Calculations executed for the 3-bladed rotor of the VIRYA-10 windmill (λ_d = 6) with the hinged side vane safety system connected to an accelerating gear box with a gear ratio i = 20.7 and a 4-pole, 15 kW asynchronous generator for grid connection

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KD 761

It is allowed to copy this report for private use and to use the described ideas. A prototype of the VIRYA-10 windmill has not yet been built and tested. This should be done only by a professional company after making detailed drawings. Although the VIRYA-10 has been designed carefully, no responsibility is accepted by Kragten Design for the proper functioning.

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1 Introduction

The original VIRYA-10 is described in report KD 715 (ref. 1). It is provided with a direct drive axial flux PM-generator of Hefei Top Grand type TGET770-H-10KW-100R. The generator is grid connected by a 3-phase inverter. The original VIRYA-10 is provided with the pendulum safety system with a torsion spring which turns the rotor out of the wind around a horizontal axis at high wind speeds. The generator and the inverter are rather expensive components and so in this report KD 761, it is investigated if it is possible to use an asynchronous generator and an accelerating gear box.

The use of an asynchronous generator and an accelerating gear box is described in report KD 578 (ref. 2) for the VIRYA-6.5 windmill. A 4-pole asynchronous generator and a 2-steps gear box with a gear ratio of 12.4 are used for the VIRYA-6.5. The design tip speed ratio of the VIRYA-6.5 is the same as used for the VIRYA-10 ($\lambda_d = 6$) and so the VIRYA-10 will turn at a rotational speed which is about a factor 6.5 / 10 = 0.65 lower. This means that the gear ratio of the gear box must be about a factor 10 / 6.5 = 1.53 higher if a 4-pole asynchronous generator is chosen. This is only possible for a 2-steps gear box with in parallel shafts. It is chosen to use a gear ratio i = 20.7. It is chosen to use a 4-pole asynchronous motor frame size 160 with a nominal motor power of 15 kW as generator.

For the gear box it is chosen to use a gear box on manufacture Rossi. These gear boxes can be supplied with a 4-pole asynchronous motor which can be used as an asynchronous generator if it turns at a rotational speed which is somewhat higher than the synchronous rotational speed of 1500 rpm at a grid frequency of 50 Hz. It is chosen to use a gear box with frame size 160. This frame size has a hollow slow shaft with an inside diameter of 80 mm. It is expected that this diameter is large enough to put a windmill rotor with a diameter of 10 m directly on the gear box shaft. The rotor hub and shaft can be made out of one piece.

A gear box is filled with oil and the oil level must have a certain position with respect to the set of gear wheels. If the pendulum safety system with a torsion spring would be used, it means that the position of the oil level changes depending on the position of the rotor shaft. So I expect that this safety system can therefore not be used. The shaft stays in the same position for each yaw angle for the hinged side vane safety system and therefore this system is chosen. This safety system is described in report KD 213 (ref. 3).

To get a certain design wind speed for the hinged side vane safety system, there must be a certain ratio in between the area and the weight of the vane blade. This means that for a certain blade material, the thickness of the vane blade must be constant. This means that the stiffness of the vane blade can become too low for big vane blades.

The VIRYA-5B3 is described in report KD 710 (ref. 4). The VIRYA-5B3 has a massive vane blade made out of 12 mm meranti plywood with a height and width of 1.22 m and so two vane blades can be made from a standard sheet size 1.22 * 2.44 m. This vane blade is just stiff enough but a massive 12 mm thick vane blade with a height and width of 2.44 mm would be much too flexible. So it is assumed that a hollow vane blade can be made from two 5.5 mm thick sheets. It is expected that the VIRYA-10 will have a rated wind speed of about 11 m/s with this vane blade. The head geometry of the VIRYA-10 is found by scaling of the head geometry of the VIRYA-5 or the VIRYA-5B3 by a factor 2. The head geometry of the VIRYA-5 is given in chapter 10 and figure 10 of report KD 614 (ref. 5).

