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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 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 note: “Ideeën over realisatie van 14 bouwpercelen en één VIRYA-14 windturbine in Boskant” (ref. 1), a plan for 14 houses and one VIRYA-14 wind turbine is described. The used house is described in a separate Dutch note: “Ideeën over een levensloopbestendig vrijstaand huis geschikt voor driedubbele bewoning” (ref. 2). Each house has 44, 300 W solar panels. At chapter 7 of the report KD 732 (ref. 3) it has been calculated that more than enough energy is generated in December by the VIRYA-14 windmill and the solar panels together. It seems possible to use a somewhat smaller wind turbine like the VIRYA-12. This is checked in chapter 7.

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 of the VIRYA-12 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 8-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. The original short-circuit armature has 84 slots in which aluminium short-circuit bars are cast. The generator is described in chapter 8 and 9.

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. 4). 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. 5). 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 14 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. 6). 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.

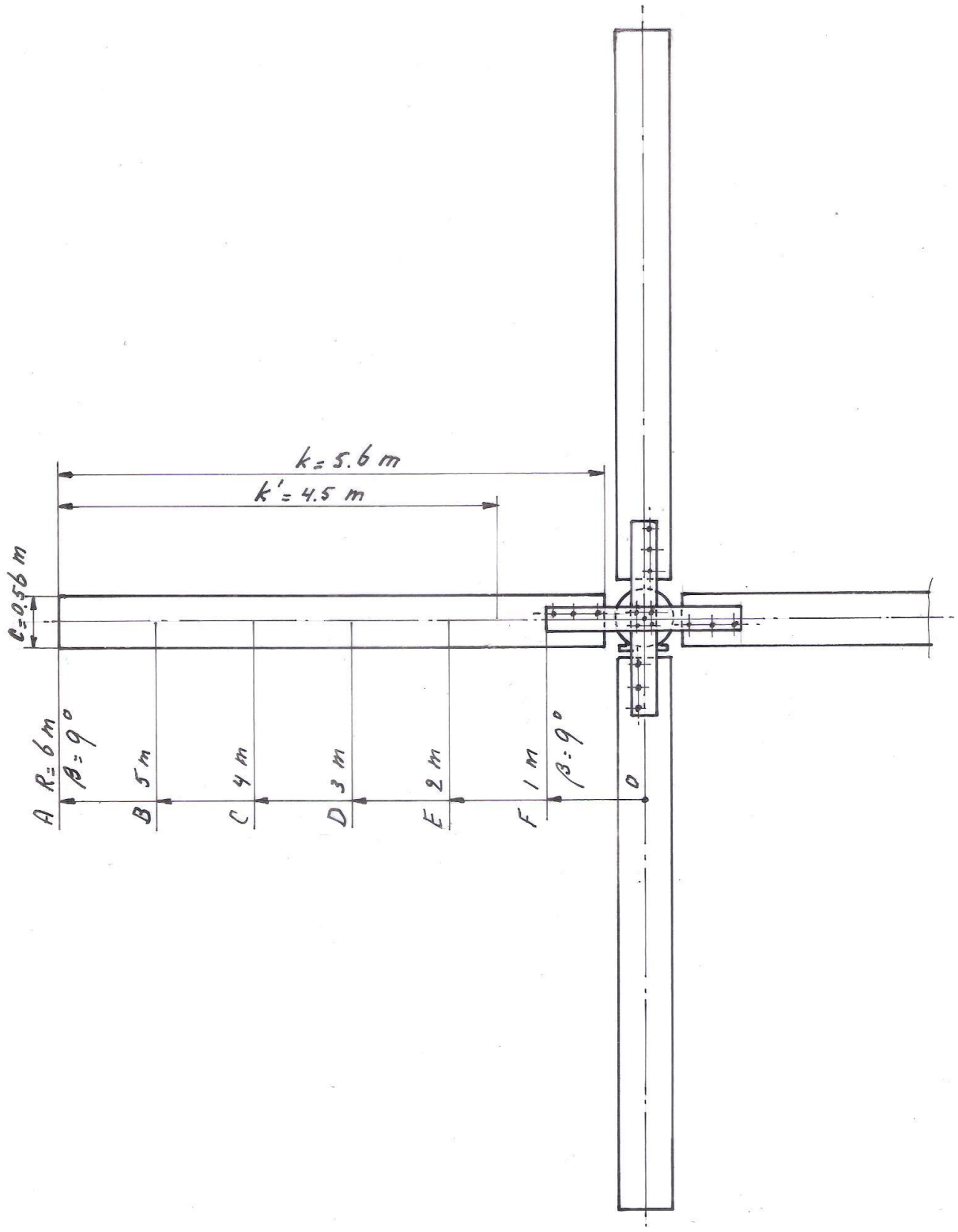


fig. 1 Sketch VIRYA-12 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 7). 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:

$$\lambda_{r\,d} = 0.8333 * r \qquad (-) \qquad (1)$$

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 = 4 and c = 0.56 m in formula (5.4) of KD 35 gives:

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

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

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

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. 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-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:

$$C_{q\,start} = 0.75 * B * (R - \tfrac{1}{2}k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (6)$$

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. 7). 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:

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

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 cogging. 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. 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 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.

