Calculations executed for the 3-bladed rotor of the grid connected VIRYA-6.5 windmill (λ_d = 6, Gö 711 airfoil, wooden blades) provided with the hinged side vane safety system

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KD 578

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1 Introduction

The VIRYA-6.5 rotor will have three blades, a design tip speed ratio λ_d = 6 and a diameter of 6.5 m. A rotor blade is made of a wooden plank of good quality. The blades have a constant chord, a constant airfoil and no blade twist. The rotor blades are connected to a flexible spoke assembly in the same way as it is also done for the VIRYA-4.6 rotor.

The VIRYA-6.5 will be provided with the hinged side vane safety system which is used for all VIRYA-windmills. This system is described in report KD 213 (ref. 1). The moment of inertia of the vane around the yawing axis is very large and this limits the maximum angular velocity of the head movement and so the gyroscopic moment is limited too. This makes that the bending moment in the blades and the rotor shaft is limited. The safety system is designed such that the rated wind speed V_{rated} is about 11 m/s. The vane blade will be made out of oucume plywood with dimensions 1530 * 1549 * 15 mm and two vane blades can just be made out of a standard sheet size 1.53 * 3.1 m. 6.5 m is the maximum rotor diameter which can be used for the hinged side vane safety system with a vane blade made out of the largest standard sheet.

The VIRYA-6.5 is meant for connection to a 50 Hz grid. The generator is a standard 4-pole, 3-phase asynchronous motor frame size 112 with a 230/400 V winding and a nominal motor power of 4 kW at a nominal rotational speed of 1435 rpm. The generator is coupled to the rotor shaft by an accelerating 2-step gear box with the slow shaft in line with the motor axis. The windmill rotor is coupled directly to the slow gear box shaft.

The tower will have a height of 18 m or 16.8 m. It can be made out of three 6 m sections similar to the three legs tubular tower of the VIRYA-4.2 and the VIRYA-4.6 or it can be made out of three 6 m pipes shifted in each other, similar to the tower of the VIRYA-3.3S.

2 Description of the rotor of the VIRYA-6.5 windmill

A blade is made out of a wooden plank with a length of 3 m. The plank is provided with the Gö 711 airfoil over the whole length. The spoke assembly is made out of three spokes size 15 * 150 * 660 mm which are welded together under an angle of 120°. Nine spokes for three windmills can be made out of a standard length of 6 m. The spoke assembly is clamped in between a hub and a clamping disk which both have a diameter of 150 mm. This prevents bending stresses in the welds of the spoke assembly. The overlap in between a blade and a spoke is 0.41 m. A blade is connected to a spoke by three M16 bolts.

The geometry and characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 2). The lower side of this airfoil is flat over 97.5 % of the chord which simplifies manufacture. The airfoil has a maximum thickness of 14.85 % of the chord. A disadvantage of this airfoil is that the aerodynamic characteristics are only available for the rather high Reynolds number Re = 4 * 10^5 but as the chord is rather large, the Reynolds values will be rather high. The chord is chosen 300 mm for the whole blade. A sketch of the rotor is given in appendix 1.

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 removing some material from the heaviest blade tips or by gluing small cylinders of lead in holes which are drilled in the lightest blade tip. It might also be an option to add balancing weights under the connecting bolts.

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 578) has its own formula numbering. Substitution of $\lambda_d = 6$ and R = 3.25 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 1.8462 * r$ (-) (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 = 3 and c = 0.3 m in formula (5.4) of KD 35 gives:

$C_l = 27.925\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.3 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 1 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.5 m of one to another. Station F corresponds to the end of a spoke. First the theoretical values are determined for C_l, α and β. Next a constant value is chosen for β such 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 this is a realistic value for a windmill with a rated wind speed of 11 m/s.

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	3.25	6	6.3	0.3	0.55	0.56	6.04	4	-1.5	-1.4	7.8	7.7	0.026
B	2.75	5.077	7.4	0.3	0.64	0.64	5.12	4	-0.3	-0.3	7.7	7.7	0.022
C	2.25	4.154	9.0	0.3	0.78	0.78	4.21	4	1.3	1.3	7.7	7.7	0.017
D	1.75	3.231	11.5	0.3	0.98	0.98	3.30	4	3.8	3.8	7.7	7.7	0.015
E	1.25	2.308	15.6	0.3	1.29	1.30	2.40	4	7.7	7.9	7.9	7.7	0.020
F	0.75	1.385	23.9	0.3	1.79	1.41	1.54	4	-	16.2	-	7.7	0.117

table 1 Calculation of the blade geometry of the VIRYA-6.5 rotor

No value for α_{th} and therefore for β_{th} is found for station F because the required C_l value can't be generated. The values β_{th} for the most important stations A up to D vary only in between 7.5° and 7.9°. If a constant value β_{lin} = 7.7° is chosen, the linearised angles are lying very close to the theoretical angles. A sketch of the rotor is given in appendix 1.