2 Description of the rotor of the VIRYA-10 windmill

The 3-bladed rotor of the VIRYA-10 windmill has a diameter D = 10 m and a design tip speed ratio $\lambda_d = 6$. The rotor has blades with a constant chord and no twist and is provided with a Gö 711 airfoil. This airfoil is described in report KD 285 (ref. 6). A blade is made out of a wooden plank with dimensions of 67 * 450 * 4610 mm. The airfoil is made over the whole blade length. The blade has no twist and so the blade angle β is the same for the whole blade.

The VIRYA-5B3 has a hub plate which is made out of one sheet. If this would also be done for the VIRYA-10, a very big sheet would be needed and a lot of material would be wasted. So for the VIRYA-10 it is assumed that three strips are welded together under an angle of 120°. The strips are made of mild steel strip with a thickness of 15 mm, a width of 300 mm and a length of 1000 mm. Each strip is twisted 7.4° right hand in between r = 150 mm and r = 390 mm to give the blade the correct blade angle. The welded hub assembly is galvanised. The overlap in between a blade and a strip is 610 mm which results in a free blade length of 4 m. The blades are connected to the hub assembly by three bolts M20 and six nuts M20. A cambered sheet size 450 * 80 * 4 mm is placed under the bolt heads to prevent damage of the wood when the bolts are tightened. The hub assembly is bolted to the generator hub housing by means of six bolts M20. The rotor is balanced by adding balance weights under the connecting bolts. A sketch of the VIRYA-10 rotor is given in figure 1. This sketch shows the PM-generator of Hefei Top Grand and so the hub used for the gear box looks different.

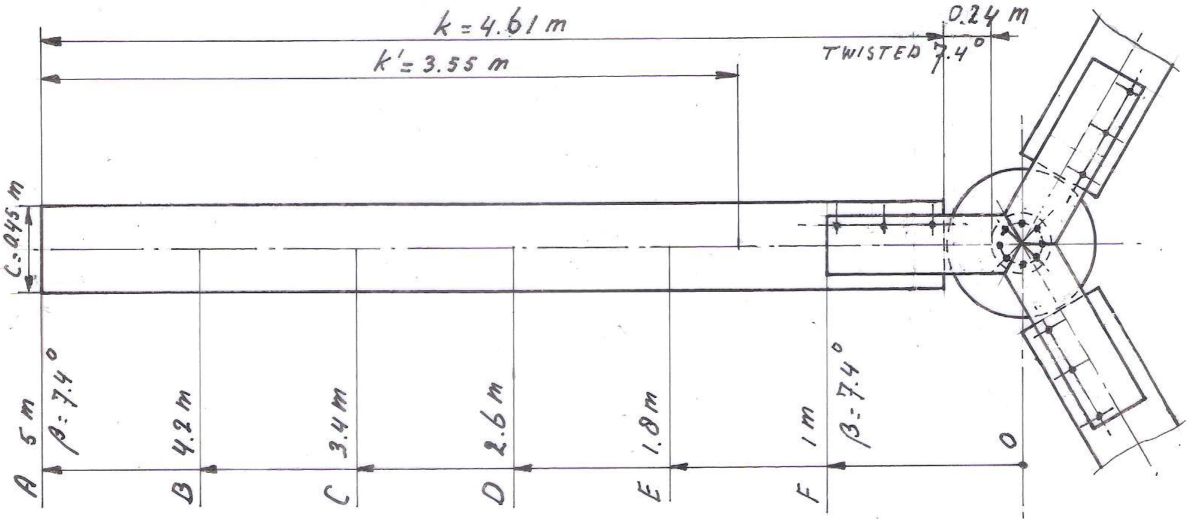

fig. 1 Sketch VIRYA-10 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 7). This report (KD 761) has its own formula numbering. Substitution of λ_d = 6 and R = 5 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 1.2 * r$ (-)   (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 = 0.45 m in formula (5.4) of KD 35 gives:

$C_l = 18.617\ r\ (1 - \cos\phi)$ (-)   (4)

Substitution of V = 5 m/s and c = 0.45 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 1.501 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-)   (5)

The blade is calculated for six stations A till F which have a distance of 0.8 m of one to another. Cross section F corresponds to the end of a strip of the hub assembly. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root.