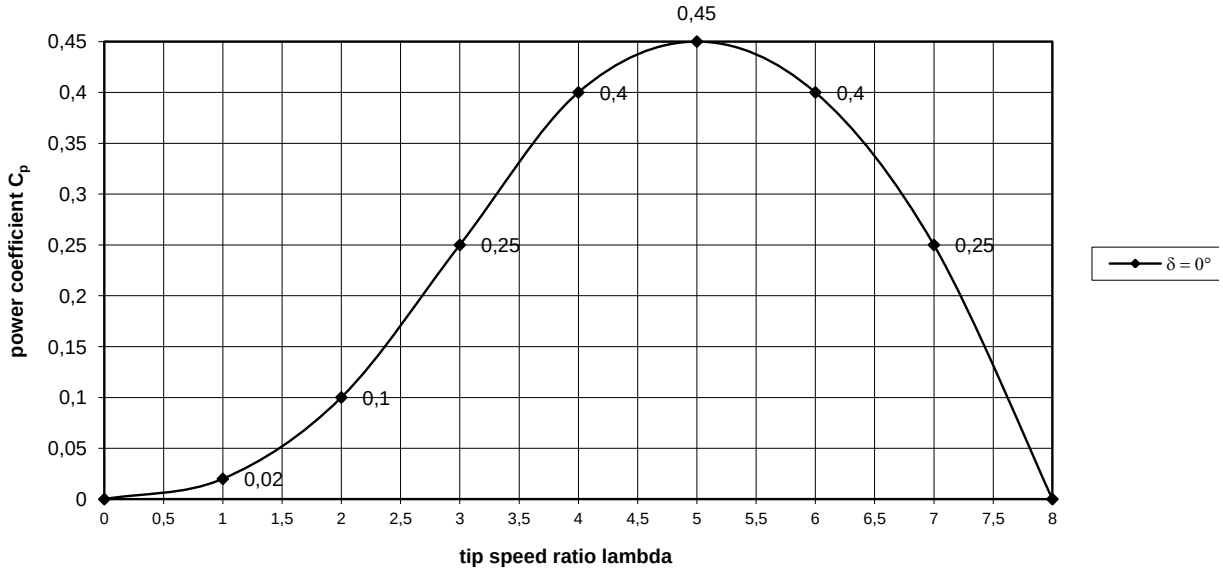


fig. 2 Estimated C_p-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

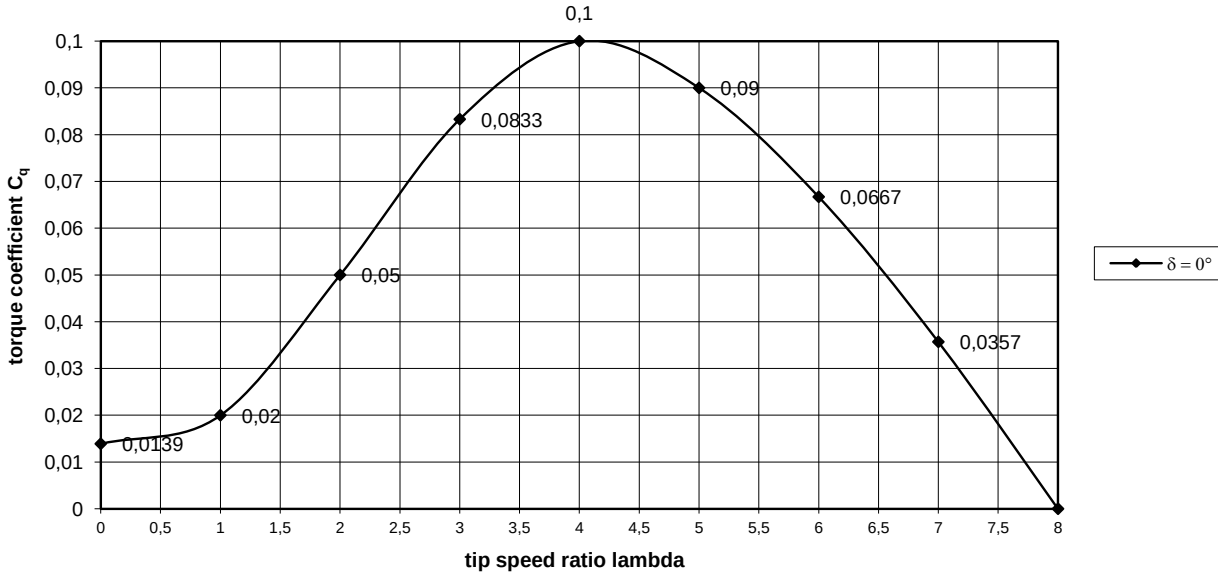


fig. 3 Estimated C_q-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 is about 20° for V = 9 m/s.

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 appears 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.