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 stations of the blade is about 0.02. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6$ and $C_d/C_l = 0.02$ gives $C_{p\ th} = 0.48$. The blade is stalling in between station E and F. Therefore for the calculation of C_p, only the effective blade length in between station A and a point half way station E and F is taken into account.

This gives an effective blade length k' = 2.25 m. Substitution of $C_{p\ th}$ = 0.48, R = 3.25 m and effective blade length k = k' = 2.25 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.43. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.43 / 6 = 0.0717.
Substitution of $\lambda_{opt} = \lambda_d = 6$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 9.6$.
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 which is the case for this rotor. The chord c = 0.3 m and the blade angle $\beta = 7.7°$ for the whole blade. If the rotor is not rotating, the angle of attack $\alpha = 90° - \beta$. So the angle of attack is 90° - 7.7° = 82.3°.

The C_l-α curves for the Gö 711 airfoil are not given for large angles α. However, the airfoil is completely stalling during starting and it is expected that the C_l-α curve for large angles α will be about the same as the C_l-α curve for the Gö 623 airfoil. 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 $\alpha = 82.3°$ it can be read in this figure that $C_l = 0.27$. During starting, the whole blade is stalling. So for calculation of the starting torque coefficient, the real blade length k = 3 m is taken into account.

Substitution of B = 3, R = 3.25 m, k = 3 m, $C_l = 0.27$ en c = 0.3 m in formula 6 gives that $C_{q\ start} = 0.0089$. For the ratio between the starting torque and the optimum torque we find that it is 0.0089 / 0.0717 = 0.124. This is acceptable for a rotor with a design tip speed ratio of 6 and a constant chord. 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 an unloaded asynchronous motor is very low because it is only caused by the bearings and the seals. The gear box will have a certain friction torque because of the bearings, the seals and the tooth contact and this should be measured for a prototype. At this moment it is assumed that the friction torque at the slow gear box shaft is 5 Nm. Substitution of Q_s = 5 Nm, $C_{q\ start}$ = 0.0089, ρ = 1.2 kg/m^3 and R = 3.25 m in formula 7 gives that V_{start} = 3 m/s. This is very low for a rotor with a design tip speed ratio of 6.

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 $\lambda = 0$.

Kragten Design has 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 $\lambda_d = 6$ 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-6.5 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.

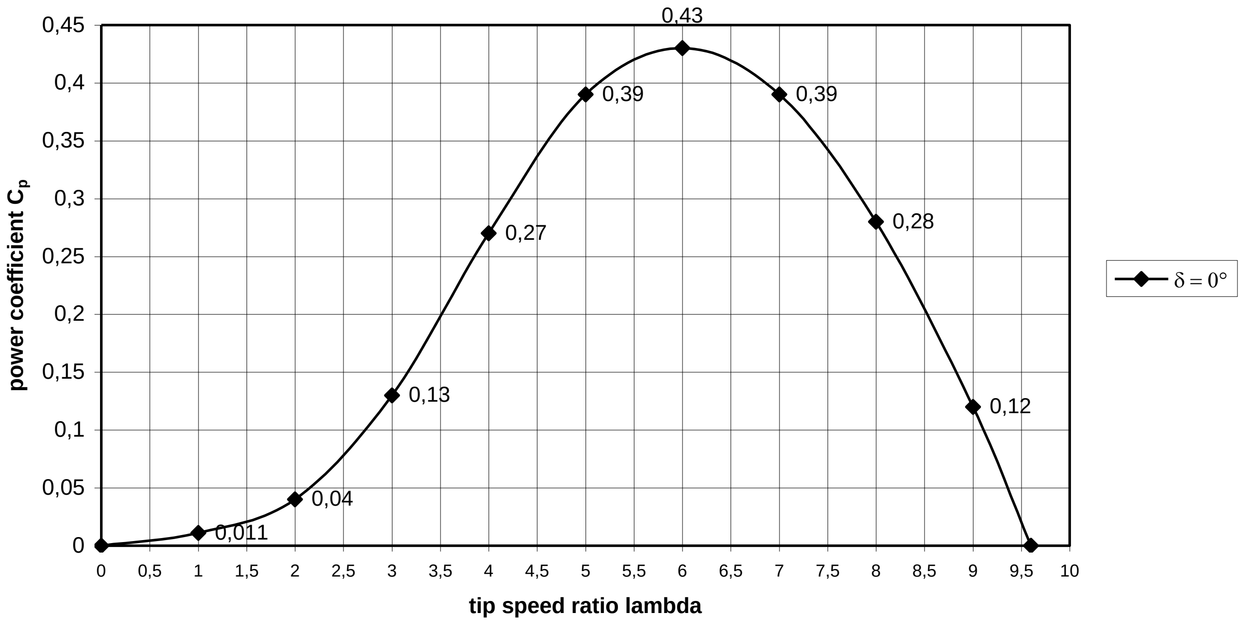

fig. 1 Estimated C_p-λ curve for the VIRYA-6.5 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