First the theoretical values are determined for C_l, α and β and next β is linearized such that the twist is constant and that the linearized values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 6). This airfoil is flat over 97.5 % of the chord and is therefore easy to manufacture. A disadvantage of this airfoil is that it has been measured only for a rather high Reynolds value of $4 * 10^5$. But as the VIRYA-10 has a rather large chord, this is no problem. 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 which is used in areas with moderate 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	6	6.3	0.45	0.56	0.57	9.06	4	-1.3	-1.1	7.6	7.4	0.025
B	4.2	5.04	7.5	0.45	0.67	0.67	7.63	4	0.1	0.1	7.4	7.4	0.020
C	3.4	4.08	9.2	0.45	0.81	0.81	6.21	4	1.8	1.8	7.4	7.4	0.016
D	2.6	3.12	11.8	0.45	1.03	1.02	4.79	4	4.5	4.4	7.3	7.4	0.015
E	1.8	2.16	16.6	0.45	1.39	1.38	3.39	4	9.3	9.2	7.3	7.4	0.023
F	1	1.2	26.5	0.45	1.96	1.30	2.06	4	-	19.1	-	7.4	0.18

table 1 Calculation of the blade geometry of the VIRYA-10 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 variation of the theoretical blade angle β_{th} is only little for the stations A up to E and varies in between 7.6° and 7.3°. Therefore it is allowed to take a constant value of $\beta_{lin} = 7.4°$ for the whole blade.

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 most important outer part of the blade is about 0.02. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6.5$ and $C_d/C_l = 0.02$ gives $C_{p\ th} = 0.48$.

The blade is stalling at station F. For the calculation of the maximum C_p therefore not the whole blade length k = 4.45 m is taken into account but only the part up to 0.45 m outside station F. This gives an effective blade length k' = 3.55 m.

Substitution of $C_{p\ th} = 0.48$, R = 5 m and effective blade length k' = 3.55 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.44$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.44 / 6 = 0.0733$. 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:

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

The blade angle is 7.4° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 7.4° = 82.6°. The aerodynamic characteristics for the Gö 711 aren't given for large angles of α in KD 285. However, it is assumed that the estimated C_l-α curve of the Gö 623 airfoil can be used for large values of α which is given as figure 5.10 of KD 35 (ref. 7). For $\alpha = 82.6°$ it can be read that $C_l = 0.26$.

The whole blade is stalling during starting and the part of the blade behind the hub assembly isn't effective. Therefore, for k now the free blade length k = 4 m is taken.

Substitution of B = 3, R = 5 m, k = 4 m, C_l = 0.26 and c = 0.45 m in formula 6 gives that $C_{q\ start}$ = 0.0080. For the ratio between the starting torque and the optimum torque we find that it is 0.0080 / 0.0733 = 0.109. This is acceptable for a rotor with λ_d = 6.

The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * \frac{1}{2}\rho * \pi R^3} \right)} \qquad \text{(m/s)} \qquad (7)$$

An asynchronous generator has no cogging torque and only a small friction torque because of the bearings and the seal on the generator shaft. However, a 2-steps gear box has friction which is caused by the gear wheels, the bearings and the seal on the slow shaft. The friction torque of the generator is multiplied by the gear ratio and therefore the friction torque measured at the slow gear box shaft can be rather high. Assume that it is 20 Nm.

Substitution of Q_s = 20 Nm, $C_{q\ start}$ = 0.0080, ρ = 1.2 kg/m^3 and R = 5 m in formula 7 gives that V_{start} = 3.3 m/s. This is acceptable for a 3-bladed rotor with a design tip speed ratio λ_d = 6 meant to be used in regions with moderate wind speeds.

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. 8). 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 wind tunnel 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-10 rotor are given in figure 2 and 3.