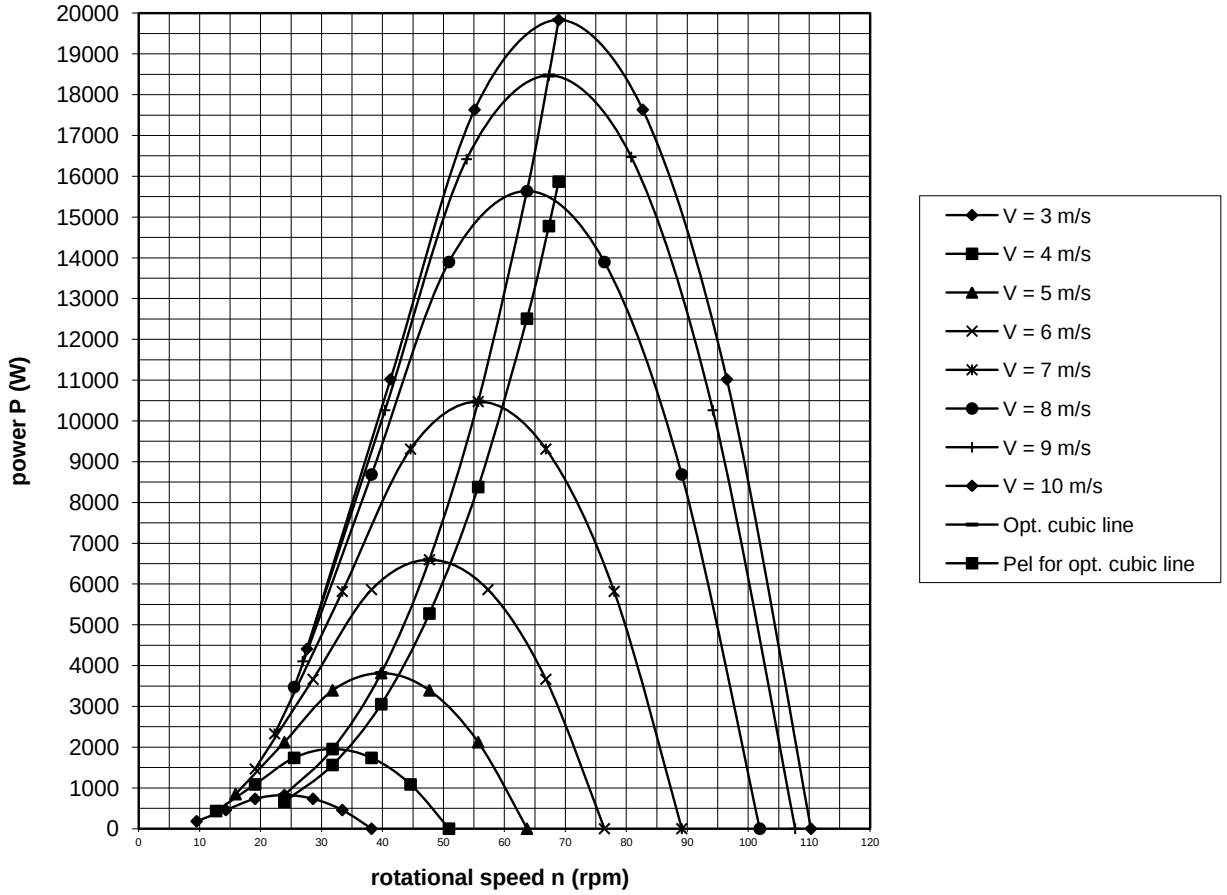


fig. 4 P-n curves of the VIRYA-12 rotor, optimum cubic line, P_{el}-n curve for the assumption that the optimum cubic line is followed and that the total efficiency of the generator and the inverter is 0.8.

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 5. 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.

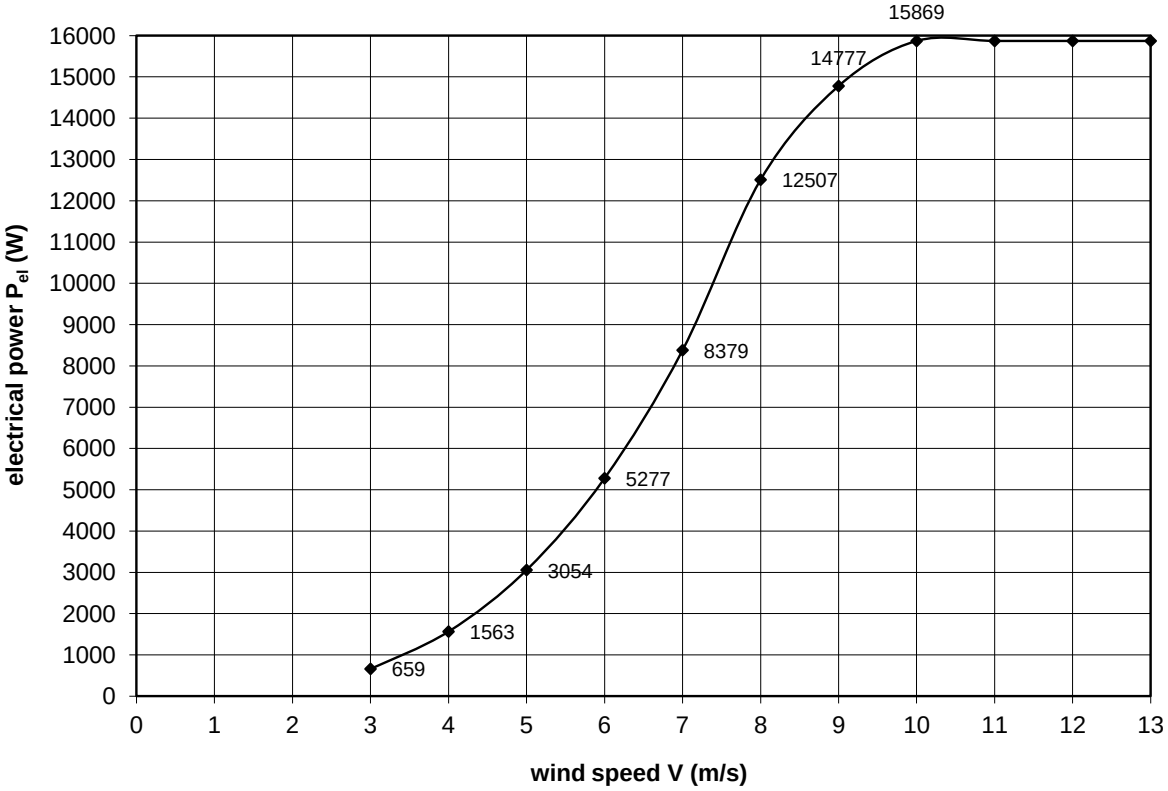


fig. 5 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

The P_{mech}-n, the P_{el}-n curves as given in figure 4 and the P_{el}-V as given in figure 5 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 14 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} = 6800 W for V = 6.5 m/s. It is assumed that this power is divided evenly in between the 14 new houses (if every house has taken an equal share in the output of the wind turbine). So every house gets an average power of 6800 / 14 = 486 W from the wind turbine in December.

The plan contains 14 new detached houses which have a width of 11 m and a depth of 11 m. In chapter 5 of the note ref. 2 it was calculated that the heat loss of the house is about 2200 W in December. If a heat pump with a COP of 4 is used, this means that the required electrical power is 2200 / 4 = 550 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 44 solar panels is 44 * 260 = 11440 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 * 11440 = 228.8 kWh. December has 31 days so 31 * 24 = 744 hours. So the average power in December is 228.8 / 744 = 0.308 kW = 308 W. So the power of the wind turbine for one house and the power of the solar panels together is 486 + 308 = 794 W. 550 W is used by the heat pump and so 794 – 550 = 244 W is left for other use than the heat pump. This may not be enough in December.

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 343 W and 572 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 only for December, the output of the windmill and the solar panels together may be too small.

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 Selection of the asynchronous motor for use as PM-generator

It is chosen to use a motor which has a stator and armature stamping of the German manufacture Kienle & Spiess because this manufacture gives detailed information about the dimensions of their stampings on their website. However, it appears that recently, the name of this company has changed into Feintool. Information about the geometry of armature and stator stampings of asynchronous motors is found by following the path: www.feintool.com – Online catalogue industry – Products – Induction Machines. One has to make an account with an e-mail address and a password to get access to the catalogue.

Very long ago, a Dutch manufacturer of asynchronous motors has given me a page of a German folder on which an overview is given of the armature and stator dimensions depending on the frame size and the number of poles. This page can't be found on the website of Feintool but it is very handy to make a choice, especially because it also gives the armature and stator length L_{Fe}. I have scanned it and added it as figure 6. It is a bit dirty and full with remarks but it still works. D_a is the outside diameter of the stator stamping. D_i is the inside diameter of the stator stamping. d_i is the diameter of the hole in the armature stamping. The frame size is the height of a foot B3 from the centre of the shaft up to the bottom of the foot.

