Calculations executed for the 3-bladed rotor of the VIRYA-6 windmill ($\lambda_d = 6$) with the pendulum safety system with a torsion spring connected to the generator type TGET620-5KW-200R for grid connection or heat generation

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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 rotor can be bolted directly to the generator housing. A hub is required for the types PMG. In this report KD 738, it is investigated if the rather large generator type TGET620-5KW-200R can be used in combination with a 3-bladed windmill rotor with a diameter D = 6 m and a design tip speed ratio $\lambda_d = 6$. This windmill is called the VIRYA-6. It is expected that the VIRYA-6 is large enough to generate the energy for heating a well isolated house during the winter months.

The VIRYA-6 will be equipped with the so called pendulum safety system with a torsion spring which is described in report KD 439 (ref. 1). The reason why this safety system is chosen is that the rotational speed, the thrust and the power are limited rather sharply. The head is kept perpendicular to the wind by a double vane with 3.25 m long vane arms and with square vane blades size 0.75 * 0.75 m mounted at an angle of 20° at the end of each vane arm. The VIRYA-6 will have a free standing tubular tower with a height of 12 m up to 18 m.

There are two options to use the generated energy. One is to rectify the 3-phase current coming out of the generator and to connect the generator to the grid by a 3-phase inverter. Rectification of the winding is described in report KD 340 (ref. 2). Selection of the right rectifier and the right inverter is out of the scope of this report. The AC power can now be used for heating using a heat pump and floor heating. The other option is to dissipate the generated energy in three resistors. The generated power is now directly used for heating. The first option gives the most energy because a heat pump has a COP of about four which means that four times more heat is produced than the electrical power to drive the compressor of the heat pump. But the investment costs of the heat pump and the floor heating are rather high. The second option is rather simple as no heat pump and no floor heating are needed. The fluctuation of the generated heat can be stored in a heat capacitor with water.

2 Description of the rotor of the VIRYA-6 windmill

The 3-bladed rotor of the VIRYA-6 windmill has a diameter D = 6 m (so R = 3 m) and a design tip speed ratio $\lambda_d = 6$. The rotor has wooden blades with a constant chord and no twist and is provided with a Gö 711 airfoil over the whole length of the blade. This airfoil is described in report KD 285 (ref. 3). A blade is made out of a wooden plank with dimensions of 41.6 * 280 * 2680 mm. The blade has a constant chord c = 280 mm = 0.28 m. The blade has no twist and so the blade angle β is the same for the whole blade.

The three blades are connected to each other by a hub assembly which is made out of three strips size 12 * 200 * 665 mm which are welded to each other in the centre under an angle of 120°. Nine strips for three hub assemblies can be made from a 6 m long standard strip. The hub assemble is connected to the generator housing by fifteen bolts M12. The generator housing is described in chapter 6. Each strip is twisted 8° right hand in between the generator and the blade root and so the blade has a constant blade angle $\beta = 8°$ (see chapter 3). A blade is connected to the hub assembly by three bolts M16. A sketch of the VIRYA-6 rotor is given in figure 1.

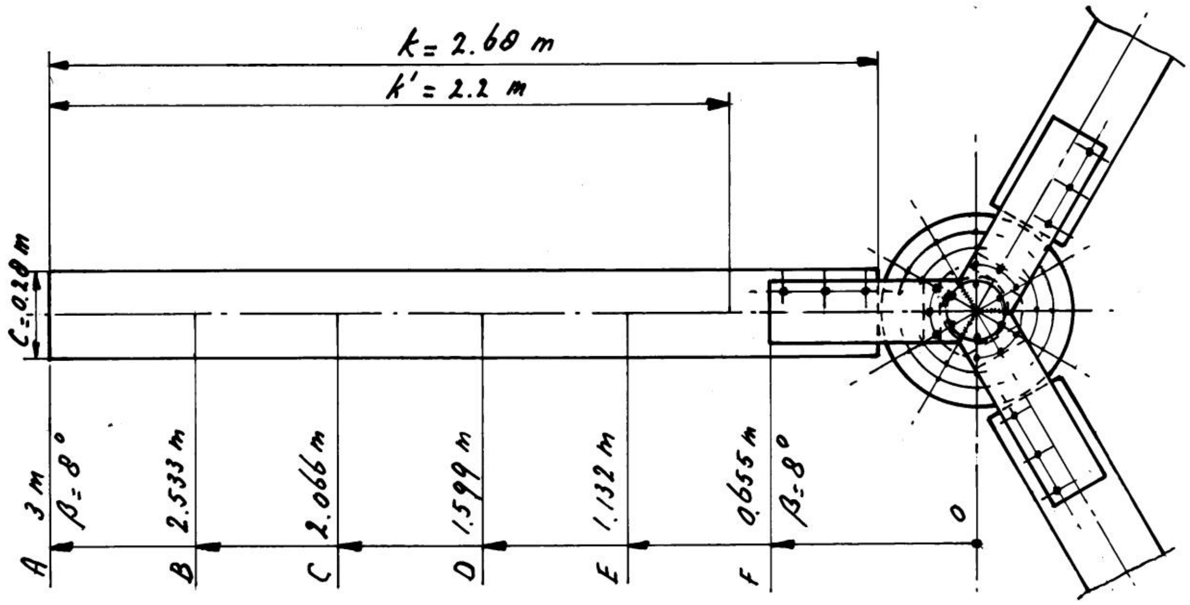

fig. 1 Sketch VIRYA-6 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 4). This report (KD 738) has its own formula numbering. Substitution of λ_d = 6 and R = 3 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 2 * r$ (-) (1)

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

$\beta = \phi - \alpha$ (°) (2)

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

Substitution of B = 3 and c = 0.28 m in formula (5.4) of KD 35 gives:

$C_l = 29.920\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.28 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.934 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.467 m of one to another. Station F corresponds to the end of the steel 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 blade angle β 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. 3). 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-6 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	3	6	6.3	0.28	0.54	0.52	5.64	4	-1.5	-1.7	7.8	8.0	0.028
B	2.533	5.066	7.4	0.28	0.64	0.62	4.77	4	-0.4	-0.6	7.8	8.0	0.023
C	2.066	4.132	9.1	0.28	0.77	0.76	3.91	4	1.2	1.1	7.9	8.0	0.017
D	1.599	3.198	11.6	0.28	0.97	0.96	3.05	4	3.7	3.6	7.9	8.0	0.015
E	1.132	2.264	15.9	0.28	1.29	1.29	2.20	4	7.9	7.9	8.0	8.0	0.020
F	0.665	1.330	24.6	0.28	1.81	1.40	1.39	4	-	16.6	-	8.0	0.120

table 1 Calculation of the blade geometry of the VIRYA-6 rotor

No value for α_{th} and therefore for β_{th} is found for station F because the required C_l value can't be generated. The variation of the theoretical blade angle β_{th} is only little for the stations A up to E and varies in between 7.8° and 8.0°. Therefore it is allowed to take a constant value of $\beta_{lin} = 8.0°$ 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 0.021. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6$ and $C_d/C_l = 0.021$ gives $C_{p\ th} = 0.475$.

The blade is stalling at station F. For the calculation of the maximum C_p therefore not the whole blade length k = 2.68 m is taken into account but only the part up to 0.135 m outside station F. This gives an effective blade length k' = 2.2 m.

Substitution of $C_{p\ th} = 0.475$, R = 3 m and effective blade length k' = 2.2 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:

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

The blade angle is 8.0° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 8.0° = 82.0°. 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. 4). For $\alpha = 82.0°$ it can be read that $C_l = 0.28$. The whole blade is stalling during starting and the part of the blade behind the strip isn't very effective. Therefore, for k now the free blade length outside the strip of the hub assembly is taken; so k = 2.335 m.

Substitution of B = 3, R = 3 m, k = 2.335 m, $C_l = 0.28$ and c = 0.28 m in formula 6 gives that $C_{q\ start} = 0.0089$. For the ratio between the starting torque and the optimum torque we find that it is 0.0089 / 0.0733 = 0.121. 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:

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

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 back bearing. The shaft diameter is 80 mm which is large enough for direct connection of a rotor with D = 6 m. So an oil seal is needed at the shaft side. It is assumed that the housing is already provided with a bore for such a seal. Assume that the total friction torque is 4 Nm.

Substitution of $Q_s = 4$ Nm, $C_{q\,start} = 0.0089$, $\rho = 1.2$ kg/m^3 and R = 3 m in formula 7 gives that $V_{start} = 3$ m/s. This is rather low for a 3-bladed rotor with a design tip speed ratio $\lambda_d = 6$ 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 $\lambda = 0$. 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. 5). 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 $\lambda_d = 6$ 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-6 rotor are given in figure 2 and 3.

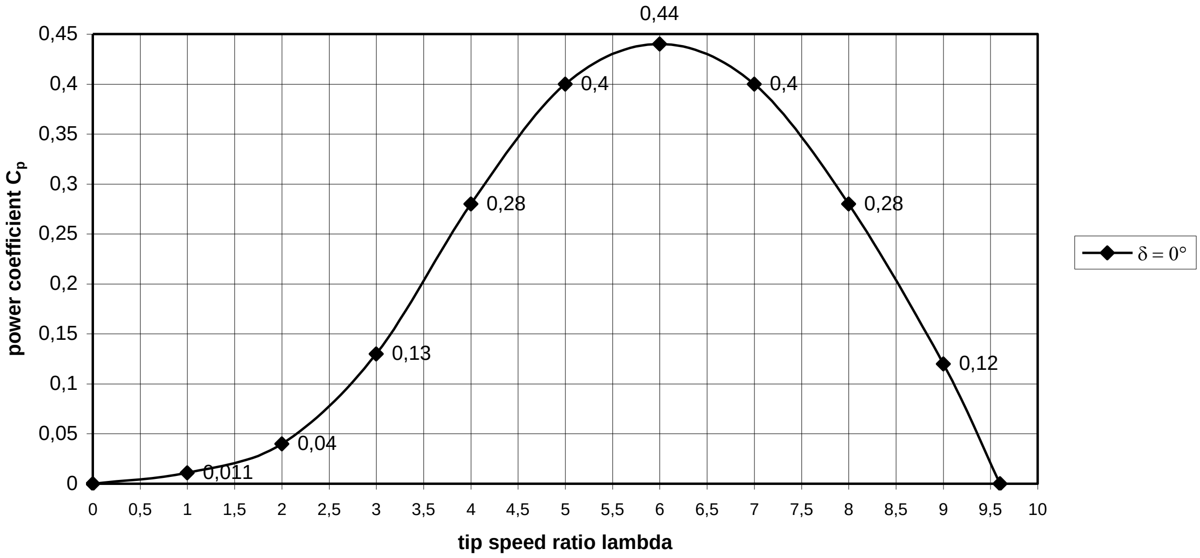

fig. 2 Estimated C_p-λ curve for the VIRYA-6 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

