolts at a pitch circle of 220 mm. Inserts at the bolts prevent squeezing of the central part. The blades will be rather flexible and therefore vibrations which are caused by the gyroscopic moment, by streaming under a certain yaw angle δ and by a non-uniform distribution of the wind speed over the rotor plane, are flattened. The rotor is balanced by adding some extra glass and epoxy to the lightest blade tip or by gluing small cylinders of lead in holes which are drilled in the lightest blade tip.

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 3). This report (KD 774) has its own formula numbering. Substitution of $\lambda_d = 7$ and R = 5 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 1.4 * r$ (-) (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 seven stations A till G which have a distance of 0.625 m (so halve a blade section) of one to another. First the theoretical values are determined for C_l, α and β. Next β is linearised such that the twist is constant in between the ends of a blade section and that the linearised values correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The Reynolds values for the stations are calculated for a wind speed of 5 m/s because for most working hours, the windmill will be used at rather low wind speeds.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ Gö 711	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	5	7	5.4	0.42	0.67	0.67	9.85	4	0.0	0.0	5.4	5.4	0.020
B	4.375	6.125	6.2	0.45	0.71	0.71	9.25	4	0.5	0.5	5.7	5.7	0.019
C	3.75	5.25	7.2	0.48	0.77	0.77	8.47	4	1.2	1.2	6.0	6.0	0.018
D	3.125	4.375	8.6	0.51	0.86	0.86	7.53	4	2.3	2.3	6.3	6.3	0.016
E	2.5	3.5	10.6	0.54	1.00	1.00	6.42	4	4.0	4.0	6.6	6.6	0.015
F	1.875	2.625	13.9	0.57	1.21	1.21	5.15	4	6.9	6.9	7.0	7.0	0.020
G	1.25	1.75	19.8	0.6	1.55	1.50	3.75	4	-	12.4	-	7.4	0.045

table 1 Calculation of the blade geometry of the VIRYA-10R rotor

No value of α_{th} is found for station G because the required C_l value can't be generated. It appears that the calculated values of β_{th} result in a linear twist of 0.3° in between stations A-B, B-C, C-D and D-E. So the linearised values β_{lin} are chosen the same as the theoretical values. The theoretical twist in between station F and E is 7° – 6.6° = 0.4°. The twist in between station G and F is taken the same resulting in β_{lin} = 7.4° for station G. A sketch of the rotor is given in appendix 2.

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

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the four most important outer stations of the blade is 0.018. Figure 4.6 of KD 35 (for B = 2) and λ_{opt} = 7 and C_d/C_l = 0.018 gives $C_{p\ th}$ = 0.465. The blade is just stalling, at station G and so for the calculation of the maximum C_p, only the part 0.1 m outside station G is taken into account. This gives an affective blade length k' = 5 – 1.35 = 3.65 m.
Substitution of $C_{p\ th}$ = 0.465, R = 5 m and effective blade length k' = 3.65 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.43. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.43 / 7 = 0.0614.
Substitution of $\lambda_{opt} = \lambda_d$ = 7 in formula 6.4 of KD 35 gives λ_{unl} = 11.2.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

Formula 6 is only valid for a blade with a constant chord and a constant blade angle but it gives a good approximation for a tapered blade if the values at half the blade length are used. Section D is lying at half the blade length. The chord at section D is 0.51 m and the blade angle β = 6.3°. If the rotor is not rotating, the angle of attack $\alpha = 90° - \beta$. So the average angle of attack is 90° – 6.3° = 83.7°.

The C_l-α curve for the Gö 711 airfoil isn't given for large angles of α in KD 285. However, the C_l-α curve for Gö 623 airfoil for large angles α is given in figure 5.10 of report KD 35 (ref. 3) and it is assumed that this curve can also be used for the Gö 711 airfoil if the airfoil is stalling. For α = 83.7° it can be read in this figure that C_l = 0.21. During starting the whole blade length is stalling and so the real blade length k = 3.75 m is used for the calculation of $C_{q\ start}$.

