Calculations executed for the rotor of the VIRYA-3.1 windmill (λ_d = 7, Gö 623 airfoil), with 2-bladed rotor made of Roofmate and glass fibre

ing. A. Kragten

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KD 532

The rotor should not be used if the windmill has no safety system which turns the rotor fluently out of the wind at high wind speeds!

Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

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1 Introduction

Already in 1977 I have designed and built a very light 2-bladed windmill rotor with a diameter D = 3.2 m and a design tip speed ratio λ_d = 8 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 width, so a sheet is shortened accurately to a length of 1240 mm.

A rotor is made of four 620 mm long blade sections and one 620 mm long central section resulting in a rotor diameter of 3.1 m. The windmill is called the VIRYA-3.1.

The VIRYA-3.1 rotor can be connected to the 4-pole VIRYA-3 generator made from an asynchronous motor (for measurements see report KD 78, ref. 1). It is possible to use the head and tower of the former VIRYA-3D windmill but it is also possible to use the head and the higher tower of the VIRYA-3 or the VIRYA-3B3 windmill.

2 Description of the rotor of the VIRYA-3.1 windmill

A blade is made of two 0.62 m 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 also has a length of 0.62 m. So the rotor radius R = 1.55 m. The whole rotor is covered with some layers of glass fibre imbedded in epoxy to make the rotor strong and stiff enough.

A blade segment is made of a 0.62 m 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-3.1 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. The rotor can be transported completely mounted.

The rotor has blades with a linearised chord and blade angle and is provided with a Gö 623 airfoil. The geometry and characteristics of the Gö 623 airfoil are given in report KD 463 (ref. 2). The maximum thickness is 12 % of the chord. The lower side of the Gö 623 airfoil is flat over 70 % of the chord which simplifies manufacture. The central part has a rectangular cross section in the middle but long transistion parts to realise a fluent transistion to the airfoil geometry. The chord is 160 mm at the blade tip and 248 mm 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. A square 2 mm thick stainless steel sheet with sizes of 248 mm is glued by epoxy to both sides of the central part to guide the forces acting on the rotor to the generator hub. The stainless steel sheets are connected to the generator hub by four M10 bolts and by one central bolt M10 which connects the hub to the tapered generator shaft. Inserts at the bolts prevent sqeezing 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. See appendix 2 for sketch of the rotor.

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 532) has its own formula numbering. Substitution of λ_d = 7 and R = 1.55 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 4.5161 * r \qquad (-) \qquad (1)$$

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

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

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

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

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

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

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

The blade is calculated for nine stations A till I which have a distance of 0.155 m (so a quart of 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 623	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	1.55	7	5.4	0.16	0.54	0.56	3.75	4.2	0.1	0.4	5.3	5	0.022
B	1.395	6.3	6.0	0.171	0.56	0.58	3.61	4.2	0.3	0.5	5.7	5.5	0.021
C	1.24	5.6	6.7	0.182	0.59	0.59	3.42	4.2	0.7	0.7	6.0	6	0.021
D	1.085	4.9	7.7	0.193	0.64	0.63	3.18	2.2	1.3	1.2	6.4	6.5	0.028
E	0.93	4.2	8.9	0.204	0.69	0.69	2.89	2.2	1.9	1.9	7.0	7	0.027
F	0.775	3.5	10.6	0.215	0.78	0.77	2.55	2.2	3.0	2.85	7.6	7.75	0.026
G	0.62	2.8	13.1	0.226	0.90	0.91	2.17	2.2	4.5	4.6	8.6	8.5	0.029
H	0.465	2.1	17.0	0.237	1.07	1.14	1.74	2.2	6.7	7.75	10.3	9.25	0.036
I	0.31	1.4	23.7	0.248	1.32	0.89	1.28	1.1	-	13.7	-	10	0.23

table 1 Calculation of the blade geometry of the VIRYA-3.1 rotor

No value for α_{th} and therefore for β_{th} is found for station I because the required C_l value can not be generated. β is linearised in between station A and E and in between station E and I. The twist per station is 0.5° in between stations A up to E and 0.75° in between stations E up to I. For these values, the linearised angles are lying close to the theoretical angles. 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 outer seven stations of the blade is about 0.025. Figure 4.6 of KD 35 (for B = 2) and λ_{opt} = 7 and C_d/C_l = 0.025 gives $C_{p\ th}$ = 0.45. The blade is stalling at station I. Therefore not the whole air foiled blade length k = 1.24 m, but only the part up to 0.09 m outside station I is taken into account for the calculation of the C_p. This gives k = k' = 1.15 m.
Substitution of $C_{p\ th}$ = 0.45, R = 1.55 m and blade length k = k' = 1.15 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.42. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.42 / 7 = 0.06.
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:

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

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 E is lying at halve the blade length. The chord at section E is 0.204 m and the blade angle β = 7°. If the rotor is not rotating, the angle of attack α = 90° - β. So the average angle of attack is 90° - 7° = 83°.

The C_l-α curve for the Gö 623 airfoil for large angles α is given in figure 5.10 of report KD 35 (ref. 3). For α = 83° it can be read in this figure that C_l = 0.25. During starting the whole blade length is stalling so the real air foiled blade length k = 1.24 is used for the calculation of $C_{q\ start}$.

Substitution of B = 2, R = 1.55 m, k = 1.24 m, C_l = 0.25 en c = 0.204 m in formula 6 gives that $C_{q\ start}$ = 0.0075. 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 $C_{q\ start}$ = 0.007. For the ratio between the starting torque and the optimum torque we find that it is 0.007 / 0.06 = 0.117. 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:

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

The sticking torque Q_s of the VIRYA-3 generator with 5RN90L04V housing has been measured and it was found that Q_s = 0.4 Nm. Substitution of Q_s = 0.4 Nm, $C_{q\ start}$ = 0.007, ρ = 1.2 kg/m^3 and R = 1.55 m in formula 7 gives that V_{start} = 2.9 m/s. This is acceptable 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 623 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-3.1 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.