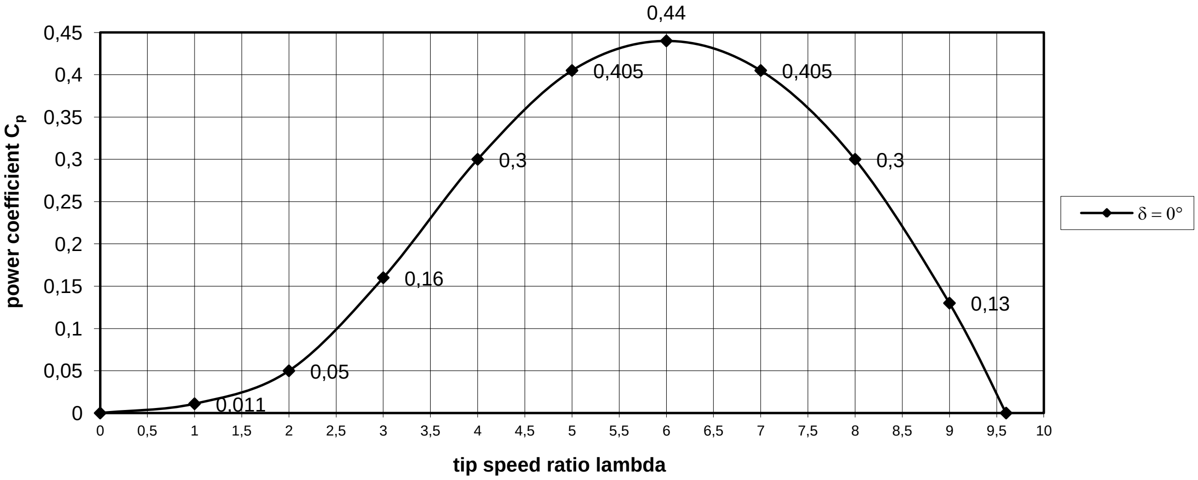

fig. 2 Estimated C_p-λ curve for the VIRYA-10 rotor for the wind direction perpendicular to the rotor (δ = 0°)

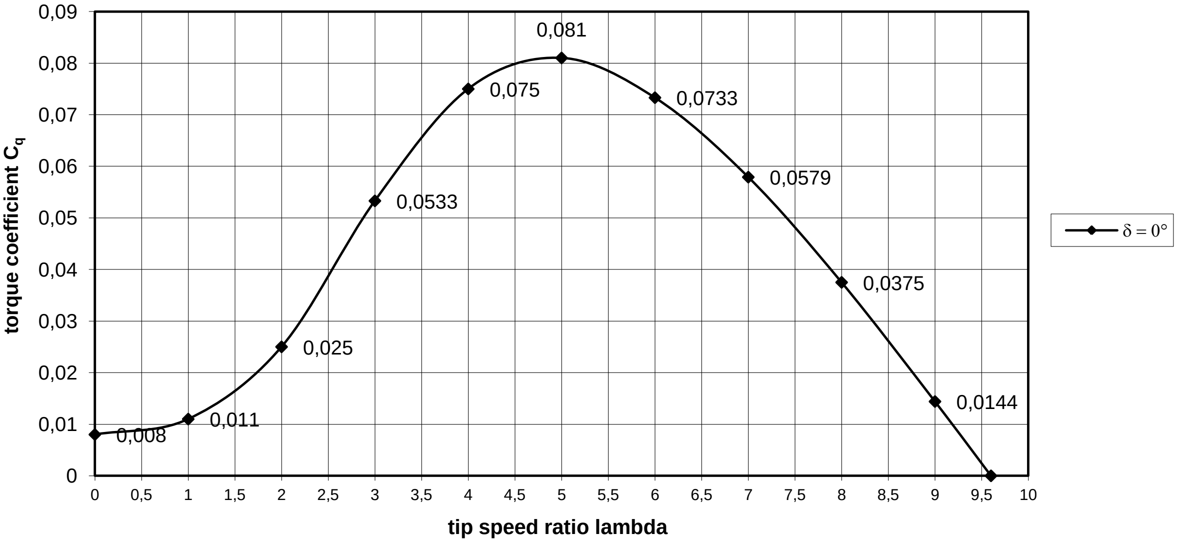

fig. 3 Estimated C_q-λ curve for the VIRYA-10 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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 C_p-λ curve is given in figure 2.