The outside diameter of the armature is somewhat smaller than D_i because of the air gap in between armature and stator but the value isn't given as this is chosen by the manufacturer of the motor. The number of stator slots is also not given but I have written it on the sheet for some frame sizes. This information is given on the website of Feintool if one goes to the selected stamping.

Information about the shaft dimensions is also not given. I have used a folder of the Dutch manufacturer ROTOR to find this information. However, ROTOR isn't using stampings of Feintool and so one can't use a motor of ROTOR for a prototype! A manufacturer which uses these stampings for their motors has still to be selected.

The VIRYA-12 has a rotor diameter of 12 m. It is assumed that the rotor hub is mounted directly on the generator shaft and so the shaft must be strong enough. It appears that a motor with frame size 355 has a shaft with a diameter of 100 mm and a length of 210 mm and it is expected that this shaft is strong enough.

Frame size 355 S and 355 L are mentioned at figure 6. The stamping diameters of both frame sizes are the same. Almost all outside dimensions of the housing are also the same except that the total length L is longer. Assume that frame size 355 S is chosen. The outside diameter D_a of the stator stamping is 580 mm for all pole numbers. The inside diameter D_i of the stator stamping depends on the pole number and is maximal for a 6-pole and an 8-pole motor. It is 425 mm. The geometry of the armature stamping is the same for the 6-pole motor as for the 8-pole motor. However, the geometry of the slots in the stator stamping differs. The 8-pole stator stamping has deeper slots and so more copper can be used for the winding. Another advantage of an 8-pole generator is that the frequency at a certain rotational speed is a factor 4/3 higher than for a 6-pole generator. So the 8-pole stamping frame size 355 S is chosen.

Frame size 355 S is used for a 132 kW and a 160 kW motor. The 160 kW motor is chosen. It might be that in reality, a 160 kW motor is only available for frame size 355 L and if this is the case, this frame size has to be chosen. In figure 6 it can be read that the stator stamping of this motor has an inside diameter of 425 mm and a length of 550 mm. The stator stamping has 72 slots. The synchronic rotational speed is 750 rpm for a grid frequency of 50 Hz.

The armature stamping has the same length as long as only the iron stamping sheets are taken into account. However, aluminium bars are cast into the armature stamping and these bars are connected at both sides of the armature by an aluminium disk with cooling fins at the outside. The real length of the armature is therefore much longer than the stator length.

The diameter of the armature is a little smaller than the inside diameter of the stator because of the needed air gap. Assume that the armature diameter is 423.6 mm. This gives an air gap of 0.8 mm. It has to be checked for the motor housing which is finally bought from a certain manufacturer, if this assumption is right.

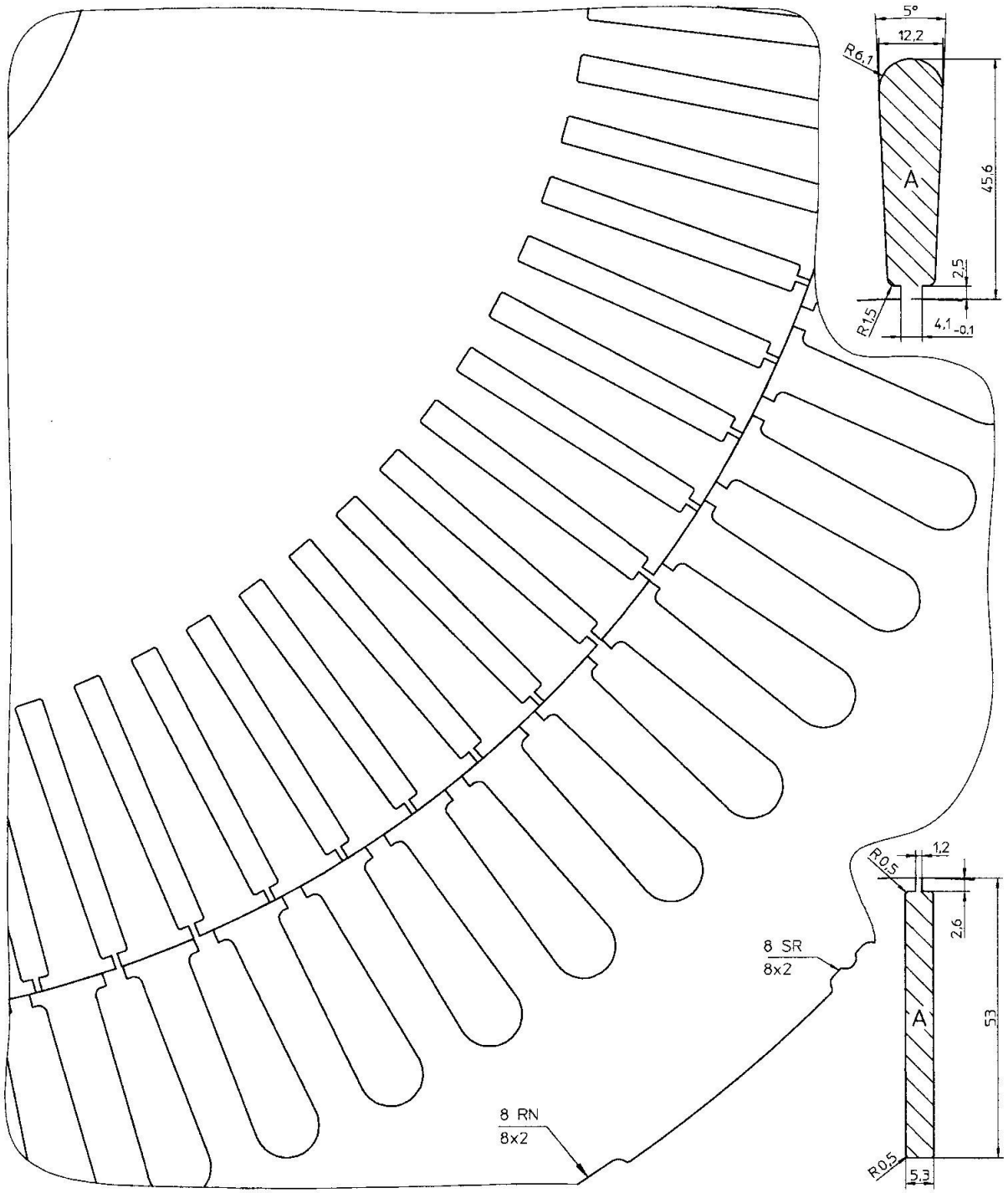
Leistungsangaben in KW bei 50 Hz nach DIN 42 673 und 42 677