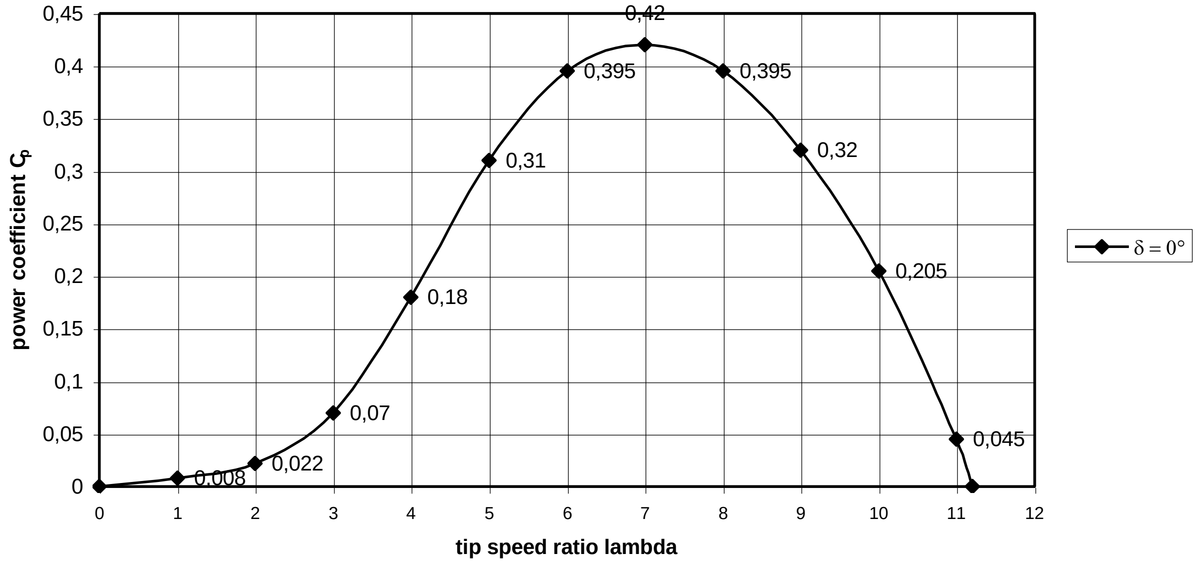

fig. 1 Estimated C_p-λ curve for the VIRYA-3.1 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

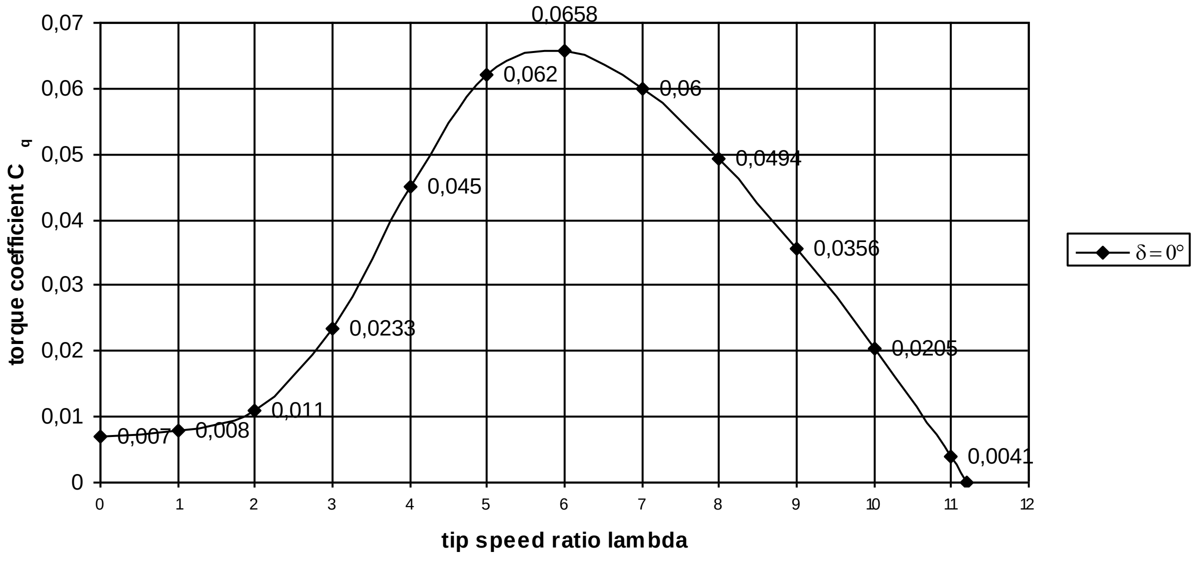

fig. 2 Estimated C_q-λ curve for the VIRYA-3.1 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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

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-3.1 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. Both windmills have a 9 mm plywood vane blade so it is expected that the δ-V curves are the same. The estimated δ-V curve is given in figure 5 of KD 213. This δ-V curve is copied as 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 9.5 m/s. It is assumed that the ideal curve is followed for wind speeds above 9.5 m/s.

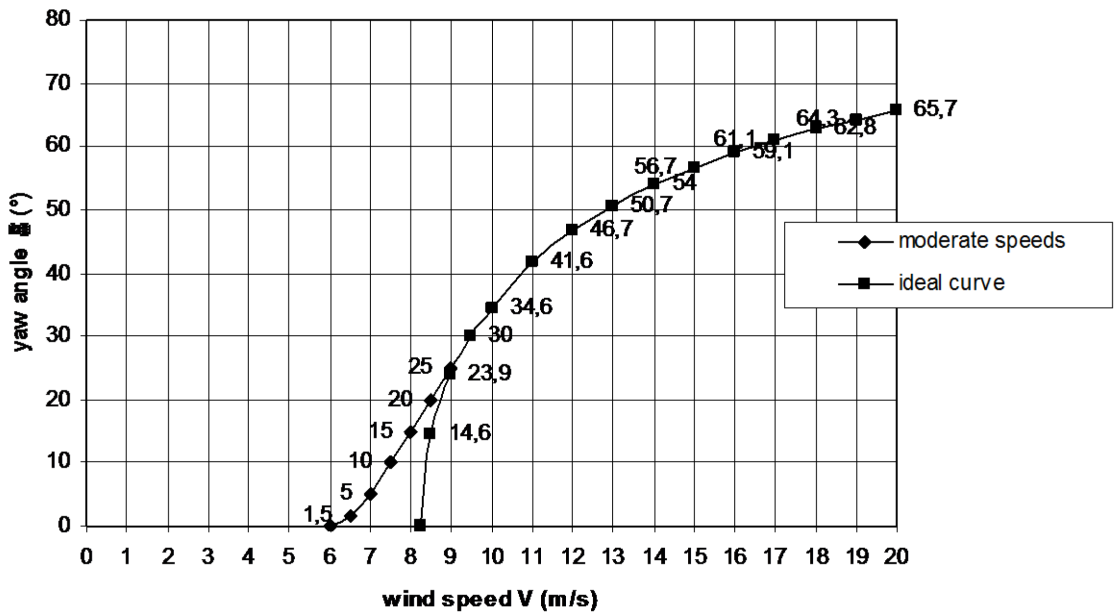

fig. 3 Estimated δ-V curve for the VIRYA-3.1 windmill

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 1). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 9.5 m/s.

