Calculations executed for the 4-bladed rotor of the VIRYA-12 windmill ($\lambda_d = 5$) with the pendulum safety system with a torsion spring connected to a PM-generator made from an asynchronous motor frame size 355

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It is allowed to copy this report for private use. A prototype of the VIRYA-12 windmill has not yet been built and tested. This should be done only by a professional company after making detailed drawings. Although the VIRYA-12 has been designed carefully, no responsibility is accepted by Kragten Design for the proper functioning.

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1 Introduction

In the Dutch report: “Ideeën over de realisatie van dertig bouwpercelen en één middelgrote windturbine in Boskant” (ref. 1), a plan for 30 houses and one DWD-18 wind turbine is described. Each house has twenty-two, 300 W peak solar panels. The DWD-18 wind turbine has a rotor diameter of 18 m and a tower height of about 24 m.

In chapter 5, alternative 1 of this report, an alternative roof is described with a roof angle of 30° in stead of 45° such that thirty-three solar panels can be used on each house. This will give an output which is 50 % higher and the wind turbine which is used to supply the shortage of energy in the winter months, can therefore be smaller. Calculations given in chapter 7 show that a wind turbine with a rotor diameter of 12 m at a 24 m high tower is just large enough for the heat pump if each house has thirty-three, 300 W peak solar panels.

A problem with using a wind turbine close to houses is the noise production and the visual acceptance. 4-bladed rotors of traditional Dutch windmills have a large acceptance even if they have a rotor diameter of about 25 m. So this is the main reason why the rotor has four blades. A technical advantage of four blades is that two opposite blades can be mounted on the same connecting strip and so no welded spoke assembly is required.

The noise production is very much dependent on the tip speed and the tip speed is proportional to the design tip speed ratio λ_d. To minimise noise production, a rather low design tip speed ratio $\lambda_d = 5$ has therefore been chosen. The rotor will have wooden blades and wood also has a sound damping influence.

The generator will be direct drive so there will be no noise of a gear box. The generator will be made of the largest standard 6-pole asynchronous motor with frame size 355. This motor has a 100 mm shaft which seems strong enough for a rotor with a diameter of 12 m if the wind turbine is provided with a proper safety system which limits the rotational speed, the thrust and the gyroscopic moment. The generator has a stator with 72 slots and an armature with 68 poles and is described in chapter 8.

The wind turbine will be equipped with the pendulum safety system with a torsion spring. This safety system is described in report KD 439 (ref. 2). Some specific calculations for the VIRYA-10 rotor are given in chapter 6 of KD 439. The calculations for a rotor with a diameter of 12 m are similar and it is assumed that the δ-V curve is the same. It is also assumed that a double vane is used to keep the rotor in the wind.

The generator has a 3-phase winding which is rectified in star (for rectification see report KD 340 ref. 3). The generator is grid connected by a 3-phase inverter. Selection of the correct rectifier and the correct inverter is out of the scope of this report. There is no wire from the windmill to each single house but it is assumed that the value of the energy production of the windmill is divided evenly over 31 houses and that this energy production reduces the energy which has to be bought.

The VIRYA-12 will have a free standing tubular tower with a height of 24 m. So the highest point of the rotor is 24 + 6 = 30 m and the lowest point is 24 – 6 = 18 m.

2 Description of the rotor of the VIRYA-12 windmill

The 4-bladed rotor of the VIRYA-12 windmill has a diameter D = 12 m and a design tip speed ratio $\lambda_d = 5$. 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. 4). A blade is made out of a wooden plank with dimensions of 83.2 * 560 * 5600 mm. The airfoil is made over the whole blade length. The blade has no twist so the blade angle β is the same for the whole blade.

For the VIRYA-12 it is assumed that two opposite blades are connected to each other by a steel strip with a width of 250 mm, a thickness of 20 mm and a length of 2000 mm. The two strips are connected to a square hub with four bolts M20 and a central bolt M24.

Each strip is twisted 9° right hand in between r = 125 mm and r = 400 mm to give the blade the correct blade angle. The strips are galvanised. The overlap in between a blade and a strip is 600 mm which results in a free blade length of 5 m. The blades are connected to the strip by three bolts M24 and six nuts M24. A cambered stainless steel sheet size 600 * 80 * 5 mm is placed under the bolt heads to prevent damage of the wood when the bolts are tightened. The rotor is balanced by adding balance weights under the connecting bolts. A sketch of the VIRYA-12 rotor is given in figure 1.