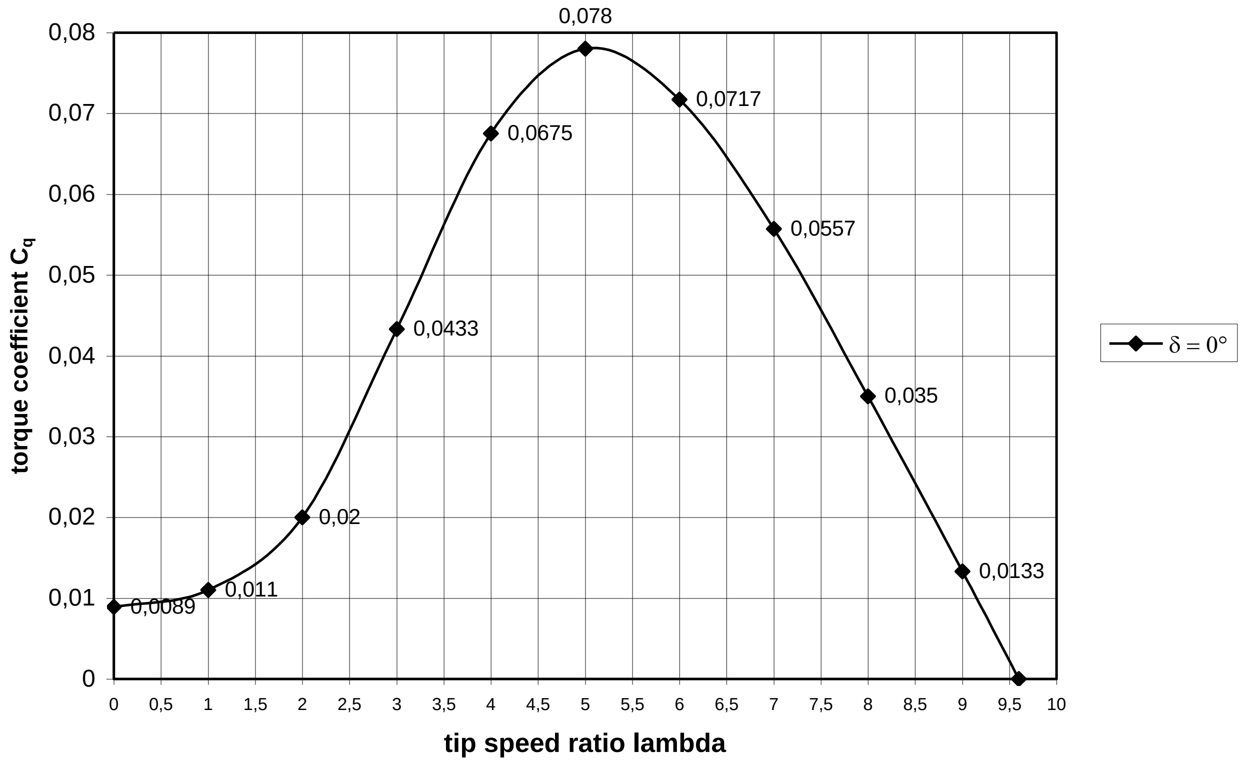

fig. 2 Estimated C_q-λ curve for the VIRYA-6.5 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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. One needs a C_p-λ curve of the rotor and the characteristics of the safety system together with the formulas for the power P and the rotational speed n. The estimated δ-V curve of the VIRYA-4.2 windmill is given in figure 5 of report KD 213 (ref. 1). The VIRYA-4.2 has a vane blade made out of 9 mm meranti plywood with a density of about $0.6 * 10^3$ kg/m^3. The rated wind speed for this vane blade is about 9.5 m/s. The VIRYA-6.5 will get a vane blade made out of 15 mm oucume plywood with a density of about $0.45 * 10^3$ kg/m^3. The rated wind speed for this vane blade will be about 11 m/s. The estimated δ-V curve for the VIRYA-6.5 is given in figure 3.