Bau-größe Frame size Hauteur d'axe	2-polig 3000 min^{-1} KW	D_a D_i d_i	mm L_{Fe}	4-polig 1500 min^{-1} KW	D_a D_i d_i	mm L_{Fe}	6-polig 1000 min^{-1} KW	D_a D_i d_i	mm L_{Fe}	8-polig 750 min^{-1} KW	D_a D_i d_i	mm L_{Fe}
56	0,09	80 40 15	45	0,06	80 45 15	45	0,04	80 50 15	45	0,03	80 50 15	45
	0,12		55	0,09		55	0,06		55	0,04		55
63	0,18	90 45 18	45	0,12	90 50 18	45	0,09	90 55 18	45	0,06	90 55 18	45
	0,25		60	0,18		60	0,12		60	0,09		60
71	0,37	106,5 55 20	50	0,25	106,5 62 20	50	0,18	106,5 70 20	50	0,12	106,5 70 20	50
	0,55		65	0,37		65	0,25		65	0,18		65
80	0,75	120 62 25	60	0,55	120 70 25	60	0,37	120 80 25	70	0,25	120 80 25	70
	1,1		80	0,75		80	0,55		90	0,37		90
90 S	1,5	135 70 30	75	1,1	135 80 30	75	0,75	135 90 30	75	0,45	135 90 30	75
90 L	2,2		100	1,5		100	1,1		100	0,55		100
100 L	3	150 80 36	90	2,2	150 90 36	90	1,5	150 103 36	120	0,75	150 103 36	90
				3		120				1,1		120
112 M	4	170 90 38	110	4	170 103 38	140	2,2	170 115 38	140	1,5	170 115 38	140
	5,5		140	3		110						
132 S	5,5	200	90	5,5	200	125	3	200	125	2,2	200	100
SX	7,5	110	120									
132 M	8,8			7,5	125	170	4	135	150	3	140	135
MX	11	50		8,8	50	170	5,5	50	180	3,3	50	150
160 M	11	240	130	11	240	160	7,5	240	165	4	240	125
	15	135	180		150			165		5,5	170	165
160 L	18,5	55	215	15	55	215	11	55	225	7,5	55	225
180 M	22	270 150 65	190	18,5	270 170 65	200		270 180 65			270 190 65	
180 L				22		240	15		240	11		240
200 L	30	300 170 75	200	30	300 190 75	250	18,5	300 200 75	230	15	300 215 75	265
	37		250				22		265			
225 S		340 190 80		37	340 215 80	240		340 240 80		18,5	340 240 80	240
225 M	45		240	45		290	30		290	22		290
250 M	55	375 215 85	240	55	375 240 85	290	37	375 260 85	290	30	375 270 85	310
280 S	75	420 240 95	250	75	420 270 100	300	45	420 290 100	275	37	420 305 100	300
280 M	90		300	90		360	55		330	45		360
315 S	110	500 290 115	275	110	500 325 115	300	75	500 375 115	300	55	500 375 115	300
315 M	132 160		330 400	132 160		370 470	90 110 132		370 450 550	75 90 110		370 450 550
355 S	200	580 325 120	370	200	580 375 130	370	160	580 425 130	470	132	580 425 130	470
	250		470	250		450	200		550	160		550
355 L	200		370	200		370	160		470	132		470
	250		470	250		450						
	315		550	315		550	200		550	160		550

Kienle & Spiess Stanz- und Druckgießwerk GmbH Postfach 3 ... Bahnhofstraße ... Tel. (0 74 42) 29-1

fig. 6 Overview of the geometries of the armature and stator stampings of asynchronous motors using a stator stamping of Kienle & Spiess (Feintool)

A detailed picture of the chosen armature and stator stamping is given on the website of Feintool and this picture is copied and given as figure 7.



IEC 355/8.425		Maße und Varianten				
		D_a	D_i	N	A	b_z
SB 580.05.X.00		580 +0,11	425 +0,08/-0.03	72	449,6	9,78
01	wie Abbildung					
RB 425.01.Y.00			d_a	N	A	b_z
d_i			425	84	266,9	kon
01	130 +0,063 K16x134,4					
Blechdicke SB und RB		0,5 / 0,65				

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fig. 7 Stamping Feintool IEC 355, 8-pole

In figure 7 it can be seen that the stator stamping has 72 slots and so 72 mechanical stator poles. So the angle in between the mechanical stator poles is 360 / 72 = 5°. In figure 7 it can be seen that the armature has 84 slots and so 84 mechanical armature poles. So the angle in between the mechanical armature poles is 360 / 84 = 4.2857°.

The number of magnetic stator and armature poles depends on the stator winding. It is assumed that the standard 400 / 690 V, 3-phase winding of an 8-pole motor is used and so the stator and the armature will have eight magnetic poles. The magnetic armature pole angle for an 8-pole PM-generator is 360 / 8 = 45°. So the optimum angle in between the right and the left leg of a stator coil should be 45° too. However, this isn't possible for a stator with 72 slots. This problem is solved by making a coil bundle consisting out of three coils which are lying inside each other. The legs of the inner coil make an angle of 35° with each other. The legs of the middle coil make an angle of 45° with each other. The legs of the outer coil make an angle of 55° with each other and so the average angle is 45°.

The winding of an 8-pole motor is a so called two layers winding. Thirty-six coils can be laid in 72 slots. Twelve coils are of phase U, twelve coils are of phase V and twelve coils are of phase W. The eighteen coils laid in the first layer are: U1, U2, U3, V1, V2, V3, W1, W2, W3, U4, U5, U6, V4, V5, V6, W4, W5 and W6. The coil heads of these eighteen coils are bent to the outside to make place for the eighteen coils of the second layer. The eighteen coils laid in the second layer are: U7, U8, U9, V7, V8, V9, W7, W8, W9, U10, U11, U12, V10, V11, V12, W10, W11 and W12. All coils have the same winding direction. All twelve coils of one phase are connected in series. The ends of the six coils of one phase in one layer are connected to the terminal box.