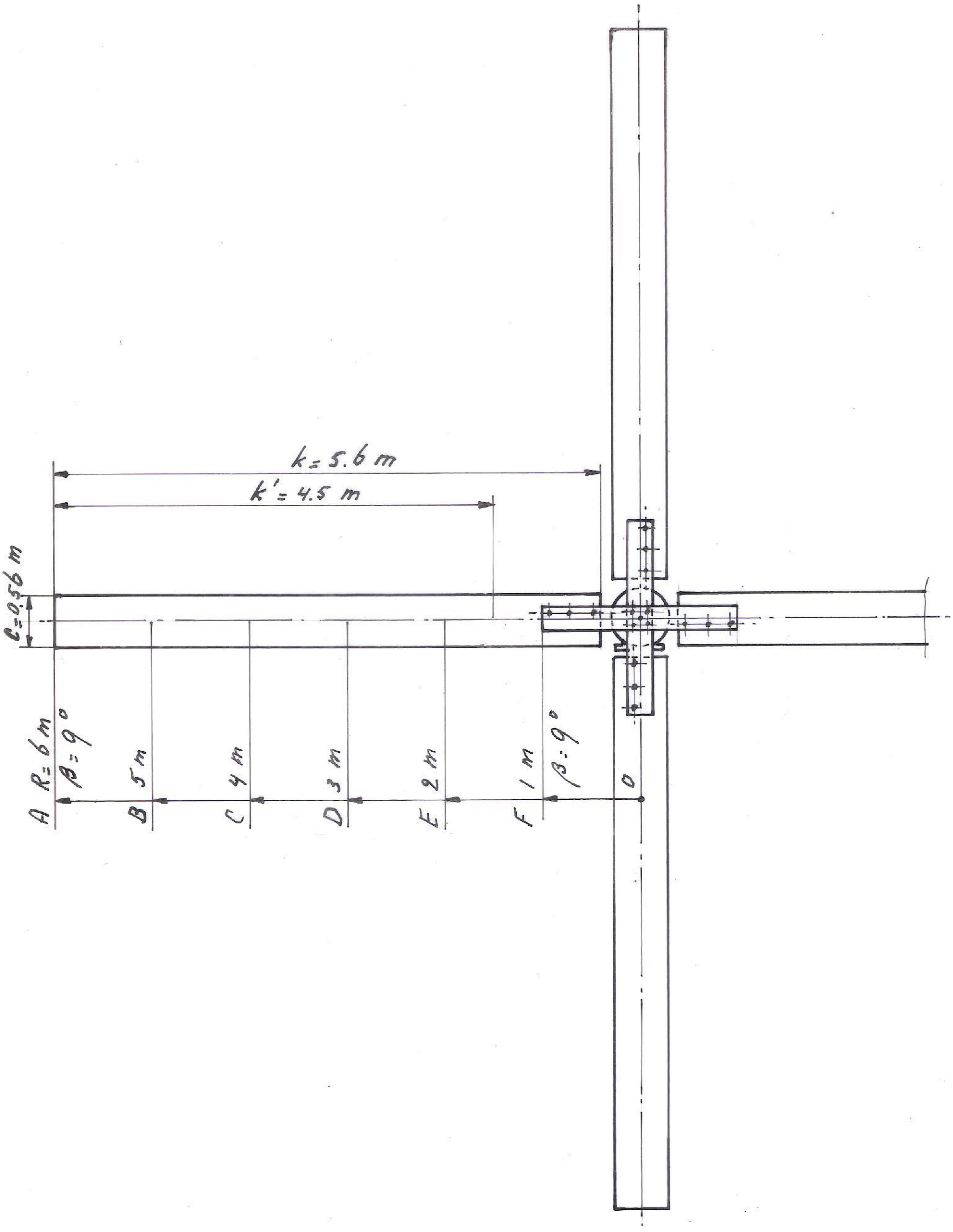

fig. 1 Sketch VIRYA-12 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 5). This report (KD 727) has its own formula numbering. Substitution of $\lambda_d = 5$ and $R = 6$ m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 0.8333 * r$ (-) (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 = 4 and c = 0.56 m in formula (5.4) of KD 35 gives:

$C_l = 11.220\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.56 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 1.868 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 1 m of one to another. Cross section F corresponds to the end of a strip. 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 linearised such that the twist is constant and that the linearised 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. 4). 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-12 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	6	5	7.5	0.56	0.58	0.54	9.42	4	-1.0	-1.5	8.5	9.0	0.027
B	5	4.167	9.0	0.56	0.69	0.67	7.88	4	0.3	0.0	8.7	9.0	0.021
C	4	3.333	11.1	0.56	0.84	0.85	6.35	4	2.0	2.1	9.1	9.0	0.016
D	3	2.5	14.5	0.56	1.08	1.11	4.83	4	5.0	5.5	9.5	9.0	0.017
E	2	1.667	20.6	0.56	1.44	1.48	3.35	4	10.3	11.6	10.3	9.0	0.031
F	1	0.833	33.5	0.56	1.86	-	1.99	4	-	24.5	-	9.0	-

table 1 Calculation of the blade geometry of the VIRYA-12 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 8.5° and 10.3°. Therefore it is allowed to take a constant value of $\beta_{lin} = 9°$ 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 0.022. Figure 4.8 of KD 35 (for B = 4) and $\lambda_{opt} = 5$ and $C_d/C_l = 0.022$ 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 = 5.6 m is taken into account but only the part up to 0.5 m outside station F. This gives an effective blade length k' = 4.5 m.

Substitution of $C_{p\ th} = 0.48$, R = 6 m and effective blade length k' = 4.5 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.45$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.45 / 5 = 0.09$. Substitution of $\lambda_{opt} = \lambda_d = 5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 8$. 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 9° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 9° = 81°. 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. 6). For $\alpha = 81°$ it can be read that $C_l = 0.32$. The whole blade is stalling during starting but the part of the blade behind the strip isn't very effective. Therefore, for k now the free blade length k = 5 m is taken.

Substitution of B = 4, R = 6 m, k = 5 m, $C_l = 0.32$ and c = 0.56 m in formula 6 gives that $C_{q\ start} = 0.0139$. For the ratio between the starting torque and the optimum torque we find that it is 0.0139 / 0.09 = 0.154. This is acceptable for a rotor with $\lambda_d = 5$.

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 generator has not yet been built and so the sticking torque Q_s isn't known. The generator has a very high pole number so there will be almost no fluctuation of the sticking torque because of clogging. So the sticking torque is mainly determined by the friction of the bearings and the seal on the generator shaft. Assume $Q_s = 12$ Nm.

Substitution of $Q_s = 12$ Nm, $C_{q\ start} = 0.0139$, $\rho = 1.2$ kg/m^3 and R = 6 m in formula 7 gives that $V_{start} = 1.5$ m/s. This is very low for a 4-bladed rotor with a design tip speed ratio $\lambda_d = 5$ 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 $\lambda = 0$. 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. 6). 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 or 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 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-12 rotor are given in figure 2 and 3.

