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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October 2021
reviewed September 2023

KD 727

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 60 mechanical 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.

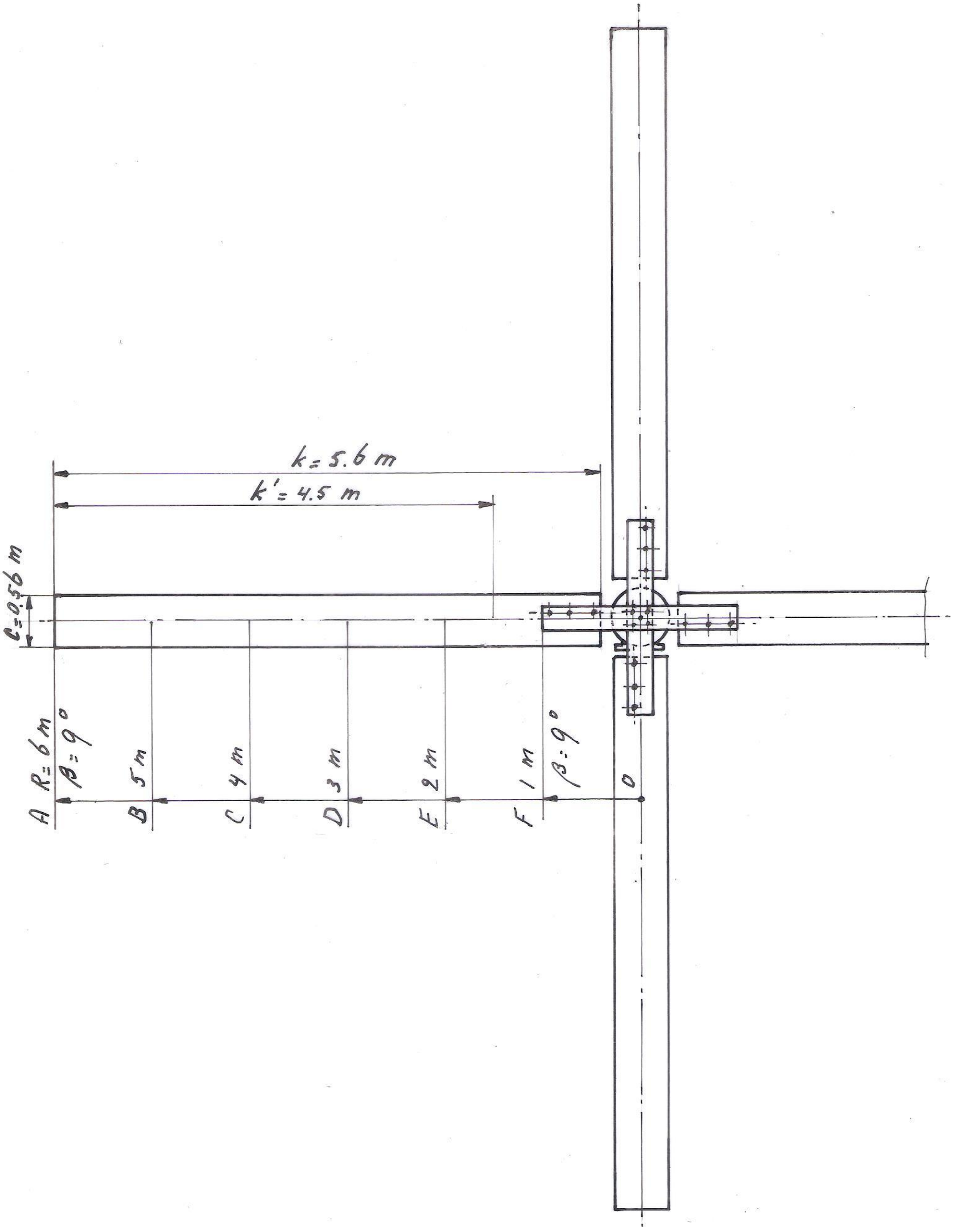

fig. 1 Sketch VIRYA-12 rotor

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

sta-tion	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.