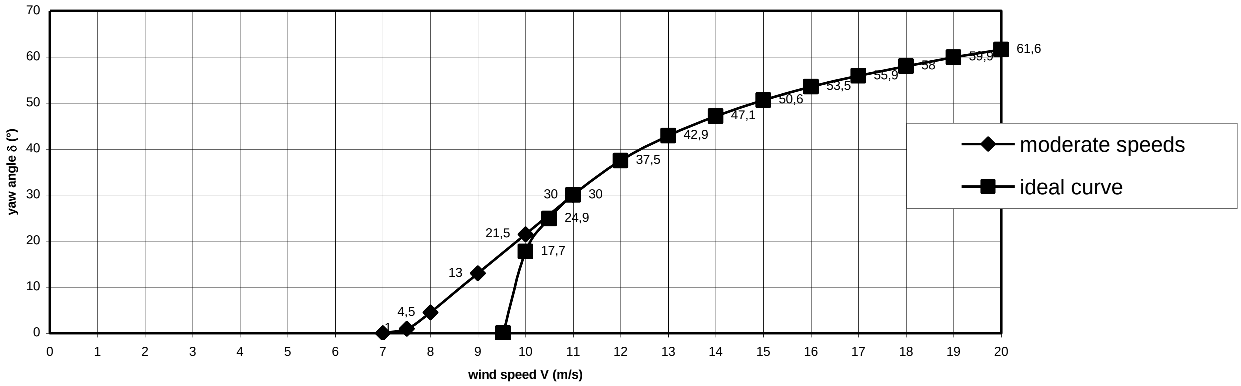

fig. 3 Estimated δ-V curve for a 15 mm oucume plywood vane blade

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 3, 4, 5, 6, 7, 8, 9 and 9.6 (see figure 1). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10 and 11 m/s. The yaw angles δ for wind speeds above 7 m/s are read from figure 3.

Substitution of R = 3.25 m in formula 7.1 of KD 35 gives:

$$n = 2.9382 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 en R = 3.25 m in formula 7.10 of KD 35 gives:

$$P = 19.910 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

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.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 0°		V = 7 m/s δ = 0°		V = 8 m/s δ = 4.5°		V = 9 m/s δ = 13°		V = 10 m/s δ = 21.5°		V = 11 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
3	0.13	26.4	70	35.3	166	44.1	324	52.9	559	61.7	888	70.3	1313	77.3	1745	82.0	2085	84.0	2238
4	0.27	35.3	145	47.0	344	58.8	672	70.5	1161	82.3	1944	93.7	2727	103.1	3625	109.4	4330	112.0	4647
5	0.39	44.1	210	58.8	497	73.5	971	88.1	1677	102.8	2663	117.2	3939	128.8	5236	136.7	6254	140.0	6713
6	0.43	52.9	231	70.5	548	88.1	1070	105.8	1849	123.4	2937	140.6	4343	154.6	5773	164.0	6896	167.9	7401
7	0.39	61.7	210	82.3	497	102.8	971	123.4	1677	144.0	2663	164.0	3939	180.4	5236	191.4	6254	195.9	6713
8	0.28	70.5	151	94.0	357	117.5	697	141.0	1204	164.5	1912	187.5	2828	206.1	3759	218.7	4490	223.9	4819
9	0.12	79.3	65	105.8	153	132.2	299	158.7	516	185.1	819	210.9	1212	231.9	1611	246.0	1924	251.9	2065
9.6	0	84.6	0	112.8	0	141.0	0	169.2	0	197.4	0	225.0	0	247.4	0	262.4	0	268.7	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-6.5 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.