The estimated δ-V curve of the VIRYA-5B5 is given in figure 4 of report KD 710. This figure is copied as figure 4. It is assumed that a hollow vane blade made out of two 5.5 mm sheets will have the same δ-V curve as a massive vane blade made out of 12 mm sheet.

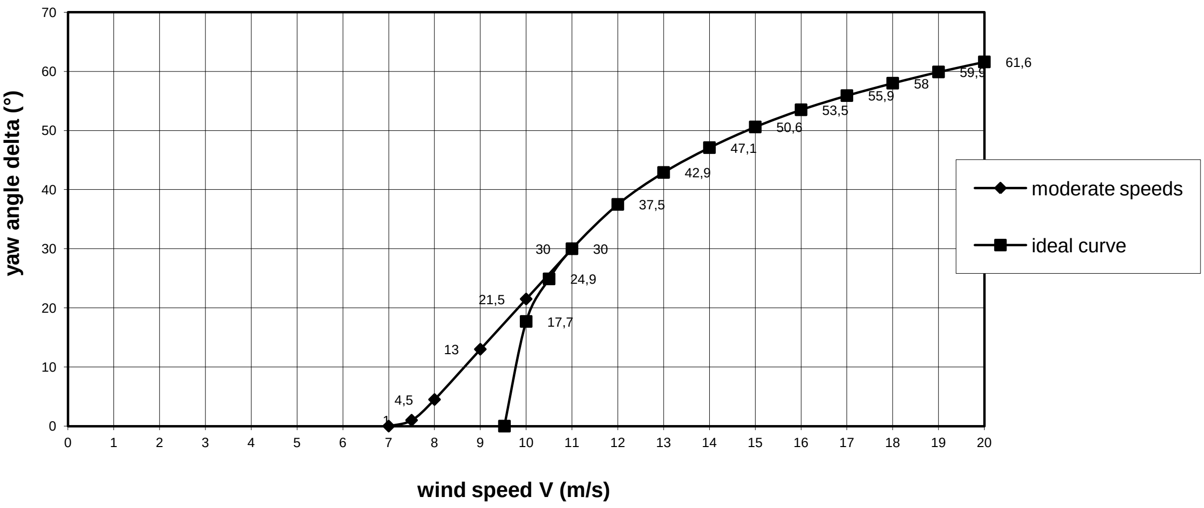

fig. 4 Estimated δ-V curve for a hollow meranti plywood vane blade

So the P-n curves of the rotor are determined for wind speeds up to 7 m/s for the rotor perpendicular to the wind and for a yaw angle as given by figure 4 for higher wind speeds. It is assumed that the curve for V = 11 m/s is also valid for wind speeds higher than 11 m/s.

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator for a certain gear ratio i (the VIRYA-10 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curve for low values of λ appear to lie very close to each other, the P-n curves are not determined for low values of λ. The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10 and 11 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 $\rho = 1.2$ kg / m^3 and R = 5 m in formula 7.10 of KD 35 gives:

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

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 2). 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. The result of the calculations is given in table 2. The calculated values for n and P are plotted in figure 4. The optimum cubic line which can be drawn through the tops of the P-n curves, is also given in figure 4.

		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	0.16	17.2	204	22.9	483	28.6	942	34.4	1629	40.1	2586	45.7	3825	50.2	5085	53.3	6073	54.6	6518
4	0.3	22.9	382	30.6	905	38.2	1767	45.8	3054	53.5	4849	60.9	7172	67.0	9534	71.1	11387	72.8	12222
5	0.405	28.6	515	38.2	1221	47.7	2386	57.3	4122	66.8	6546	76.2	9682	83.7	12871	88.9	15372	91.0	16499
6	0.44	34.4	560	45.8	1327	57.3	2592	68.8	4479	80.2	7112	91.4	10518	100.5	13983	106.6	16700	109.2	17925
7	0.405	40.1	515	53.5	1221	66.8	2386	80.2	4122	93.6	6546	106.6	9682	117.2	12871	124.4	15372	127.4	16499
8	0.3	45.8	382	61.1	905	76.4	1767	91.7	3054	107.0	4849	121.9	7172	134.0	9534	142.2	11387	145.6	12222
9	0.13	51.6	165	68.8	392	85.9	766	103.1	1323	120.3	2101	137.1	3108	150.7	4131	159.9	4934	163.7	5296
9.6	0	55.0	0	73.3	0	91.7	0	110.0	0	128.3	0	146.2	0	160.8	0	170.6	0	174.7	0