Substitution of B = 2, R = 5 m, k = 3.75 m, C_l = 0.21 and c = 0.51 m in formula 6 gives that $C_{q\ start}$ = 0.0048. The real starting torque coefficient will be somewhat lower than the calculated value because we have used the average chord and the average blade angle. It is assumed that $C_{q\ start}$ = 0.0046. For the ratio in between the starting torque and the optimum torque we find that it is 0.0046 / 0.0614 = 0.075. This is acceptable for a rotor met a design tip speed ratio of 7. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

For the sticking torque Q_s of the generator it is specified that it is smaller than 0.5 Nm. However, this is the case if no oil seal is mounted. An extra oil seal is needed for horizontal positioning of the generator shaft. It is assumed that the sticking torque with an oil seal is 4 Nm. Substitution of Q_s = 4 Nm, $C_{q\ start}$ = 0.0046, ρ = 1.2 kg/m^3 and R = 5 m in formula 7 gives that V_{start} = 1.9 m/s. This is very low for a 2-bladed rotor with a design tip speed ratio of 7.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for λ = 0. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 4). With this method, it can be determined that the C_q-λ curve is about straight and horizontal for low values of λ if a Gö 711 airfoil is used. A scale model of a three bladed rotor with constant chord and blade angle and with a design tip speed ratio λ_d = 6 has been measured in the open wind tunnel of the University of Technology Delft already on 20-11-1980. It has been found that the maximum C_p was more than 0.4 and that the C_q-λ curve for low values of λ was not horizontal but somewhat rising. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-10R rotor are given in figure 1 and 2. The low C_q and C_p values at low values of λ are caused by stalling of the airfoil.

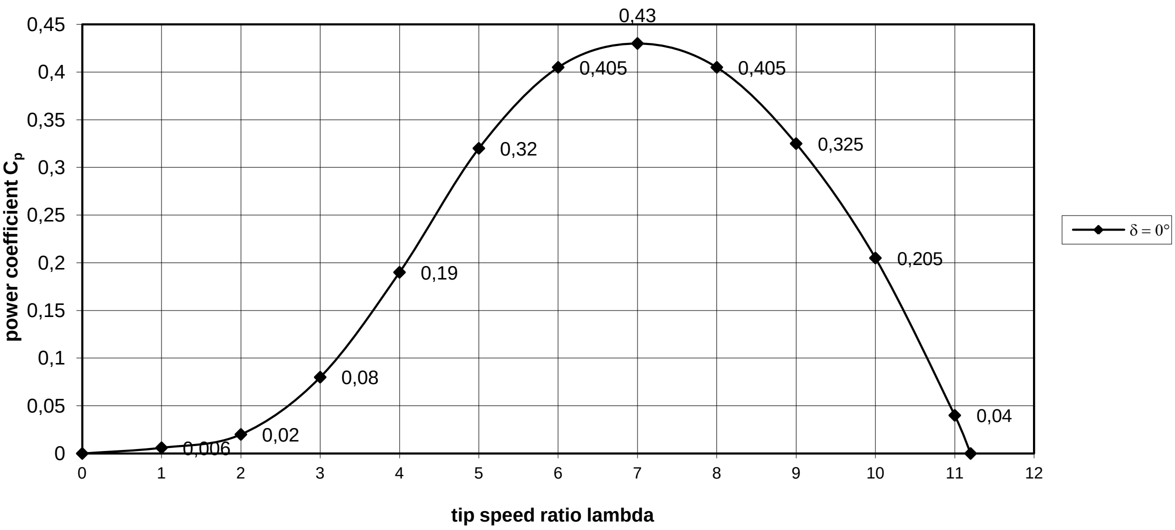

fig. 1 Estimated C_p-λ curve for the VIRYA-10R rotor for the wind direction perpendicular to the rotor (δ = 0°)