Substitution of R = 1.55 m in formula 7.1 of KD 35 gives:

$$n = 6.161 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 1.55 m in formula 7.10 of KD 35 gives:

$$P = 4.529 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

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.

		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 = 5°		V = 8 m/s δ = 15°		V = 9 m/s δ = 25°		V = 9.5 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	0.18	73.9	22.0	98.6	52.2	123.2	101.9	147.9	176.1	171.9	276.4	190.4	376.2	201.0	442.4	202.8	454.0
5	0.31	92.4	37.9	123.2	89.9	154.0	175.5	184.8	303.3	214.8	476.1	238.0	647.8	251.3	761.9	253.4	781.9
6	0.395	110.9	48.3	147.9	114.5	184.8	223.6	221.8	386.4	257.8	606.6	285.7	825.5	301.5	970.9	304.1	996.2
7	0.42	129.4	51.4	172.5	121.7	215.6	237.8	258.8	410.9	300.7	645.0	333.3	877.7	351.8	1032	354.8	1059
8	0.395	147.9	48.3	197.2	114.5	246.4	223.6	295.7	386.4	343.7	606.6	380.9	825.5	402.0	970.9	405.5	996.2
9	0.32	166.3	39.1	221.8	92.8	277.2	181.2	332.7	313.0	386.7	491.4	428.5	668.7	452.3	786.5	456.2	807.1
10	0.205	184.8	25.1	246.4	59.4	308.1	116.1	369.7	200.5	429.6	314.8	476.1	428.4	502.5	503.9	506.9	517.0
11.2	0	207.0	0	276.0	0	345.0	0	414.0	0	481.2	0	533.2	0	562.8	0	567.7	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-3.1 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.

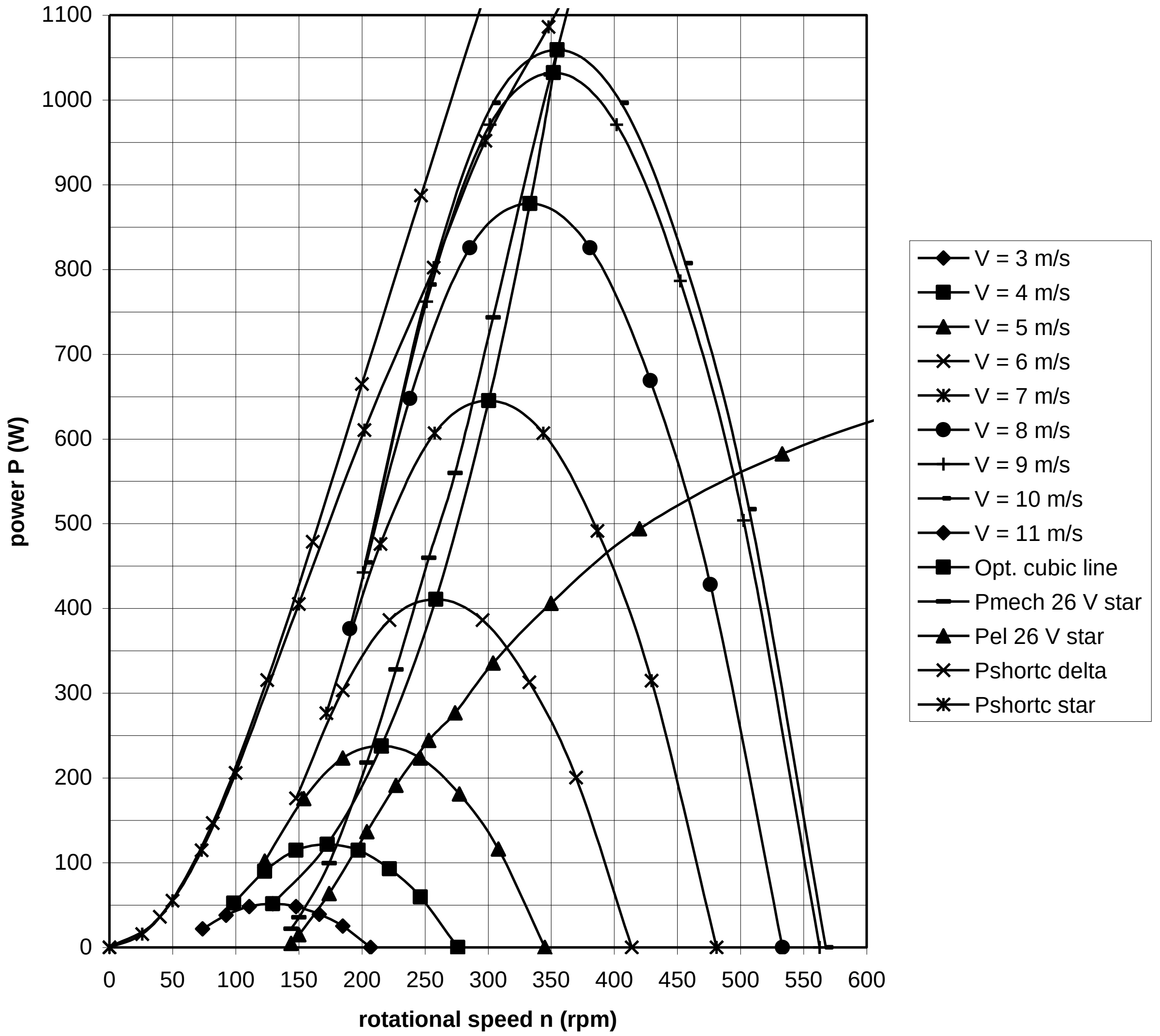

fig. 4 P-n curves of the VIRYA-3.1 rotor for V_{rated} = 9.5 m/s, optimum cubic line, P_{mech}-n and P_{el}-n curves VIRYA-3 generator for 26 V star for a modified 115/200 V winding and P-n curves for short-circuit in delta and star

The measurements of the VIRYA-3 generator are described in report KD 78 (ref. 1). For charging of a 24 V battery, the original 230/400 V winding has to be modified into a 115/200 V winding. How this is done is explained in report KD 341 (ref. 6). The winding has to be rectified in star for 24 V battery charging. Rectification of 3-phase generators is explained in report KD 340 (ref. 7). The generator has been measured for the original 230/400 V winding for 52 V star. The characteristics for the original winding for 52 V star will be the same as the characteristics for the modified 115/200 V winding for 26 V star. The modified P_{mech}-n and P_{el}-n curves of the generator for 26 V star are also plotted in figure 4. A voltage of 26 V is the average charging voltage for a 24 V battery.

The point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The electrical power P_{el} for that wind speed is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 5). The charging voltage at high powers will be somewhat higher than the average charging voltage of 26 V and therefore the generator efficiency will be somewhat higher too. This results in a somewhat higher electrical power. The P_{el}-V curve is corrected for this effect for high wind speeds.