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

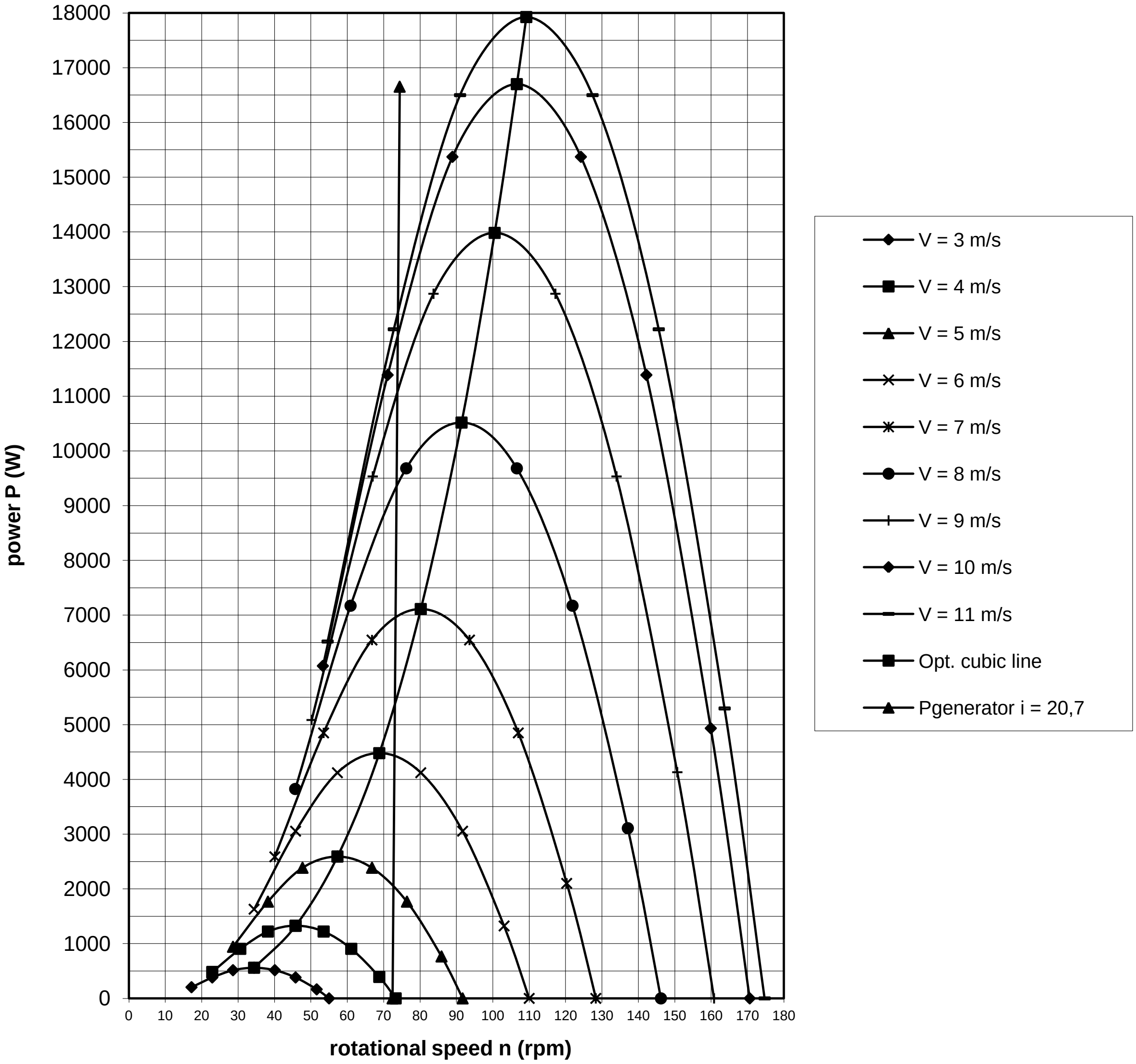

fig. 4 P-n curves of the VIRYA-10 rotor, optimum cubic line, P_{mech}-n curve of a 15 kW, 4-pole asynchronous generator for i = 20.7

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 15 kW, 4-pole motor frame size 160 L is 1460 rpm, so the slip is 40 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 = 15000 W and n = 1460 rpm in formula 10 gives Q = 98.1 Nm.