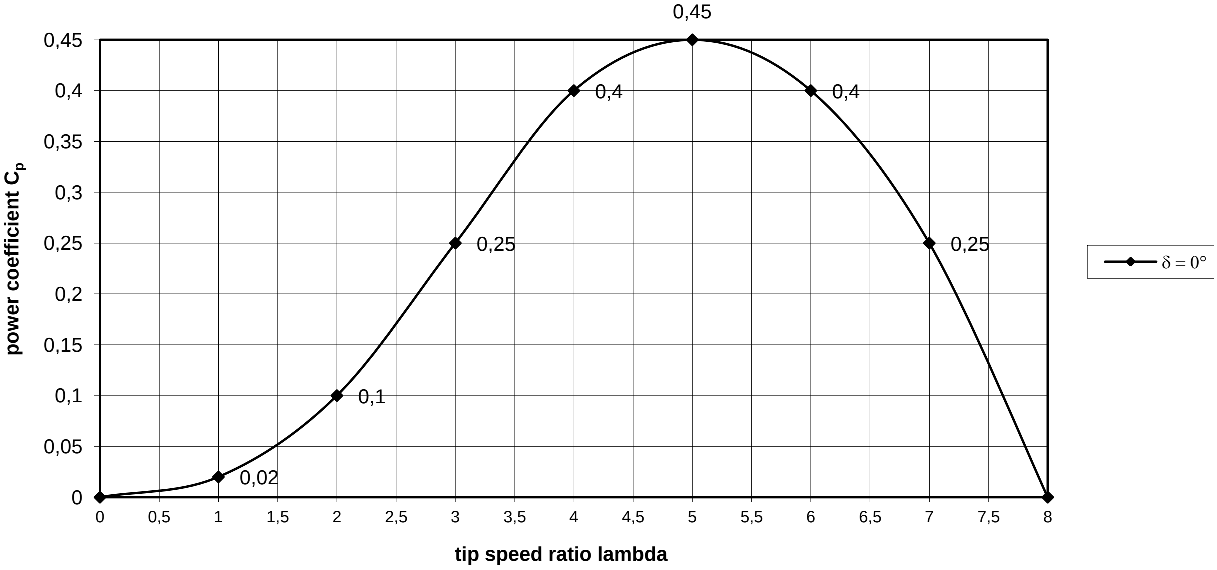

fig. 2 Estimated C_p-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

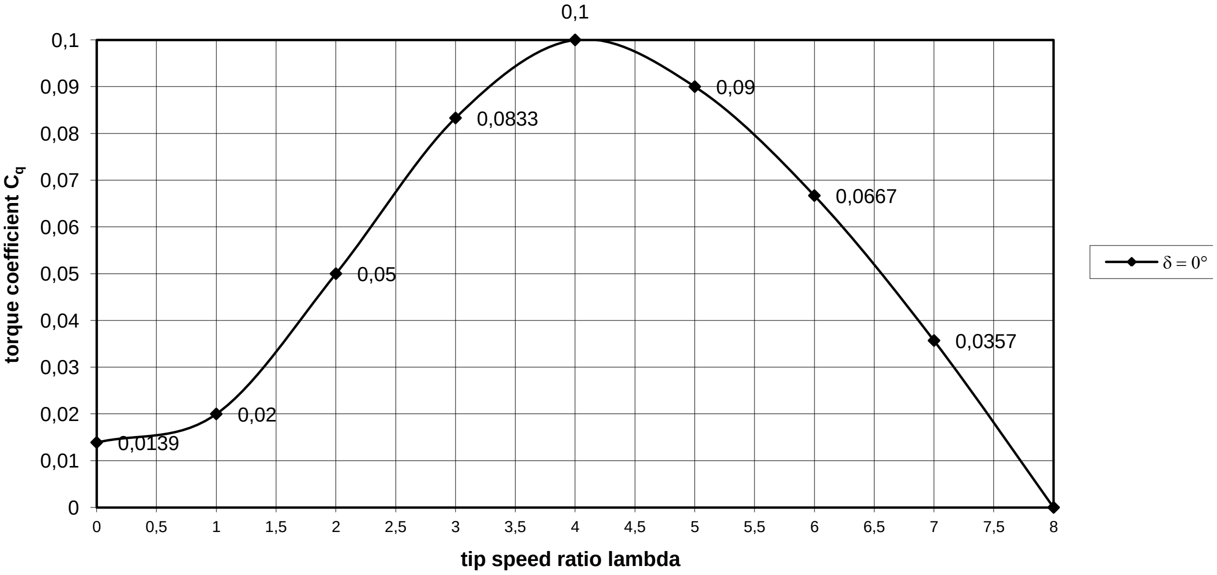

fig. 3 Estimated C_q-λ curve for the VIRYA-12 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 $\rho = 1.2 \text{ kg / m}^3$ 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.