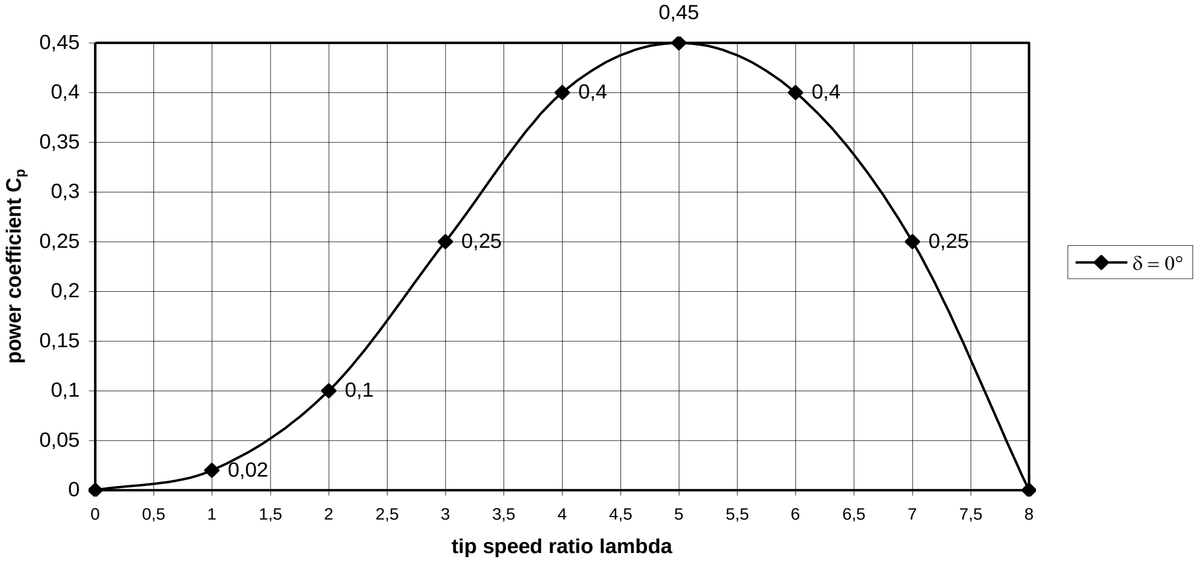

fig. 2 Estimated C_p-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

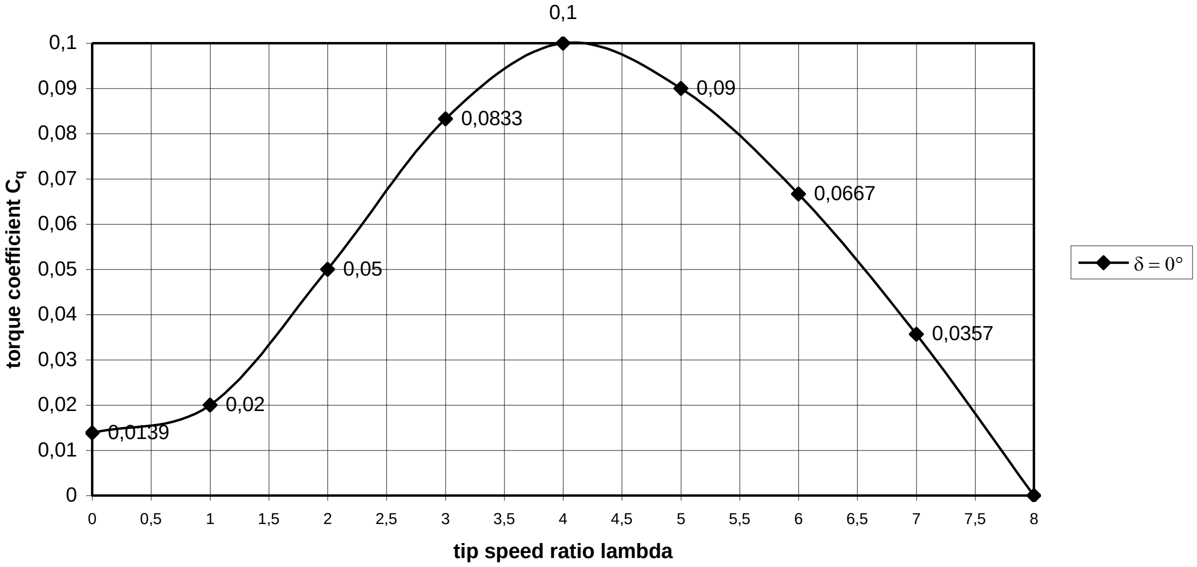

fig. 3 Estimated C_q-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

5 Determination of the P-n curves and the optimum cubic line

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. 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 characteristics of the safety system are derived in chapter 3 of KD 439 for a design wind speed V_d = 8 m/s. This means that the rotor starts yawing around the horizontal axis at a wind speed of 8 m/s. In figure 8, 9 and 10 of KD 439 it can be seen that the rotational speed, the thrust, the torque and the power are about maximal for a wind speed of 10 m/s. So a wind speed of 10 m/s is the rated wind speed V_{rated}. In figure 7 of KD 439 it can be seen that the yaw angle δ is about 30° for V = 10 m/s and that the yaw angle for V = 9 m/s is about 20°.

So the P-n curves of the rotor are determined for wind speeds up to 8 m/s for the rotor perpendicular to the wind, for V = 9 m/s for a yaw angle $\delta = 20°$ and for V = 10 m/s for a yaw angle $\delta = 30°$.

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-12 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 and 10 m/s. Substitution of R = 6 m in formula 7.1 of KD 35 gives:

$$n = 1.5915 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 6 m in formula 7.10 of KD 35 gives:

$$P = 67.858 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ is 2, 3, 4, 5, 6, 7 and 8 (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.

		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 = 0°		V = 9 m/s δ = 20°		V = 10 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2	0.1	9.5	183	12.7	434	15.9	848	19.1	1466	22.3	2328	25.5	3474	26.9	4105	27.6	4408
3	0.25	14.3	458	19.1	1086	23.9	2121	28.6	3664	33.4	5819	38.2	8686	40.4	10262	41.3	11019
4	0.4	19.1	733	25.5	1737	31.8	3393	38.2	5863	44.6	9310	50.9	13897	53.8	16419	55.1	17630
5	0.45	23.9	824	31.8	1954	39.8	3817	47.7	6596	55.7	10474	63.7	15634	67.3	18471	68.9	19834
6	0.4	28.6	733	38.2	1737	47.7	3393	57.3	5863	66.8	9310	76.4	13897	80.8	16419	82.7	17630
7	0.25	33.4	458	44.6	1086	55.7	2121	66.8	3664	78.0	5819	89.1	8686	94.2	10262	96.5	11019
8	0	38.2	0	50.9	0	63.7	0	76.4	0	89.1	0	101.9	0	107.7	0	110.3	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-12 rotor

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.