The chosen motor can supply a much larger peak torque than 98.1 Nm but not for a long time because the winding will become too hot. Provisionally a 15 kW, 4-pole motor of manufacture ROTOR is chosen. This motor has a mass of 115 kg. I have a folder of this manufacturer and it is given that the peak torque is a factor 2.7 higher than the nominal torque and so Q_{peak} = 2.7 * 98.1 = 264.9 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 so the slip is 160 rpm. This gives a rotational speed of 1500 - 160 = 1340 rpm for the peak torque.

Substitution of Q_{peak} = 264.9 Nm and n = 1340 rpm in formula 11 gives that P_{peak} = 37172 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 – 98.1 Nm at n = 1500 + 40 = 1540 rpm and the peak torque for generator use is – 264.9 Nm for n = 1500 + 160 = 1660 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 = 98.1 Nm and n = 1540 rpm in formula 11 gives that P = 15820 W.
Substitution of Q_{peak} = 264.9 Nm and n = 1660 rpm in formula 11 gives that P_{peak} = 46049 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 15000 W at 1460 rpm is given as η_m = 90 %. So the nominal electrical motor power P_{elm} = 15000 / 0.9 = 16667 W. So the heat losses in the stator and the armature are given by P_{heat} = 16667 – 15000 = 1667 W.

It was calculated that the nominal mechanical generator power at 1540 rpm is 15820 W. If the generator efficiency η_g is expected to be the same as η_m, so if η_g = 90 %, the supplied electrical power will be P_{el} = 15820 * 0.9 = 14238. The heat losses are P_{heat} = 15820 – 14238 = 1582 W. This is 85 W less than the heat losses for the nominal power at motor use. A mechanical generator power P = 15820 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 15820 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-steps 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 gear box of manufacture Rossi. I have the catalogue G94 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 2-steps gear box size 160 with in parallel shafts. The supplier of the gear box also supplies the 15 kW, 4-pole motor and it is assumed that the characteristics are the same as for the 15 kW, 4-pole motor of ROTOR.

The slow gear box shaft is hollow and has an inside diameter of 80 mm, an outside length of 272 mm and a standard key groove. This shaft is expected to be strong enough for direct coupling to a windmill rotor with a diameter of 10 m. The rotor hub and shaft can be made out of one piece. The head frame of the windmill must have a mounting plate in parallel to the rotor plane and the gear box is mounted at the back side of this plate.

The specification of the chosen gear box motor combination is given at page 58 of the catalogue G94. A picture is given at page 68 of the catalogue. It is chosen to use a gear box motor combination with specification MR 2I 160 – 160 L 4 with a gear ratio i = 20.7. This gear box motor combination has a rotational speed n of the slow gear box shaft of 67.7 rpm if the motor is running at 1401 rpm. The motor runs at 1460 rpm for the nominal power, so n is higher. The safety factor fs is 2.5 which is rather high and which guaranties a long lifetime.

The P-n curve at the generator shaft starts at n = 1500 rpm. So for i = 20.7, it starts at the rotor shaft at n = 1500 : 20.7 = 72.46 rpm. The P-n curve at the generator shaft has a point P = 15820 W at 1540 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 15820 / 0.95 = 16653 W. The rotational speed at the rotor shaft is 1540 : 20.7 = 74.40 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.

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 lies at a rotational speed of about 73 rpm and a power of about 5300 W. This point belongs to a wind speed of about 6.35 m/s. So the design wind speed V_d is 6.35 m/s and a gear ratio i = 20.7 is a good choice for a moderate wind regime.