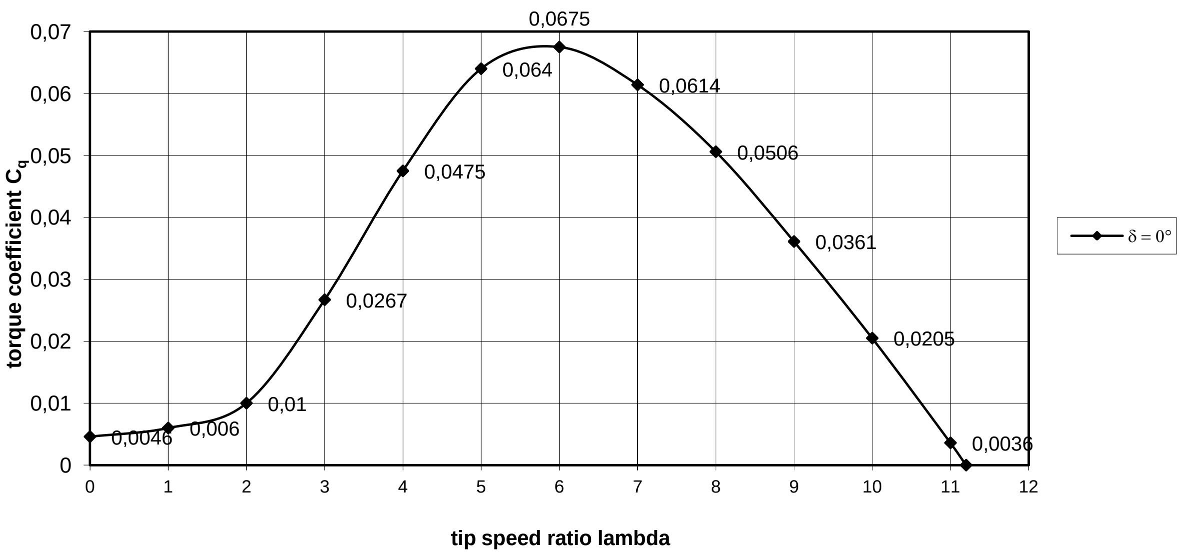

fig. 2 Estimated C_q-λ curve for the VIRYA-10R rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 (ref. 3). One needs a C_p-λ curve of the rotor and the δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The VIRYA-10R will be executed with the hinged side vane safety system which is described in report KD 213 (ref. 5) for the VIRYA-4.2 windmill. The VIRYA-10R head is derived from the head of the VIRYA-5 by scaling the outside dimensions with a factor 2. The VIRYA-5 head is described in chapter 10 of report KD 614 (ref. 6). However, the vane blade is hollow and made out of two sheets of 5.5 mm thick okoume plywood resulting in a rated wind speed of about 10 m/s. The estimated δ-V curve is given in figure 3. The rotor starts turning out of the wind at a wind speed of about 6 m/s. The rotor is turned out of the wind 30° at a wind speed of 10 m/s. It is assumed that the ideal curve is followed for wind speeds above 10 m/s.

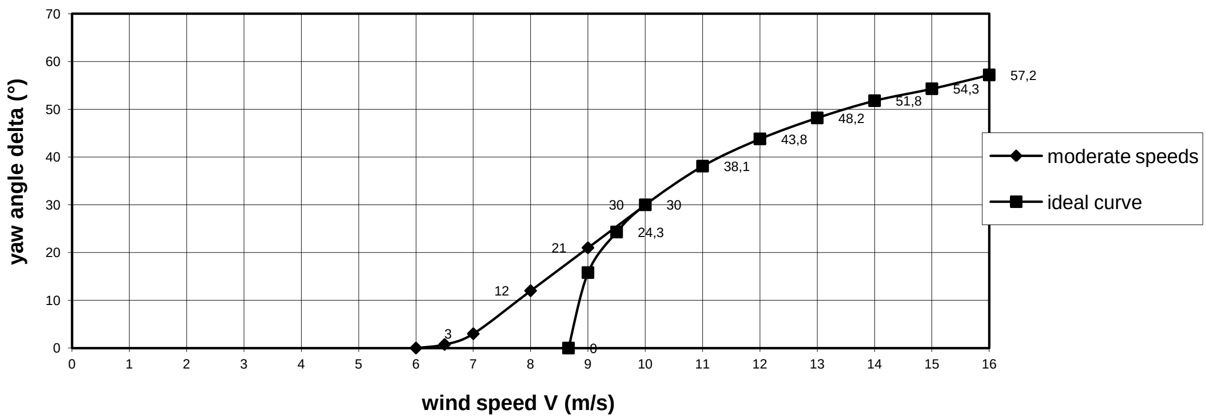

fig. 3 Estimated δ-V curve for a hollow okoume plywood vane blade

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator and to determine the P_{el}-V curve. Because the P-n curve for low values of λ appears to lie very close to each other, the P-n curves are not determined for very low values of λ. The P-n curves are determined for C_p values belonging to λ is 4, 5, 6, 7, 8, 9, 10 and 11.2 (see figure 2). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 10 m/s.

Substitution of R = 5 m in formula 7.1 of KD 35 gives:

$$n = 1.9099 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of ρ = 1.2 kg / m^3 and R = 5 m in formula 7.10 of KD 35 gives:

$$P = 47.124 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed. For wind speeds higher than 6 m/s, the yaw angle δ is taken into account. The result of the calculations is given in table 2.

