Calculations executed for the 3-bladed rotor of the VIRYA-4S windmill (λ_d = 4.25, galvanised steel blades) for connection to the generator type PMG380-I-5KW-500R or PMG380-I-3KW-300R for 48 V battery charging, water pumping or grid connection

ing. A. Kragten

February 2025
reviewed August 2025

KD 776

Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

Contains page

1 Introduction

The VIRYA-4S has a 3-bladed rotor with galvanised steel blades and a design tip speed ratio λ_d = 4.25. The VIRYA-4S is an alternative for the 2-bladed VIRYA-4.2 with wooden blades and a design tip speed ratio λ_d = 8. The VIRYA-4.2 uses a radial flux PM-generator which is made from an asynchronous motor. The VIRYA-4S uses a Chinese axial flux PM-generator of manufacture Hefei Top Grand type PMG380-I-5KW-500R. Both wind turbines make use the same head and the same tower. However, the generator bracket of the head is modified to fit to the axial flux generator. The VIRYA-4S is meant for 48 V battery charging if the generator winding is rectified in star. It might also be possible to use the VIRYA-4S for grid connection or for driving the electric motor of a pump.

The windmill is provided with the so called hinged side vane safety system which results in a rated wind speed of about 9.5 m/s for the VIRYA-4.2. As the rotor diameter of the VIRYA-4S is smaller, it is expected that the rated wind speed is a little higher and so it is expected that V_{rated} = 10 m/s for the VIRYA-4S.

2 Description of the rotor of the VIRYA-4S windmill

The 3-bladed rotor of the VIRYA-4S windmill has a diameter D = 4 m and a design tip speed ratio λ_d = 4.25. The main advantages of a 3-bladed rotor are that gyroscopic moment in the rotor shaft isn't fluctuating and that a 3-bladed rotor looks better than a 2-bladed one.

The rotor has blades with a constant chord and no blade twist and is provided with a 7.14 % cambered airfoil. A starting point for the rotor geometry is that twelve blades for four rotors can be made from a standard 3 mm thick galvanised steel sheet size 1.5 * 3 m. This results in a strip width of 3000 / 12 = 250 mm. Mostly a sheet is somewhat longer than 3000 mm and so one has to be alert that the last strip also has a width of 250 mm. The 250 mm wide strips are 7.14 % cambered. The chord c is a little less than the strip width and is about 247 mm = 0.247 m. A press for cambering has still to be developed.

The spoke assembly is formed by three steel strips size 100 * 8 mm with each a length of 750 mm which are welded together at the centre under an angle of 120°. The outer 250 mm of a spoke is cambered with the same radius as the blade. A 250 mm long strip size 50 * 6 mm is welded square to the outside of a spoke. This strip is also cambered with the same radius as the blade. So the overlap in between a blade and a spoke is 300 mm resulting in a free blade length of 1200 mm. This free blade length in combination with a sheet thickness of 3 mm must be short enough to prevent blade flutter at high tip speeds. A blade is connected to a spoke by five bolts M12 * 45 and five self locking nuts M12.

The generator has a shaft with a diameter of 50 mm and a length of 94 mm. At the end of this shaft there is a threaded part with thread M42 * 1.5 and a length of 33 mm. The shaft has a 10 mm wide and 50 mm long key groove. The housing has a collar with a diameter of 140 mm at each side. Ten threaded holes M12 at a pitch circle of 120 mm are made in each collar. The ten threaded holes at the back side of the hub are used to connect the generator to the generator bracket of the head.

The hub is made out of a piece of stainless steel bar with a diameter of 100 mm and a length of 80 mm. The hub has a central inside hole of 50 mm and a 10 mm wide key groove. The spoke assembly has a 42 mm central hole. The spoke assembly is clamped in between the hub and a 9 mm thick disk by three inner hexagon bolts M12 * 110 and three self locking nuts M12. The axial fixation of the hub is realised by a special nut M42 * 1.5. The rotor is balanced by adding balancing weights at the two connecting bolts. After balancing, the blades, the spokes, and the balancing weights and are marked. The total mass of the rotor including the hub is about 46 kg which is acceptable for a steel rotor with a diameter of 4 m.

The rotor is balanced by balancing weights which are mounted under the connecting bolts of the blades. The blades, the balancing weights and the spoke assembly are marked after balancing.

3 Calculation of the rotor geometry (see figure 1)

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 1). This report (KD 776) has its own formula numbering. Substitution of $\lambda_d = 4.25$ and R = 2 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 2.125 * r$ (-) (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 = 0.247 m in formula (5.4) of KD 35 gives:

$C_l = 33.917\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5.5 m/s and c = 0.247 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.906 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.3 m of one to another. The blade has a constant chord and the calculations therefore correspond to 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 zero 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 a 7.14 % cambered airfoil are given in report KD 398 (ref. 2). The inner part of a blade is disturbed because of the spoke but it is assumed that the characteristics of the 7.14 % cambered airfoil can also be used for this part of the blade. The Reynolds values for the stations are calculated for a wind speed of 5.5 m/s because this is a reasonable wind speed for a windmill with V_{rated} = 10 m/s. The Reynolds numbers are used which are lying closest to the calculated values.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\ th}$ (-)	$C_{l\ lin}$ (-)	$R_{e\ r} * 10^{-5}$ V = 5.5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\ lin}$ (-)
A	2	4.25	8.8	0.247	0.80	0.79	3.90	3.4	0.2	0.1	8.6	8.7	0.036
B	1.7	3.6125	10.3	0.247	0.93	0.93	3.33	3.4	1.6	1.6	8.7	8.7	0.036
C	1.4	2.975	12.4	0.247	1.11	1.11	2.76	2.5	3.7	3.7	8.7	8.7	0.039
D	1.1	2.3375	15.4	0.247	1.35	1.36	2.20	2.5	6.6	6.7	8.8	8.7	0.068
E	0.8	1.7	20.3	0.247	1.69	1.43	1.65	1.7	-	11.6	-	8.7	0.13
F	0.5	1.0625	28.8	0.247	2.10	1.26	1.14	1.2	-	20.1	-	8.7	0.34

table 1 Calculation of the blade geometry of the VIRYA-4S rotor

No value for α_{th} and therefore for β_{th} is found for station E and F because the required C_l values can't be generated. The theoretical blade angle β_{th} for stations A up to D varies in between 9.6° and 8.8°. If a constant blade angle of 8.7° is chosen for the whole blade, the linearised blade angles β_{lin} and the linearised angles of attack α_{lin} are lying close to the theoretical values for the most important outer part of the blade. Each spoke is twisted 8.7° right hand in between the hub and the blade root. A sketch of the rotor is given in fig. 1.

