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

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KD 732

It is allowed to copy this report for private use. A prototype of the VIRYA-14 windmill has not yet been built and tested. This should be done only by a professional company after making detailed drawings. Although the VIRYA-14 has been designed carefully, no responsibility is accepted by Kragten Design for the proper functioning.

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1 Introduction

The Chinese company Hefei Top Grand supplies permanent magnet generators with an inner rotor (type PMG) and with an outer rotor (type TGET). Specifications of these generators are given at the website: www.china-topgrand.com at the menu product. The whole generator housing is rotating for the type TGET. The three electrical cables for the type TGET are coming out of the hollow generator shaft. The type PMG has a massive shaft and the three electrical cables are coming out of the housing at a large distance from the shaft.

The advantage of the types TGET for use in a wind turbine, is that no hub is required and that the hub assembly can be bolted directly to the generator housing. A hub is required for the types PMG. The biggest generator type TGET770-H-10KW-100R is used for the VIRYA-10 windmill which is described in report KD 715 (ref. 1). However, the type PMG is available in an even bigger size with an outside diameter of the housing of 895 mm. In this report KD 732 it is investigated if the type PMG900-I-30KW-100 can be used for a rotor with a diameter of 14 m. The generator shaft has a diameter of only 100 mm. Therefore a 120 mm auxiliary shaft is used in front of the generator shaft. The windmill is called the VIRYA-14.

The VIRYA-10 is provided with the so called pendulum safety system which is described in report KD 439 (ref. 2). The same safety system will also be used for the VIRYA-14. It is assumed that the system is adjusted such that the same δ-V curve is valid.

I have written several Dutch reports about the use of a medium size wind turbine in combination with a group of houses on my property but these reports are no longer public. In the Dutch public report “Ideeën over realisatie van 34 halfvrijstaande huizen geschikt voor dubbele bewoning” (ref. 3), no wind turbine is used but the house specified in chapter 4 of this report is used in chapter 7 to demonstrate that about twenty of those houses can be used in combination with the VIRYA-14.

The VIRYA-14 is grid connected. For use in combination with an inverter, the 3-phase current has to be rectified. Rectification of the winding is described in report KD 340 (ref. 4). Selection of the right rectifier and the right inverter is out of the scope of this report.

The head is kept perpendicular to the wind by a double vane with 7.5 m long vane arms and with square vane blades size 1.5 * 1.5 m at the end of each vane arm. The VIRYA-14 will have a free standing tubular tower with a height of 24 m.

2 Description of the rotor of the VIRYA-14 windmill

The 3-bladed rotor of the VIRYA-14 windmill has a diameter D = 14 m and a design tip speed ratio λ_d = 6. The rotor has blades with a constant chord and no twist and is provided with a Gö 711 airfoil. This airfoil is described in report KD 285 (ref. 5). A blade is made out of a wooden plank with dimensions of 97 * 640 * 6540 mm. The airfoil is made over the whole blade length. The blade has no twist and so the blade angle β is the same for the whole blade.

The VIRYA-5B3 has a hub plate which is made out of one sheet. It this would also be done for the VIRYA-14, a very big sheet would be needed and a lot of material would be wasted. So for the VIRYA-14 it is assumed that three strips are welded together under an angle of 120°. This hub assembly is bolted to a stainless steel hub with an outside diameter of 250 mm. The strips are made of bare drawn mild steel strip with a thickness of 25 mm, a width of 400 mm and a length of 1200 mm. Each strip is twisted 7.6° right hand in between r = 125 mm and r = 460 mm to give the blade the correct blade angle. The welded hub assembly is galvanised. The overlap in between a blade and a strip is 740 mm which results in a free blade length of 5.8 m. The blades are connected to the hub assembly by three bolts M36 and six nuts M36. A cambered sheet size 740 * 150 * 8 mm is placed under the bolt heads to prevent damage of the wood when the bolts are tightened. The hub assembly is bolted to the hub by means of three bolts M36. The hub is clamped to the tapered shaft end by one central bolt M42. The rotor is balanced by adding balance weights under the connecting bolts.

A sketch of the VIRYA-14 rotor is given in figure 1.

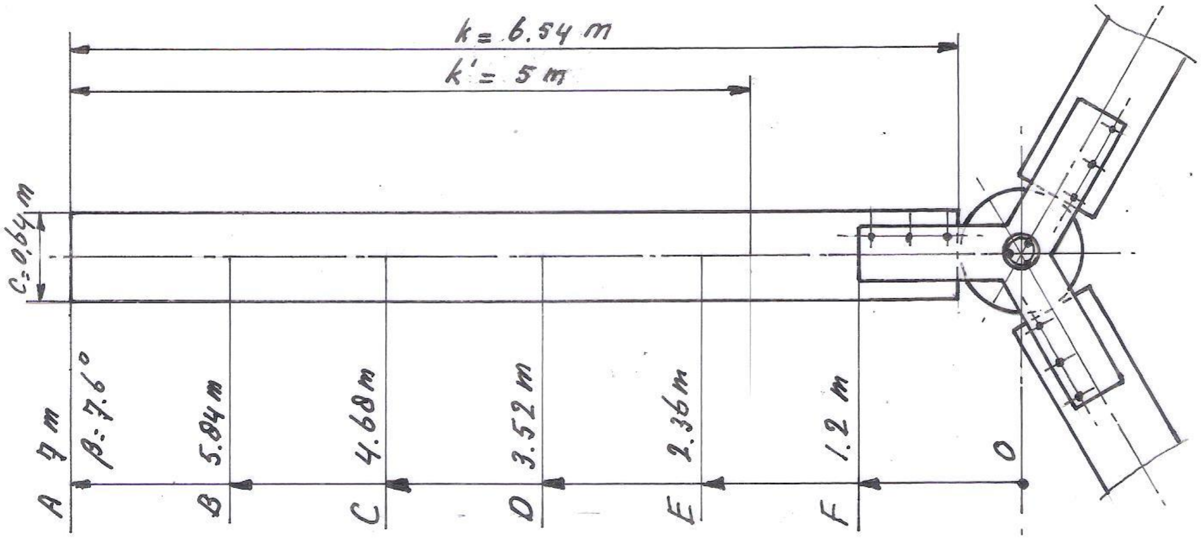

fig. 1 Sketch VIRYA-14 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 6). This report (KD 732) has its own formula numbering. Substitution of $\lambda_d = 6$ and R = 7 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 0.8571 * r$ (-) (1)

Formula's (5.2) and (5.3) of KD 35 stay the same so:

$\beta = \phi - \alpha$ (°) (2)

$\phi = 2/3 \arctan 1 / \lambda_{r\,d}$ (°) (3)

Substitution of B = 3 and c = 0.64 m in formula (5.4) of KD 35 gives:

$C_l = 13.090\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.64 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 2.134 * 10^5 * \sqrt{}\,(\lambda_{r\,d}^2 + 4/9)$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 1.16 m of one to another. Cross section F corresponds to the end of a strip of the hub assembly. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root.