The synchronic rotational speed of an 8-pole motor is 750 rpm for a grid frequency of 50 Hz. The loaded rotational speed is somewhat lower because a short-circuit current is only created in the aluminium bars of the armature if the armature has a certain slip with respect to the rotating magnetic field which is created in the stator if the stator is connected to the grid.

In the folder of ROTOR it was found that the nominal rotational speed for a 160 kW, 8-pole motor is 740 rpm. So the slip is only 10 rpm at the nominal power. The nominal torque is 2065 Nm. It is assumed that the slip is the same if the motor is used as asynchronous generator for the same torque. So the rotational speed is 750 + 10 = 760 rpm for a torque of 2065 Nm.

9 Choice of the permanent magnet armature construction (see figure 8)

There are several ways how an asynchronous armature can be transformed into a permanent magnet (PM) armature. For my older 4-pole VIRYA generators, I have made a complete new armature and a new stainless steel shaft. This procedure is described in report KD 341 (ref. 9). The magnets are positioned radial in grooves which make a certain angle with the generator shaft to prevent fluctuation of the cogging torque. The shaft must be made out of stainless steel to prevent magnetic short-circuit in between the armature poles. These generators have good characteristics but manufacture of the armature is rather complicated and the generator costs are rather high. It is a pity that the original shaft and armature can't be used. So for this new VIRYA-12 generator, it is investigated if it is possible to use at least the original motor shaft and if possible, also the short-circuit armature. There are two ways to make an armature using the original motor shaft.

1) Assume that the original armature is removed from the shaft and replaced by a mild steel bush with a diameter of 425 mm and a length of 550 mm. This bush is turned to a diameter of 423.4 mm after pressing it onto the shaft and so the air gap is 0.8 mm. The grooves for the permanent magnets are made in this bush. However, this is a very heavy bush and it is a pity that the original short-circuit armature isn't used.

2) Assume that the original armature is used and that the grooves for the magnets are made directly in this armature. This option looks the most promising and therefore it is chosen. However, it gives some complications. This option is now discussed further.

A similar armature for a PM-generator made out of a motor frame size 200 is given in report KD 760 (ref. 10). In figure 7 it can be seen that the short-circuit armature has 84 slots in which the aluminium short-circuit bars are cast. These aluminium short-circuit bars don't guide a magnetic field. So the magnet grooves must be chosen such that they lay in between the aluminium bars. It is chosen to use magnets only for the north poles. The south poles are formed by the remaining material of the armature. This has as attendant advantage that the magnets don't contact the stator when the armature is mounted in the stator. It is chosen to use neodymium magnets size 40 * 10 * 10 mm. These magnets are supplied by the Polish company Enes Magnets website: www.enesmagnets.pl. The magnet quality is N38 which means that the remanence B_r is about 1.24 T. The current price including VAT but excluding costs of transport is € 1.86 per piece if a minimum number of 200 magnets is ordered.

In figure 7 it can be seen that the aluminium bars have a constant width of 5.3 mm. So the mild steel armature poles in between the aluminium bars have a width which decreases as the armature radius is smaller. The armature diameter at this smallest point is 425 – 2 * 53 = 319 mm. So the armature pole pitch at this point is π * 319 / 84 = 11.93 mm. So the width of the iron armature pole at this point is 11.93 – 5.3 = 6.63 mm. The flux density in an armature pole will be maximal at this point.

Assume that the armature diameter is 423.4 mm and that the magnet grooves have a depth of 10.2 mm. So the armature diameter at the bottom of the groove is 423.4 – 2 * 10.2 = 403 mm. So the armature pole pitch at this point is π * 403 / 84 = 15.07 mm. So the width of the iron armature pole at this point is 15.07 – 5.3 = 9.77 mm. The tolerance on the magnet width is ± 0.1 mm. So the width of the groove must be made 10.2 mm for 10 mm wide magnets to make that the magnets always fit. This means that the outer sides of the groove at the bottom will just be cut in the aluminium of the bars. So a magnet width of 10 mm seems a good choice.

In figure 7 it can be seen than an armature pole is widest just at the outside of the armature because the width of the aluminium bar is only 1.2 mm at the outside. This means that a lot of small iron particles will be created if a 10.2 mm wide groove is made in between the aluminium bars. It is expected that these iron particles can be removed easily from the aluminium bars. If it appears that this is difficult, it will be required to remove the aluminium bar up to a depth of about 5 mm for all bars which make contact with a magnet groove.

The magnetic stator pole angle is 360 / 8 = 45°. This corresponds to 72 / 8 = 9 mechanical stator poles. An armature pole angle of 45° corresponds to 84 / 8 = 10.5 armature poles if the armature has 84 slots. So this gives a problem but this problem is solved by using 11 armature poles for the north poles which are formed by the magnets and by using 10 armature poles for the south poles which are formed by the remaining material of the armature.

The stator slots are in parallel to the motor axis. However, the armature slots are not. This isn't visible in figure 7 but for all short-circuit armatures which I have seen, the armature stamping is twisted such that there is just one stator pitch overlap of the slots in between the left and the right side of the stamping. This is done to prevent fluctuation of the torque with a high frequency. So if you look at the small line formed by an aluminium bar at the outside of the armature, you will see that it makes a small angle with the armature shaft. The line isn't straight but it is a helical line although the difference in between a straight line and a helical line is very small. The angle can be calculated easily if it is assumed that it is a straight line.

The inside diameter of the stator is 425 mm. So the inside stator circumference is 425 * π = 1335.18 mm. So the stator pole pitch is 1335.18 / 72 = 18.54 mm. The armature length is 550 mm. So for the angle ϕ in between the aluminium line and the armature axis it is valid that ϕ = inv tg 18.54 / 550 = 1.93°. It must be measured if this angle is really used.