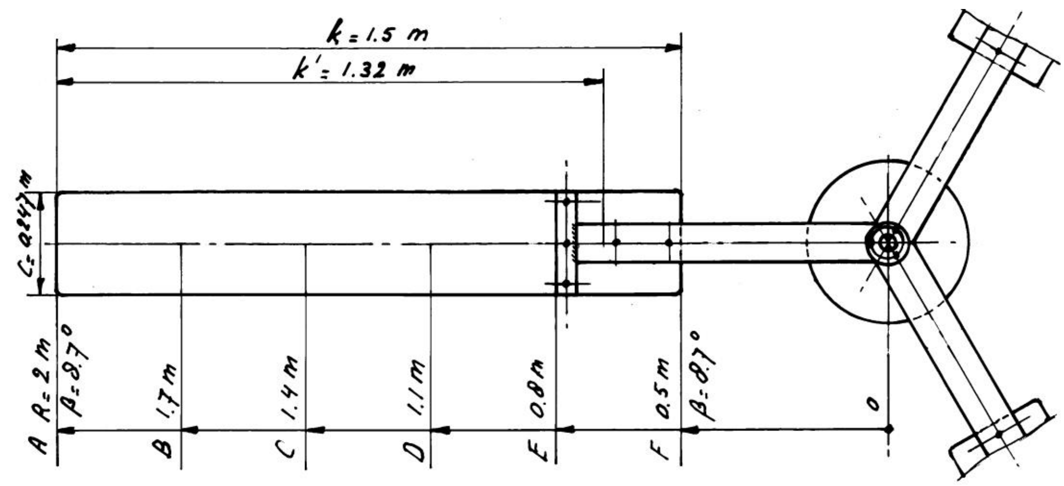

fig. 1 Sketch of the VIRYA-4S rotor

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 0.04. Figure 4.7 of KD 35 (for B = 3) and λ_{opt} = 4.25 and C_d/C_l = 0.04 gives $C_{p\ th}$ = 0.43. The blade stalls in between station E and F. Therefore not the whole blade length k = 1.5 m, but only the part up to 0.18 m outside station F is used for the calculation of the C_p. This gives an effective blade length k' = 1.32 m.
Substitution of $C_{p\ th}$ = 0.43, R = 2 m and blade length k = k' = 1.32 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.38. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.38 / 4.25 = 0.0894.
Substitution of $\lambda_{opt} = \lambda_d$ = 4.25 in formula 6.4 of KD 35 gives λ_{unl} = 6.8.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \quad (-) \qquad (6)$$

The blade angle is chosen 8.7° for the whole blade. For a non rotating rotor, the average angle of attack α is therefore 90° - 8.7° = 81.3°. The C_l-α curve isn't given for large angles of α for the 7.14 % cambered airfoil. However, during starting the whole blade is stalling and therefore it is assumed that the curve of the 10 % cambered airfoil can be used. The C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 81.3° it can be read that C_l = 0.29. The whole blade is stalling during starting. Therefore now the real blade length k = 1.5 m is taken. Substitution of B = 3, R = 2 m, k = 1.5 m, C_l = 0.29 and c = 0.247 m in formula 6 gives that $C_{q\ start}$ = 0.012. For the ratio in between the starting torque and the optimum torque we find that it is 0.012 / 0.0894 = 0.134. This is good for a rotor with a design tip speed ratio of 4.25. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3} \right)} \quad (m/s) \qquad (7)$$

For the generator it is mentioned by the manufacturer that the sticking torque is less than 0.3 Nm. However, this is the case if no oil seal is mounted at the shaft. This is allowed if the shaft is vertical but for a horizontal shaft, a seal is certainly required to prevent the entrance of water. Assume that the sticking torque with a seal is 1 Nm. Substitution of Q_s = 1 Nm, $C_{q\ start}$ = 0.012, ρ = 1.2 kg/m^3 and R = 2 m in formula 7 gives that V_{start} = 2.4 m/s. This is very low for a 3-bladed rotor with a design tip speed ratio of 4.25.

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 a S-shaped line which is horizontal for $\lambda = 0$. Kragten Design has developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 3). With this method, it can be determined that the C_q-λ curve is about horizontal for low values of λ if a Gö 711 airfoil is used. A scale model of a 3-bladed wooden rotor with constant chord blades and a design tip speed ratio of 6 has been tested in the wind tunnel already in about 1984 and it was found that the C_q-λ curve is slightly rising at low values of λ. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-4S rotor are given in figure 2 and 3.

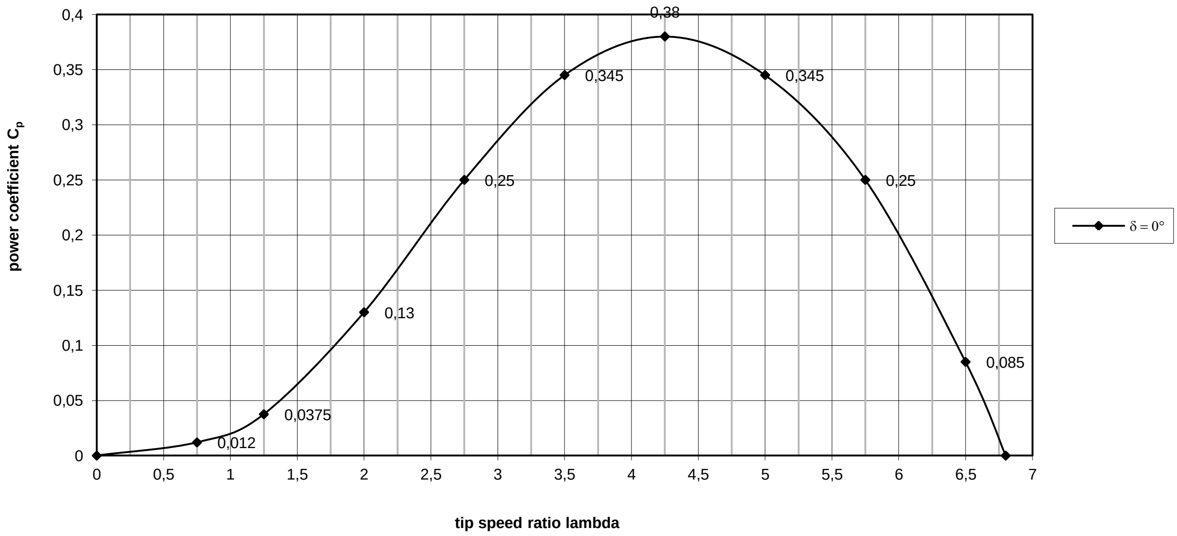

fig. 2 Estimated C_p-λ curve for the VIRYA-4S rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