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

The aerodynamic characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 5). 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-14 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	7	6	6.3	0.64	0.55	0.56	12.88	4	-1.4	-1.3	7.7	7.6	0.026
B	5.84	5.006	7.5	0.64	0.66	0.66	10.78	4	-0.1	-0.1	7.6	7.6	0.021
C	4.68	4.011	9.3	0.64	0.81	0.81	8.68	4	1.7	1.7	7.6	7.6	0.016
D	3.52	3.017	12.2	0.64	1.04	1.05	6.59	4	4.5	4.6	7.7	7.6	0.016
E	2.36	2.023	17.5	0.64	1.44	1.42	4.55	4	10.2	9.9	7.3	7.6	0.025
F	1.2	1.029	29.4	0.64	2.03	-	2.62	4	-	21.8	-	7.6	-

table 1 Calculation of the blade geometry of the VIRYA-14 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 very little for the stations A up to E and varies in between 7.7° and 7.3°. Therefore it is allowed to take a constant value of β_{lin} = 7.6° for the whole blade.

4 Determination of the C_p-λ and the C_q-λ curves

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the most important outer part of the blade is about 0.02. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6$ and $C_d/C_l = 0.02$ gives $C_{p\ th} = 0.48$.

The blade is stalling at station F. For the calculation of the maximum C_p therefore not the whole blade length k = 6.54 m is taken into account but only the part up to 0.8 m outside station F. This gives an effective blade length k’ = 5 m.

Substitution of $C_{p\ th} = 0.48$, R = 7 m and effective blade length k’ = 5 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.44$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.44 / 6 = 0.0733$. Substitution of $\lambda_{opt} = \lambda_d = 6$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 9.6$. The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

The blade angle is 7.6° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 7.6° = 82.4°. 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 α = 82.4° it can be read that $C_l = 0.27$. The whole blade is stalling during starting and the part of the blade behind the hub assembly isn’t effective. Therefore, for k now the free blade length k = 5.8 m is taken.

Substitution of B = 3, R = 7 m, k = 5.8 m, $C_l = 0.27$ and c = 0.64 m in formula 6 gives that $C_{q\ start} = 0.0086$. For the ratio between the starting torque and the optimum torque we find that it is 0.0086 / 0.0733 = 0.119. This is acceptable for a rotor with $\lambda_d = 6$.

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

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

In the specification of the generator it is mentioned that the starting torque is smaller than 0.5 Nm. This is very low for this generator size and I doubt if this is correct if the generator has a seal on the shaft. The generator can be used without a seal for a vertical axis wind turbine but for a horizontal axis wind turbine, a seal is certainly necessary to prevent that water enters the bearings. As a shaft diameter of 100 mm is too small for direct connection of a rotor with D = 14 m, an auxiliary shaft is positioned in front of the generator and in line to the generator shaft. This shaft has one bearing at the front side. At the back side it is supported by the generator shaft. The front bearing and the seal of this bearing gives an extra friction torque. Assume that the total friction torque is 20 Nm.

Substitution of Q_s = 20 Nm, $C_{q\ start}$ = 0.0086, ρ = 1.2 kg/m^3 and R = 7 m in formula 7 gives that V_{start} = 1.9 m/s. This is very low for a 3-bladed rotor with a design tip speed ratio λ_d = 6 meant to be used in regions with moderate wind speeds.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for λ = 0. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 7). With this method, it can be determined that the C_q-λ curve is about straight and horizontal for low values of λ if a Gö 711 airfoil is used. A scale model of a three bladed rotor with constant chord and blade angle and with a design tip speed ratio λ_d = 6 has been measured in the wind tunnel already on 20-11-1980. It has been found that the maximum C_p was more than 0.4 and that the C_q-λ curve for low values of λ was not horizontal but somewhat rising. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-14 rotor are given in figure 2 and 3.

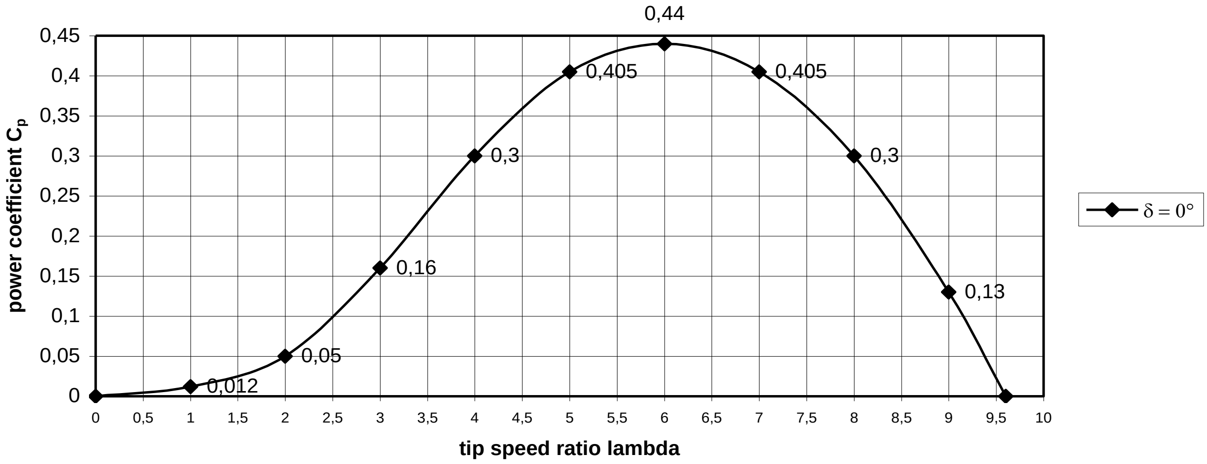

fig. 2 Estimated C_p-λ curve for the VIRYA-14 rotor for the wind direction perpendicular to the rotor (δ = 0°)