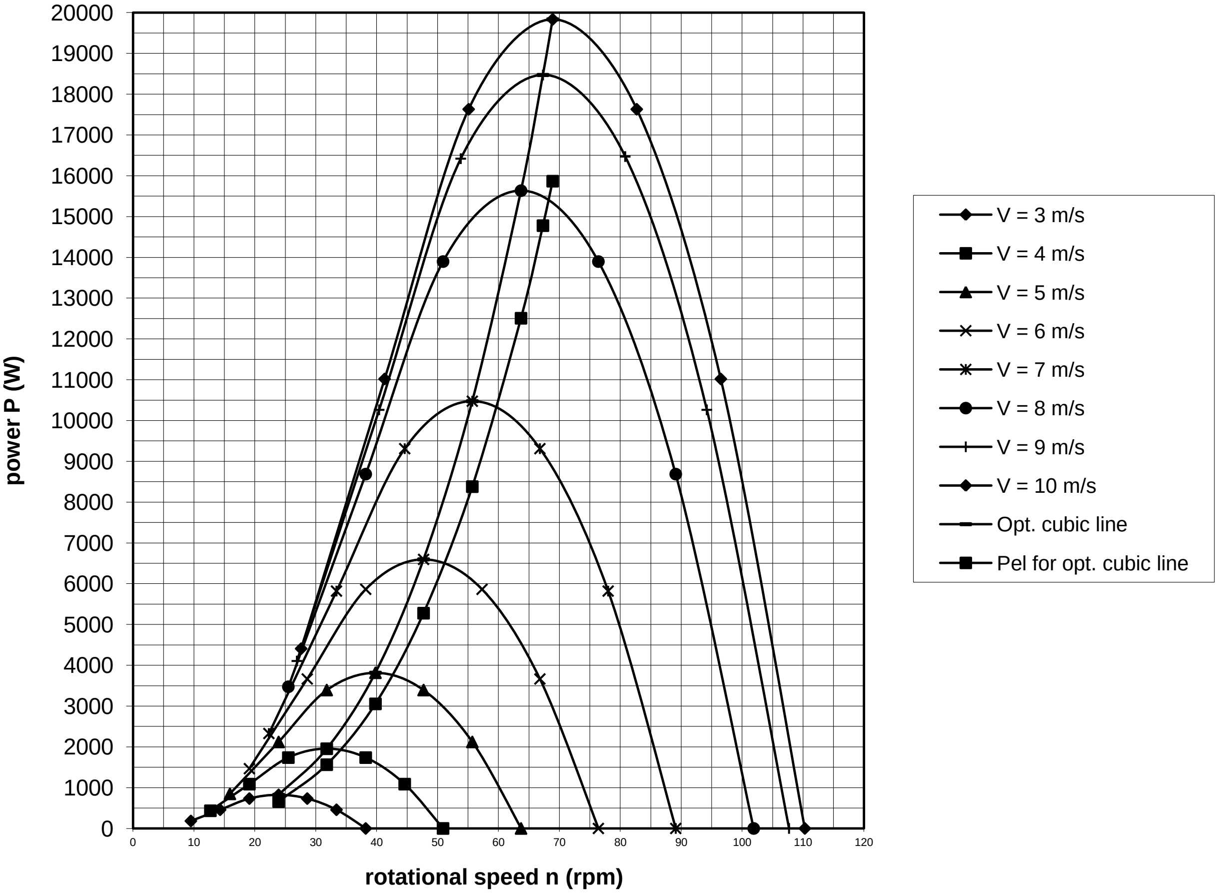

fig. 4 P-n curves of the VIRYA-12 rotor, optimum cubic line, P_{el}-n curve for the assumption that the optimum cubic line is followed and that the total efficiency of the generator and the inverter is 0.8.

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.

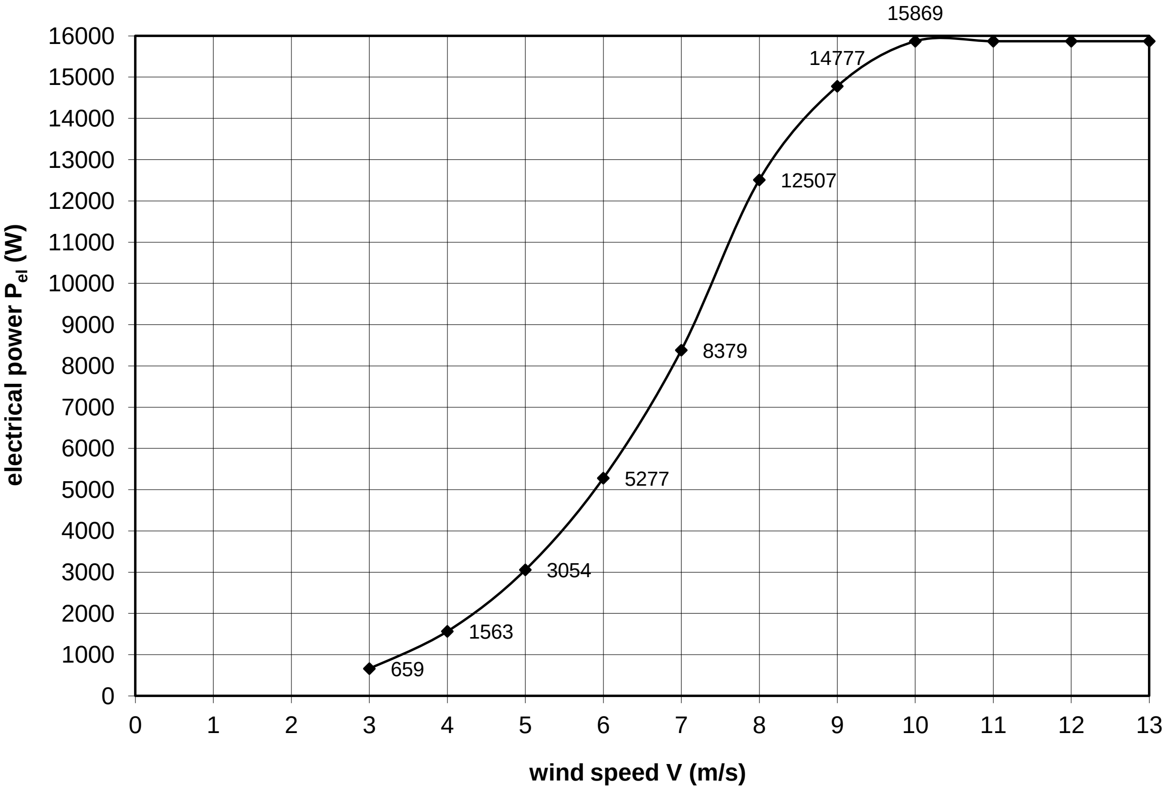

fig. 7 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

The P_{mech}-n, the P_{el}-n curves as given in figure 4 and the P_{el}-V as given in figure 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 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. It is assumed that frame size 355L is used for the 200 kW version. The stator has 72 slots in which the coils are laid. The stator can have the standard 6-pole, 400/690 V, 3-phase winding or it can have a special 12-pole, 3-phase winding with a special voltage.