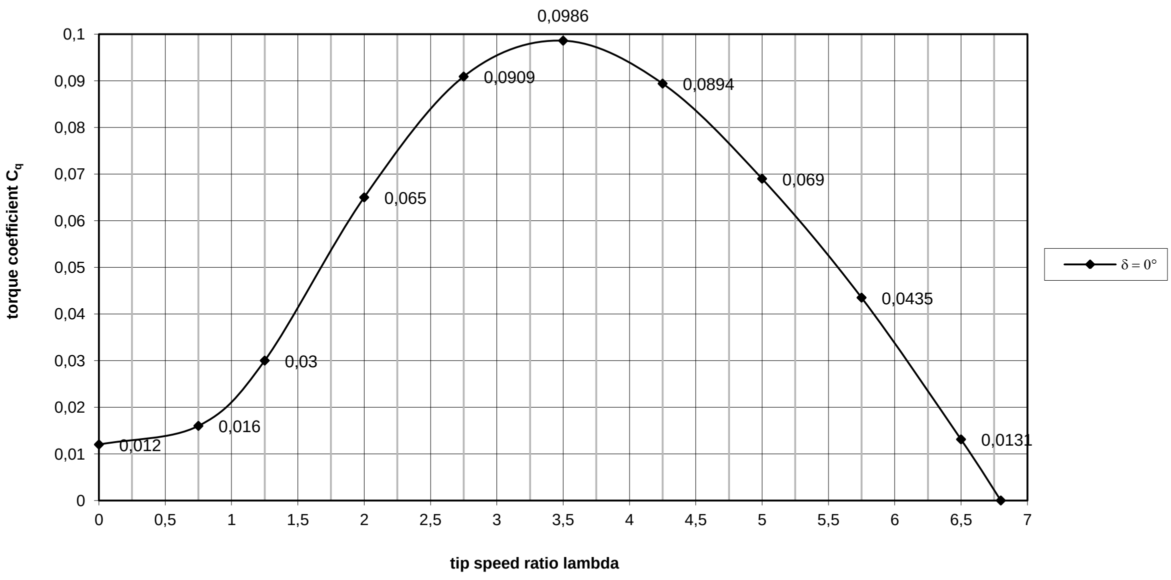

fig. 3 Estimated C_q-λ curve for the VIRYA-4S rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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 a 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 1. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 9 mm meranti plywood. In report KD 213 (ref. 4) a method is given to check the estimated δ-V curve and the estimated δ-V curve of the VIRYA-4.2 windmill is checked as an example. The estimated and calculated curves appear to lie very close to each other so it is allowed to use the estimated curve. The estimated δ-V curve is given in figure 4.

The head starts to turn away at a wind speed of about 6 m/s. For wind speeds above 10 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 10 m/s will therefore also be valid for wind speeds higher than 10 m/s.

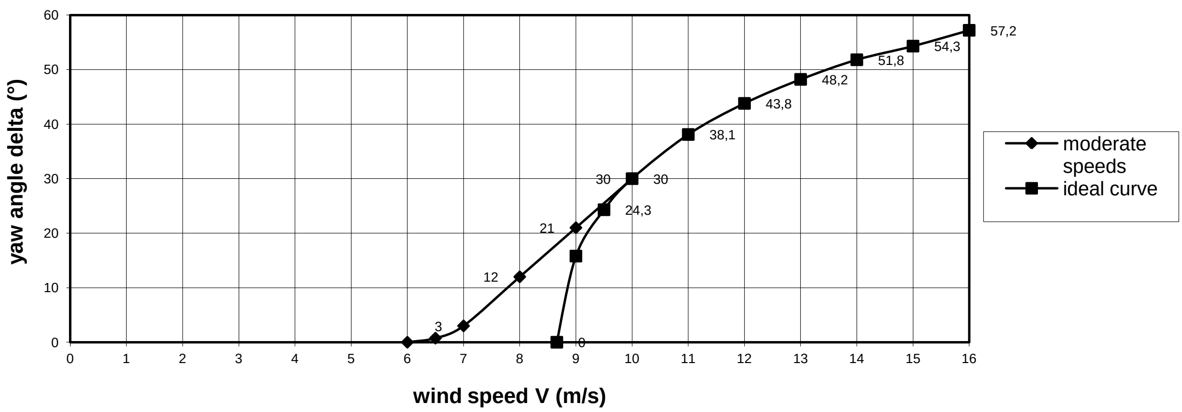

fig. 4 δ-V curve VIRYA-4S safety system with V_{rated} = 10 m/s

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-4S 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. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 2 m in formula 7.1 of KD 35 gives:

$$n_\delta = 4.7746 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of ρ = 1.2 kg / m^3 and R = 2 m in formula 7.10 of KD 35 gives:

$$P_\delta = 7.5398 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ is 2, 2.75, 3.5, 4.25, 5, 5.75, 6.5 and 6.8 (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. For the higher wind speeds the yaw angle as given by figure 4, is taken into account. 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 = 3°		V = 8 m/s δ = 12°		V = 9 m/s δ = 21°		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_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2	0.13	28.6	26	38.2	63	47.7	123	57.3	212	66.8	335	74.7	470	80.2	581	82.7	637
2.75	0.25	39.4	51	52.5	121	65.7	236	78.8	407	91.8	644	102.7	903	110.3	1118	113.7	1224
3.5	0.345	50.1	70	66.8	166	83.6	325	100.3	562	116.8	889	130.8	1246	140.4	1543	144.7	1690
4.25	0.38	60.9	77	81.2	183	101.5	358	121.8	619	141.8	979	158.8	1373	170.5	1700	175.7	1861
5	0.345	71.6	70	95.5	166	119.4	325	143.2	562	166.9	889	186.8	1246	200.6	1543	206.7	1690
5.75	0.25	82.4	51	109.8	121	137.3	236	164.7	407	191.9	644	214.8	903	230.7	1118	237.8	1224
6.5	0.085	93.1	17	124.1	41	155.2	80	186.2	128	216.9	219	242.9	307	260.8	380	268.8	416
6.8	0	97.4	0	129.9	0	162.3	0	194.8	0	227.0	0	254.1	0	272.8	0	281.2	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-4S rotor

The calculated values for n and P are plotted in figure 5. The optimum cubic line which is going through the maximum of the P-n curves is also given in figure 5.