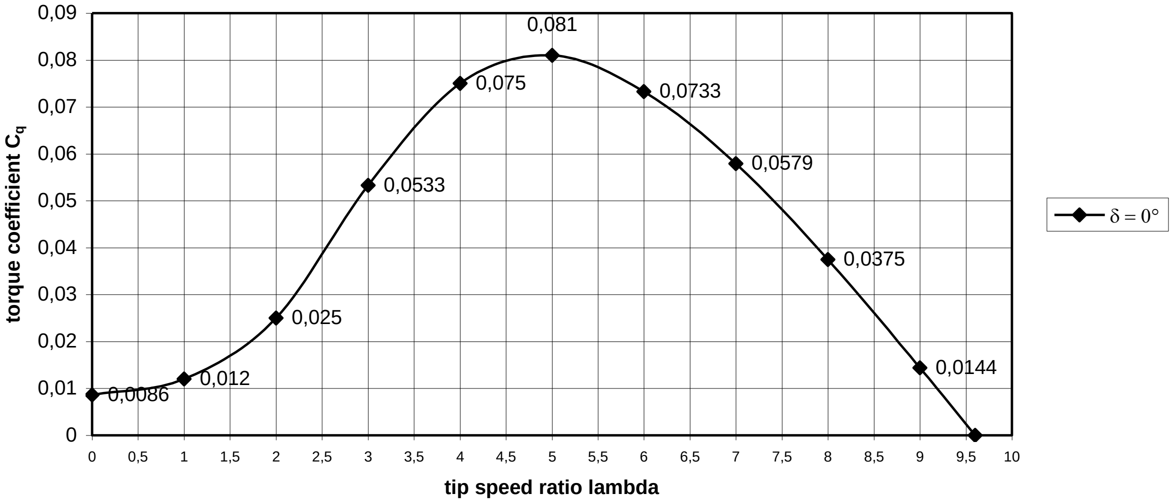

fig. 3 Estimated C_q-λ curve for the VIRYA-14 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 δ = 20° and for V = 10 m/s for a yaw angle δ = 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-14 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves 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 = 7 m in formula 7.1 of KD 35 gives:

$$n = 1.3642 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2\ \text{kg} / \text{m}^3$ and R = 7 m in formula 7.10 of KD 35 gives:

$$P = 92.363 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ is 3, 4, 5, 6, 7, 8, 9 and 9.6 (see figure 2). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed. The result of the calculations is given in table 2.

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

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 0°		V = 7 m/s δ = 0°		V = 8 m/s δ = 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)
3	0.16	12.3	399	16.4	946	20.5	1847	24.6	3192	28.6	5069	32.7	7566	34.6	8939	35.4	9599
4	0.3	16.4	748	21.8	1773	27.3	3464	32.7	5985	38.2	9504	43.7	14187	46.1	16761	47.3	17997
5	0.405	20.5	1010	27.3	2394	34.1	4676	40.9	8080	47.7	12831	54.6	19152	57.7	22628	59.1	24297
6	0.44	24.6	1097	32.7	2601	40.9	5080	49.1	8778	57.3	13939	65.5	20808	69.2	24583	70.9	26396
7	0.405	28.6	1010	38.2	2394	47.7	4676	57.3	8080	66.8	12831	76.4	19152	80.8	22628	82.7	24297
8	0.3	32.7	748	43.7	1773	54.6	3464	65.5	5985	76.4	9504	87.3	14187	92.3	16761	94.5	17997
9	0.13	36.8	324	49.1	768	61.4	1501	73.7	2594	85.9	4118	98.2	6148	103.8	7263	106.3	7799
9.6	0	39.3	0	54.6	0	65.5	0	78.6	0	91.7	0	104.8	0	110.8	0	113.4	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-14 rotor