It seems simplest to give the magnet grooves this angle. However, this would mean that the groove depth is maximal at the centre of the armature but that it is less deep at the sides of the armature and that the magnets will jut out of the grooves at the sides of the armature if the grooves aren't made deep enough. This can be solved by giving each magnet its own groove.
The magnets have a length of 40 mm and the armature has a length of 550 mm. Assume that thirteen magnets are used in one row. So the armature length available for one magnet is 550 / 13 = 42.31 mm. Assume that it is chosen to take a distance of 2.3 mm in between the magnets in one row and a distance of 1.2 mm in between a magnet and the side of the armature. These distances can be used to give each magnet its own groove.

Assume that the grooves are made with a 10.2 mm cutter and that the groove depth is 10.2 mm to be sure that a magnet isn't jutting out of a groove. Thirteen levels are distinguished.
The groove heart of level 1 has a distance of 21.2 mm from the left side of the armature.
The groove heart of level 2 has a distance of 63.5 mm from the left side of the armature.
The groove heart of level 3 has a distance of 105.8 mm from the left side of the armature.
The groove heart of level 4 has a distance of 148.1 mm from the left side of the armature.
The groove heart of level 5 has a distance of 190.4 mm from the left side of the armature.
The groove heart of level 6 has a distance of 232.7 mm from the left side of the armature.
The groove heart of level 7 has a distance of 275.0 mm from the left side of the armature.
The groove heart of level 8 has a distance of 317.3 mm from the left side of the armature.
The groove heart of level 9 has a distance of 359.6 mm from the left side of the armature.
The groove heart of level 10 has a distance of 401.9 mm from the left side of the armature.
The groove heart of level 11 has a distance of 444.2 mm from the left side of the armature.
The groove heart of level 12 has a distance of 486.5 mm from the left side of the armature.
The groove heart of level 13 has a distance of 528.8 mm from the left side of the armature.

One starts with the grooves of level 1. So the heart of these grooves lay at a distance of 40 / 2 + 1.2 = 21.2 mm from the left side of the armature. The groove must be made just in the middle of two adjacent aluminium lines under an angle of 1.93° with the shaft axis. The armature shaft has to be mounted in a turn table with a horizontal axis for which the angle of rotation can be adjusted accurately. The first groove has a length of the part for which the sides are in parallel of 40 mm. So the total length including the curved ends is 50.2 mm.

After making the first groove, the armature is rotated 360 / 84 = 4.2857° and next the second groove of level 1 is made. This procedure is followed ten times and so the first bundle of eleven grooves of level 1 is made.

Next the armature is rotated 90° - 10 * 4.2857° = 47.1429° and the 12th groove of level 1 is made. After making the 12th groove, the armature is rotated 4.2857° again and next the 13th groove of level 1 is made. This procedure is followed ten times and so the second bundle of eleven grooves of level 1 is made.

Next the armature is rotated 47.1429° again and the 23th groove of level 1 is made. After making the 23th groove, the armature is rotated 4.2857° again and next the 24th groove of level 1 is made. This procedure is followed ten times and so the third bundle of eleven grooves of level 1 is made.

Next the armature is rotated 47.1429° again and the 34th groove of level 1 is made. After making the 34th groove, the armature is rotated 4.2857° again and next the 35th groove of level 1 is made. This procedure is followed ten times and so the fourth bundle of eleven grooves of level 1 is made.

The angle in between two different levels is 360 / (72 * 13) = 0.3692°. Next the armature is rotated 0.3692° in the direction which corresponds to the direction of the aluminium lines. Next the cutter is shifted to the second level which lies at a distance of 63.5 mm from the left side of the armature and the forty-four grooves of level 2 are made following the same procedure as described for level 1. The same procedure is followed for the forty-four grooves of level 3, level 4, level 5, level 6, level 7, level 8, level 9, level 10, level 11, level 12 and level 13. So totally 13 * 44 = 572 grooves are made. So totally 572 magnets are needed resulting in a total magnet costs of about € 1064 without costs of transport, which is very low for a PM-generator of this size.

There will be a small overlap in the curved parts of the grooves for adjacent levels as there is a distance of 2.3 mm in between adjacent magnets but this won't be a problem. The curved part of the grooves of level 1 and 13 are also partly made in the aluminium disks cast at each side of the armature but this is also not a problem.

The magnets are glued in the grooves by epoxy glue or by anaerobe glue such that they have the right position and such that the north pole of all magnets is facing outwards. One has to develop a tool with which a magnet can be held on both 10 * 10 mm sides during mounting.

The peak on the cogging torque will be very low for this PM-generator because only 4 of the 572 magnets will be exactly opposed to a stator pole at the same time. This reduces the starting wind speed for the VIRYA-6.5 rotor.

Eleven magnetic loops are coming out of the eleven rows of magnets of the north poles N1 up to N11. The 5 ½ loops coming out of N1 – N5 and half N6 are turning left hand and are guided through the stator iron to the south poles S40, S39, S38, S37 and S36. The 5 ½ loops coming out of half N6 and N7 – N11 are turning right hand and are guided through the stator iron to the south poles S1, S2, S3, S4 and S5. As eleven mechanical north poles are combined with ten mechanical south poles it means that the flux density in the south poles is higher. A magnetic loop passes two air gaps. The air gap at the south poles is 0.8 mm. The average air gap at the north poles is about 1 mm. So the total air gap is about 1.8 mm. The magnet thickness is 10 mm

The flux density in the air gap is reduced by the total air gap and by the fact that the magnets have a length of 40 mm instead of 42.3 mm. The flux density in the air gap B is calculated for a remanence B_r = 1.24 T and it is found that B is about 0.99 T which is rather high. The flux density in the bridges in between the aluminium bars of the north poles is almost the same at the bottom of the grooves as there, the bridges have about the same width as the magnets. However at the narrowest point, the bridge has a width of only 6.63 mm and so the flux density is concentrated by a factor 10 : 6.63 = 1.51 resulting in a flux density of 1.51 * 0.99 = 1.49 T. The flux density in the bridges in between the aluminium bars at the south pole is increased by a concentration factor of 11 / 10 = 1.1 and so the flux density at these bridges is about 1.49 * 1.1 = 1.64 T. Iron is saturated at about 1.6 T which means that the iron of the armature is saturated at the narrowest point of an armature south pole. This demonstrates that it is useless to use thicker or wider magnets.