36 coils can be laid in a stator with 72 slots. So 12 coils are of phase U, 12 coils are of phase V and 12 coils are of phase W. The armature pole angle for a 6-pole armature is 60°. This means that the optimum angle in between the two legs of a coil is 60° too. However, this isn’t possible for all coils, if the stator has 72 slots. This is solved as follows for the original 6-pole, 3-phase winding. The winding of one phase is formed by three bundles of four coils. The four coils of one bundle are lying within each other. For the most inner coil, the coil angle is 45°, for the next coil the coil angle is 55°, for the next coil the coil angle is 65° and for the most outer coil the coil angle is 75°. So the average coil angle is 60°. For the alternative 12-pole, 3-phase winding, six coil bundles with each two coils are used for one phase and the average coil angle for the two coils of one bundle is now 30°.

The armature will be provided with 60 mechanical poles. 30 north poles will be formed by neodymium magnets glued in 30 armature grooves. The grooves are made in parallel to the armature axis and the angle in between the heart of the grooves is 6°. The 30 south poles are formed by the remaining material left in between the poles formed by the magnets. These poles are called the iron poles. The sequence of the orientation of the north and south poles of the magnets depends on the winding of the stator. A similar 16-pole generator for a housing with 36 slots with a 3-phase, 4-pole winding is described in report KD 718 (ref. 7).

If the standard 6-pole stator winding is used, the armature must have six magnetic poles. This means that one magnetic pole corresponds to 60 / 6 = 10 mechanical poles. So ten adjacent grooves with magnets with the north pole to the outside are used for one magnetic north pole. A magnetic south pole is formed by ten iron poles. The iron poles are separated by 2.2 mm wide and 3 mm deep grooves. If a 12-pole stator winding is used, the armature must have twelve magnetic poles. This means that one magnetic pole corresponds to 60 / 12 = 5 mechanical poles. So five adjacent grooves with magnets with the north pole to the outside are used for one magnetic north pole. A magnetic south pole is formed by five iron poles.

The air gap in between an iron armature pole and the stator is chosen 0.5 mm. So the armature diameter is 424 mm. The armature pole pitch is π * 424 / 60 = 22.2 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 magnets. It is chosen to use neodymium magnets size 80 * 20 * 10 mm. These magnets are supplied by the Polish supplier Enes Magnets website: www.enesmagnets.pl. The quality is N35H. The current price (December 2022) including 23 % VAT is € 23.09 exclusive costs of transport if at least 20 magnets are ordered.

The armature length is chosen 560 mm so seven magnets are glued in each groove. The armature juts out 5 mm at each side of the 550 mm wide stator stamping. So totally 7 * 30 = 210 magnets are needed for one armature. This results in a total magnet costs of € 4849 excluding mailing costs and so in about € 5000 including mailing costs. This is rather high but it might be acceptable for such a very big PM-generator.

The armature can be made in different ways. The cheapest way is to use the original short-circuit armature and to turn the diameter down to about 390 mm. Next an iron bush with an inner diameter of 390 mm, an outer diameter of 425 mm and a length of 560 mm has to be made. This bush is glued on the original short-circuit armature with epoxy or anaerobe glue. Next the outside is turned to a diameter of 424 mm with the correct eccentricity to the bearing seats. Next thirty, 20 mm wide and 10.3 mm deep grooves are made in the iron bush. The angle in between the heart of the grooves must be 6°. The magnets are not jutting outside the armature for a groove depth of 10.3 mm. A 3 mm high rim separates adjacent grooves.

The pole pitch for all 60 poles of the armature is 360 / 60 = 6°. The pole pitch of a stator with 72 slots is 360 / 72 = 5°. The armature will have a preference position if an armature pole is just opposite a stator pole. So this happens every 1° and so the generator will have 360 preference positions per revolution. It can be expected that the fluctuation of the sticking torque is almost completely flattened for these many preference positions per revolution.

It is assumed that the original 400/690 V stator winding can be used for the magnetic 6-pole armature and that an inverter can be found which matches with the generated voltage and frequency. For the magnetic 12-pole armature, a new winding has to be designed. The frequency of the 12-pole version is double that of the 6-pole version. A new winding can be designed such that the generated voltage at the rather low maximum rotational speed of the VIRYA-12 is higher. Therefore it might be easier to find the correct inverter. Determination of the correct winding for the magnetic 12-pole armature is out of the scope of this report.

9 Ideas about a real 60-pole PM-generator

The 6-pole generator as described in chapter 8 has as advantage that the original 400/690 V, 3-phase winding can be used. However, a 6-pole generator generates a frequency of 50 Hz at a rotational speed of 1000 rpm. In figure 4 it can be seen that the maximum loaded rotational speed is about 69 rpm at a wind speed of 10 m/s. So the frequency at this rotational speed is only 50 * 69 / 1000 = 3.45 Hz. The frequency for the 12-pole version will be 6.9 Hz but this is still rather low. It seems possible to use the same magnets for a real 60-pole PM-generator. A 60-pole generator will have a frequency of 50 Hz at a rotational speed of 100 rpm.