The matching of rotor and generator is very good because the P_{mech}-n curve of the generator is lying close to the optimum cubic line for wind speeds in between 4 and 9.5 m/s. In the P_{el}-V curve it can be seen that the maximum power is 430 W and that supply of power starts already at a wind speed of 2.6 m/s ($V_{cut\ in}$ = 2.6 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. In chapter 4 it was calculated that V_{start} = 2.9 m/s so there is some hysteresis in the P_{el}-V curve in between 2.6 m/s and 2.9 m/s.

The generator has been measured for short-circuit in delta and for short-circuit in star. Short-circuit in delta is identical to short-circuit in star if the star point is short-circuited too. The P-n curves for short-circuit in delta and star are also plotted in figure 4. The P-n curve for short-circuit in delta is lying left from the P-n curve of the rotor for V = 9.5 m/s and higher. This means that the rotor will slow down to almost stand still for every wind speed if short-circuit in delta is made. The P-n curve for short-circuit in star is about touching the P-n curve of the rotor for V = 9 m/s so the rotor will only stop for wind speeds below 9 m/s. So making short-circuit in star to stop the rotor is not allowed because the rotor will not stop at high wind speeds and after a certain time the winding will burn.

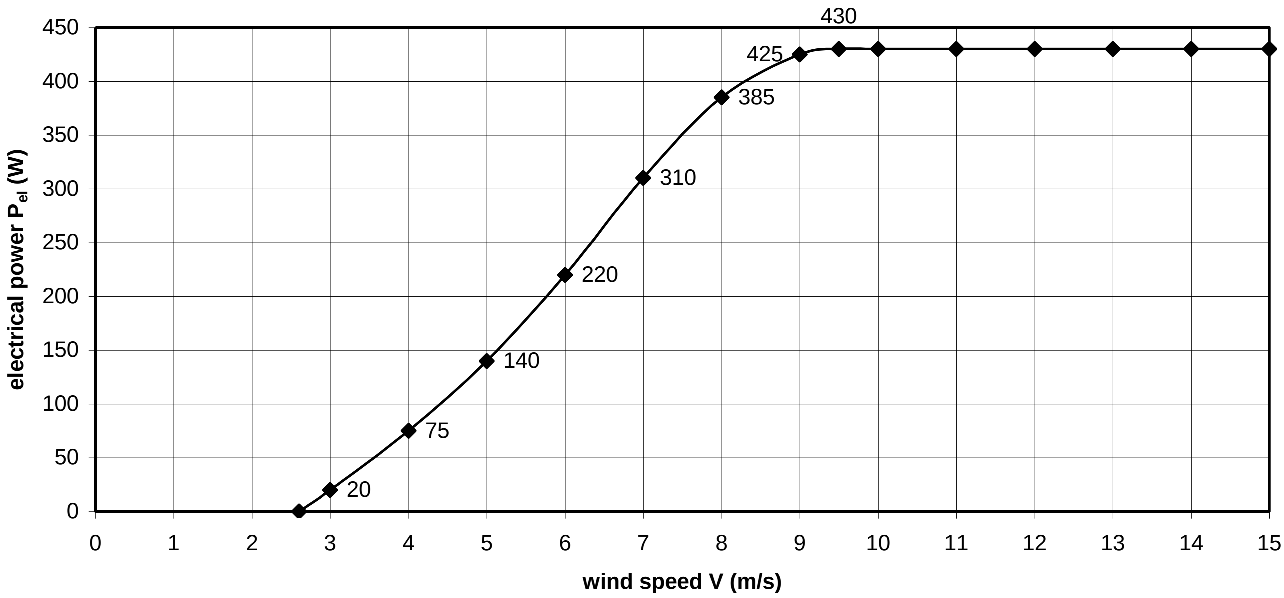

fig. 5 P_{el}-V curve of the VIRYA-3.1 windmill for 24 V battery charging for a modified 115/200 V winding and rectification in star

6 Use of the rotor with the axial flux generator TGET260-0.5KW-350R

Chapter 5 describes the matching of the VIRYA-3.1 rotor with the VIRYA-3 generator developed by Kragten Design. Although the measuring report of this generator is public, the generator drawing is not and a licence is required to obtain this drawing. Another problem might be that the generator armature has to be manufactured and this requires good skils and machines. It might be possible to connect the VIRYA-3.1 rotor to an axial flux generator of Chinese manufacture.

I have experience with the Chinese company Hefei Top Grand and have bought the small axial flux PM-generator type: TGET165-0.15KW-500R in 2015 and tested this generator on a test rig for a 12 V battery load. The measurements are given in report KD 595 (ref. 8). The measurements don't match well with the manufacturers specification but the generator isn't bad and can be used with the proper windmill rotor.

So I have looked on the website of Hefei Top Grand if there is a generator which might be usable in combination with the VIRYA-3.1 rotor. I searched for the largest generator which can be used for 24 V battery charging and I found the TGET260-0.5KW-350R through the path: www.china-topgrand.com – product – outer rotor – page 2 - TGET260-0.5KW-350R. A copy of the folder of this generator is given in appendix 3.

In point 5 of this folder the performance parameters are given. It is specified that the rated voltage is 56/28 V. This means that the generator is supplied with two different windings and that one has to specify 28 V if one wants to use the generator for 24 V battery charging. 28 V is the maximum charging voltage for a full 24 V lead acid battery. It is specified that the rated power is 0.5 kW = 500 W and the rated rotational speed is 350 rpm.

The on-load P_{el}-n curve is given on the last page of the folder and in this curve it can be read that P_{el} = 500 W for n = 350 rpm. So this matches with the specification. The on-load voltage curves are given for both windings. It is assumed that on-load means loaded. The right graph must be the graph for the winding which belongs to a rated voltage of 28 V. This graph has a strange notation for the voltage at the y-axis. The following voltages are mentioned on the y-axis: 0, 6, 12, 18, 25, 31, 37. It is difficult to read which voltage belongs to a rotational speed of 350 rpm but it is about 33.5 V. This is much higher than the rated voltage of 28 V as given in the specification! A loaded voltage of 28 V is supplied at a rotational speed of about 290 rpm. In the P_{el}-n curve it can be read that P_{el} = 360 W for n = 290 rpm. So if this generator is used for 24 battery charging and if the maximum charging voltage is limited to 28 V, the given specification of 28 V for 350 rpm is strongly confusing.