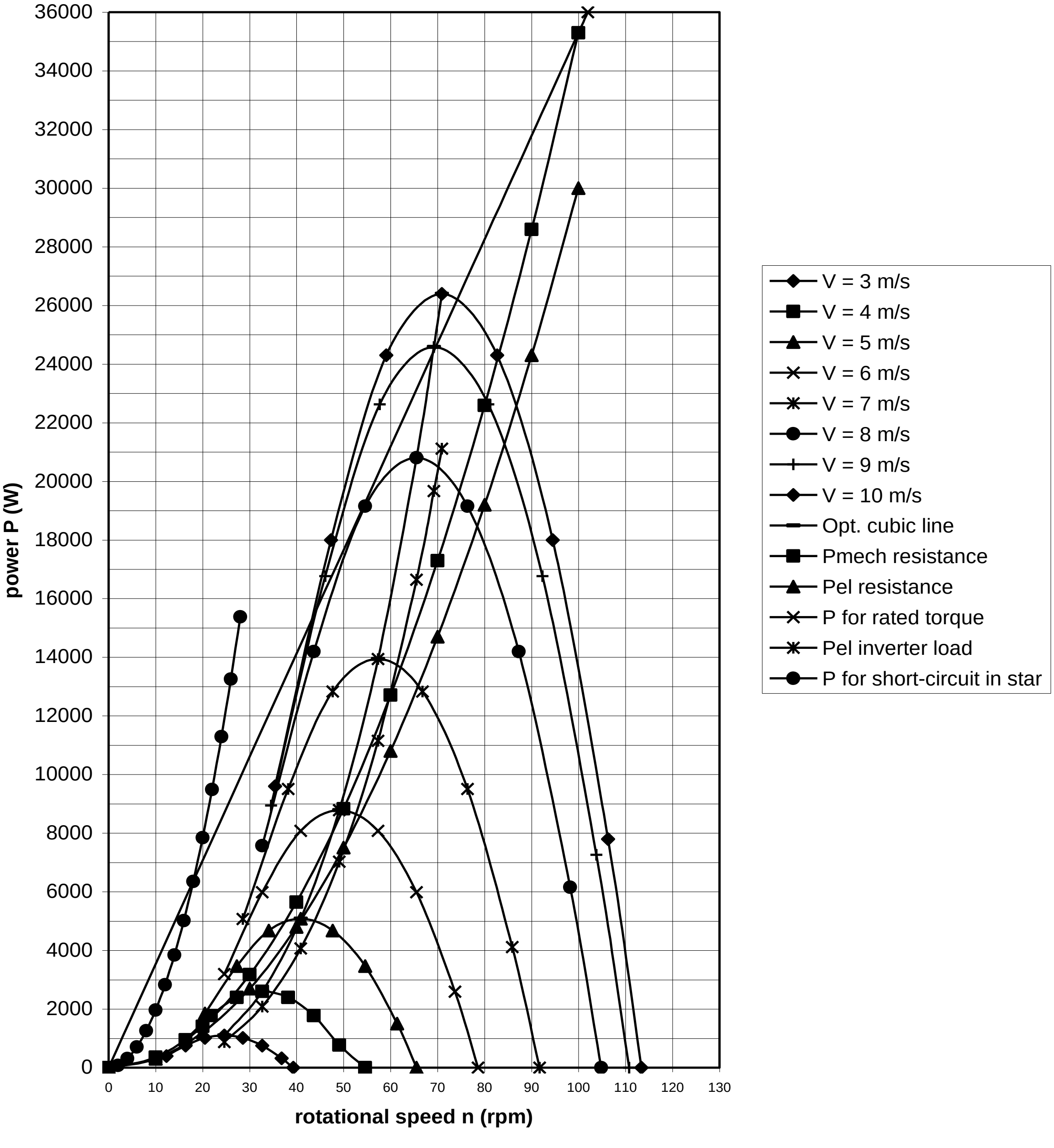

fig. 4 P-n curves of the VIRYA-14 rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the PMG900-I-30KW-100R generator with a resistance load such that P_{el} = 30000 W at n = 100 rpm, P-n curve for the rated torque Q = 3370 Nm, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

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

An axial flux generator of Chinese manufacture has been chosen. Axial flux means that the magnetic flux which is flowing through the coils is in parallel to the generator axis. There is no iron in the coils and so the sticking torque is only determined by the friction of the bearings and the seal on the shaft. As there is no iron in the coils, there are no magnetic losses and the peak efficiency is rather high. Such generators are supplied by different Chinese suppliers like Hefei Top Grand, Xinda Green Energy, Hiestmotor and Qiangsheng Magnets. I have chosen Hefei Top Grand, website: www.china-topgrand.com because they gave the clearest answers on my questions. I have bought and tested a much smaller generator type TGET165-0.15kW-500R at this company and they keep their promises. Measurements for this generator and experiments with a small wind turbine are given in report KD 595 (ref. 9).

For the VIRYA-14, I have chosen the generator with biggest available housing type PMG900 (900 refers to about the housing diameter in mm, the real diameter is 895 mm). The type PMG900-I-30KW-100R is chosen because this type has the lowest nominal rotational speed. A data sheet can be found on the website of the supplier following the path: www.china-topgrand.com – product – Permanent Magnet Generator Inner Rotor – page 5.

In the data sheet it is specified that the efficiency is higher than 85 % which seems realistic if the load is a constant resistance. It is also specified that the electrical power is 30000 W, so 30 kW at n = 100 rpm. Next it is assumed that the efficiency is 85 % or 0.85 (-). So the required mechanical power is 30000 / 0.85 = 35294 W. The generator has a mass of 300 kg which seems acceptable for the VIRYA-14.

The rated loaded voltage at n = 100 rpm is specified as 400 VAC. So no DC voltage is specified but the loaded DC voltage can be calculated. This generator has a 3-phase winding with an internal star point and three phase wires are coming out of the generator housing. The given voltage is the voltage in between two of the three phases and not the phase voltage U_f, which is the voltage in between the star point and one of the phases. U_f is a factor √ 3 lower, so 230.94 VAC. A large 3-phase rectifier (not included) must be used to get a DC current which is needed for the inverter. Rectification of a 3-phase current is explained in report KD 340 (ref. 3). However, it might be that the rectifier is included in the inverter and in this case the three phase wires are directly connected to the inverter. To stop the rotor, a 3-phase switch has to be mounted at the tower foot. The switch must be mounted before the rectifier and as close as possible to the generator to prevent a voltage drop over the lines in between the generator and the switch.

The rated line current I is specified as I = 43.30 A at n = 100 rpm. So the rated power generated by one phase is U_f * I = 230.94 * 43.30 = 10000 W. So the rated power generated by three phases is 3 * 10000 = 30000 W. This matches well with the given rated power of 30 kW.

The sticking torque of the generator is very low without an oil seal and is only caused by the friction of the bearings. It is specified that this torque is less than 0.5 Nm. An oil seal is needed if the axis is horizontal. The sticking torque will be much higher if an oil seal is mounted and if an auxiliary shaft is used but it is expected that it is low enough for the VIRYA-14 rotor (see calculation of the starting wind speed in chapter 4).

The generator has a shaft with a diameter of 100 mm which is only 2 mm larger than the shaft diameter of the generator with housing TGET770-10kW-100R which is used for the VIRYA-10. So a 120 mm auxiliary shaft is used. The generator shaft has a 16 mm wide key groove. The front side of the shaft is provided with thread M80 * 2. A composite drawing of the auxiliary shaft and the head have still to be made.

The generator housing has a collar with a diameter of 240 mm at the front side. In the photo of the generator it can be seen that this collar is provided with eight threaded holes but the thread and the pitch circle are not specified. As these threaded holes are used to connect the generator to the head frame, the measures should have been given. The measures have still to be gained from the supplier to design the head frame.