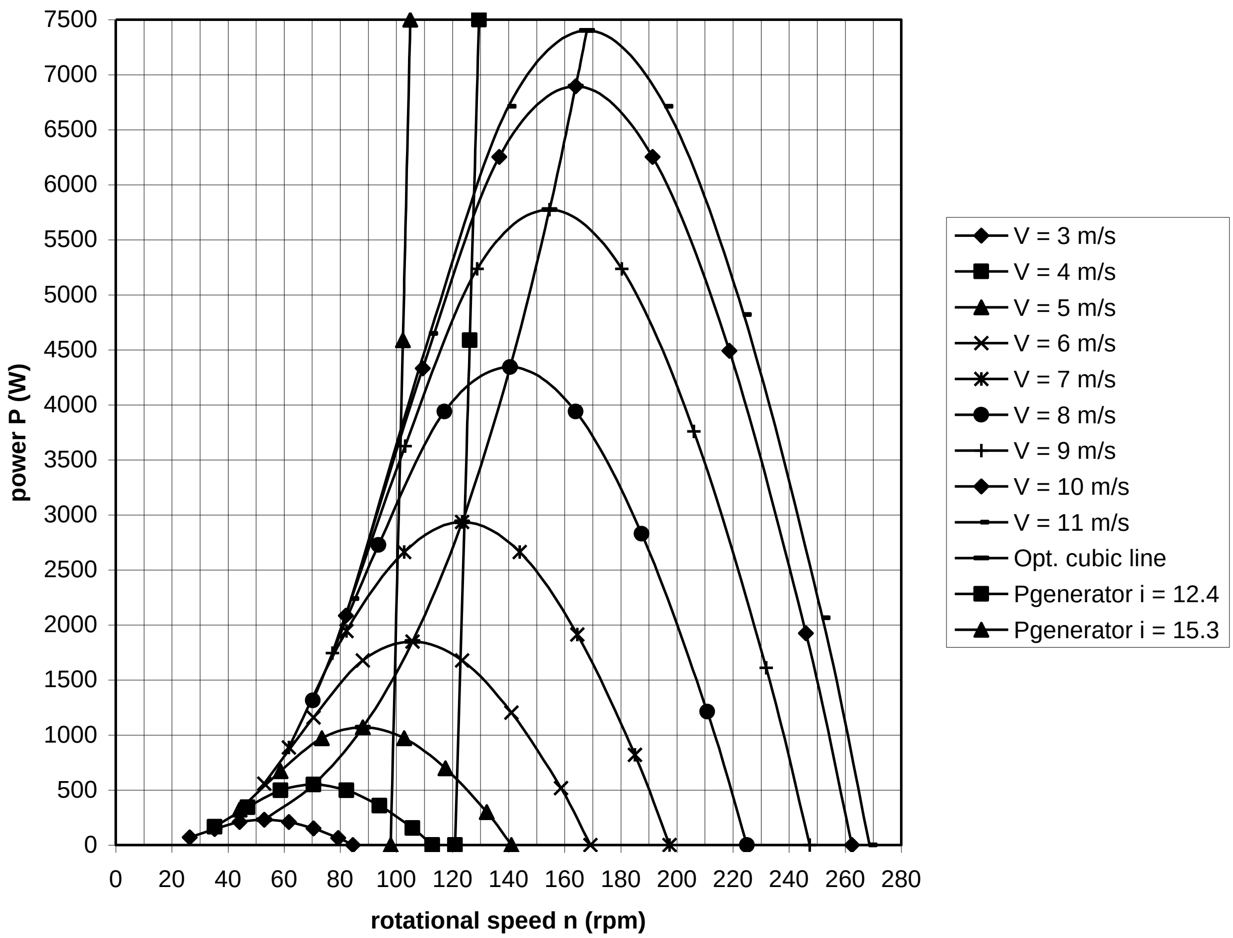

fig. 4 P-n curves and optimum cubic line for the VIRYA-6.5 rotor. P-n curve of a 4-pole, 4 kW asynchronous generator and an accelerating gear box with a gear ratios i = 12.4 and i = 15.3.

If the rotor is loaded such that the optimum cubic line is followed, the maximum power will be generated for each wind speed. However, an asynchronous generator has a very steep P_{mech}-n curve which will intersect with the optimum cubic line at a certain point. This point is called the design point. The corresponding rotational speed is called the design rotational speed n_d. The corresponding mechanical power is called the design power P_d. The corresponding wind speed is called the design wind speed V_d.

The design point depends on the number of generator poles, the gear ratio and a little on the generator size. In the first instance it is decided to chose the asynchronous generator and the gear ratio such V_d = 7 m/s with a corresponding n_d = 124.14 rpm and P_d = 3326 W (see figure 4 and table 2). In the next chapter it will be explained how this can be realised.

6 Determination of the generator characteristics

An asynchronous motor can be used as an asynchronous generator if it is driven at rotational speeds higher than the synchronous rotational speed. The synchronous rotation speed depends on the pole number of the generator and the grid frequency. The synchronous rotational speed is 1500 rpm for a 4-pole motor and a grid frequency of 50 Hz.

An asynchronous motor is the simplest motor which exists. It contains a housing in which a laminated stator is pressed which is provided with a 3-phase winding. It has a laminated armature in which aluminium short-circuit bars are cast. It has two bearing covers and the armature shaft rotates in two bearings. There is a fan at the back bearing cover for cooling of the housing. If a 3-phase grid is connected to the stator winding, a rotating magnetic field is created. This magnetic field creates short-circuit currents in the aluminium bars of the armature and these currents make the armature magnetic. The armature therefore has a tendency to follow the rotating magnetic field of the stator. However, short-circuit currents are only created if the armature runs at a lower rotational speed than the rotational speed of the stator. So the armature can only supply a torque if it runs at a lower rotational speed than the rotational speed of the stator field and this type of motor is therefore called an asynchronous motor. The difference in rotational speed is called the slip. The slip is rather small for the nominal motor power. The synchronous rotational speed for a 4-pole motor is 1500 rpm. The nominal asynchronous rotational speed for a 4 kW, 4-pole motor frame size 112 is 1435 rpm so the slip is 65 rpm. The relation in between the torque Q (Nm), the mechanical power P (W) and the rotational speed n (rpm) is given by:

$$Q = 30\ P / (\pi * n) \qquad \text{(Nm)} \qquad (10)$$

This formula can also be written as:

$$P = Q * n * \pi / 30 \qquad \text{(W)} \qquad (11)$$

Substitution of P = 4000 W and n = 1435 rpm in formula 10 gives Q = 26.6 Nm.