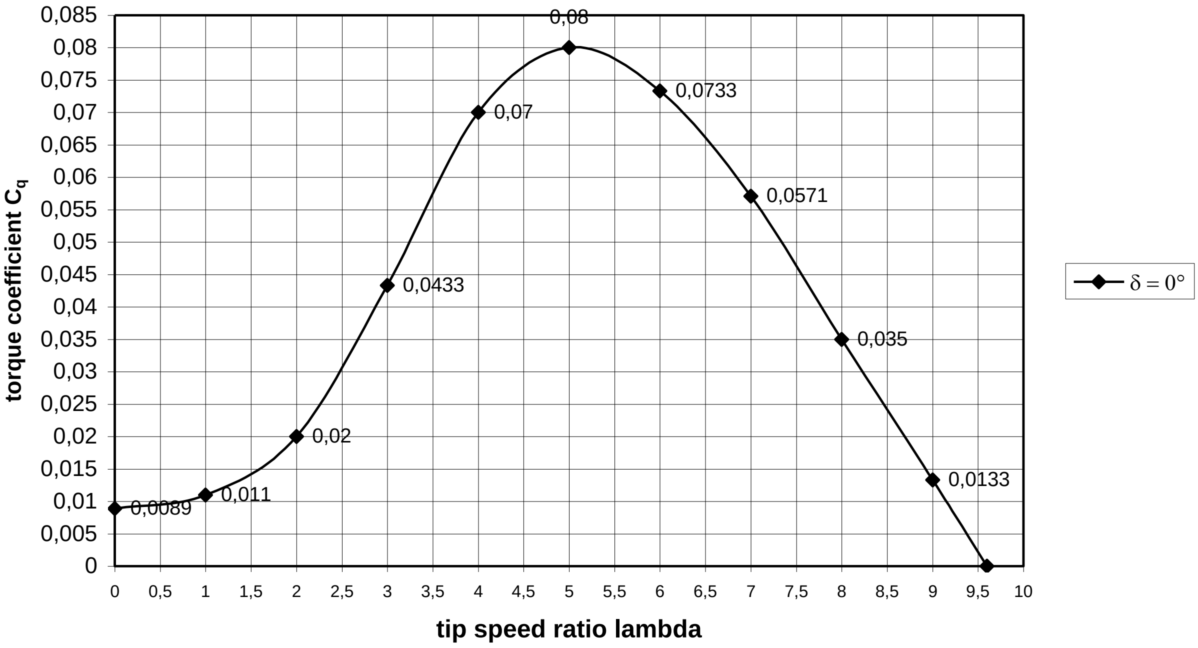

fig. 3 Estimated C_q-λ curve for the VIRYA-6 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 δ-V curve 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-6 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 = 3 m in formula 7.1 of KD 35 gives:

$$n_\delta = 3.1831 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

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

$$P_\delta = 16.965 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

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. For wind speeds higher than 10 m/s, it is assumed that the head turns out of the wind such that the rotational speed is constant. This means that the P-n curve for V = 10 m/s is also valid for higher wind speeds than 10 m/s. 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	0.13	28.6	60	38.2	141	47.7	276	57.3	476	66.8	756	76.5	1129	80.8	1334	82.7	1432
4	0.28	38.2	128	50.9	304	63.7	594	76.4	1026	89.1	1629	102.1	2432	107.7	2873	110.3	3085
5	0.4	47.7	183	63.7	434	79.6	848	95.5	1466	111.4	2328	127.6	3474	134.6	4105	137.8	4408
6	0.44	57.3	202	76.4	478	95.5	933	114.6	1612	133.7	2560	153.1	3822	161.5	4515	165.4	4848
7	0.4	66.8	183	89.1	434	111.4	848	133.7	1466	156.0	2328	178.6	3474	188.4	4105	193.0	4408
8	0.28	76.4	128	101.9	304	127.3	594	152.8	1026	178.3	1629	204.1	2432	215.4	2873	220.5	3085
9	0.12	85.9	55	114.6	130	143.2	254	171.9	440	200.5	698	229.6	1042	242.3	1231	248.1	1322
9.6	0	91.7	0	122.2	0	152.8	0	183.3	0	213.9	0	244.9	0	258.4	0	264.6	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-6 rotor