In the specification it is given that the efficiency η is larger than 85 %. This might be true for the given P_{el}-n curve which is about a parabola. A parabolic P_{el}-n curve is about obtained if the load is a fixed resistor. This was found in my report KD 78 for a resistance as load. But the P_{mech}-n and P_{el}-n curves for a battery load differ very much from the characteristics for a resistance as load. The effciciency η for a battery load has a peak at a rather low power and rotational speed and decreases at increasing rotational speed. For a 24 V battery load, the charging voltage varies in between 24 V for an almost empty battery and a very low current and in between 28 V for high currents. To prevent over charging of a full battery, the battery must be equipped with a battery charge controller and dump load which limits the maximum charging voltage up to 28 V. So the average charging voltage is about 26 V and that's the reason why the VIRYA-3 generator was measured for 26 V. The P_{mech}-n and P_{el}-n curves for a voltage of 28 V are lying only a little bit more to the right side and give a better matching at high powers but a slightly worse matching at low powers.

Next it is tried to construct the P_{mech}-n and P_{el}-n curves of the axial flux generator for a constant voltage of 28 V. It is assumed that the given values of the P_{el}-n curve and U-n curve for n = 290 rpm are right. So P_{el} = 360 W, U = 28 V and η = 85 % for n = 290 rpm.

The mechanical power P_{mech} is given by:

$P_{mech} = 100 * P_{el} / \eta$ (W) (10)

Substitution of P_{el} = 360 W and η = 85 % in formula 10 gives that P_{mech} = 424 W (for n = 290 rpm). The torque Q is given by:

$Q = 30 * P_{mech} / (\pi * n)$ (Nm) (11)

Substitution of P_{mech} = 424 W and n = 290 rpm in formula 11 gives that Q = 14 Nm. In KD 78 it was found that the Q-n curves for a constant voltage are about straight lines if the torque isn't close to the peak torque which the generator can supply. The Q-n curve for 28 V starts at the rotational speed for which the generator supplies an open voltage of 28 V. Unfortunatly no open U-n curve is given for the chosen axial flux generator so the rotational speed for which the open voltage is 28 V has to be estimated.

It is assumed that the unloaded voltage at n = 290 rpm is a factor 1.38 higher than the loaded voltage, so the unloaded voltage is 1.38 * 28 = 38.6 V at n = 290 rpm. The unloaded U-n curve is a straight line through the origine. This means that the rotational speed at an unloaded voltage of 28 V is 290 * 28 / 38.6 = 210 rpm. So the Q-n line for 28 V is about a straight line which starts at n = 210 rpm and which is 14 Nm at n = 290 rpm. Some points lying on this line are given in table 3. Formula 11 can be written as:

$P_{mech} = Q * \pi * n / 30$ (W) (12)

The P_{mech}-n curve can be derived from the Q-n curve using formula 12. For the determination of the P_{el}-n curve, a realistic η-n curve has to be estimated. This was done such that η = 85 % for n = 290 rpm. It is assumed that η has a peak value of η = 93 % for n = 250 rpm and that η = 60 % for n = 370 rpm.

n (rpm)	Q (Nm)	P_{mech} (W)	η (%)	P_{el} (W)
210	0	0	0	0
230	3.5	84.3	80	67.4
250	7	183.3	93	170.5
270	10.5	296.9	91	270.2
290	14	425	85	361
310	17.5	568.1	78	443.1
330	21	725.7	70.5	511.6
350	24.5	898	65	583.7
370	28	1084.9	60	650.9

table 3 Estimated value for Q, P_{mech}, η and P_{el} as a function of n for a constant voltage of 28 V

Figure 4 is now copied as figure 6 and the P_{mech}-n and P_{el}-n curve of the VIRYA-3 generator are replaced by the estimated curves of the axial flux generator type TGET260-0.5KW-350R. No measurements for short-circuit of the generator are given so the P-n curves for short-circuit in delta and star are cancelled. The generator has an internal star point so it can only be used for short-circuit in star. Only if a real generator has been measured, it can be determined if the P-n curve for short-circuit is lying enough left from the P-n curves of the rotor to use the generator as a brake! The matching is good for wind speeds above 5 m/s. In the same way as it was done for figure 5, the P_{el}-V curve is derived and given in figure 7. The maximum power is about 640 W which is higher than for the VIRYA-3 generator. This is caused by the high generator efficiency but it chould be checked if this is really true!