The combination of a gear box size 160 and a 4-pole, 15 kW motor frame size 160 is also available for a higher gear ratio i = 24.6 and so reduction of the design wind speed by choosing a larger gear ratio is possible for the VIRYA-10. But this will result in a strong reduction of the power at high wind speeds and therefore it isn’t taken into account.

In figure 4 it can be seen that the P-n curve of the generator starts at a rotational speed of 72.46 rpm. This rotational speed is reached for an unloaded rotor for a wind speed of about 4 m/s. So no energy is produced for wind speeds below 4 m/s. The rotor runs at the maximum C_p for a wind speed of 6.35 m/s but it has a rather high C_p for wind speeds in between about 5 m/s and 8 m/s. However, the C_p for wind speeds lower than 5 m/s and higher than 8 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.

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 = 74 rpm and P = 12500 W. This power is lower than the nominal mechanical generator power of 15820 W and so the generator is certainly strong enough for the VIRYA-10 rotor and it even has a rather large reserve because the peak power is a lot higher than the nominal power.

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 $\eta_g = 0.9$ and that $\eta_{tr} = 0.95$. Substitution of these values in formula 12 gives that $\eta_{tot} = 0.855$. 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 0.855. The electrical power found this way as a function of the wind speed is given in the P_{el}-V curve of figure 5.

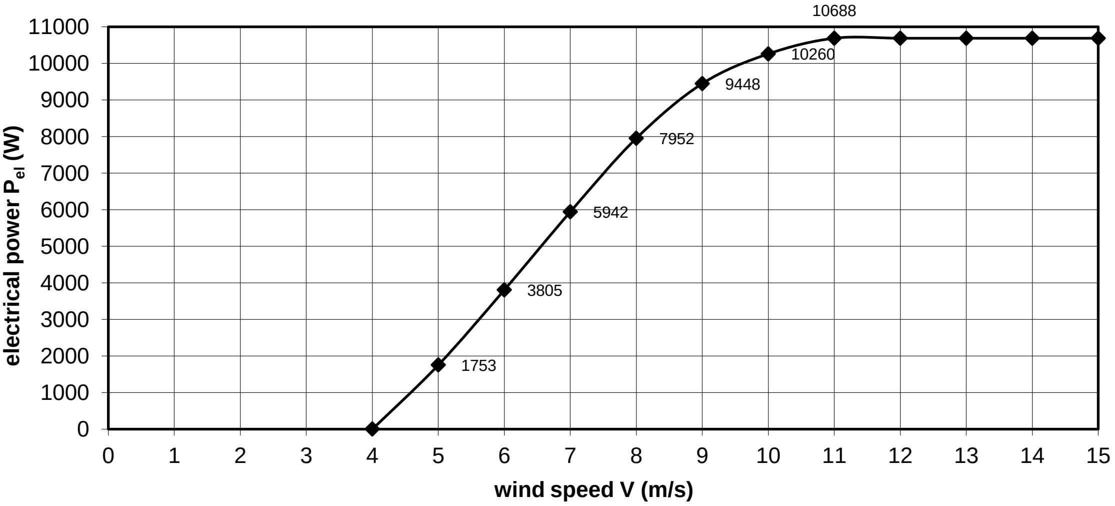

fig. 5 Estimated P_{el}-V curves VIRYA-10 windmill for a gear box with i = 20.7

The maximum electrical power is 10688 W so more than 10 kW. This is a reasonable maximum power for a wind turbine with a rotor diameter of 10 m and a rated wind speed of 11 m/s. The power for the design wind speed V_d = 6.35 m/s is about 4550 W, so about 4.5 kW. A design wind speed of 6.35 m/s seems a reasonable value for a region with a good wind regime with an average yearly wind speed at the heart of the rotor of at least 5 m/s.

It must be possible to stop the rotor which can be done by a spring loaded electromagnetic brake mounted on the generator shaft 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 but I won’t do this. This must be done by the company which has interest to build the VIRYA-10. I am available to check the drawings. This company must have skills and machines to build and test a prototype. The VIRYA-10 is much too complicated and too heavy to be built by an amateur, so I won’t support amateurs.

7 References

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