The bridges in between the slots in the stator have a width of about 10 mm so much wider than the minimum width of the bridges of the armature. The armature can have a position such that ten armature south poles are opposed to nine stator poles but the stator poles are that wide that the stator iron is far from saturation.

So it seems possible to use all components of a standard 8-pole asynchronous motor including the housing, the stator winding, the shaft and the armature. Only the short-circuit armature has to be modified into a PM-armature by cutting grooves in the armature and by gluing magnets in the grooves. This generator will therefore be relatively cheap for its size. A prototype has to be built and tested to prove that it is strong enough for the VIRYA-12 but I won't do that. A cross section in between the first armature sheet and the aluminium disk is given in figure 8. The aluminium bars are not given in the cross section.

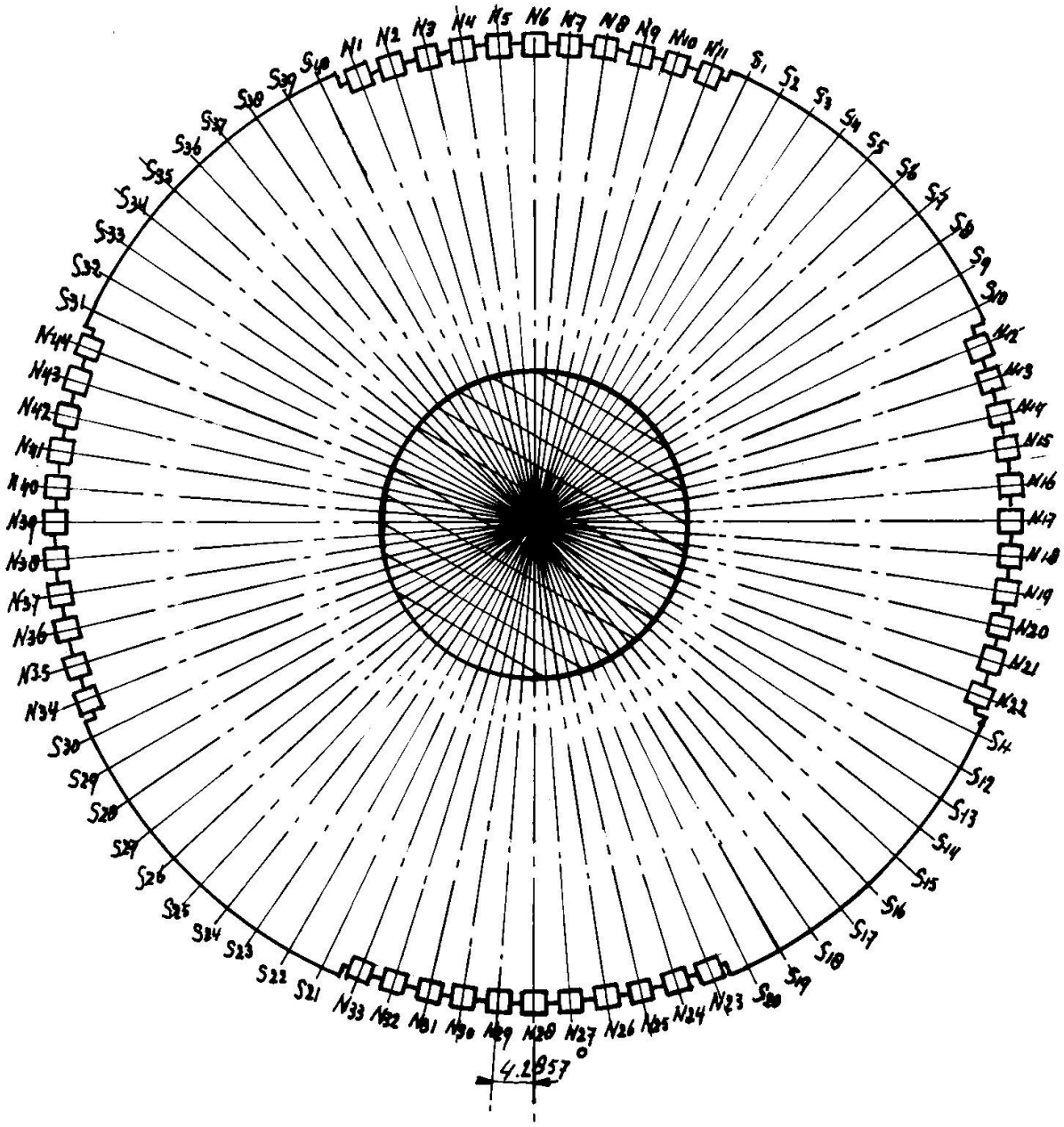

fig. 8 PM-armature for 8-pole motor frame size 355 S for VIRYA-12 (aluminium short-circuit bars not drawn in cross section)

10 References

1 Kragten A. Ideeën over realisatie van 14 bouwpercelen en één VIRYA-14 windmolen in Boskant (in Dutch), 17-6-2023, (no longer available; replaced by the note: “Ideeën over realisatie van negentien bouwpercelen in Boskant”) engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands. This report is given at the bottom of the menu “KD-reports” at my website.

2 Kragten A. Ideeën over een levensloopbestendig vrijstaand huis geschikt voor dubbele bewoning (in Dutch), 1-6-2022, reviewed 8-12-2025, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands. This report is given at the menu “No wind energy” at my website.

3 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-14 windmill ($\lambda_d = 6$) with the pendulum safety system with a torsion spring connected to the generator type PMG900-I-30KW-100R for grid connection, June 2022, reviewed June 2023, report KD 732, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 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.

5 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed January 2022, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. The Gö 711 airfoil for use in windmill rotor blades, June 2006, reviewed November 2023, free public report KD 285, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, reviewed February 2017, free public rapport KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Determination of C_q for low values of λ. Deriving the C_p-λ and C_q-λ curves of the VIRYA-1.8D rotor, July 2002, reviewed January 2020, free public rapport KD 97, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

9 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, reviewed April 2025, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

10 Kragten A. Ideas about a big direct drive PM-generator for the VIRYA-6.5 windmill using the housing, winding and armature of an 8-pole asynchronous motor frame size 200, December 2023, reviewed January 2024, report KD 760, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.