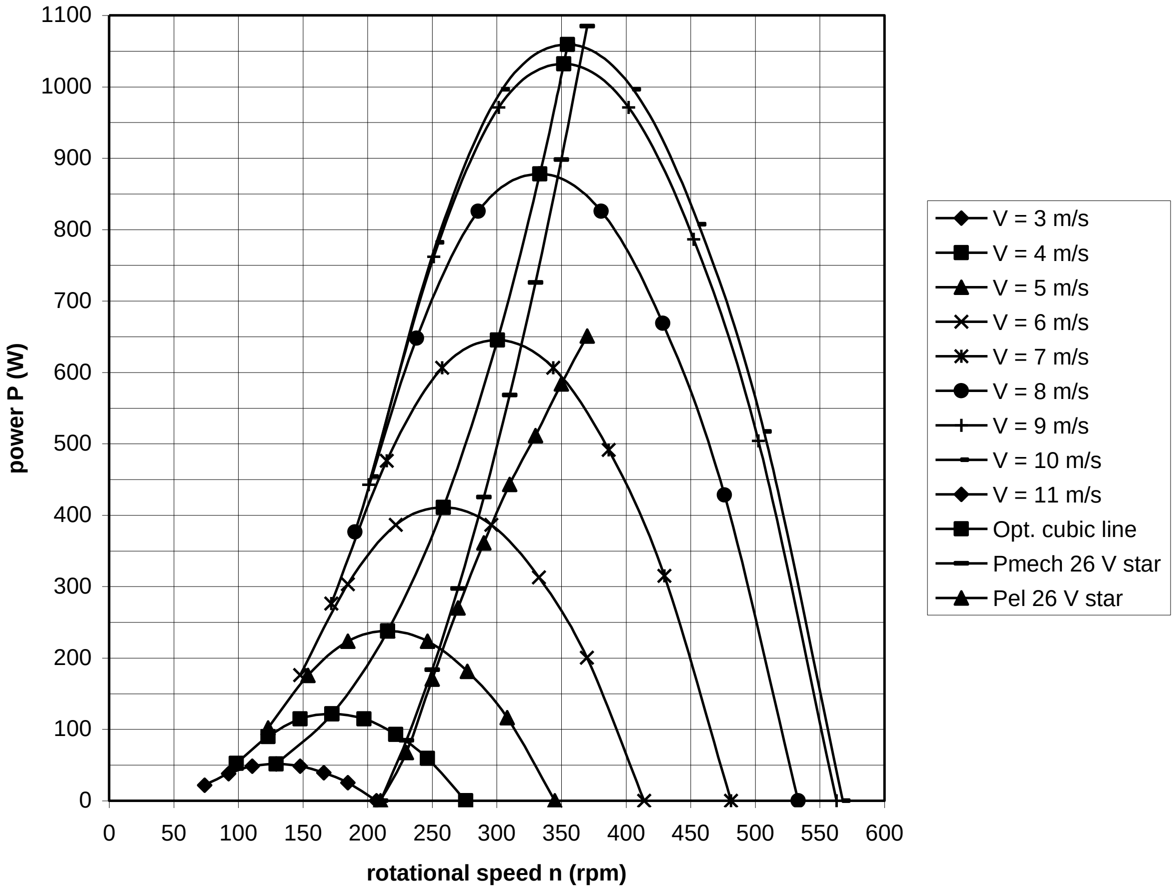

fig. 6 P-n curves of the VIRYA-3.1 rotor for V_{rated} = 9.5 m/s, optimum cubic line, P_{mech}-n and P_{el}-n curves for 26 V star for axial flux generator TGET260-0.5KW-350R

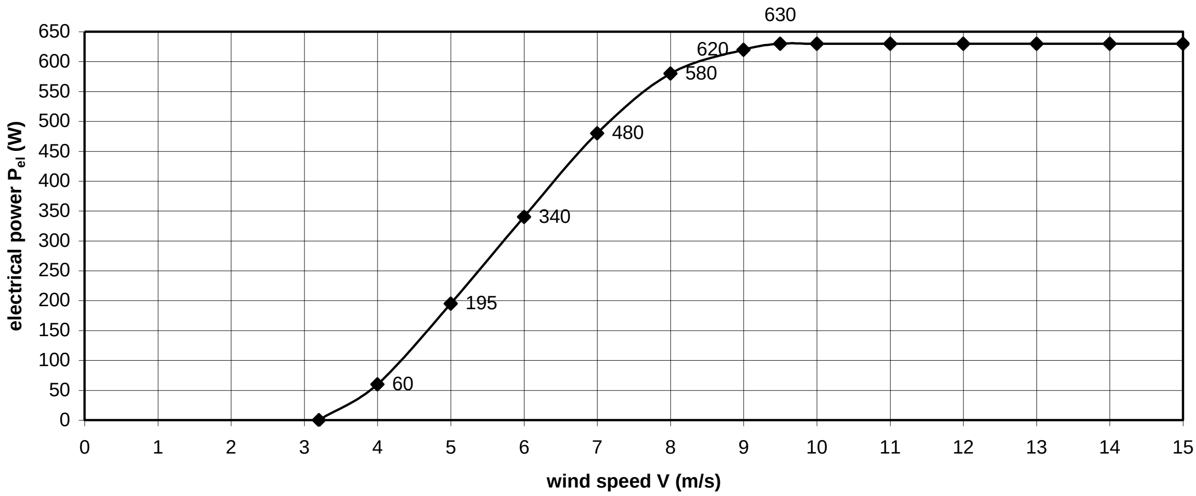

fig. 7 Estimated P_{el}-V curve of the VIRYA-3.1 windmill for 28 V for the axial flux generator TGET260-0.5KW-350R

So it seems that the axial flux generator TGET260-0.5KW-350 can be used in combination with the VIRYA-3.1 rotor but to be really sure a generator has to be bought and measured on a test rig for a real 24 V battery or for a battery simulator adjusted at 26 V. The rotor should have a hole pattern which matches to the generator hub. The head frame must have a generator bracket in which the generator shaft can be clamped.

7 More accurate calculations of $C_{q\ start}$

The starting torque coefficient $C_{q\ start}$ has been calculated in chapter 4 by using formula 6. This formula is valid for a blade with a constant chord and blade angle. The VIRYA-3.1 has tapered and twisted blades. Therefore the average chord and blade angle has been used but this gives some unaccuracy. It was calculated that $C_{q\ start}$ = 0.0075 but this value was reduced to 0.007 because of the unaccuracy of the calculation. It will now be checked if this correction is correct by using the method of calculation of $C_{q\ start}$ for a tapered blade as given in report KD 697 (ref. 9).

For this methode, the blade is divided into a limited number of blade sections and the contribution of the starting torque coefficient of each blade section $\Delta C_{q\ start}$ to $C_{q\ start}$ is calculated. In KD 697, the blade is devided into five blade sections but four blade sections is logic for the VIRYA-3.1 blade because of the chosen stations for which the blade was calculated. Table 1 and appendix 2 show that the blade was calculated for nine stations which lie at a distance of 0.155 m from each other. So it is chosen that each blade section has a length k = 0.31 m. The sections are named to the station which lies at the heart of a section. So we get stations B, D, F and H.

The starting torque coefficient of each blade section $\Delta C_{q\ start}$ is calculated using formula 3 out of KD 697. This formula is copied as formula 13.

$$\Delta C_{q\ start} = \frac{0.75 * B * r_m * C_l * c * k}{\pi R^3} \quad (-) \qquad (13)$$

In this formula, B is the number of blades (-), r_m is the radius (m) at the heart of a blade section, C_l is the lift coefficient (-) for the angle of attack α at the heart of a blade section, c is the chord (m) at the heart of a blade section, k is the length (m) of a blade section and R is the rotor radius (m). C_l is read in figure 5.10 of KD 35 (ref. 3) for the given value of α for which it is valid that $\alpha = 90° - \beta$.

Blade section B

B = 2, r_m = 1.395 m, α = 84.5° so C_l = 0.19, c = 0.171 m, k = 0.31 m and R = 1.55 m. Substitution of these values in formula 13 gives that $\Delta C_{q\ start\ B}$ = 0.00180.

Blade section D

B = 2, r_m = 1.085 m, α = 83.5° so C_l = 0.22, c = 0.193 m, k = 0.31 m and R = 1.55 m. Substitution of these values in formula 13 gives that $\Delta C_{q\ start\ D}$ = 0.00183.

Blade section F

B = 2, r_m = 0.775 m, α = 82.25° so C_l = 0.27, c = 0.215 m, k = 0.31 m and R = 1.55 m. Substitution of these values in formula 13 gives that $\Delta C_{q\ start\ F}$ = 0.00179.

Blade section H

B = 2, r_m = 0.465 m, α = 80.75° so C_l = 0.33, c = 0.237 m, k = 0.31 m and R = 1.55 m. Substitution of these values in formula 13 gives that $\Delta C_{q\ start\ H}$ = 0.00145.