The generator characteristics are given in point 6 of the data sheet. The P_{el}-n and the loaded U-n curves are given. The curves show measuring points but the measuring points aren't given in a table. The U-n curve is about a straight line through the origin and the P_{el}-n curve is about a parabola. This is an indication that the load is a fixed resistance for the whole range of measurements. I have performed this kind of measurements on a radial flux PM-generator made from an asynchronous motor. These measurements are given in chapter 7 and 9 of report KD 78 (ref. 10). These measurements show that the P_{mech}-n and P_{el}-n curves are about parabolas if the resistance isn't very low, that the U-n and Q-n curves are about straight lines through the origin and that the efficiency is about constant for a certain resistance. So these curves are estimated for the given generator of Hefei Top Grand from the given rated values at n = 100 rpm.

The given rated voltage is the alternating voltage U_{AC} in between two of the three phases. For an inverter, the winding must be rectified. The rectified DC voltage U_{DC} is a factor $0.955 * \sqrt{2} = 1.3506$ higher than U_{AC} (if the voltage drop of the rectifier diodes is neglected). The unloaded or open voltage U_{open} is also not specified. For a smaller generator type TGET320-1KW-350R, it has been found in chapter 3 of report KD 705 (ref. 11) that the ratio U_{open} / U_{DC} is about 68 / 56 = 1.2143. It is assumed that this ratio is also valid for the generator type PMG900-I-30KW-100R. So for the loaded DC voltage U_{DC} at n = 100 rpm it is valid that U_{DC} = 1.3506 * 400 = 540 VDC. For the open DC voltage U_{open} at n = 100 rpm it is valid that U_{open} = 1.2143 * 1.3506 * 400 = 650 VCD. The calculated values are given in the bottom line of table 3.

n (rpm)	U_{AC} (V)	U_{DC} (V)	U_{open} (V)	P_{el} (W)	η_{gen} (-)	P_{mech} (W)	Q (Nm)	P_{heat} (W)
0	0	0	0	0	-	0	0	0
10	40	54	65	300	0.85	353	337	53
20	80	108	130	1200	0.85	1412	674	212
30	120	162	195	2700	0.85	3176	1011	476
40	160	216	260	4800	0.85	5647	1348	847
50	200	270	325	7500	0.85	8824	1685	1324
60	240	324	390	10800	0.85	12706	2022	1906
70	280	378	455	14700	0.85	17294	2359	2594
80	320	432	520	19200	0.85	22588	2696	3388
90	360	486	585	24300	0.85	28588	3033	4288
100	400	540	650	30000	0.85	35294	3370	5294

table 3 U_{AC}, U_{DC}, U_{open}, P_{el}, η_{gen}, P_{mech}, Q and P_{heat} as a function of n

No rated torque Q is given for the generator. However, it is specified at point 5 of the data sheet that the generator efficiency η_{gen} is at least 85 %. In figure 33 of KD 78 (ref. 10) it can be seen that the efficiency for a resistance load is about constant for every rotational speed and that it is high if the load resistance isn't low. It is easy to give the efficiency as a factor of 1 and it is assumed that η_{gen} = 0.85 for all rotational speeds. As the generator has no iron in the coils, the heat losses P_{heat} are only caused by the copper losses in the winding. The P_{mech}-n, the P_{heat}-n and the Q-n curves of the generator can be derived by the formulas:

$$P_{mech} = P_{el} / \eta_{gen} \quad \text{(W)} \qquad (10)$$

$$P_{heat} = P_{mech} - P_{el} \quad \text{(W)} \qquad (11)$$

$$Q = 30\, P_{mech} / (\pi * n) \quad \text{(Nm)} \qquad (12)$$

First the values of P_{mech}, P_{heat} and Q are determined for n = 100 rpm. Substitution of $P_{el} = 30000$ W and $\eta_{gen} = 0.85$ in formula 10 gives that $P_{mech} = 35294$ W. Substitution of $P_{mech} = 35294$ and $P_{el} = 30000$ W in formula 11 gives that the heat loss $P_{heat} = 5294$ W. Substitution of $P_{mech} = 35294$ W and n = 100 rpm in formula 12 gives that Q = 3370 Nm. These values are also given in the bottom line of table 3.

The values for other rotational speeds are now calculated assuming that the U-n and Q-n curves are straight lines through the origin and that the P-n curves are parabolas. The wanted curves can now be derived from table 3. The U_{AC}-n, the U_{DC}-n and the U_{open}-n curves are given in figure 5.