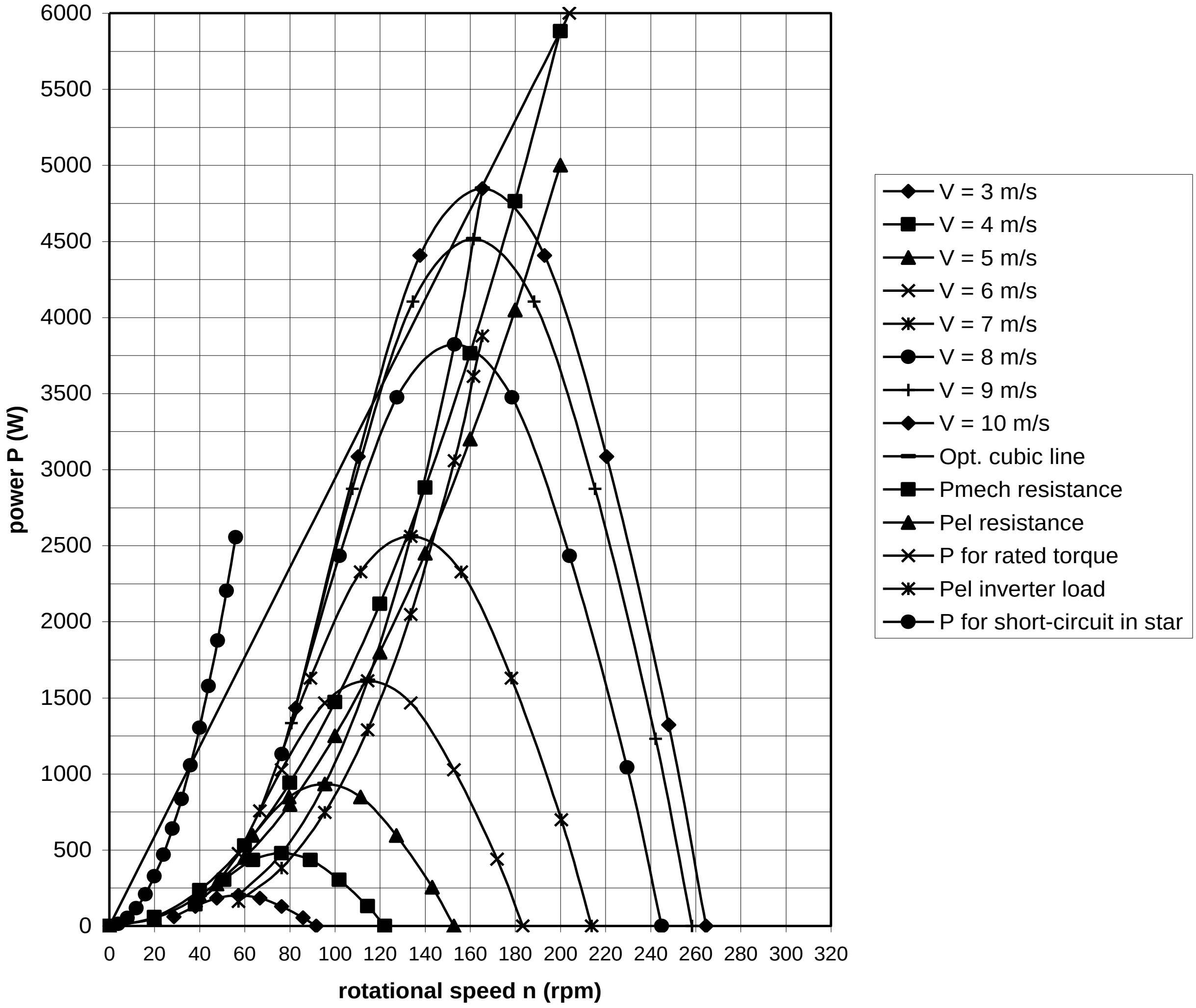

fig. 4 P-n curves of the VIRYA-6 rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the TGET620-5KW-200R generator with a resistance load such that P_{el} = 5000 W at n = 200 rpm, P-n curve for the rated torque Q = 280 Nm, P_{el}-n curve for an inverter load, P-n curve for short-circuit in 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. 6).

For the VIRYA-6, I have chosen the generator with type TGET620 (620 refers to about the housing diameter in mm, the real diameter is 625 mm). The type TGET620-5KW-200R is chosen. A data sheet can be found on the website of the supplier following the path: www.china-topgrand.com – product – Permanent Magnet Generator – Outer Rotor – page 3 – TGET620-5KW-200R.

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 5000 W, so 5 kW at n = 200 rpm. Next it is assumed that the efficiency is 85 % or 0.85 (-). So the required mechanical power is 5000 / 0.85 = 5882 W. The generator has a mass of 110 kg which seems acceptable for the VIRYA-6.

The rated loaded voltage at n = 200 rpm is specified as 380 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 hollow generator shaft. 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 $\sqrt{3}$ lower, so 219.4 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. 2). 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 = 7.6 A at n = 200 rpm. So the rated power generated by one phase is U_f * I = 219.4 * 7.6 = 1667 W. So the rated power generated by three phases is 3 * 1667 = 5001 W. This matches well with the given rated power of 5 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 higher if an oil seal is mounted but it is expected that it is low enough for the VIRYA-6 rotor (see calculation of the starting wind speed in chapter 4).

The generator has a shaft with a diameter of 80 mm. The generator shaft has a 22 mm wide key groove. The front side of the shaft is provided with thread M72 * 2.

The generator housing has a collar with a diameter of 200 mm at the front side. This collar is provided with six threaded holes M12 at a pitch circle of 180 mm. The housing has twelve ribs at the front side and twelve ribs at the back side. Every front rib is provided with three threaded holes M12. These threaded holes are positioned at pitch circles of 300 mm, 400 mm and 500 mm. The maximum diameter of the ribs is 550 mm. The axial distance in between the collar and the ribs is 33 mm.

It is expected that six threaded holes M12 at the collar are not enough to connect the hub assembly to the generator housing. So the threaded holes at a pitch circle of 300 mm are added. As there is an axial distance of 33 mm in between the collar and the ribs, a 33 mm thick, 40 mm wide and 200 mm long aluminium bar is used in between each strip and three ribs. The hub assembly is connected to the generator housing by nine outer bolts M12 * 70 and six inner bolts M12 * 40. Locking liquid has to be used at these bolts. The hub assembly has a flat central part with a radius of 160 mm. The outer parts of the three strips with a length of 345 mm are also flat. Each strip end is twisted 8° right hand in between r = 160 mm and r = 320 mm.

The generator characteristics are given in point 6 of the data sheet. The P_{el}-n curve, the loaded U-n curve and the Q-n curve 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. 7). 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 = 200 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. 8) 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 TGET620-5KW-200R. So for the loaded DC voltage U_{DC} at n = 200 rpm it is valid that U_{DC} = 1.3506 * 380 = 513 VDC. For the open DC voltage U_{open} at n = 200 rpm it is valid that U_{open} = 1.2143 * 1.3506 * 380 = 623 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
20	38	51.3	62.3	50	0.85	59	28	9
40	76	102.6	124.6	200	0.85	235	56	35
60	114	153.9	186.9	450	0.85	529	84	79
80	152	205.2	249.2	800	0.85	941	112	141
100	190	256.5	311.5	1250	0.85	1471	140	221
120	228	307.8	373.8	1800	0.85	2118	168	318
140	266	359.1	436.1	2450	0.85	2882	196	432
160	304	410.4	498.4	3200	0.85	3764	224	564
180	342	461.7	560.7	4050	0.85	4764	252	714
200	380	513	623	5000	0.85	5882	280	882

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 at the performance parameters. 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. 7) 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:

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

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

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

First the values of P_{mech}, P_{heat} and Q are determined for n = 200 rpm. Substitution of P_{el} = 5000 W and η_{gen} = 0.85 in formula 10 gives that P_{mech} = 5882 W. Substitution of P_{mech} = 5882 and P_{el} = 5000 W in formula 11 gives that the heat loss P_{heat} = 882 W. Substitution of P_{mech} = 5882 W and n = 200 rpm in formula 12 gives that Q = 280 Nm. These values are also given in the bottom line of table 3.