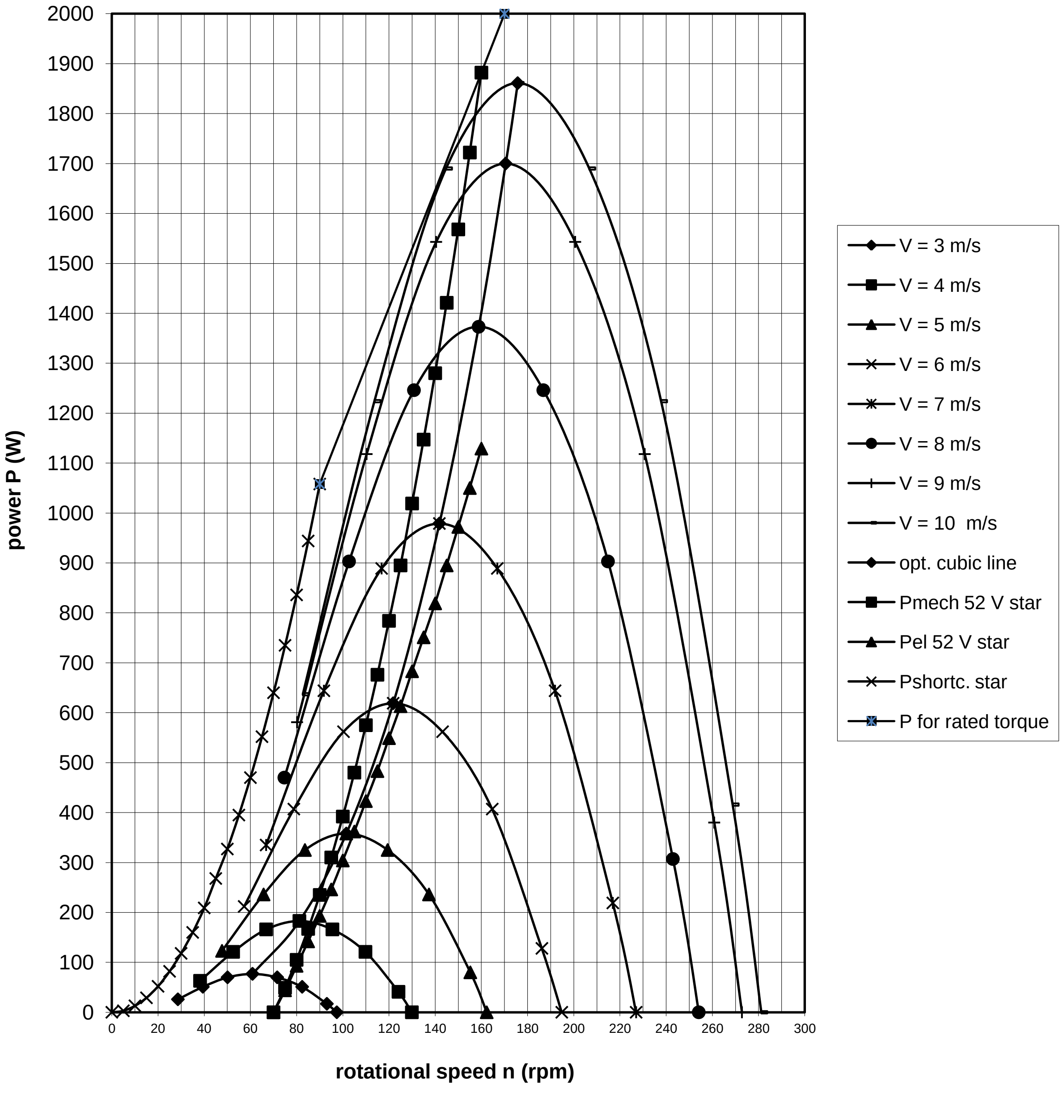

fig. 5 P-n curves of the VIRYA-4S rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves of the generator for 52 V star, P-n curve for short-circuit in star and for rated torque

6 Derivation of the generator characteristics

For checking of the matching in between rotor and generator and for the determination of the P_{el}-V curve, measured P_{mech}-n and P_{el}-n curves of the generator for a 48 V battery load are needed. A 48 V battery is charged at an average charging voltage of about 52 V so the P_{mech}-n curve and the P_{el}-n curve should have been measured for this constant voltage. However, Hefei Top Grand supplies only a P_{el}-n curve for a resistance load. The resistance R is chosen that high that the electrical power is 5 kW = 5000 W at a rotational speed of 500 rpm and a loaded alternating voltage of 220 VAC. But the characteristics for a resistance load differ very much from the characteristics for a constant voltage. So the characteristics for a constant voltage of 52 V have to be estimated to check the matching in between rotor and generator. This is done in chapter 7.

My PM-generator using a motor housing 5RN90L04V has been measured for different load conditions. The measurements are given in report KD 78 (ref. 5). The measurements for a constant resistance are given at chapter 7 and 9 of KD 78. The unloaded U-n curve is a straight line through the origin (see KD 78 figure 1) but it can be derived that the U-n curve and the Q-n curve for a resistance load are also about straight lines through the origin. Figure 31 and figure 32 of KD 78 show that the P_{mech}-n and P_{el}-n curves are about parabolas if the torque is not close to the maximum torque level which the generator can supply. This is in accordance with the U_{AC}-n and P_{el}-n curves given at point 6 of the data sheet of Hefei Top Grand. These curves give measuring points every 50 rpm but the values of the measuring points are not given. So these curves are estimated from the given values at n = 500 rpm.

The winding is a 3-phase winding connected in star. The star point is lying internal so only the three phase wires are coming through the hollow generator shaft. The given voltage is the alternating voltage U_{AC} in between two of the three phases. For battery charging, 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. 6) 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 PMG380-5KW-500R. So for the loaded DC voltage U_{DC} at n = 500 rpm it is valid that $U_{DC} = 1.3506 * 220 = 297$ VDC. For the open DC voltage U_{open} at n = 500 rpm it is valid that $U_{open} = 1.2143 * 0.955 * \sqrt{2} * 220 = 361$ 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
50	22	29.7	36.1	50	0.85	59	11.23	9
100	44	59.4	72.2	200	0.85	235	22.46	35
150	66	89.1	108.3	450	0.85	529	33.69	79
200	88	118.8	144.4	800	0.85	941	44.92	141
250	110	148.5	180.5	1250	0.85	1471	56.15	221
300	132	178.2	216.6	1800	0.85	2118	67.38	318
350	154	207.9	252.7	2450	0.85	2882	78.61	432
400	176	237.6	288.8	3200	0.85	3765	89.84	565
450	198	267.3	324.9	4050	0.85	4765	101.07	715
500	220	297	361	5000	0.85	5882	112.3	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. 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. 5) 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:

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

$P_{heat} = P_{mech} - P_{el}$ (W) (11)

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

First the values of P_{mech}, P_{heat} and Q are determined for n = 500 rpm. Substitution of P_{el} = 5000 W and η_{gen} = 0.85 in formula 1 gives that P_{mech} = 5882 W. Substitution of P_{mech} = 5882 and P_{el} = 5000 W in formula 2 gives that the heat loss P_{heat} = 882 W. Substitution of P_{mech} = 5882 W and n = 500 rpm in formula 3 gives that Q = 112.3 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 6.