The chosen motor can supply a much larger peak torque than 26.6 Nm but not for a long time because the winding will become too hot. Provisionally a 4 kW, 4-pole motor of manufacture ROTOR is chosen. This motor has a mass of 42 kg. I have a folder of this manufacturer and it is given that the peak torque is a factor 3.1 higher than the nominal torque and so Q_{peak} = 82.5 Nm. The rotational speed for the peak torque isn't given but I expect that the slip is a factor four larger than for the nominal torque and this gives a rotational speed of 1500 - 260 = 1240 rpm for the peak torque.

Substitution of Q_{peak} = 82.5 Nm and n = 1240 rpm in formula 11 gives that P_{peak} = 10713 W.

The torque curve for generator use is found if the torque curve for motor use is rotated 180°. So the nominal torque for generator use is – 26.6 Nm at n = 1500 + 65 = 1565 rpm and the peak torque for generator use is – 82.5 Nm for n = 1500 + 260 = 1760 rpm. The generator torque is only negative if the motor torque is taken positive. For use as a generator in a windmill, the generator torque will now be taken positive.

Substitution of Q = 26.6 Nm and n = 1565 rpm in formula 11 gives that P = 4359 W. Substitution of Q_{peak} = 82.5 Nm and n = 1760 rpm in formula 11 gives that P_{peak} = 15205 W.

The P-n curve starts at n = 1500 rpm. However, at n = 1500 rpm, a small torque and so a small power has to be supplied even if the generator runs unloaded and if the stator winding is not connected to the grid. This is because of the bearing friction and because of the ventilator losses. If the stator winding is connected to the grid at exactly 1500 rpm, some current will flow and this current gives I^2 R losses in the winding and therefore some more mechanical power is needed to keep the generator running at 1500 rpm. So at a certain low wind speed, the rotor may supply just enough power to overcome the bearing and ventilator losses at 1500 rpm of the generator.

If the grid is connected at that rotational speed, the needed power will increase because of the losses in the winding and this power can't be supplied by the rotor at that wind speed. So the rotor speed will reduce and the connection will be broken at a lower rotational speed. This causes instability and some intelligent switching device is needed which prevents many connecting and breaking actions. But this can't prevent that sometimes the generator is working as a motor and some power is extracted from the grid at low wind speeds.

The motor efficiency η_m at the nominal mechanical power of 4000 W at 1435 rpm is given as η_m = 84.5 %. So the nominal electrical motor power P_{elm} = 4000 / 0.845 = 4734 W. So the heat losses in the stator and the armature are given by P_{heat} = 4734 – 4000 = 734 W.

It was calculated that the nominal mechanical generator power at 1565 rpm is 4359 W. If the generator efficiency η_g is expected to be the same as η_m, so if η_g = 84.5 %, the supplied electrical power will be P_{el} = 4359 * 0.845 = 3683. The heat losses are P_{heat} = 4359 – 3683 = 676 W. This is 58 W less than the heat losses for the nominal power at motor use. A mechanical generator power P = 4359 W is therefore certainly allowed for long periods. For use of the generator in a wind turbine, high electrical powers are mostly supplied only during wind gusts and the generator is cooled well by the wind. So it is expected that a much higher mechanical power than 4359 W is allowed in practice.

Up to now the Q-n and P-n curves are described for the generator shaft. For checking of the matching with the rotor these curves have to be transformed to the rotor shaft. There is a 2-step accelerating gear box in between the rotor shaft and the generator shaft with a gear ratio i. The possible gear ratios depend on the brand and the size of the gear box. Provisionally it is chosen to use a coaxial gear box of manufacture Rossi. I have the catalogue E94 in which these gear boxes are described but the catalogue can also be downloaded from Internet through www.rossi-group.com . It is chosen to take a gear box size 100 with a foot B6 (such that the foot can be bolted to the right side of a vertical sheet). The supplier of the gear box also supplies the 4 kW, 4-pole motor and it is assumed that the motor characteristics are about the same as for the 4 kW, 4-pole motor of ROTOR.

The slow gear box shaft has a diameter of 48 mm and a length of 110 mm and a standard key groove. This shaft is expected to be strong enough for a 6.5 m diameter rotor with elastic blade connection because the moment of resistance of a 48 mm shaft is a factor three larger 1.93 than the moment of resistance of a strip size 15 * 150 which is used for the spokes of the spoke assembly. The rotor hub has to be designed such that it fits to the slow gear box shaft.

Provisionally it is chosen to use a gear box motor combination with specification MR 2I 100 – 112 M 4. This gear box motor combination has a rotational speed of the slow gear box shaft of 113 rpm if the motor is running at 1400 rpm. The total gear ratio is 12.4. The safety factor fs is 2.8 which is very high and which guaranties a long lifetime.