The total starting torque coefficient $C_{q\ start}$ is calculated by formula 4 out of KD 697. Substitution of $\Delta C_{q\ start\ B}$ = 0.00180, $\Delta C_{q\ start\ D}$ = 0.00183, $\Delta C_{q\ start\ F}$ = 0.00179 and $\Delta C_{q\ start\ H}$ = 0.00145 in formula 4 of KD 697 gives that $C_{q\ start}$ = 0.00687. So this value is lower than the value $C_{q\ start}$ = 0.0075 which was calculated with formula 6. The reduced value $C_{q\ start}$ = 0.007 is lying close to the value $C_{q\ start}$ = 0.00687 which was found by formula 13. So for this rotor it is allowed to use formula 13 if the calculated value is reduced somewhat.

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Appendix 1

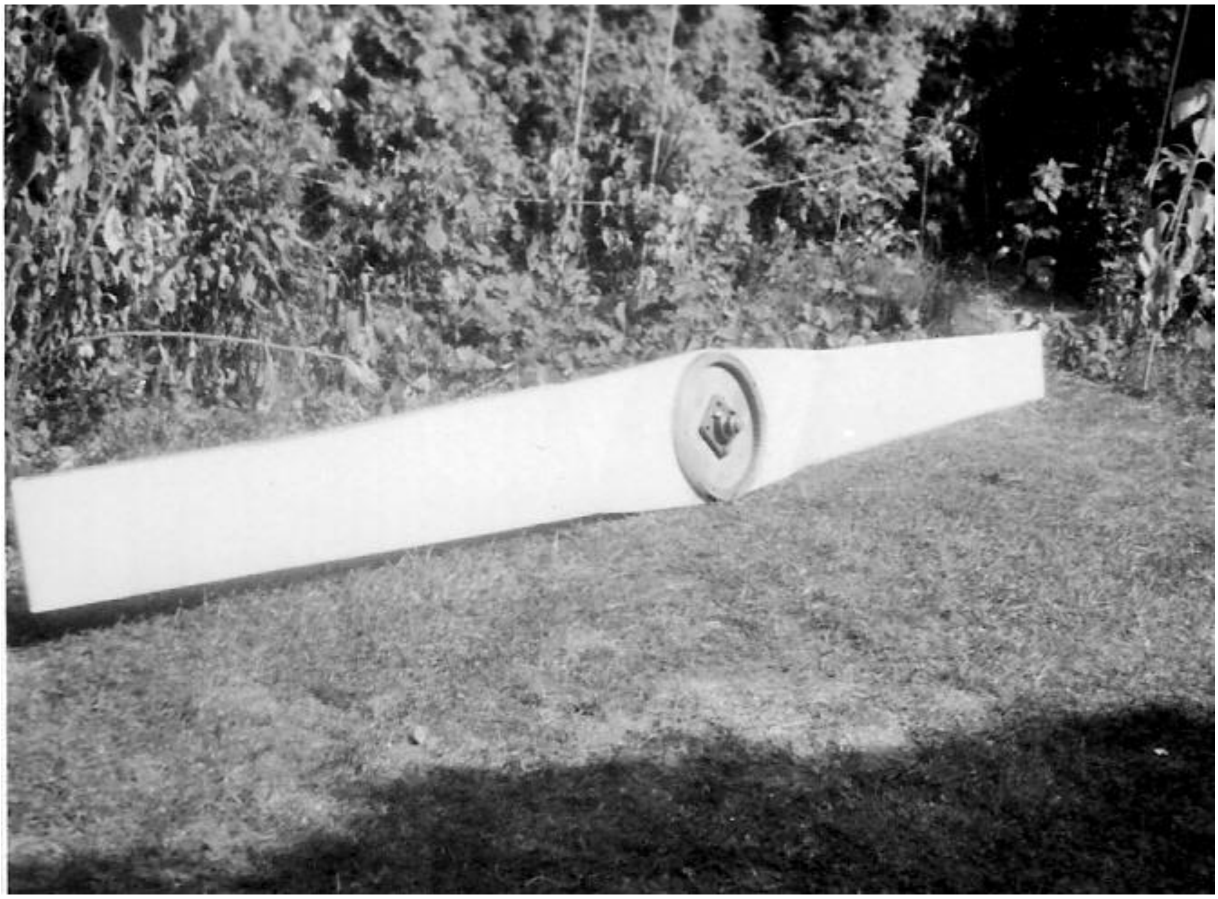
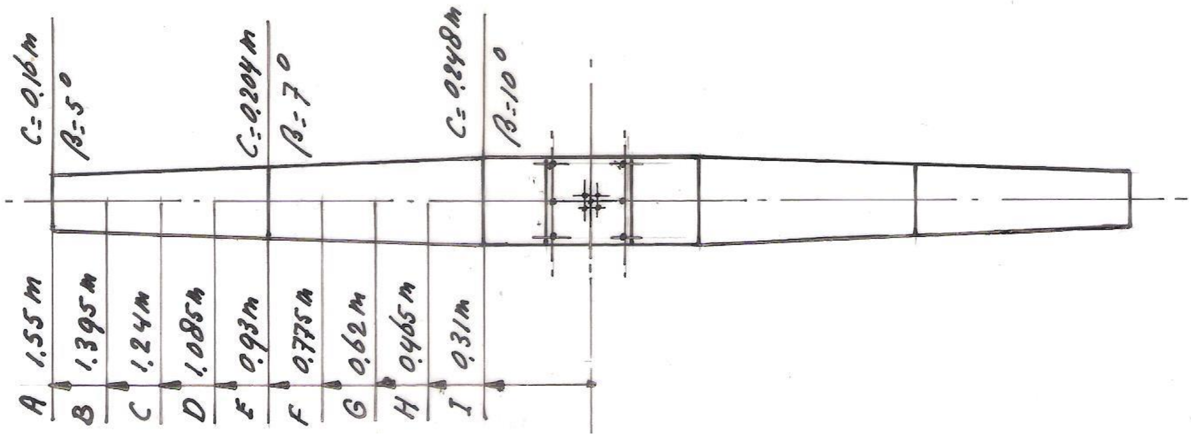