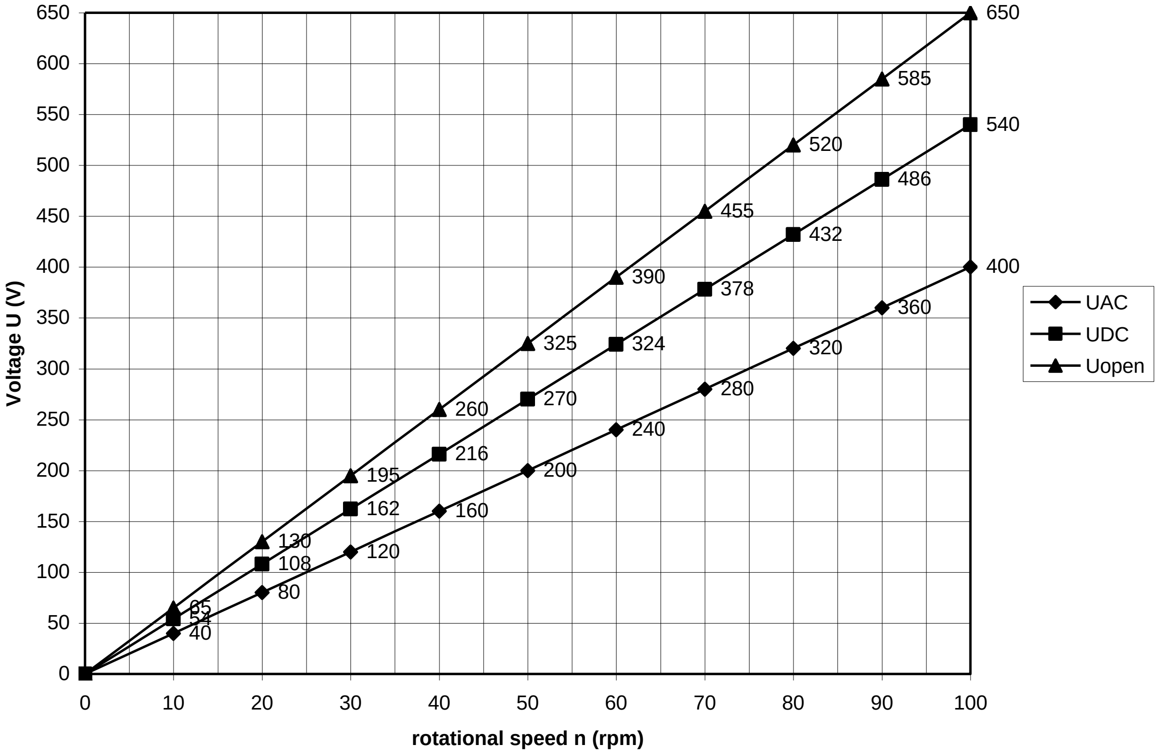

fig. 5 U_{AC}, U_{DC} and U_{open} as a function of n for a resistance load

The Q-n curve is given in figure 6. Figure 6 also contains the curve for U = 540 V DC and for short-circuit in star.

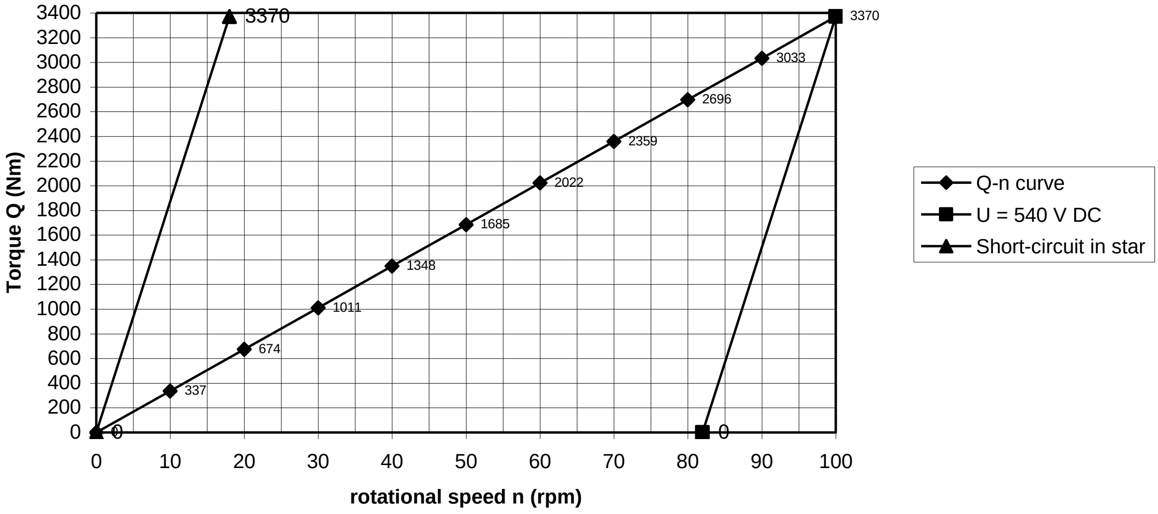

fig. 6 Loaded torque Q as a function of n for a resistance load, Q-n curves for 540 V DC and for short-circuit in star

The P_{mech}-n and P_{el}-n curves for the given resistance load are given in figure 4. In figure 4 it can be seen that the optimum cubic line is intersecting with the P_{mech}-n line for a resistance load at a wind speed of about 6 m/s. So below this wind speed, the load is lower than for the given resistance load if the optimum cubic line is followed. This means that the generator efficiency is somewhat higher than for a resistance load. For wind speeds higher than 6 m/s, the optimum cubic line is lying higher than for the given resistance load and so the efficiency is somewhat lower than for a resistance load. It is assumed that the inverter is programmed such that the optimum cubic line is followed.

So these figures are based on the manufactures specification for a resistance load at n = 100 rpm. The load resistance R can be calculated if it is assumed that three identical resistors are connected in star to the three phase wires. The voltage over one resistor is equal to the phase voltage U_f = 230.94 V. The line current I = 43.30 A at n = 100 rpm. So according to the law of Ohm, the resistance R is given by R = U / I or R = 230.94 / 43.30 = 5.33 Ω.

If three resistors are used as load, the winding of one phase is used for all the time to generate power. This power varies according to a $\sin^2\alpha$ function. The power fluctuation is given in figure 2 of report KD 340 (ref. 3). If a 3-phase winding is rectified in star, only two of the three phases are generating power at the same time. This means that in one phase, power is only generated for $30° < \alpha < 150°$ and for $210 < \alpha < 330°$. This means that no power is generated for $0° < \alpha < 30°$, for $150° < \alpha < 210°$ and for $330° < \alpha < 360°$. The loss of generated power because of this effect is about 7 % of the power generated for a resistance load. But this effect is neglected and so it is assumed that the generator is able to generate a DC power of 30 kW at n = 100 rpm.

In the last column of table 3 it can be seen that the heat losses are maximal for n = 100 rpm. This is because the voltage and so also the current decrease at decreasing rotational speed. In figure 6 it can be seen that the torque for a resistance load decreases linear to the decrease of the rotational speed. A PM-generator can also have high torques at low rotational speeds so the chosen value of the resistance gives only a large torque for the rated rotational speed n = 100 rpm. To know the real capacity of the generator, it should also be measured for lower values of the resistance at lower rotational speeds than 100 rpm up to at least the rated torque Q = 3370 Nm which is valid for n = 100 rpm.

As the current I is proportional to the torque Q, the copper losses and so P_{heat}, will then be the same for lower rotational speeds and the rated torque. The efficiency will be lower than for the given resistance load but this is acceptable.

A constant rated torque means that the power increases linear to the rotational speed. So a linear P-n curve "rated torque" through P = 0 W and n = 0 rpm and P = 35294 W and n = 100 rpm is also drawn in figure 4. The line is extended to the right up to a power of 36000 W. Use of the generator below this line is certainly acceptable without getting a too high value of P_{heat}. In figure 4 it can be seen that the optimum cubic line is lying lower than the line for the rated torque for $V < 9$ m/s and only for $V > 9$ m/s it is lying a little higher. But the generator can supply a maximum torque which is even a lot higher than the rated torque of 3370 Nm. This is an indication that the generator is strong enough for a rotor with a diameter of 14 m. So it is assumed that the pendulum safety system with a design wind speed of 8 m/s and so with a rated wind speed of 10 m/s, is a good choice and that the maximum power is limited enough for this design wind speed. However, if it would appear in practice that the maximum rotor torque is too high, the safety system can easily be changed to a lower design wind speed by changing of the balance of moments.