So now there are 30 north poles formed by the magnets and 30 iron south poles in between. Thirty 20 mm wide and 10.3 mm deep grooves are made under an angle of 12°. A 2.2 mm wide and 6.3 mm deep groove is made at each side of a magnet groove to make that the south poles also have a width of about 20 mm and to prevent magnetic short-circuit in between the sides of the magnets. The poles are numbered N1, S1, N2, S2, N3, S3, N4 and so on. A side view of the armature and stator is given in figure 6.

The stator has 72 slots and so 72 poles. The stator poles are numbered 1, 2, 3, 4 and so on. A coil is placed around one stator spoke. The coil U1 is placed around spoke 1. The coil V1 is placed around spoke 3. The coil W1 is placed around spoke 5 and so on. Figure 6 is drawn such that magnet N1 is just opposed to spoke 1 and so just opposed to coil U1. All twelve coils of one phase are connected in series.

In figure 6 it can be seen that opposed to coil U2 there is the iron south pole S3. So the winding direction of coil U2 must be opposed to the winding direction of coil U1 to make that the voltage generated in coil U1 is strengthened by the voltage generated in coil U2. It is supposed that coil U1 is wound right hand and so coil U2 must be wound left hand. The north pole N6 is opposed to coil U3 and so coil U3 must be wound right hand again. The winding direction of the coils is given above the coils.

For a 3-phase winding there must be a phase angle $\alpha = 120°$ in between the coils U, V and W. The armature has the same magnetic position if it has rotated 12°. So an angle of rotation $\beta = 12°$ corresponds to a phase angle $\alpha = 360°$. So an angle of rotation $\beta = 1°$ corresponds to a phase angle $\alpha = 30°$.

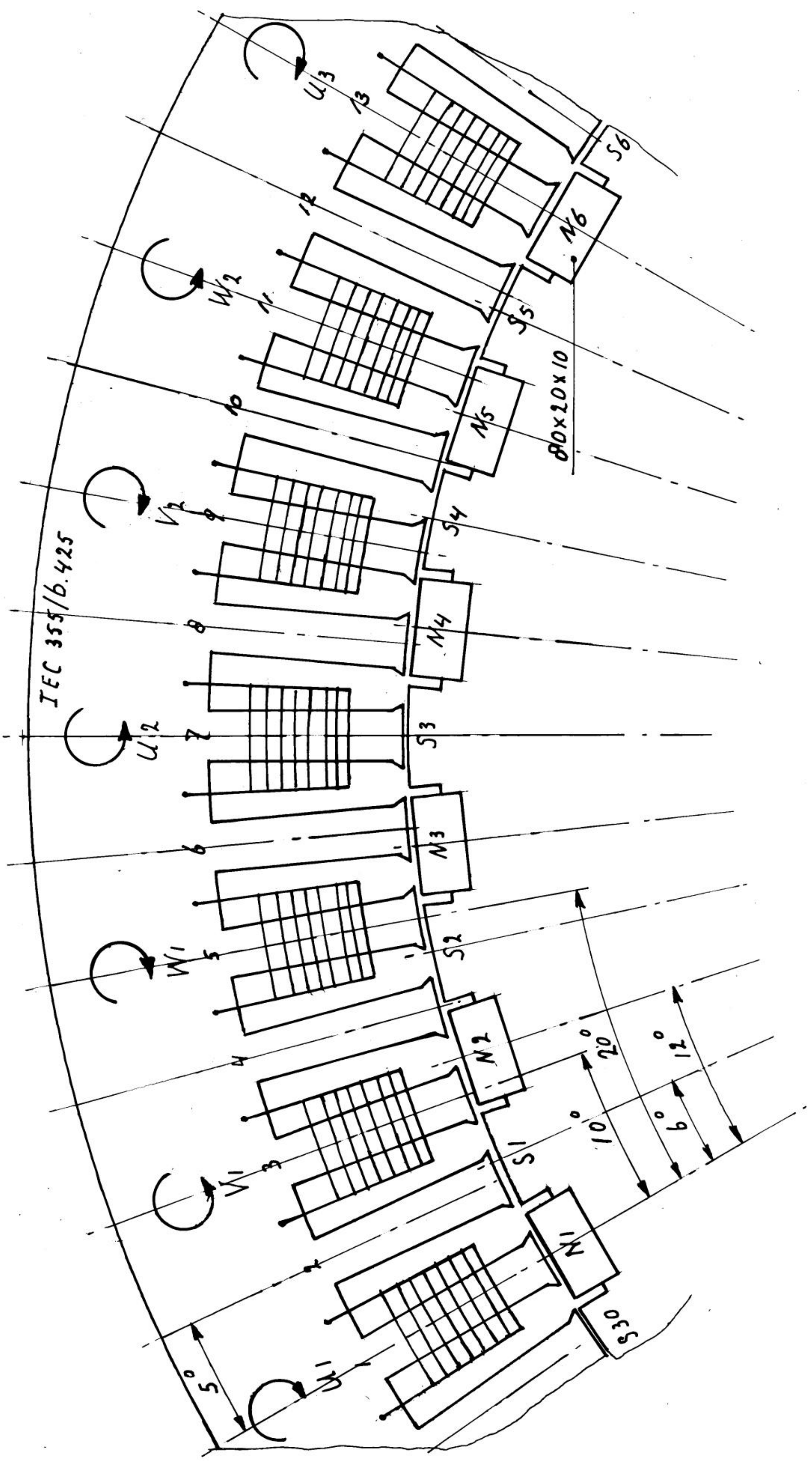

fig. 6 Side view of armature and stator of a 60-pole PM-generator frame size IEC 355/6.425