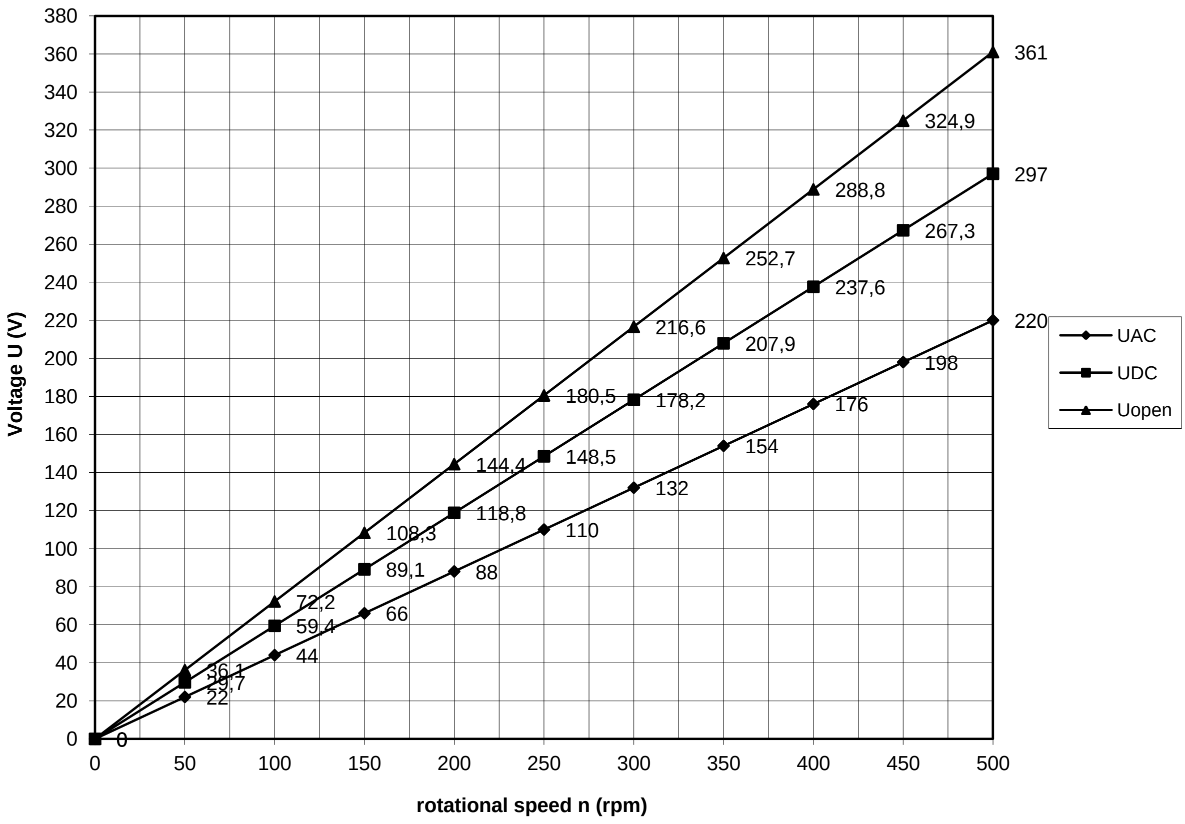

fig. 6 U_{AC}, U_{DC} and U_{open} as a function of n for a resistance load

The P_{mech}-n and the P_{el}-n curves are given in figure 7.