The generator efficiency is assumed to be 0.85 for a resistance load. If the optimum cubic line is followed, the real load is lower than the given resistance load if V is lower than 6 m/s. This means that the efficiency will be somewhat higher than 0.85. The real electrical power depends also on the losses in the rectifier and on the efficiency of the inverter. Rectifier losses are low for high voltages. Modern inverters have a very high efficiency. It is assumed that the total efficiency of generator, rectifier and inverter $\eta_{tot} = 0.8$. The P_{el}-n curve for an inverter load such that the optimum cubic line is followed and for a constant efficiency of 0.8 is also given in figure 4. The P_{el}-n curve is determined for wind speeds up to 10 m/s. 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. The electrical power for a certain wind speed is found by going down vertically from the working point until the P_{el}-n curve is crossed. The values of P_{el} have been determined this way for wind speeds up to 10 m/s and are given in the P_{el}-V curve of figure 7. It is assumed that P_{el} for higher wind speeds than 10 m/s is the same as the value for V = 10 m/s.

The electrical power is about 21 kW at a wind speeds of 10 m/s and higher which is very good for a windmill with a rotor diameter of 14 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-14.

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 $P_{el} = 878$ 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 1.9 m/s which is much lower than 3 m/s. So the rotor will turn almost always but it will generate no power for $1.9 < V < 3$ 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 $P_{el} = 4064$ W. Assume we have a wind speed of 7 m/s for one hour and of 3 m/s for one hour. So the average wind speed is 5 m/s. The power for V = 3 m/s is 878 W. The power for V = 7 m/s is 11151 W. The average power is (878 + 11151) / 2 = 6015 W. This is 1951 W more or a factor 6015 / 4064 = 1.48 higher than for a constant wind speed of 5 m/s.

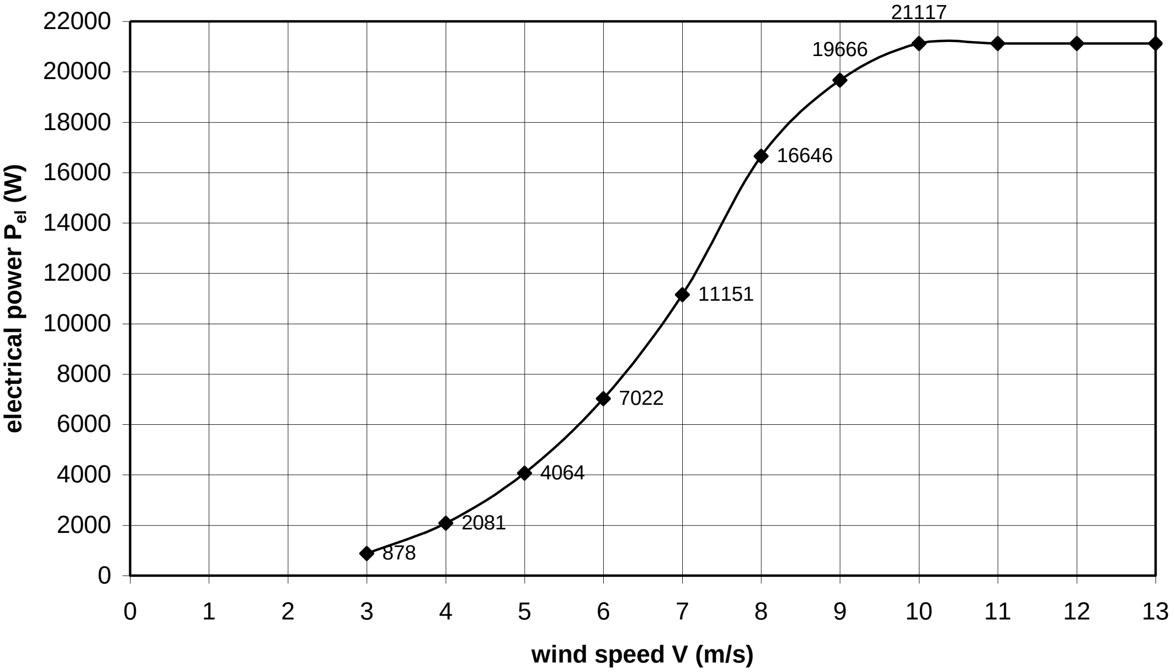

fig. 7 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

The P_{mech}-n, the P_{el}-n curves as given in figure 4 and the P_{el}-V as given in figure 7 are estimated and not measured. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the chosen generator of Hefei Top Grand, it is necessary to buy one and to test it at a very 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 know the P-n curve for short-circuit in star but this curve isn't given. The PM-generator which is used for the measurements as given in KD 78 (ref. 10) was measured for different constant voltages rectified in star. The Q-n curves for 26 V star, 52 V star and 76 V star are given in figure 8 of chapter 4 of KD 78. The Q-n curve for short-circuit in star before the rectifier is given in figure 4 of chapter 3 of KD 78. If these curves are compared, it can be seen that all curves have about the same shape but that the curve is shifted to the right if the voltage is higher. All curves have about the same maximum value of about 29 Nm. The first part of each curve, up to about 2/3 of the peak value, so up to a torque of about 20 Nm, is about a straight line but the curves bend to the right for higher torques. The curves start at the rotational speed for which the open generator voltage is equal to the average charging voltage. This phenomenon is used to derive the wanted P-n curve for short-circuit in star for the VIRYA-14 generator.

In figure 5 it can be seen that the loaded DC voltage U_{DC} = 540 V DC at n = 100 rpm. The unloaded open DC voltage U_{open} = 650 V at n = 100 rpm. As the U-n curves are straight lines through the origin, it can be read that U_{open} = 540 V DC at n = 82 rpm. This is 18 rpm lower than n_{rated} = 100 rpm. Next it is assumed that Q-n line for a constant voltage of 540 V is a straight line in between the point Q = 0 Nm and n = 82 rpm and the point Q = 3370 Nm and n = 100 rpm. This curve is also given in figure 6.