In the figure at point 6 of the specification it can be read that Q is about 250 Nm at n = 200 rpm. If this is true, it would mean that the efficiency is much higher than 0.85 which I don’t believe. So it is assumed that the calculated torque Q = 280 Nm at n = 200 rpm is right.

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.

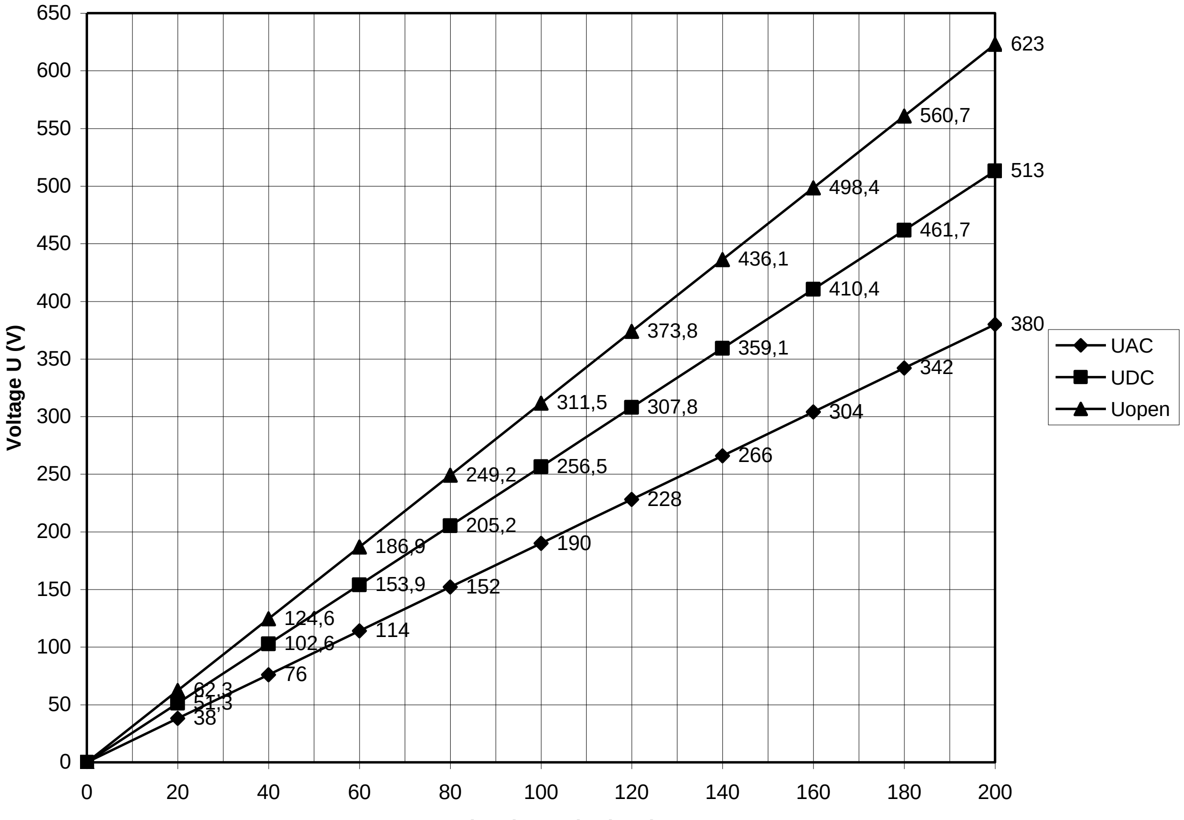

fig. 5 U_{AC}, U_{DC} and U_{open} as a function of n for a resistance load

The Q-n curve is given in figure 6. Figure 6 also contains the curve for U = 513 V DC and for short-circuit in star.

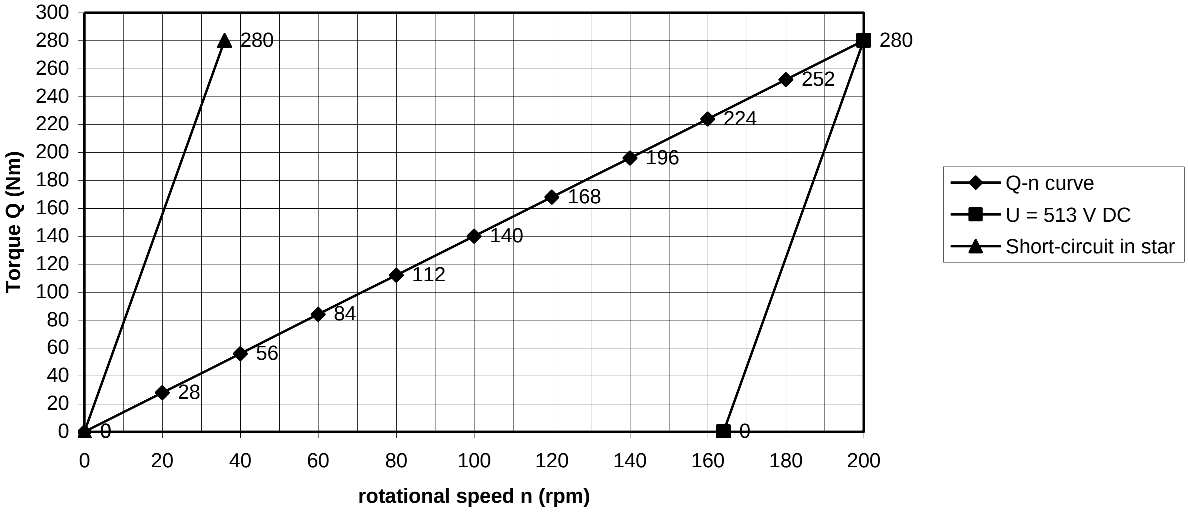

fig. 6 Loaded torque Q as a function of n for a resistance load, Q-n curves for 513 V DC and for short-circuit in star

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 7.3 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 7.3 m/s, the optimum cubic line is lying a little higher than for the given resistance load and so the efficiency is somewhat lower than for a resistance load. First it is assumed than an inverter is used and 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 = 200 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 = 219.4 V. The line current I = 7.6 A at n = 200 rpm. So according to the law of Ohm, the resistance R is given by R = U / I or R = 219.4 / 7.6 = 28.87 Ω.