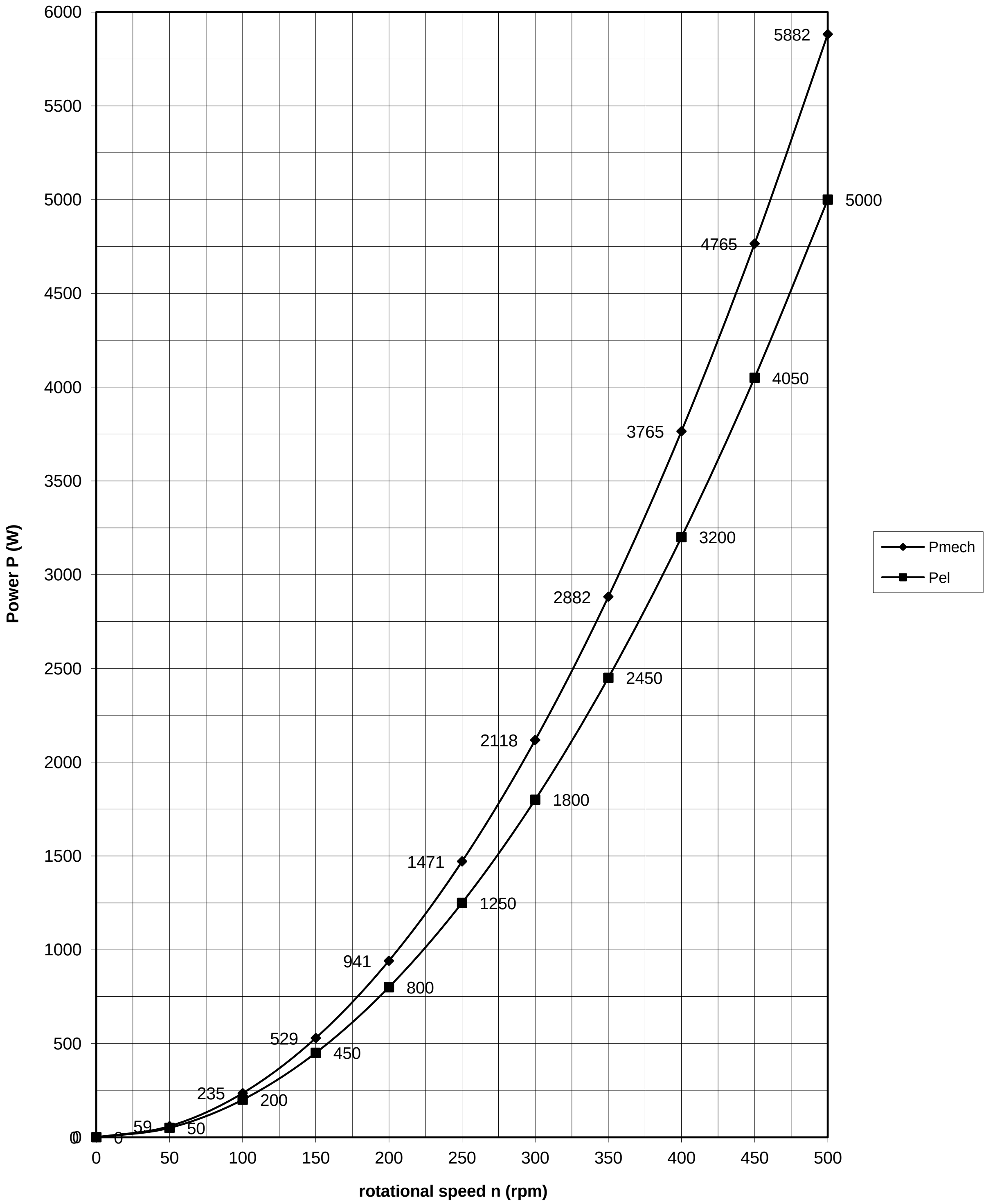

fig. 7 P_{mech} and P_{el} as a function of n for a resistance load

The Q-n curve is given in figure 8.

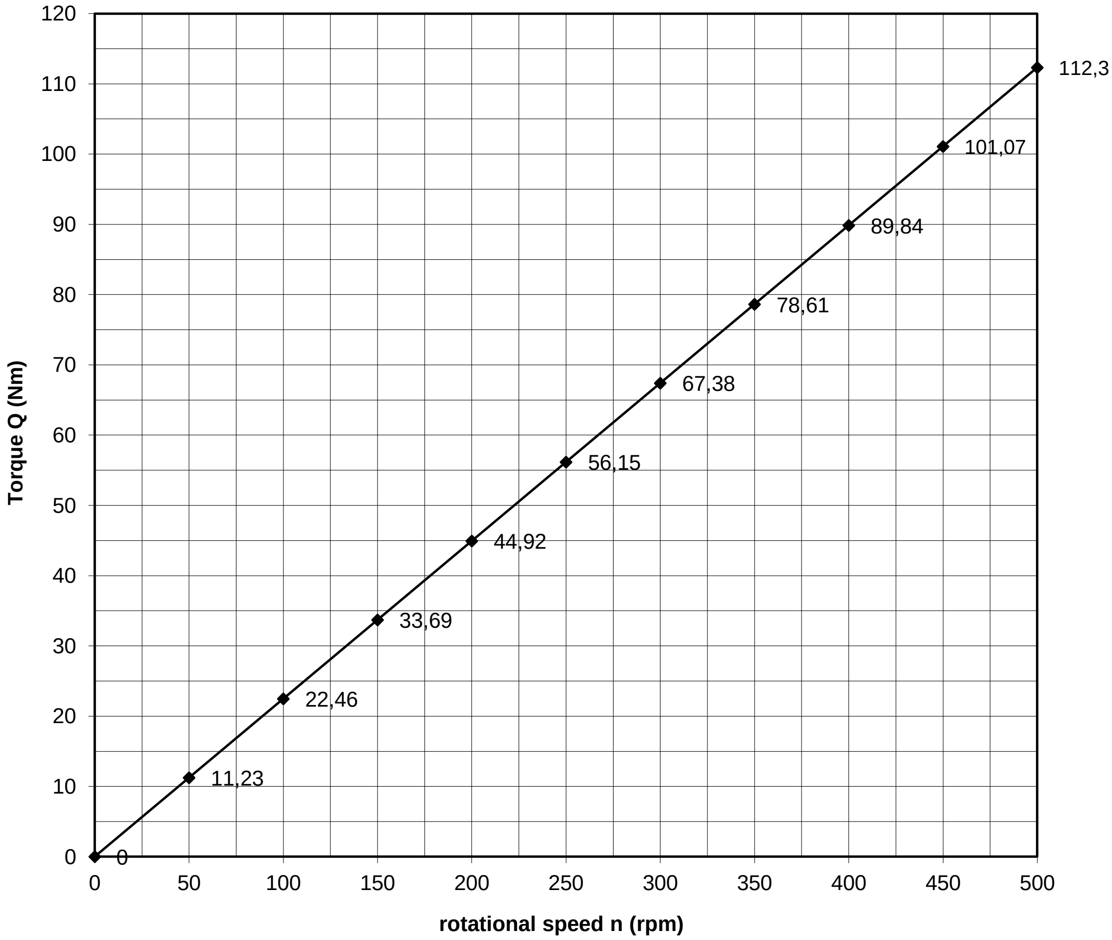

fig. 8 Loaded torque Q as a function of n for a resistance load

So figure 6, 7 and 8 are based on the manufactures specification for a resistance load at n = 500 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 given UC voltage is the voltage in between two of the three phases. The phase voltage U_f is a factor √3 lower and so it is 220 / √3 = 127.02 V. The voltage over one resistor is equal to the phase voltage. The current I = 13.12 A at n = 500 rpm. So according to the law of Ohm, the resistance R is given by R = U / I or R = 127.02 / 13.12 = 9.68 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. 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° < α < 150° and for 210 < α < 330°. This means that no power is generated for 0° < α < 30°, for 150° < α < 210° and for 330° < α < 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 = 500 rpm.

7 Determination of the P_{mech}-n and the P_{el}-n curves for 52 V star

If this generator is used for 48 V battery charging, it is used at much lower rotational speeds than the nominal rotational speed of 500 rpm. It is assumed that the average charging voltage for a 48 V lead acid battery is 52 VDC. So P_{mech}-n and P_{el}-n curves for 52 V star are needed to check the matching in between rotor and generator and to derive the P_{el}-V curve. The best way is to buy a generator and to test it on a large accurate test rig. I have used the test rig of the University of Technology Eindhoven to test the original VIRYA-4.2 generator. But obtaining the generator and hiring of the test rig is expensive and I won't do that. So it is tried to estimate the wanted characteristics from the curves as given in chapter 6.

The PM-generator which is used for the measurements as given in KD 78 (ref. 5) 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 52. 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. The phenomenon is used to derive the wanted characteristics of the VIRYA-4S generator.