In figure 6 it can be seen that north pole N1 is opposed to coil U1. It is assumed that the phase angle α = 0° for this position. In figure 6 it can be seen that there is an angle β = 10° in between north pole N1 and coil V1. So this corresponds to a phase angle α = 10 * 30 = 300° if the winding direction of coil V1 would be the same as that of coil U1. An angle of 300° isn't correct for a 3-phase winding. However, if the winding direction of coil V1 is taken left hand instead of right hand, the phase angle is shifted 180°. So then the phase angle becomes 300° - 180° = 120° which is correct for a 3-phase winding. In figure 6 it can be seen that there is an angle β = 20° in between north pole N1 and coil W1. So this corresponds to a phase angle α = 20 * 30 = 600° if the winding direction of coil W1 is the same as that of coil U1. A phase angle of 600° is the same as 600° – 360° = 240°. So there is a phase angle of 120° in between the coils U1, V1 and W1 and so the winding is a 3-phase winding. The same procedure makes that the coils U2 and W2 must be wound left hand and that the coils V2 and U3 must be wound right hand. So adjacent coils must have a different winding direction!

10 Ideas about other PM-generators with a high pole number

The coil configuration as used in chapter 9 for a 60-pole generator can also be used if the generator has more than 60 poles. However, the winding direction and the connection of the coils depend on the pole number. The optimum magnet size also depends on the pole number. The possible pole numbers are: 64, 68, 70, 74 or 76. 72 is no realistic option because then the winding becomes a 1-phase winding and the armature will get 72 very strong preference positions per revolution.

If the armature has 64 poles, the winding becomes a 9-phase winding. A 9-phase winding for an armature with 32 poles and a stator with 36 poles is described in chapter 7 of report KD 712 (ref. 8). If the number of armature poles and stator poles are both doubled, the sequence of the phases stays the same but now there are four instead of two rows of nine coils. All 36 coils have the same winding direction. The winding is rectified according to the way given in chapter 6.2 of KD 712. A 32-pole generator has 288 preference positions per revolution. So a 64-pole generator will get 2 * 288 = 576 preference positions per revolution.

If the armature has 68 poles, the winding becomes a 3-phase winding. A 3-phase winding for an armature with 34 poles and a stator with 36 poles is described in chapter 2 of report KD 580 (ref. 9). If the number of armature poles and stator poles are both doubled, the sequence of the phases stays the same. The coil sequence is now: U1, U2, U3, W4, W5, W6, V1, V2, V3, U4, U5, U6, W1, W2, W3, V4, V5, V6, U7, U8, U9, W10, W11, W12, V7, V8, V9, U10, U11, U12, W7, W8, W9, V10, V11 and V12. It is assumed that all coils are wound right hand and that all twelve coils of the same phase are connected in series. However, the coils must be coupled such that if the current in coils 1, 2, 3, 7, 8 and 9 is flowing right hand, the current in coils 4, 5, 6, 10, 11 and 12 is flowing left hand. A 34-pole generator has 612 preference positions per revolution. So a 68-pole generator will get 2 * 612 = 1224 preference positions per revolution.

If the armature has 76 poles, the winding also becomes a 3-phase winding. A 3-phase winding for an armature with 38 poles and a stator with 36 poles is described in chapter 7.4 of report KD 580 (ref. 9). If the number of armature poles and stator poles are both doubled, the sequence of the phases stays the same. The coil sequence and the way the coils have to be connected is the same as for the 68-pole generator. A 38-pole generator has 684 preference positions per revolution. So a 76-pole generator will get 2 * 684 = 1368 preference positions per revolution.

If the armature has 70 poles, the winding also becomes a 3-phase winding. However, the coil sequence is different as for a 68-pole or 76-pole generator. The coil sequence is now: U1, U2, U3, U4, U5, U6, W7, W8, W9, W10, W11, W12, V1, V2, V3, V4, V5, V6, U7, U8, U9, U10, U11, U12, W1, W2, W3, W4, W5, W6, V7, V8, V9, V10, V11 and V12.

It is assumed that all coils are wound right hand and that all twelve coils of the same phase are connected in series. However, the coils must be coupled such that if the current in coils 1, 2, 3, 4, 5 and 6 is flowing right hand, the current in coils 7, 8, 9, 10, 11 and 12 is flowing left hand. The armature pole angle is 360° / 70 = 5.1429°. The stator pole angle is 360 / 72 = 5°. So the difference is 0.1429°. This means that there is a preference position every 0.1429° and so there are 360° / 0.1429° = 2520 preference positions per revolution.

If the armature has 74 poles, the winding also becomes a 3-phase winding. The coil sequence and the way the coils have to be connected is the same as for the 70-pole generator. The armature pole angle is 360° / 74 = 4.8649°. The stator pole angle is 360 / 72 = 5°. So the difference is 0.1351°. This means that there is a preference position every 0.1351° and so there are 360° / 0.1351° = 2664 preference positions per revolution.