If three resistors are used as load, the winding of one phase is used for all the time to generate power. This power in one phase varies according to a $\sin^2\alpha$ function. The power fluctuation is given in figure 2 of report KD 340 (ref. 2). 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 5 kW at n = 200 rpm.

In the last column of table 3 it can be seen that the heat losses are maximal for n = 200 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 = 200 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 200 rpm up to at least the rated torque Q = 280 Nm which is valid for n = 200 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 = 5882 W and n = 200 rpm is also drawn in figure 4. The line is extended to the right up to a power of 6000 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 whole optimum cubic line is lying lower than the line for the rated torque. But the generator can supply a maximum torque which is even a lot higher than the rated torque of 280 Nm. This is an indication that the generator is strong enough for the VIRYA-6 rotor and the pendulum safety system with a torsion spring and with a rated wind speed of 10 m/s.

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 about 7.3 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 η_{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 almost 4 kW at a wind speeds of 10 m/s and higher which is very good for a windmill with a rotor diameter of 6 m and a rated wind speed of 10 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-6.

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} = 162 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 3 m/s. So the rotor will turn almost always but it will generate no power for 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} = 746 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 162 W. The power for V = 7 m/s is 2040 W. The average power is (162 + 2040) / 2 = 1101 W. This is 355 W more or a factor 1101 / 746 = 1.48 higher than for a constant wind speed of 5 m/s.

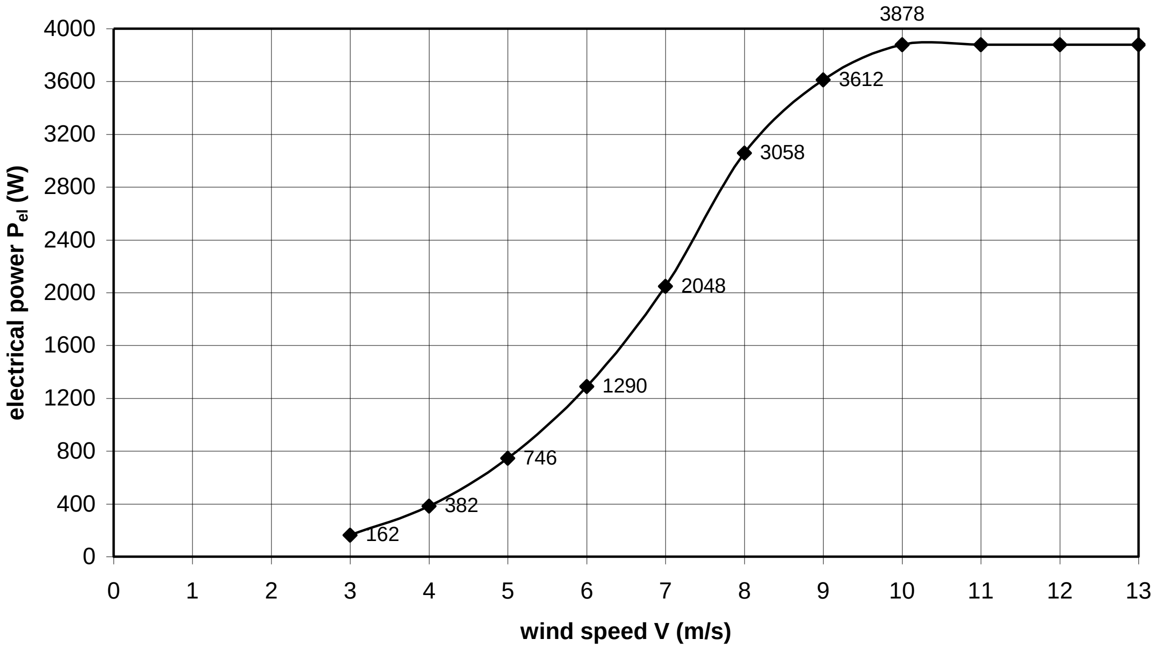

fig. 7 P_{el}-V curve for an inverter load such that the optimum cubic line is followed for 3 m/s < V < 10 m/s

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 and for a resistance load with the correct resistance. 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. 7) 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-6 generator.

In figure 5 it can be seen that the loaded DC voltage U_{DC} = 513 V DC at n = 200 rpm. The unloaded open DC voltage U_{open} = 623 V at n = 200 rpm. As the U-n curves are straight lines through the origin, it can be read that U_{open} = 513 V DC at n = 164 rpm. This is 36 rpm lower than n_{rated} = 200 rpm. Next it is assumed that Q-n line for a constant DC voltage of 513 V is a straight line in between the point Q = 0 Nm and n = 164 rpm and the point Q = 280 Nm and n = 200 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 513 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 = 280 Nm and n = 36 rpm. This curve is also given in figure 6.

Formula 12 can be written as:

$P_{mech} = Q * \pi * n / 30$ (W) (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 4 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 56 rpm and the Q-n and P-n curves are extended up to this rotational speed. For higher rotational speeds than about 56 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 56 rpm.

n (rpm)	Q (Nm)	P (W)
0	0	0
4	31.1	13
8	62.2	52
12	93.3	117
16	124.4	208
20	155.6	326
24	186.7	469
28	217.8	639
32	248.9	834
36	280	1056
40	311.1	1303
44	342.2	1577
48	373.3	1876
52	404.4	2202
56	435.6	2554

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 56 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.