In figure 8 it can be seen that the nominal torque Q at 500 rpm is 112.3 Nm. The generator can supply this torque also at lower rotational speeds. In figure 6 it can be seen that the loaded DC voltage U_{DC} is 297 VDC at n = 500 rpm. So first the Q-n curve is determined for a constant voltage of 297 VDC. A horizontal line is drawn in figure 6 for U = 297 VDC until it intersects with the U_{open}-n curve. The point of intersection lies about at a rotational speed of 410 rpm. It is assumed that the sticking torque of the generator can be neglected and so the unloaded torque is zero at n = 410 rpm. It is also assumed that the nominal torque Q = 112.3 Nm is lying that far from the peak torque that it is allowed to assume that the Q-n curve for a constant voltage of 297 VDC is a straight line. Figure 8 is now copied as figure 9 and the Q-n curve for 297 VDC is added. So the Q-n curve for 297 VDC is a straight line going through the point Q = 0 Nm and n = 410 rpm and the point Q = 112.3 Nm and n = 500 rpm. This curve is also drawn in figure 9. The difference in between the rotational speeds is 500 – 410 = 90 rpm.

Next the Q-n curve for 52 VDC is determined by shifting the Q-n curve for 297 VDC to the left. It must be shifted that far, that is starts at the rotational speed belonging to an open voltage of 52 VDC. In figure 6 it can be seen that an open voltage of 52 VDC is reached at a rotational speed of about 70 rpm. To get a Q-n curve for 52 VDC which is in parallel to the Q-n curve for 297 VDC, the maximum torque of 112.3 Nm must lie at a rotational speed of 70 + 90 = 160 rpm. So the Q-n curve for 52 VDC is a straight line going through the point Q = 0 Nm and n = 70 rpm and the point Q = 112.3 Nm and n = 160 rpm. This curve is also drawn in figure 9.

Next the Q-n curve for short-circuit in star is determined by shifting the Q-n curve for 297 VDC that far to the left that it starts at the origin of the graph. So the Q-n curve for short-circuit in star is a straight line going through the point Q = 0 Nm and n = 0 rpm and the point Q = 112.3 Nm and n = 90 rpm. This curve is also drawn in figure 9.

It will be clear that the efficiency for short-circuit in star is zero as all generated power is dissipated as heat in the winding. The efficiency for 52 V star is only 0.85 for the point of intersection of the Q-n curve for a resistance load and the Q-n curve for 52 VDC. This point of intersection lies about at a rotational speed of 85 rpm. The efficiency may have a maximum of about 0.9 for a rotational speed of about 75 rpm. The efficiency for rotational speeds higher than 85 rpm will be lower than 0.85.

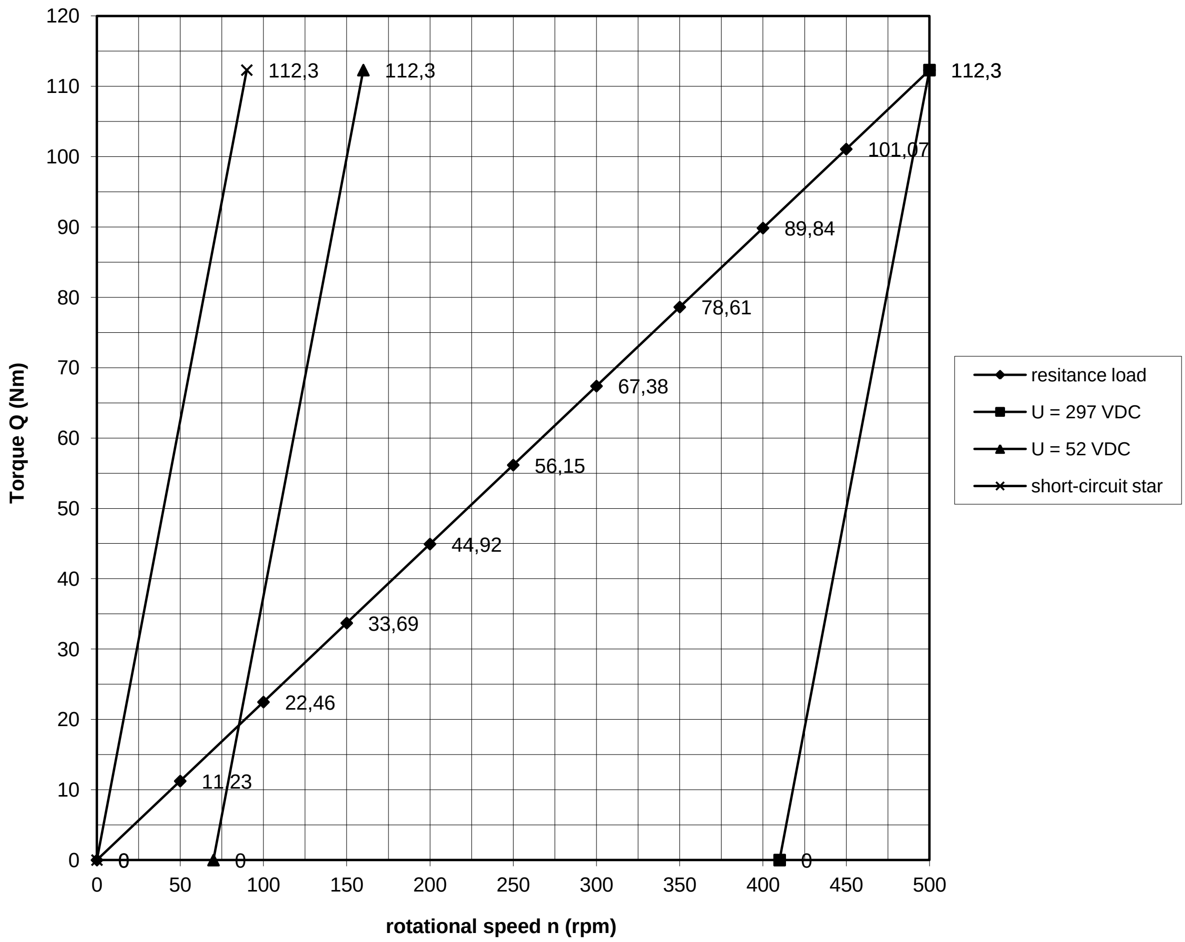

fig. 9 Q-n curve for a resistance load, for constant voltages of 297 VDC and for 52 VDC and for short-circuit in star

For the determination of the P_{mech}-n and the P_{el}-n curves it is necessary to take several points on the Q-n curves. The curves for 52 V star are determined first. The values of Q are determined for rotational speeds of 70 rpm up to 160 rpm in steps of 5 rpm. The results are given in table 4. P_{mech} and P_{el} are calculated with:

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

$$P_{el} = \eta_{gen} * P_{mech} \qquad (W) \qquad (14)$$

So for the determination of P_{el}, it is necessary to estimate a η_{gen}-n curve. The estimated η_{gen}-n curve is given in figure 10. It is assumed that the efficiency curve has a peak η_{gen} = 0.9 for n = 75 rpm, that η_{gen} = 0.85 for n = 85 rpm and that η_{gen} = 0.6 for n = 160 rpm.