Short-circuit means a constant voltage U = 0 V. So the Q-n curve for short-circuit in star is found by moving the Q-n curve for 540 V DC that much to the left that it intersects with the origin. This means that it must go through the point Q = 0 Nm and n = 0 rpm and the point Q = 3370 Nm and n = 18 rpm. This curve is also given in figure 6.

Formula 12 can be written as:

$$P_{mech} = Q * \pi * n / 30 \quad (W) \qquad (13)$$

To determine the P-n curve for short circuit in star, several points have to be chosen on the Q-n curve for short-circuit in star. This was done for every 2 rpm. P is then calculated for every point using formula 13. The result of this procedure is given in table 4. It is assumed that the Q-n curve is about straight for rotational speeds up to 28 rpm and the Q-n and P-n curves are extended up to this rotational speed. For higher rotational speeds than about 28 rpm, the Q-n curve for short-circuit in star will bend to the right and will have a maximum value at a certain rotational speed. This part of the curve can only be determined by measuring. So the P-n curve for short-circuit in star can’t be determined for rotational speeds higher than about 28 rpm.

n (rpm)	Q (Nm)	P (W)
0	0	0
2	374.4	78
4	748.9	314
6	1123.3	706
8	1497.8	1255
10	1872.2	1961
12	2246.7	2823
14	2621.1	3843
16	2995.6	5019
18	3370	6352
20	3744.4	7842
22	4118.9	9489
24	4493.3	11293
26	4867.8	13254
28	5242.2	15371

table 4 Calculated values of Q and P as a function of n for short-circuit in star

The P-n curve for short-circuit in star can now be derived from table 4 and is also given in figure 4. It can be seen that there is a large distance in between the P-n curve for short-circuit in star and the P-n curve of the rotor for V = 10 m/s. The P-n curve for short-circuit in star couldn’t be determined for higher rotational speeds than 28 rpm but by interpolation it can be concluded that the generator can very well be used as a brake to stop the rotor at any wind speed.

Building of a prototype of the VIRYA-14 with the chosen PM-generator of Hefei Top Grand 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-14. The VIRYA-14 is certainly not a windmill which can be built by an amateur.

7 Use of the VIRYA-14 in combination with twenty semi-detached houses

In chapter 4 of the Dutch report: “Ideeën over realisatie van 34 halfvrijstaande huizen geschikt voor dubbele bewoning” (ref. 2), a semi-detached house is described which has two separate entrances and so it can be used by two families. The width of one house is 7 m and the depth is 10 m. Twenty-eight, 300 W solar panels are used on the roof of each house.

This plan contains no wind turbine as there isn’t enough space but the houses can be used in another plan with more space for a wind turbine.

In chapter 5 of this report, the heat loss is calculated during the month December and it is also calculated how much power is generated by the solar panels in December. December is the most difficult month for solar panels as only about 2 % of the yearly output is generated in this month. It was found that the heat loss is about 1360 W. If floor heating and a heat pump with a COP value of 4 are used, it means that the required electrical power for the heat pump is about 1340 / 4 = 340 W. The power generated by the 28 solar panes is only 196 W in December, so 144 W too small. But there is also other electric equipment than the heat pump.

Next assume that one VIRYA-14 windmill is added and that the generated energy is used for twenty houses. There is no electricity cable from the wind turbine to each house but it is assumed that there is a contract for which the momentary power of the wind turbine is balanced with the momentary power consumption of all twenty houses together. So power of the wind turbine is only sold if the power output of the wind turbine is larger than the power consumption of all twenty houses together. This means that during the winter months, almost all power of the wind turbine will be used for the heat pumps of the twenty houses.

The power output of the wind turbine in December depends on the wind regime and the tower height. Provisionally it is assumed that the wind turbine is placed in my village Boskant which is a part of the town Meierijstad. The wind map of The Netherlands shows that 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 December will be higher. Assume that it is 5 m/s at a height of 10 m in open terrain.

Assume that the tower height is 24 m. This means that the bottom of the rotor lies at a height of 17 m which is high enough to have only a little turbulence caused by buildings and trees. The top of the rotor lies at a height of 31 m which is low enough to give no radar disturbance of the airfield Volkel or Welschap. The average wind speed for a tower height of 24 m in non open terrain will be higher than the wind speed at 10 m in open terrain. Assume that it is 5.5 m/s. The power for a certain average wind speed is higher than for the same constant wind speed because the power increases to the cube of the wind speed. Assume that therefore the P_{el}-V curve can be read at a wind speed of 6 m/s.

The P_{el}-V curve is given in figure 7 and in this figure it can be seen that P_{el} = 7022 W for V = 6 m/s. If this power is distributed equally over the twenty houses, every house receives about 351 W. This is even more than the power of 340 W needed for the heat pump in December. So the wind turbine can supply all the power for the heat pumps of twenty houses if the power is averaged over December. So the power supply of the solar panels in December can be used for other electric equipment.

A very well isolated house equipped with floor heating and a heat pump has a large heat capacity. So this means that there can be a strong variation of the incoming power of the wind turbine and the solar panels together without large fluctuation of the internal temperature of the house. But if there are long periods of low wind power and low solar power in December it is still possible that power has to be bought from the grid if the internal temperature of the house becomes too low. The situation becomes better for January and February as about 3 % of the yearly output of the solar panels is generated in January and about 5 % of the yearly output of the solar panels is generated in February.

The output of solar panels is maximal during the summer months and the output of the wind turbine is maximal during the winter months and therefore both energy suppliers balance each other. But the electric energy consumption is highest during the winter month and the energy supply of the wind turbine during the winter months is therefore much more important than the energy supply of the solar panels during the summer months.

At this moment we still have the so called “salderingsregeling” in The Netherlands which means that you receive the same amount of money for supplied energy than you have to pay for consumed energy. But this will be changed starting at 2023 and the whole procedure will be ended in 2030.

So in 2030 one will receive only a little amount of money for a supplied kWh and one will have to pay a large amount of money for a consumed kWh. This effect will strongly support the use of a wind turbine in the winter.

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