The P-n curve at the generator shaft starts at n = 1500 rpm. So for i = 12.4 it starts at the rotor shaft at n = 1500 : 12.4 = 121.0 rpm. The P-n curve at the generator shaft has a point P = 4359 W at 1565 rpm. The required power at the rotor shaft will be a little higher because of the transmission efficiency. Assume the transmission efficiency η_{tr} = 95 %. So the required mechanical power on the rotor shaft is 4359 / 0.95 = 4588 W. The rotational speed at the rotor shaft is 1565 : 12.4 = 126.2 rpm. The first part of the P-n curve is about a straight line and the line found this way is added to figure 4 and extended to the top of the graph.

In figure 4 it can be seen that the point of intersection of the P-n curve of the generator with the optimum cubic line of the rotor is almost lying on the working point for V_d = 7 m/s. So with the available gear ratio i = 12.4 an acceptable matching is realised.

In figure 4 it can be seen that the P-n curve of the generator starts at a rotational speed of 121 rpm. This rotational speed is reached for an unloaded rotor for a wind speed of about 4.3 m/s. So no energy is produced for wind speeds below 4.3 m/s. The rotor runs at the maximum C_p for a wind speed of 7 m/s but it has a rather high C_p for wind speeds in between about 5.5 and 11 m/s.

However, the C_p for wind speeds in between 4.3 m/s and 5.5 m/s is rather low. This is the main disadvantage of the use of an asynchronous generator. The main advantages are that the generator is simple and cheap and that no rectifier and no inverter are needed. A much more expensive direct drive PM-generator plus rectifier and a 3-phase inverter are required if one wants a load such that the optimum cubic line of the windmill is followed.

The point of intersection of the P-n curve of the generator and the P-n curve of the rotor for a wind speed of 11 m/s lies about at n = 128 rpm and P = 5900 W. This power is 1312 W higher than the nominal mechanical generator power of 4588 W but I think that this is allowed.

The mechanical P-n curve of the generator intersects with the P-n curve of the rotor for a certain wind speed. This point of intersection is the working point for that wind speed. The mechanical power P can be read for each working point in figure 4. The electrical power P_{el} depends on the generator efficiency η_g and on the transmission efficiency η_{tr}. The efficiencies are not used in % but as a factor of 1. The total efficiency η_{tot} is given by:

$$\eta_{tot} = \eta_g * \eta_{tr} \qquad (-) \qquad (12)$$

It is assumed that the efficiencies are constant for each working point and that η_g = 0.845 and that η_{tr} = 0.95. Substitution of these values in formula 12 gives that η_{tot} = 0.8. The mechanical power was determined for each working point using figure 4 and the electrical power was found by multiplying the mechanical power by a factor 0.8. The electrical power found this way as a function of the wind speed is given in the P_{el}-V curve of figure 5.