7 Using of a resistance as load for heating

Instead of using an inverter, it is also possible to use a resistance as load. The generated power in the resistance can be used for heating of a room. Assume that the same resistance is used as used for the measurements of the manufacturer. So this means that the P_{mech}-n and P_{el}-n curves for a resistance load as given in figure 4 are followed. The matching is good for wind speeds in between 6 m/s and 10 m/s because the working point is lying close to the optimum cubic line. However, the P_{mech}-n curve is about touching the P-n curve of the rotor for V = 5 m/s. This means that the load is too strong at low wind speeds and the rotor will slow down to almost stand still for a wind speed below 5 m/s. The rotor will certainly not start with the load connected. This problem can be solved by connecting the load at about 120 rpm (reached unloaded at about V = 4 m/s) and disconnecting the load at about 80 rpm.

However, this has as disadvantage that no power is generated for wind speeds below 4 m/s. This problem can be solved by using a star-delta switch and a higher value for the load resistance. The generator winding is now connected in star for low rotational speeds and connected in delta for high rotational speeds.

At page 12 it has been calculated that the resistance use by the manufacturer is 28.87 Ω if the load resistors are connected in star. The load resistance must be a factor three higher, so 86.61 Ω, to generate the same power if the resistors are connected in delta. This follows directly from the law of Ohm as the power is given by $P = U^2 / R$ (W). The AC voltage over one resistor is a factor √3 higher in delta than in star. The voltage in between two phases U = 380 V for n = 200 rpm. So the power in one phase is $380^2 / 86.61 = 1667$ W. So the power of three resistors is 3 * 1667 = 5001 W. This is the same as for three resistors of 28.87 Ω connected in star. So this will also result in the same P_{mech}-n and P_{el}-n curves.

However, if three 86.61 Ω resistors are connected in star, the load resistance is a factor three higher than for three 28.87 Ω resistors connected in star and the required mechanical power will therefore be a factor three lower. This will give an acceptable matching for low wind speeds. The matching at low rotational speeds can better be checked in the Q-n curve than in the P-n curve because the P-n curves for low rotational speeds all go to zero for n = 0 rpm. The Q-n curves are made in the same way as the P-n curves but the C_q-λ curve and the formula for the torque Q have to be used. The C_q-λ curve is given in figure 3. The Q-n curves are made for wind speeds up to 8 m/s for which the rotor is still perpendicular to the wind, so δ = 0°. The formula for Q is given as formula 4.3 of report KD 35. Substitution of $\rho = 1.2$ kg/m^3 and R = 3 m in this formula gives formula 14.

$$Q = 50.894 * C_q * V^2 \qquad \text{(Nm)} \qquad (14)$$

Formula 8 for δ = 0° changes into:

$$n = 3.1831 * \lambda * V \qquad \text{(rpm)} \qquad (15)$$

The result of the calculations is given in table 5.

		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°	
λ	C_q	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)
0	0.0089	0	4.1	0	7.2	0	11.3	0	16.3	0	22.2	0	29.0
1	0.011	9.5	5.0	12.7	9.0	15.9	14.0	19.1	20.2	22.3	27.4	25.5	35.8
2	0.02	19.1	9.2	25.5	16.3	31.8	25.4	38.2	36.6	44.6	49.9	50.9	65.1
3	0.0433	28.6	19.8	38.2	35.3	47.7	55.1	57.3	79.3	66.8	108.0	76.5	141.0
4	0.07	38.2	32.1	50.9	57.0	63.7	89.1	76.4	128.3	89.1	174.6	102.1	228.0
5	0.08	47.7	36.6	63.7	65.1	79.6	101.8	95.5	146.6	111.4	199.5	127.6	260.6
6	0.0733	57.3	33.6	76.4	59.7	95.5	93.3	114.6	134.3	133.7	182.8	153.1	238.8
7	0.0571	66.8	26.2	89.1	46.5	111.4	72.7	133.7	104.6	156.0	142.4	178.6	186.0
8	0.035	76.4	16.0	101.9	28.5	127.3	44.5	152.8	64.1	178.3	87.3	204.1	114.0
9	0.0133	85.9	6.1	114.6	10.8	143.2	16.9	171.9	24.4	200.5	33.2	229.6	43.3
9.6	0	91.7	0	122.2	0	152.8	0	183.3	0	213.9	0	244.9	0

table 5 Calculated values of n and Q as a function of λ and V for the VIRYA-6 rotor

The Q-n curves derived from table 5 are given in figure 8. The optimum parabola which can be drawn through the points for λ = 6 is also given in figure 8. The torque for a resistance load is given in table 3 and figure 6. This is a straight line through the origin and is given for three 28.87 Ω resistors connected in star. The same line is found for three 86.61 Ω resistors connected in delta. The line for three 86.61 Ω resistors connected in delta is also given in figure 8. The line for three 86.61 Ω resistors connected in star is laying a factor 3 lower. This line is also given in figure 8.