Photo Roofmate rotor with D = 3.2 m and λ_d = 8 made in 1977

Appendix 2



Sketch of the VIRYA-3.1 rotor

Appendix 3 Folder Hefei Top Grand TGET260-0.5KW-350R

PRODUCT DETAIL

1. Model: TGET260-0.5KW-350R

2. Character

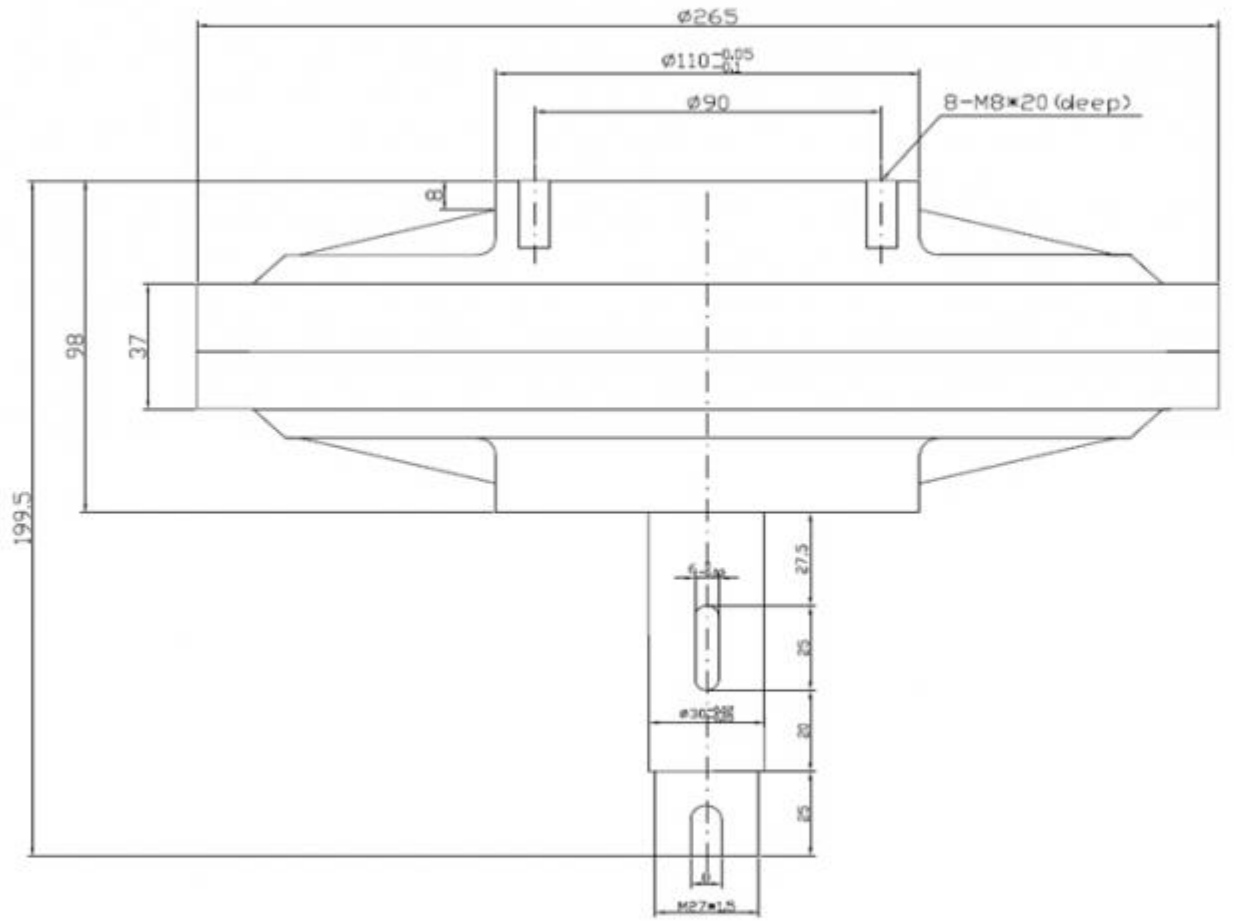
Our disc coreless PMG have advantage in low Rated speed, Low starting wind speed, Small volume, Energy Small, Light weight, Compact structure,High efficiency etc.

1) Coreless, anhysteresis, slotless, have low starting torque.
2) No iron loss, have high efficiency
3) Adopt unique coreless precision winding technology design precision coil
4) Adopt the rare earth permanent magnet, which is multipole, mean gap, high power density and high output power.
5) Low speed direct driving, no torque fluctuations
6) Compact structure, high ratio of power to volume
7) No iron loss, low calorific value, small temperature rise
8) Simple structure, easy to install
9) The brushless structure, free maintenance

3. Range Of Application

0.05-0.3 kw wind turbine; gasoline generators; hydroelectric generator

4. Shape Drawing



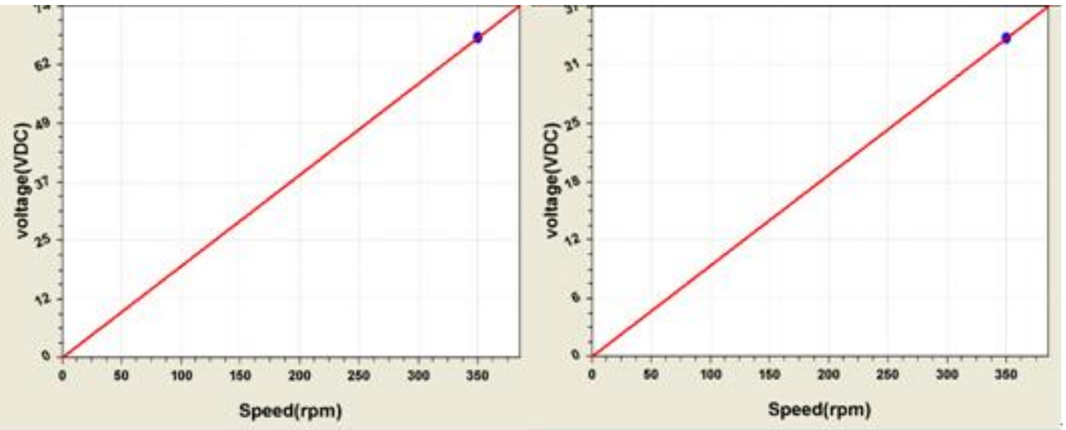
5. Performance Parameter

NO.	PARAMETER	UNITS	DATA
1	Rated power	KW	0.5
2	Rated speed	RPM	350
3	Rated voltage	V	56/28VDC
4	Rated Line Current		6.44/12.88
6	Efficiency		>85%
7	Resistance (Line-Line)		-
8	Winding type		Y
9	Insulation Resistance		100Mohm Min(500V DC)
10	Leakage level		<5 ma
11	Start torque	N/M	<0.1
12	Phase		Three phase
13	Structure		outer rotor
14	Stator		coreless
15	Rotor		Permanent magnet type (outer rotor)
16	Gen. Diameter	mm	265
17	Gen. Length	mm	199.5
18	Gen. Weight	kg	11
19	Shaft. Diameter	mm	30
20	Housing Material		Aluminum (Alloy)

21	Shaft Material		Steel
22	Gross Weight	KG	15

6. Curve Graph

ON-LOAD Power Curve



ON-LOAD Voltage Curve