		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 = 3°		V = 8 m/s δ = 12°		V = 9 m/s δ = 21°		V = 10 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	$n_δ$ (rpm)	$P_δ$ (W)	$n_δ$ (rpm)	$P_δ$ (W)	$n_δ$ (rpm)	$P_δ$ (W)	$n_δ$ (rpm)	$P_δ$ (W)
4	0.19	22.9	242	30.6	573	38.2	1119	45.8	1934	53.4	3058	59.8	4290	64.2	5311	66.2	5816
5	0.32	28.6	407	38.2	965	47.7	1885	57.3	3257	66.8	5151	74.7	7226	80.2	8945	82.7	9795
6	0.405	34.4	515	45.8	1221	57.3	2386	68.8	4122	80.1	6519	89.7	9145	96.3	11321	99.2	12396
7	0.43	40.1	547	53.5	1297	66.8	2533	80.2	4377	93.5	6922	104.6	9709	112.3	12020	115.8	13161
8	0.405	45.8	515	61.1	1221	76.4	2386	91.7	4122	106.8	6519	119.6	9145	128.4	11321	132.3	12396
9	0.325	51.6	414	68.8	980	85.9	1914	103.1	3308	120.2	5232	134.5	7339	144.4	9085	148.9	9948
10	0.205	57.3	261	76.4	618	95.5	1208	114.6	2087	133.5	3300	149.5	4629	160.5	5730	165.4	6275
11.2	0	64.2	0	85.6	0	107.0	0	128.3	0	149.5	0	167.4	0	179.7	0	185.3	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-10R rotor