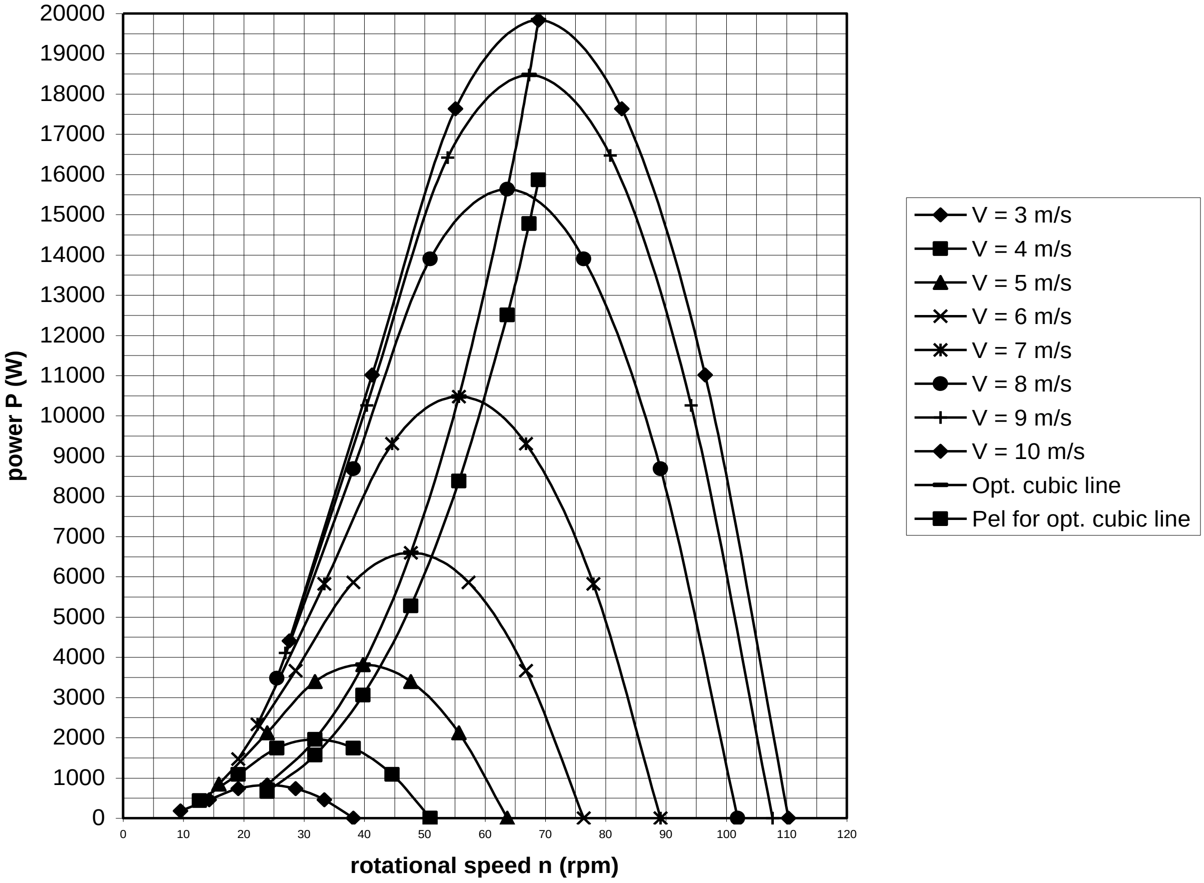

fig. 4 P-n curves of the VIRYA-12 rotor, optimum cubic line, P_{el}-n curve for the assumption that the optimum cubic line is followed and that the total efficiency of the generator and the inverter is 0.8.