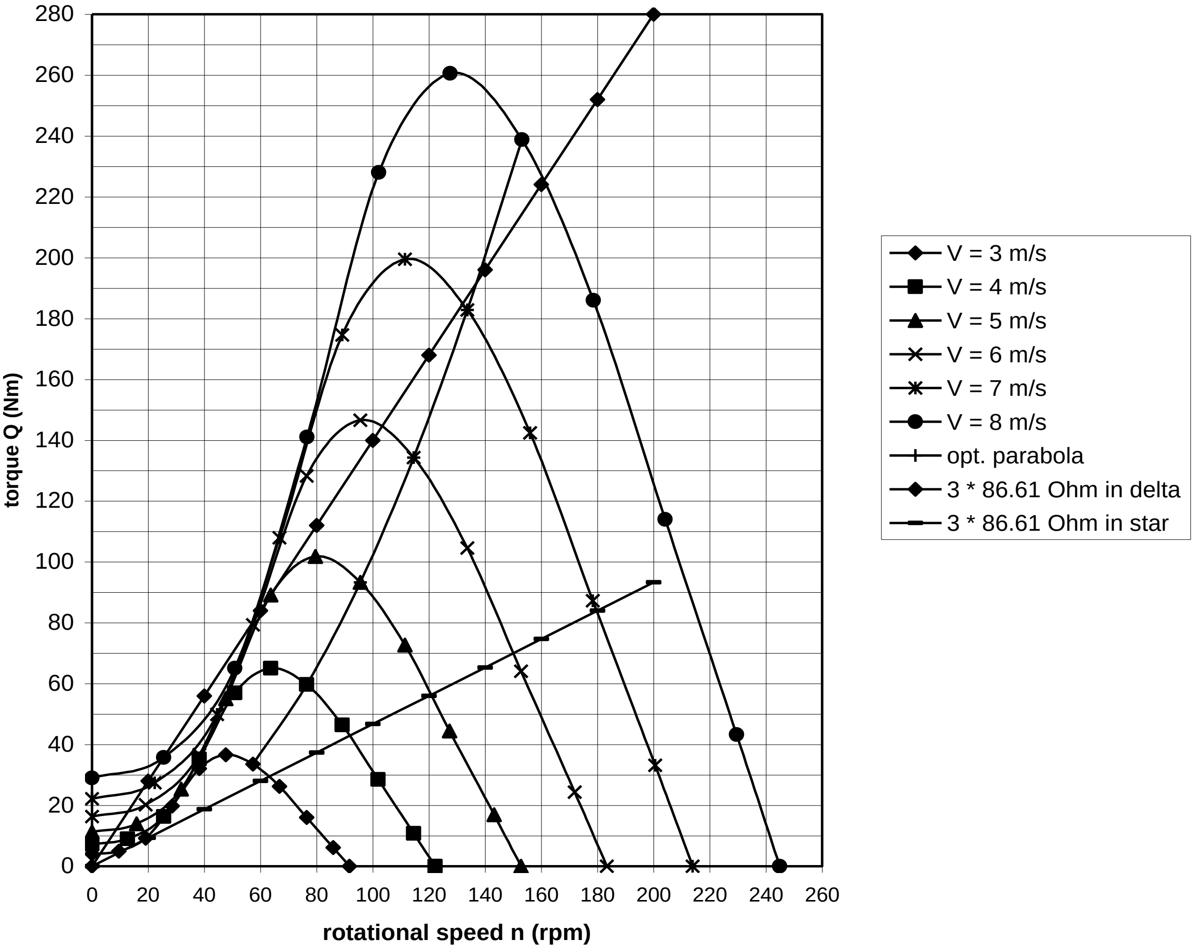

fig. 8 Q-n curves of the VIRYA-6 rotor, optimum parabola

In figure 8 it can be seen that the line for 86.61 Ω for connection in delta is about touching the Q-n curve of the rotor for V = 5 m/s at a rotational speed of about 60 rpm. However, for rotational speeds in between about 25 rpm and 55 rpm it is lying even higher than the Q-n curve of the rotor for V = 8 m/s. This means that if the rotor starts from stand still position, it will reach only a rotational speed of about 25 rpm at V = 8 m/s and so it will not accelerate to rotational speeds for which a stable working point is reached.

In figure 8 it can be seen that the line for 86.61 Ω for connection in star is about touching the Q-n curve of the rotor for V = 3 m/s at a rotational speed of about 15 rpm. So the rotor will start at a wind speed of 3 m/s if the 86.61 Ω load connection in star is connected to the generator at stand still position. It will reach a stable working point at V = 3 m/s for a rotational speed of about 63 rpm. This stable working point is lying close to the optimum parabola.

Next it is assumed that it is switched from star to delta if a rotational speed of 100 rpm is reached. This rotational speed belongs to a wind speed of about 4.3 m/s. So at this point, the torque increases from about 47 Nm up to about 140 Nm. This torque can’t be supplied at a wind speed of 4.3 m/s and so the rotational speed will slow down. Next it is assumed that it is switched back from delta to star at a rotational speed of 60 rpm. So for moderate wind speeds the connection is switched in between star and delta. For higher wind speeds delta connection is maintained. This results in a positive power for wind speeds higher than 3 m/s and so a star delta switch is a good option to prevent loss of power at low wind speeds.

It might be possible to rectify the 3-phase current and to develop an electronic circuit and a dump load with three resistors of different resistance values. The electronic circuit switches the resistors such that the optimum parabola is about followed.

Building of a prototype of the VIRYA-6 with the chosen PM-generator of Hefei Top Grand is only possible if a composite drawing is made and if detailed drawings are available. This includes detailed drawings of the rotor, the head with the vanes and torsion springs and the tower plus foundation but I won't make them.

If the wind turbine is used for grid connection, the right inverter has to be found. If the wind turbine is used for direct generation of heat, one has to design a controller and a heat capacitor with a water reservoir in which the load resistors are imbedded. The hot water out of the heat capacitor has to be guided in the correct way to the radiators in the living room for which the generated energy of the wind turbine is used. The main disadvantage of a resistance load is that the generated power can only be used for heating. Further development of such a system is a lot of work. So only companies with enough engineering and manufacturing capacity should start with the VIRYA-6. The VIRYA-6 is certainly not a windmill which can be built by an amateur.

8 References

1 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.

2 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.

3 Kragten A. The Gö 711 airfoil for use in windmill rotor blades, June 2006, reviewed July 2021, free public report KD 285, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 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.

5 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.

6 Kragten A. Measurements on a Chinese axial flux generator of Hefei Top Grand model TGET-165-0.14 kW-500R for a 12 V battery load, September 2015, reviewed December 2021, free public report KD 595, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Kragten A. Measurements performed on a generator with housing 5RN90L04V and a 4-pole armature equipped with neodymium magnets, March 2011, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Ideas about the use of the 3-bladed VIRYA-3B3 rotor (λ_d = 6.5) in combination with the axial flux generator of Hefei Top Grand type TGET320-1KW-350R for 48 V battery charging, August 2020, free public report KD 705, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.