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

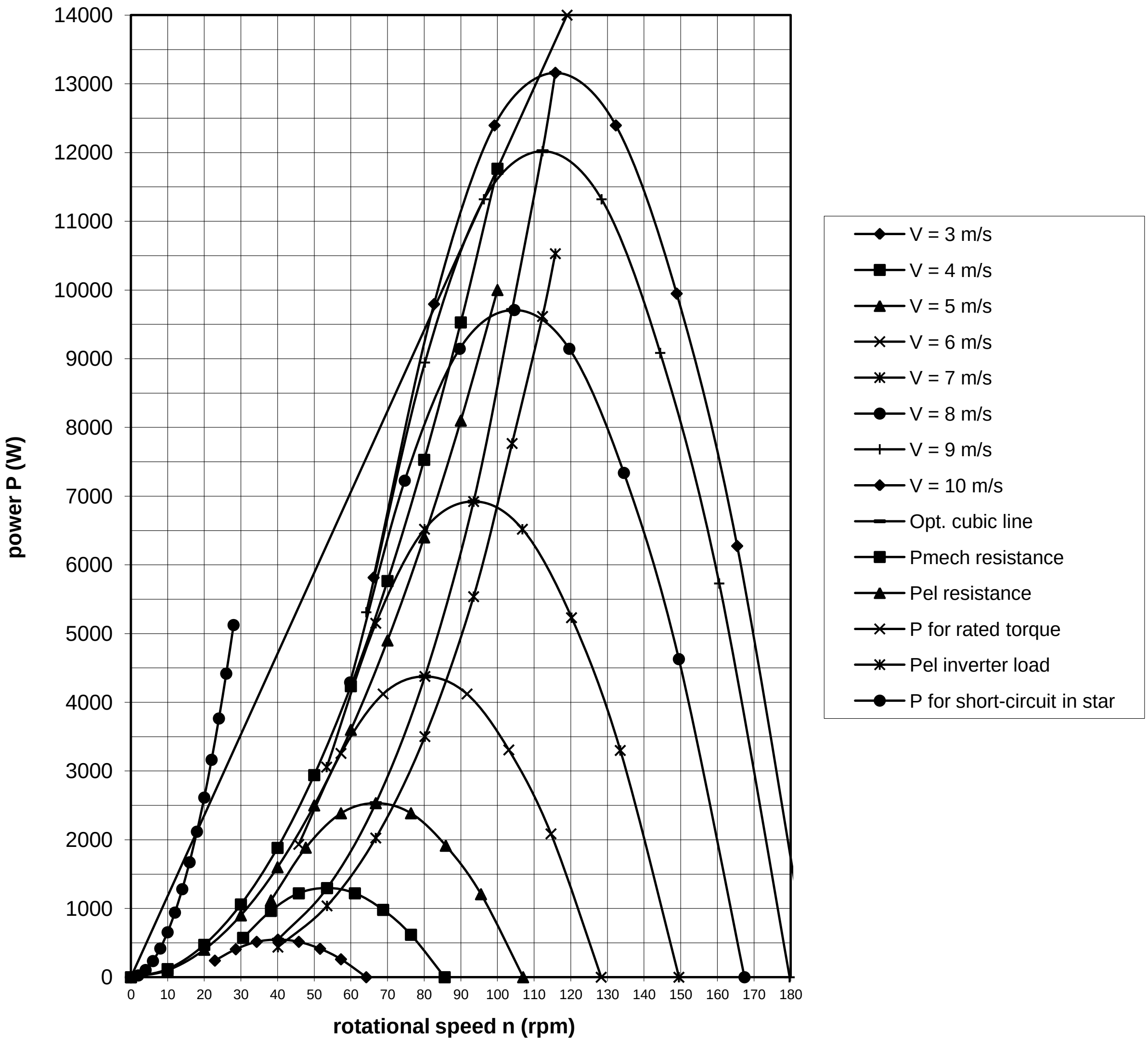

fig. 4 P-n curves of the VIRYA-10R rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the PMG770-I-H-10KW-100R generator with a resistance load such that P_{el} = 10000 W at n = 100 rpm, P-n curve for the rated torque Q = 1123.5 Nm, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

The optimum cubic line of the VIRYA-10 rotor with λ_d = 6 as given in figure 4 of KD 715, is lying left from the straight line for the rated torque for wind speeds above 8 m/s. So the generator is over loaded for high wind speeds. This isn't the case for the VIRYA-10R rotor because its higher λ_d = 7, makes that the optimum cubic line is shifted to the right.

6 Use of the VIRYA-10R rotor with the axial flux generator TGET770-H-10KW-100R

The characteristics of the generator of Hefei Top Grand type TGET770-H-10KW-100R are derived in chapter 6 of KD 715 for a resistance load with a value of the resistance such that the electrical power is 10 KW at a rotational speed of 100 rpm. The P_{mech}-n and P_{el}-n curve for a resistance load are copied in figure 4. It can be seen that the whole P_{mech}-n curve for a resistance load is lying far left from the optimum cubic line.

The rated torque is 1123.5 Nm for n = 100 rpm. The P-n curve for the rated torque is also given in figure 4. This is a straight line through the origin. This line is extended up to a power of 14000 W. The optimum cubic line of the rotor for V = 10 m/s is lying to the right side of the P-n curve for the rated torque and so the generator is certainly strong enough for the VIRYA-10R.

It is assumed that the inverter can be adjusted such that the optimum cubic line is followed and that the total efficiency of generator, rectifier and inverter is 0.8. The P_{el}-n curve for an inverter load is also given in figure 4. So if the optimum cubic line is followed, the load is much lighter than a resistance load. The maximum mechanical power at a wind speed of 10 m/s is 13161 W at a rotational speed of 115.8 rpm. This point is lying below the straight line for the rated torque.

The working point for an inverter load is the point of intersecting of the optimum cubic line with the P-n curve of the rotor for a certain wind speed. The electrical power for a certain wind speed V is found by going down vertically from the working point until the P_{el}-n curve for an inverter load is crossed. The P_{el}-V curve found this way is given figure 5.