6 Estimation of the generator characteristics and the P_{el}-V curve

The PM-generator has not yet been designed, built and tested, so the generator characteristics are not yet known. However, I have built and tested several other PM-generators and it can be expected that the generator efficiency is at least 85 % or a factor 0.85. The alternating 3-phase current is rectified and grid connected by a 3-phase inverter. It is assumed that the inverter can be programmed such that the optimum cubic line of the rotor is followed. It is also assumed that the total efficiency of the rotor, the rectifier and the inverter is 0.8 for all working points. For this assumption, the P_{el}-n curve can be determined by multiplying the P-values of the optimum cubic line by a factor 0.8. The estimated P_{el}-n curve is also given in figure 4.

The working point for a certain wind speed is the point of intersection of the P-n curve of the rotor for that wind speed with the optimum cubic line. So it is the point of intersection of the optimum cubic line with the P-n curve of the rotor for that wind speed if the optimum cubic line is followed. The electrical power for a certain wind speed is found by going down vertically from the working point until the P_{el}-n curve is crossed. The values of P_{el} have been determined this way for wind speeds up to 10 m/s and are given in the P_{el}-V curve of figure 7. It is assumed that P_{el} for higher wind speeds than 10 m/s is the same as the value for V = 10 m/s.

The rated electrical power is almost 16 kW at a wind speeds of 10 m/s and higher which is very good for a windmill with a rotor diameter of 12 m and a design wind speed of 8 m/s. If the generated energy is used to power a heat pump, about four times more heat is generated than the input electrical power. So even at moderate wind speeds, a substantial amount of heat will be generated by the VIRYA-12.

It is expected that the inverter needs a minimum input voltage to function. So the rotor must have a certain minimal rotational speed. This speed isn't known but at the moment it is supposed that the voltage is too low for wind speeds below 3 m/s. This means that the little energy available in wind speeds below 3 m/s can't be captured. So this is the reason why the P_{el}-V curve starts suddenly with P_{el} = 659 W at V = 3 m/s. The critical voltage may lie lower and if this is the case, the P_{el}-V curve starts at a lower wind speed. In chapter 4 it was calculated that the starting wind speed is only 1.5 m/s which is much lower than 3 m/s. So the rotor will turn almost always but it will generate no power for 1.5 < V < 3 m/s.

The P_{el}-V curve is valid for constant wind speeds and not for average wind speeds. The output for a certain average wind speed is larger than for a certain constant wind speed. This can be demonstrated as follows. Assume we have a constant wind speed of 5 m/s. In the P_{el}-V curve it can be read that P_{el} = 3054 W. Assume we have a wind speed of 3 m/s for one hour and of 7 m/s for one hour. So the average wind speed is 5 m/s. The power for V = 3 m/s is 659 W. The power for V = 7 m/s is 8379 W. The average power is (659 + 8379) / 2 = 4519 W. This is 1465 W more or a factor 4519 / 3054 = 1.48 higher than for a constant wind speed of 5 m/s.