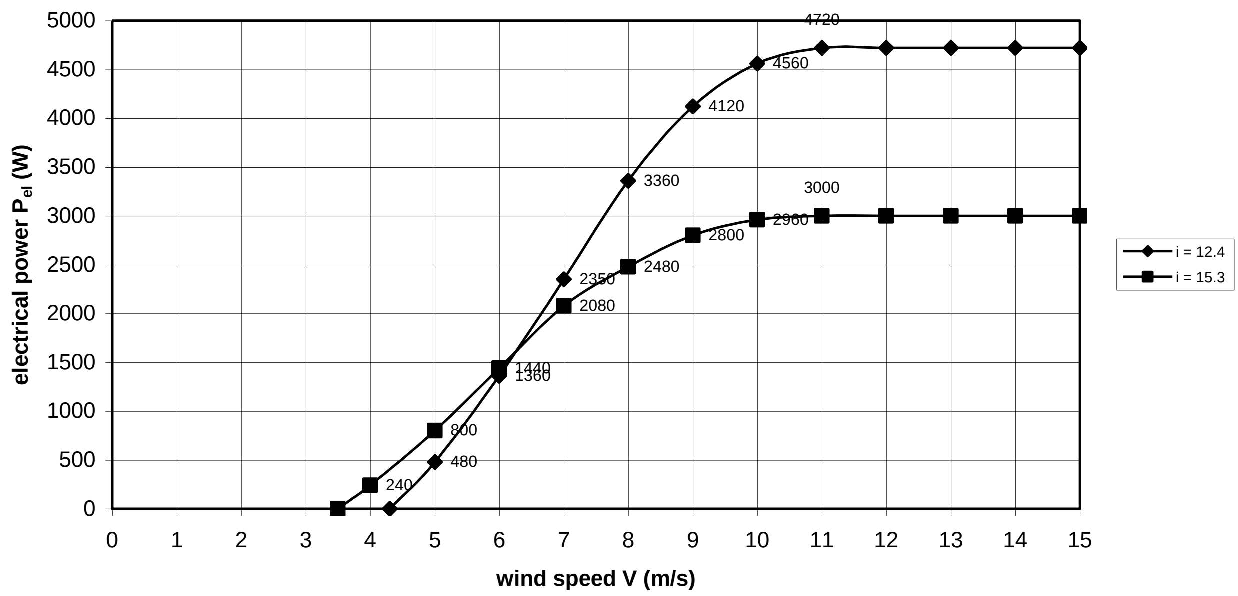

fig. 5 Estimated P_{el}-V curves VIRYA-6.5 for i = 12.4 and i = 15.3

The maximum electrical power is 4720 W so almost 5 kW. This is still a reasonable maximum power for a wind turbine with a rotor diameter of 6.5 m. The design power for V_d = 7 m/s is 2350 W, so 2.35 kW. A design wind speed of 7 m/s seems a reasonable value for a region with a good wind regime. For regions with low wind speeds it seems better to use a larger gear ratio. The next available larger gear ratio for the same motor gear box combination is i = 15.3. The P-n curve has been determined for this gear ratio in the same way as it was done for i = 12.4 and the P-n curve was also drawn in figure 4.

The design mechanical power is now about 1500 W, the design rotational speed is about 99 rpm and the design wind speed is about 5.7 m/s. The maximum mechanical power at V = 11 m/s is reduced to about 3750 W. The P_{el}-V curve is determined in the same way as it was done for i = 12.4. The P_{el}-V curve for i = 15.3 is also given in figure 5. The maximum electrical power for i = 15.3 is about 3000 W. Both curves intersect at a wind speed of about 6.3 m/s. So for regions with low wind speeds a gear ratio of 15.3 seems a better option but the higher power at low wind speeds goes at the cost of a much lower power at high wind speeds.

This report KD 578 is made public to get comment on the idea. It is a first investigation of the qualities of a grid connected medium size wind turbine with an asynchronous generator. More details have to be researched and more calculations will be needed. These calculations are given in report KD 579 (ref. 5).

It must be possible to stop the rotor which can be done by a spring loaded electromagnetic brake or by a device which lifts the vane blade to the horizontal position which makes the rotor turning out of the wind. Detailed drawings of the whole windmill have to be made. I will do this only if someone is willing to build and test a prototype and pay the licence fee. I will not build and test a prototype myself. The licence fee for the VIRYA-6.5 wind turbine will be € 2.500. Just as for my other VIRYA windmills (except the VIRYA-1.04 and the VIRYA-1.36) a licence will only be available to professional engineering companies which have the intention to start serial manufacture. The VIRYA-6.5 is much too complicated and too heavy to be built by an amateur. But one is free to make its own design on its own risk using the information given in this report.

7 References

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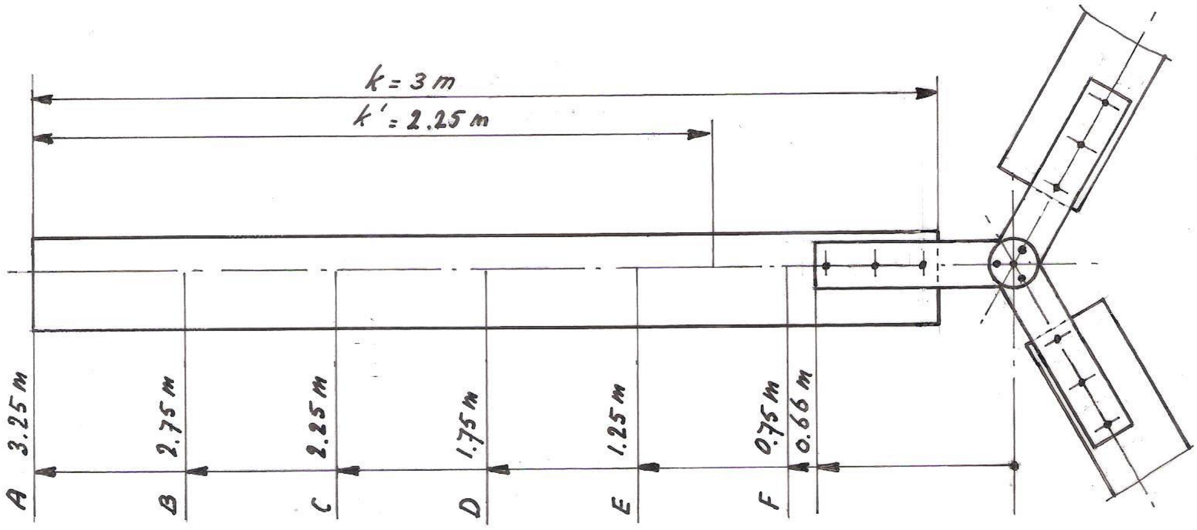
Appendix 1



Sketch of the VIRYA-6.5 rotor