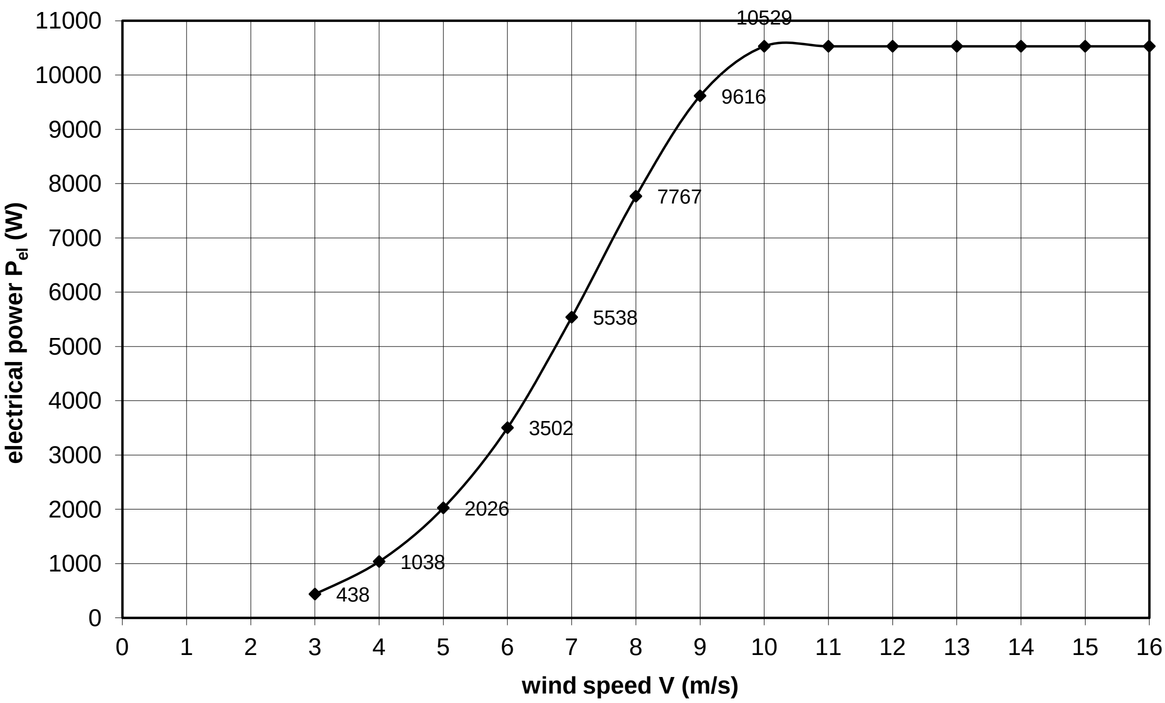

fig. 5 P_{el}-V curve VIRYA-10R for a load such that the optimum cubic line is followed.

The inverter needs a minimum voltage to start functioning. It is assumed that this voltage is generated at V = 3 m/s. This is the reason why the P_{el}-V curve starts suddenly with P_{el} = 438 W at V = 3 m/s. In chapter 4 it was calculated that the starting wind speed is 1.9 m/s and so there is no hysteresis in the P_{el}-V curve. The maximum power is about 10.5 kW at a wind speed of 10 m/s or higher which is very good for a wind turbine with a rotor diameter of 10 m and a rated wind speed of 10 m/s.

The maximm C_p of the 3-bladed VIRYA-10 is 0.44 and of the 2-bladed VIRYA-10R is 0.43. Both wind turbines have the same rated wind speed V_{rated} = 10 m/s and the yaw angle δ = 30° for V_{rated}. The P_{el}-V curve of the VIRYA-10R is therefore lying only a very little lower than that of the VIRYA-10. In chapter 7 of KD 715 it is shown that the VIRYA-10 is able to supply the needed energy in December for the heat pumps of eight well isolated detached houses. So the same is the case for the VIRYA-10R.