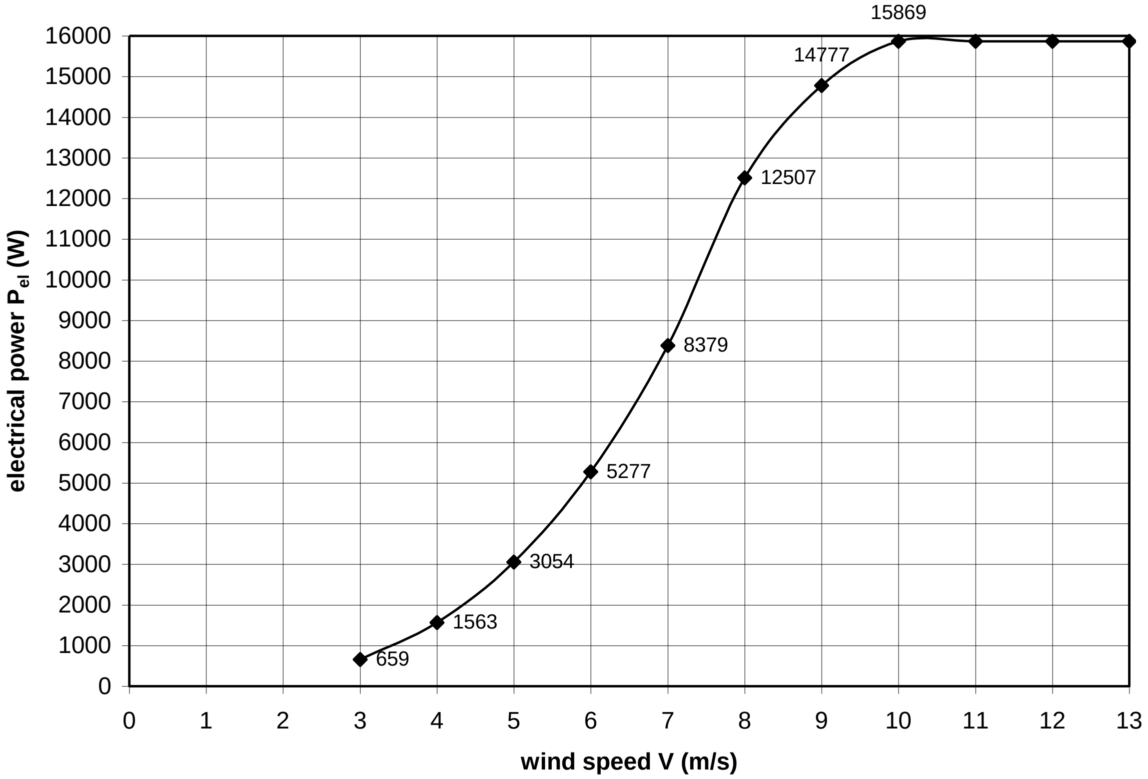

fig. 7 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

The P_{mech}-n, the P_{el}-n curves as given in figure 4 and the P_{el}-V as given in figure 7 are estimated and not measured. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the chosen generator, it is necessary to build one and to test it at a large test rig with which it is possible to also measure the torque Q. One should also select and buy an inverter and measure the real electrical output for grid connection. Finally a complete windmill has to be built and tested with the correct load.

It might be possible to use the rotor as a brake to stop the rotor. To verify if this is possible at any wind speed, one should also measure the P-n curve for short-circuit. Short-circuit in delta gives a higher maximum torque than for short-circuit in star because higher harmonic currents can circulate in the winding for short-circuit in delta. Short-circuit in delta is the same as short-circuit in star if the star point is short-circuited too. The short-circuit switch should be mounted at the tower foot to minimise a voltage drop over the lines. So apart from the three phase wires, an extra cable must be used in between the star point and the short-circuit switch.

Building of a prototype of the VIRYA-12 with the chosen PM-generator is only possible if a composite drawing is made and if detailed drawings are available but I won’t make them. So only companies with enough engineering and manufacturing capacity should start with the VIRYA-12. The VIRYA-12 is certainly not a windmill which can be built by an amateur.

7 Checking if the wind turbine is large enough for the project

The project with 30 new houses (see ref. 1) is situated in Boskant which is a part of Sint-Oedenrode which is a part of Meierijstad. The average yearly wind speed in Boskant is about 4 m/s at a height of 10 m in open terrain. The average wind speed during the winter month December is higher than the average yearly wind speed. Assume that the average wind speed in December is 5 m/s at a height of 10 in open terrain. The VIRYA-12 will get a tower with a height of 24 m but it will be surrounded with houses and trees. Assume that the average wind speed at a height of 24 m is 6 m/s during December. The output at a certain average wind speed is higher than at the same constant wind speed. Therefore it is assumed that the P_{el}-V curve can be read at V = 6.5 m/s for an average wind speed of 6 m/s in December. In figure 7 it can be seen that P_{el} = 6900 W for V = 6.5 m/s. It is assumed that this power is divided evenly in between the 30 new houses and the one existing house (if every house has taken an equal share in the output of the wind turbine). So every house gets an average power of 6900 / 31 = 222 W from the wind turbine in December.

The plan contains 28 new houses which have a width of 6 m and a depth of 11 m and two bigger new houses. In chapter 6 of the report ref. 1 it was calculated that the heat loss of the 28 houses is about 1800 W in December. If a heat pump with a COP of 4 is used, this means that the required electrical power is 1800 / 4 = 450 W.

On the website: www.essent.nl it is given that one 300 W peak solar panel has a yearly output of about 260 kWh. So the yearly output of 33 solar panels is 33 * 260 = 8580 kWh. December is the month with the lowest output for solar panels and it is given that only 2 % of the yearly output is generated for this month. So the output in December is 0.02 * 8580 = 172 kWh. December has 31 days so 31 * 24 = 744 hours. So the average power in December is 172 / 744 = 0.231 kW = 231 W. So the shortage is 450 – 231 = 219 W for December. The output of the wind turbine is about 222 W for each house and so the wind turbine is just large enough for December if the assumed wind speeds and the estimated P_{el}-V curve are correct.