11 Use of a PM-generator of Hefei Top Grand type PMG900-I-30KW-100R

The generators as described in chapter 8, 9 and 10 make use of the housing of the biggest asynchronous motor. The magnet costs of these generators are very high and measured characteristics are not available. Building of a prototype is expensive and a very large test rig is needed to measure the characteristics. It seems possible to use the same axial flux generator for the VIRYA-12 as the one which is also used for the VIRYA-14. This generator has the largest frame size as supplied by Hefei Top Grand and it has type PMG900-I-30KW-100R. The characteristics of this generator are derived in chapter 6 of report KD 732 (ref. 10). An extra advantage of this generator is that it has no iron in the coils and therefore it has no cogging torque.

The generator has a shaft diameter of 100 mm. For the VIRYA-14, which has a rotor diameter of 14 m, this shaft diameter isn’t large enough and so an auxiliary shaft with a diameter of 120 mm has to be mounted in front of the generator shaft. It is expected that a shaft diameter of 100 mm is large enough for the VIRYA-12 and so the rotor hub can be mounted directly on the generator shaft. This simplifies the construction considerably. The square rotor hub will be made out of two parts which are clamped around the shaft. The two blade strips are connected to the rotor hub with four bolts M20.

The generator characteristics for the resistance load which is used by the manufacturer are derived in chapter 6 of KD 732 and are given in figure 4 of KD 732. The P-n curve for short-circuit in star is also derived in chapter 6 of KD 732 and is given in figure 4 of KD 732. This figure is copied as figure 7. The P-n curves of the VIRYA-14 are replaced by the P-n curves of the VIRYA-12 as given in figure 4.

In figure 7 it can be seen that the optimum cubic line of the rotor is intersecting with the P_{mech}-n curve of the generator for a resistance load at a wind speed of about 7.3 m/s. So at wind speeds lower than 7.3 m/s, the generator load is lower than for the measured resistance load. At wind speeds higher than 7.3 m/s it is somewhat higher but this is certainly allowed because the whole P-n curve for V = 10 m/s is lying lower than the curve for the rated torque.

It is assumed that the inverter can be adjusted such that the optimum cubic line of the rotor is followed. So the optimum cubic line is the P_{mech}-n curve for an inverter load. The generator has an efficiency of at least 0.85. The efficiency of modern inverters is very high. It is assumed that the combined efficiency of the generator and the inverter is 0.8. So the P_{el}-n curve for an inverter load is found by multiplying all points of the optimum cubic line with a factor 0.8. The P_{el}-n curve for an inverter load is also given in figure 7.

The working point for a certain wind speed for an inverter load is the point of intersection f the optimum cubic line with the P-n curve for that wind speed. The electrical power for that wind speed is found by going downwards vertically from the working point until the P_{el}-n curve for an inverter load is intersected. The values of P_{el} found this way are given in the P_{el}-V curve of figure 8. The P_{el}-V curve of figure 8 is the same as the P_{el}-V curve of figure 5 because the same efficiencies have been used.