7 References

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Appendix 1

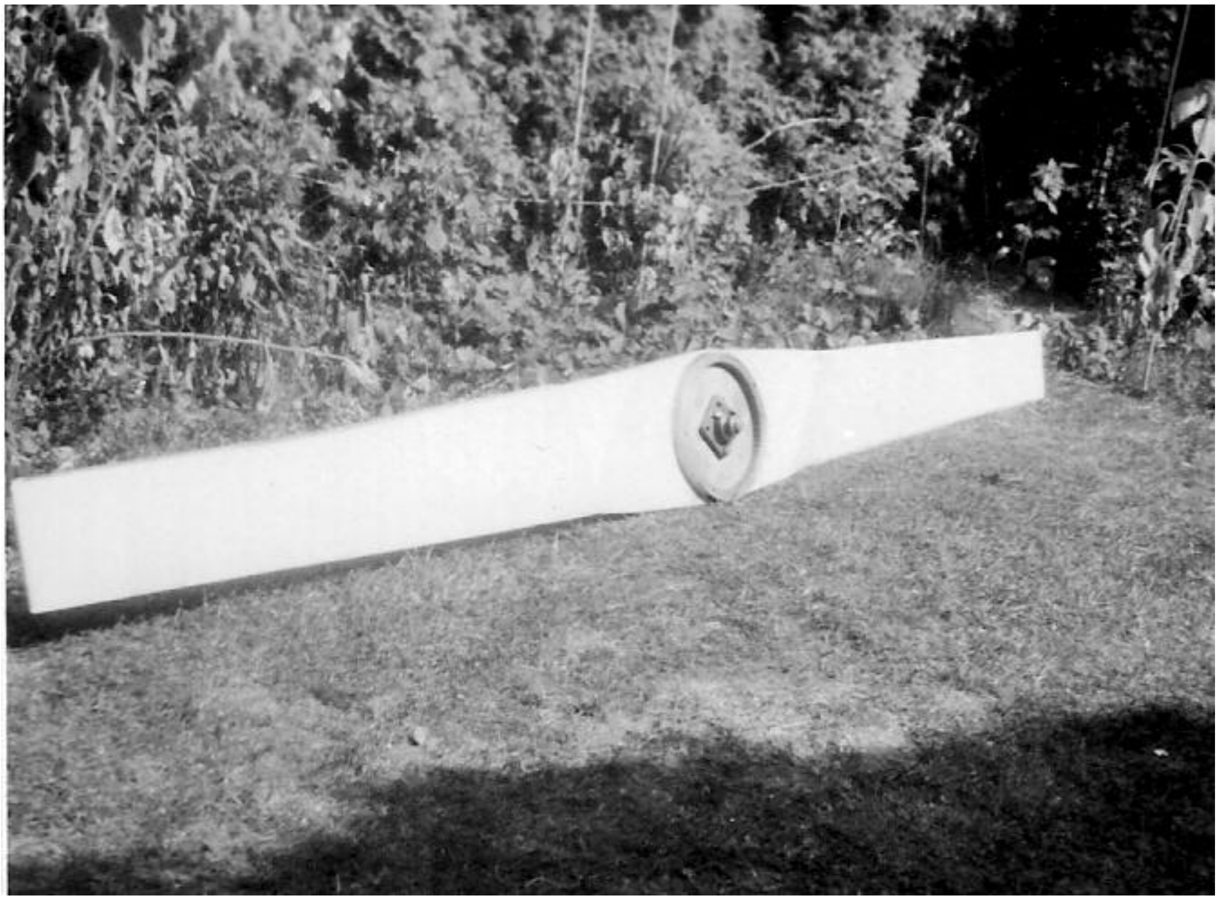
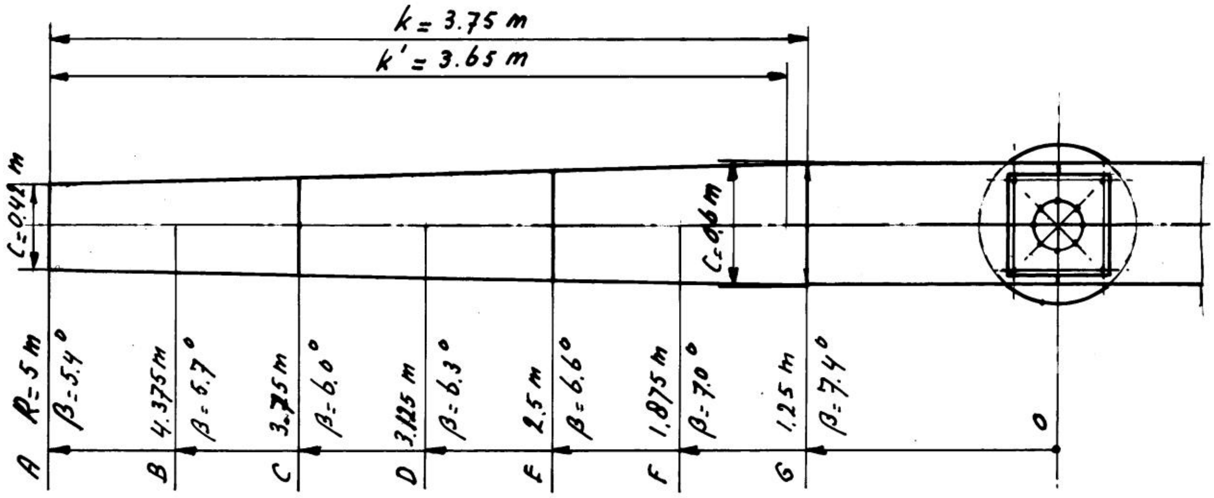


Photo Roofmate rotor with D = 3.2 m and λ_d = 8 made in 1977

Appendix 2



Sketch of the VIRYA-10R rotor