The output of the solar panels is 3 % for January and 5 % for February. So for these months, the output of the solar panels is respectively 257 W and 429 W. The output of the wind turbine will be about the same as for December and so there will be no shortage of power for these months. The output of the solar panels for the other months is much higher and the outside temperature is also higher so the heat loss of the house is less. So for all months except December there will be a positive output of the windmill and the solar panels together which can be used for other energy consumers or which can be fed into the grid.

The calculation is based on average powers. The houses have a large warmth capacity and fluctuation of the input power will result in only small fluctuations of the internal temperature. However, if there are long periods in December for which there is almost no sun or wind energy it will still be required to extract energy from the grid. But the risk that this is necessary, is much smaller if one VIRYA-12 wind turbine is added than if the houses have only solar panels.

8 Description of the PM-generator

The maximum torque level of a rotor with a diameter of 12 m and a design tip speed ratio of 5 is very high at a wind speed of 10 m/s. It can be calculated that it is 2748 Nm. So this requires a direct drive PM-generator with a very large armature volume. It was already chosen to make the generator from the largest 6-pole standard asynchronous motor frame size 355 because this frame size has a shaft diameter of 100 mm. The 6-pole motor has the largest inside diameter of the stator so therefore a 6-pole motor is chosen. It is also chosen to use a stator stamping of manufacture Kienle & Spiess (website: www.kienle-spiess.de).

The outside diameter of the stator stamping is 580 mm. The inside diameter of the stator stamping is 425 mm. The length of the stator stamping depends on the nominal power. It is 470 mm for the 160 kW version and 550 mm for the 200 kW version. The length of the stator stamping is chosen 550 mm so this gives the largest armature volume which is possible. The stator has 72 slots in which the coils are laid. The stator will get a special winding.

The armature will be provided with 68 poles. The 34 north poles will be formed by neodymium magnets. The 34 south poles will be formed by the remaining material left in between the north poles.

I have designed several PM-generators with a high pole number. A rather big 34-pole PM-generator for the VIRYA-5 is described in chapter 6, figure 5 of public report KD 622 (ref. 7). This generator has a stator with 36 slots. 18 coils can be laid in 36 slots and therefore every phase has six coils. The coils are mounted in two bundles of three coils. If a north pole is just opposite to the middle coil of one bundle, a south pole will be just opposite to the middle of the other coil bundle. All coils have the same winding direction but the coil bundles have to be connected to each other such that the direction of the current in one coil bundle is opposite the direction of the current in the other one. It can be calculated that this generator has 612 preference positions per revolution which is very high and almost no fluctuation of the sticking torque will therefore be felt.

A generator with a 68-pole armature and a stator with 72 slots can be seen as doubling all aspects of a generator with a 34-pole armature and a stator with 36 slots. So this generator will have four bundles of three coils for each phase and it will have 2 * 612 = 1224 preference positions per revolution.

The air gap in between armature and stator is chosen 0.5 mm. So the armature diameter is 424 mm. The armature pole pitch is π * 424 / 68 = 19.59 mm. The width of the magnets must be somewhat smaller than the armature pole pitch because there must be a certain distance in between the poles. It is chosen to use neodymium magnets size 40 * 18 * 10 mm. These magnets are supplied by the Polish supplier Enes website: www.enesmagnets.pl. The quality is N38. The current price including 23 % VAT is € 3.11 if at least 150 magnets are ordered.

The armature length is chosen 560 mm so the armature juts out 5 mm at each side of the stator stamping. Thirty-four, 18 mm wide and 10.2 mm deep grooves are made in the armature under an angle of 360 / 34 = 10.588°. Fourteen magnets are glued in each groove so totally 14 * 34 = 476 magnets are needed for one armature. So the total magnet costs are about 476 * 3.11 = € 1480 excluding mailing costs and about € 1500 including mailing costs. This seems acceptable for such a big PM-generator.

A 6.2 mm deep and 1.5 mm wide groove is made at each side of the magnet groove. This makes that the width of a south pole, which is formed by the remaining material in between the grooves is also about 18 mm. These 1.5 mm grooves prevent direct magnetic short-circuit in between the sides of the magnets.

The procedure how to determine the wire thickness and the number of turns per coil is described in chapter 6 of report KD 622. As the generator is very big, it will be very difficult to measure it for the correct load and for the low rotational speeds for which it is used in the VIRYA-12 wind turbine. So one needs special skills to develop this generator.

9 References

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2 Kragten A. Development of a pendulum safety system with a torsion spring and e = 0.2 R. March 2010, reviewed June 2021, free public report KD 439, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

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