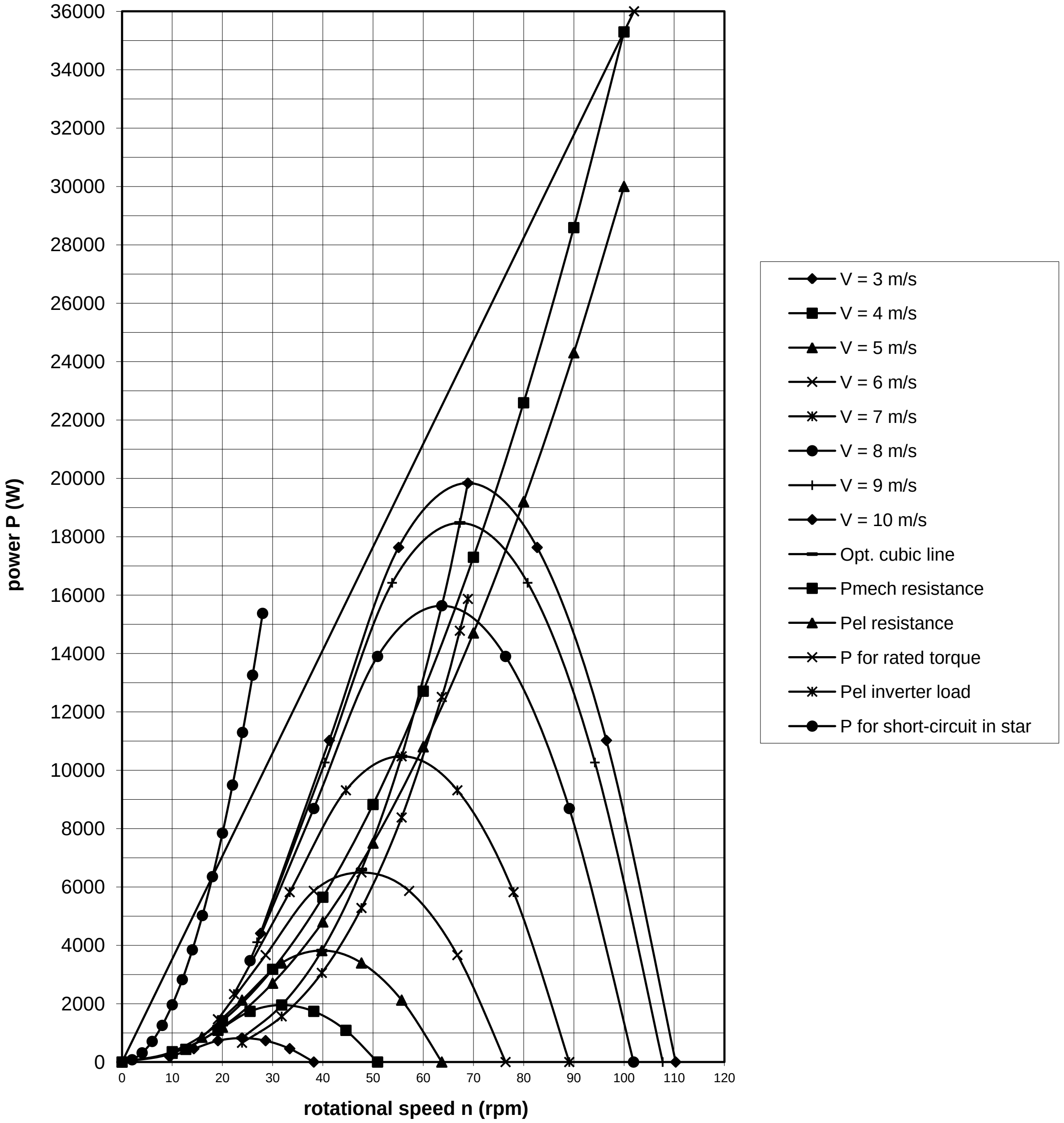

fig. 7 P-n curves of the VIRYA-12 rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the PMG900-I-30KW-100R generator with a resistance load such that P_{el} = 30000 W at n = 100 rpm, P-n curve for the rated torque Q = 3370 Nm, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

The estimated P-n curve for short-circuit in star is lying far left from the P-n curve of the rotor for V = 10 m/s. So it is possible to stop the rotor by making short-circuit at any wind speed. The rotor will rotate only at a very low rotational speed if short-circuit is made.

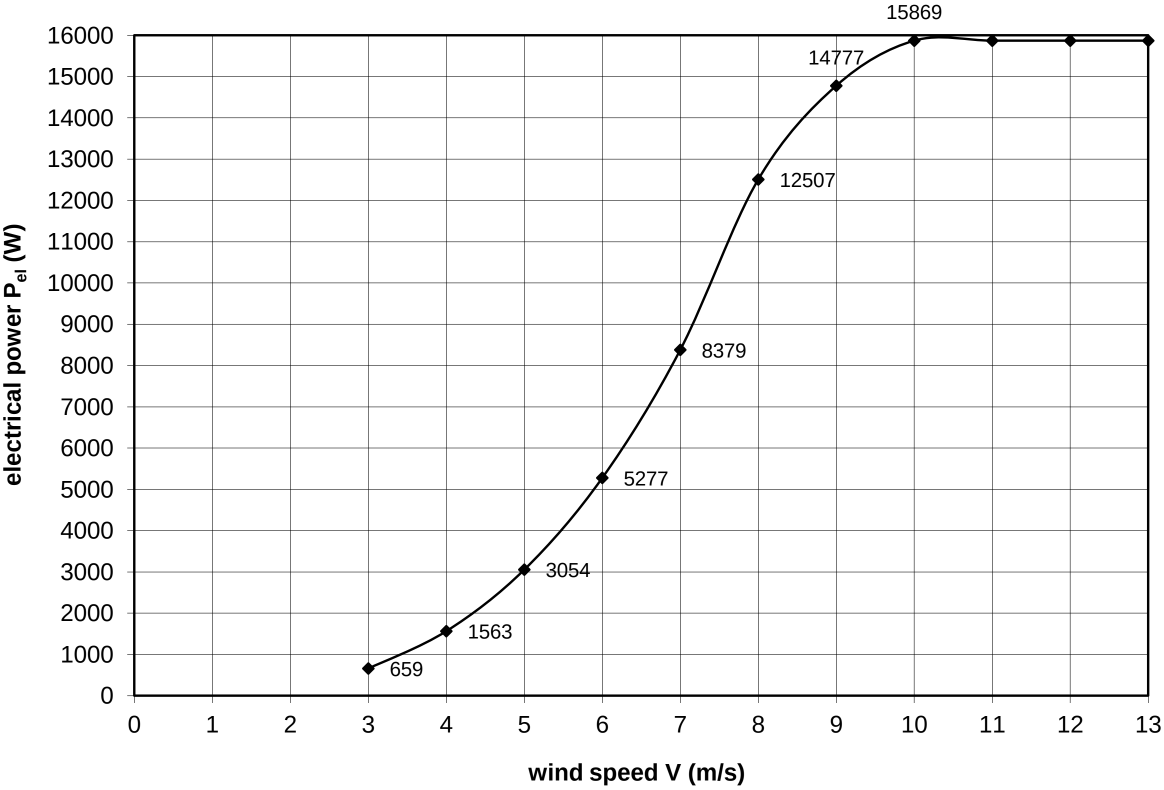

fig. 8 P_{el}-V curve for an inverter load of the generator type PMG900-I-30KW-100R such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

The maximum power is almost 16 kW which is very good for a wind turbine with a rotor diameter of 12 m and a rated wind speed of 10 m/s.

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