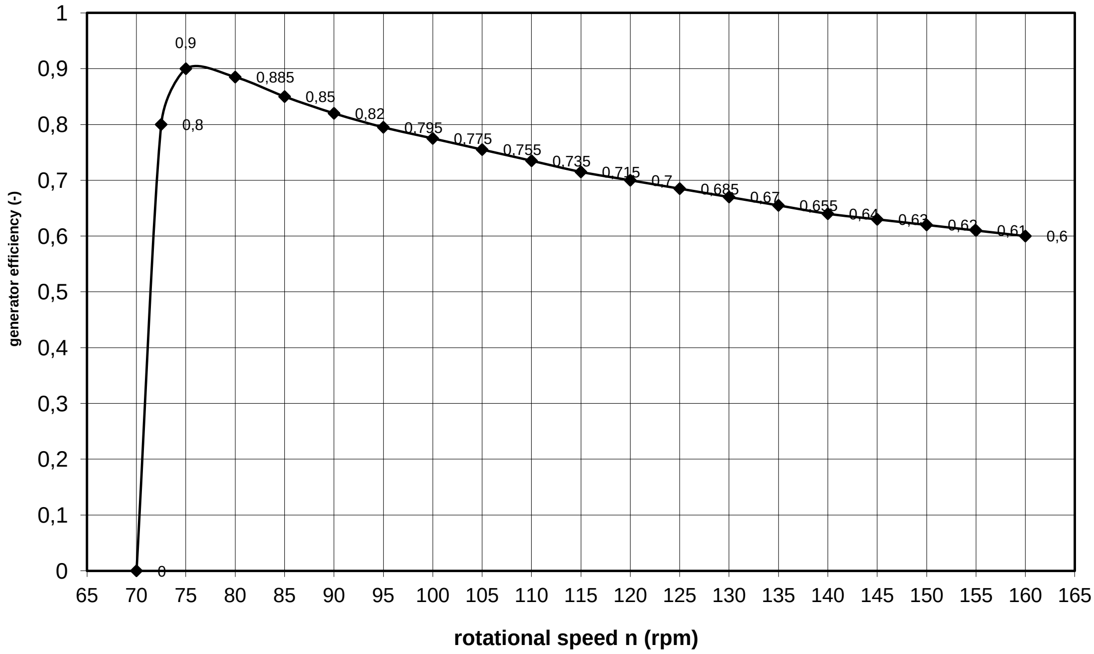

fig. 10 Estimated η_{gen}-n curve for 52 V star

n (rpm)	Q (Nm)	P_{mech} (W)	η_{gen} (-)	P_{el} W	P_{heat} (W)
70	0	0	0	0	0
75	6.24	49	0.9	44	5
80	12.48	105	0.885	93	12
85	18.72	167	0.85	142	25
90	24.96	235	0.82	193	42
95	31.19	310	0.795	246	64
100	37.43	392	0.775	304	88
105	43.67	480	0.755	362	118
110	49.91	575	0.735	423	152
115	56.15	676	0.715	483	193
120	62.39	784	0.7	549	235
125	68.63	895	0.685	613	282
130	74.87	1019	0.67	683	336
135	81.11	1147	0.655	751	396
140	87.34	1280	0.64	819	461
145	93.58	1421	0.63	895	526
150	99.82	1568	0.62	972	596
155	106.06	1722	0.61	1050	672
160	112.3	1882	0.6	1129	753

table 4 Calculated values of Q, P_{mech}, η_{gen}, P_{el} and P_{heat} as a function of n for 52 V star

The P_{mech}-n and P_{el}-n curves can now be derived from table 4 and are given in figure 5. The P_{mech}-n curve for 52 V star is intersecting with the optimum cubic line of the rotor for a wind speed of about 4.5 m/s but the matching is good for wind speeds above V = 3 m/s because the P_{mech}-n curve of the generator for 52 V star is lying close to the optimum cubic line of the rotor. At high wind speeds, the rotor is running with a tip speed ratio of about 3.75 which reduces the noise level.

The P-n curve for short-circuit in star is determined in the same way as the P_{mech}-n curve for 52 V star. So the values of Q as a function of n are first given in table 5. P_{mech} is calculated using formula 13 and is also given in table 5.

n (rpm)	Q (Nm)	P_{mech} (W)
0	0	0
5	6.24	3
10	12.48	13
15	18.72	29
20	24.96	52
25	31.19	82
30	37.43	118
35	43.67	160
40	49.91	209
45	56.15	268
50	62.39	327
55	68.63	395
60	74.87	470
65	81.11	552
70	87.34	640
75	93.58	735
80	99.82	836
85	106.06	944
90	112.3	1058

table 5 Calculated values of Q and P as a function of n for short-circuit in star

Next, the P-n curve for short-circuit in star is also given in figure 5. It can be seen that the P-n curve for short-circuit in star is lying left from the P-n curve of the rotor for V = 10 m/s and higher. So the generator can be used as a brake to stop the rotor at any wind speed. The rotor will rotate only slowly if short-circuit is made.

The point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for a certain wind speed is the working point for that wind speed. The electrical power for that wind speed is found by going downwards vertical until the P_{el}-n curve is reached. The values of P_{el} found this way is given in the P_{el}-V curve of figure 11. At high powers, the voltage is somewhat higher than 52 V resulting in a somewhat higher generator efficiency. This results in a somewhat higher power. The P_{el}-V curve starts at a wind speed of about 2.5 m/s so the $V_{cut\ in}$ = 2.5 m/s. This means that the VIRYA-4.2 can be used in regions with rather low wind speeds. In chapter 4 it has been calculated that the starting wind speed V_{start} = 2.4 m/s if the sticking torque of the generator is 1 Nm. This means that there is no hysteresis in the P_{el}-V curve.

The maximum power is about 1000 W for V = 10 m/s or higher. The mechanical power at V = 10 m/s is about 1850 W. This gives for the heat losses that P_{heat} = 1850 – 1000 = 850 W. This is lower than P_{heat} = 882 W at n = 500 rpm with a resistance load (see table 3). So the generator can be used in combination with the VIRYA-4S rotor for 48 V battery charging.

A 48 V battery bank means that four 12 V lead acid batteries of the same capacity and age have to be connected in series. The maximum charging voltage of two batteries has to be limited up to up to 27.6 V to prevent over charging if the batteries are full.

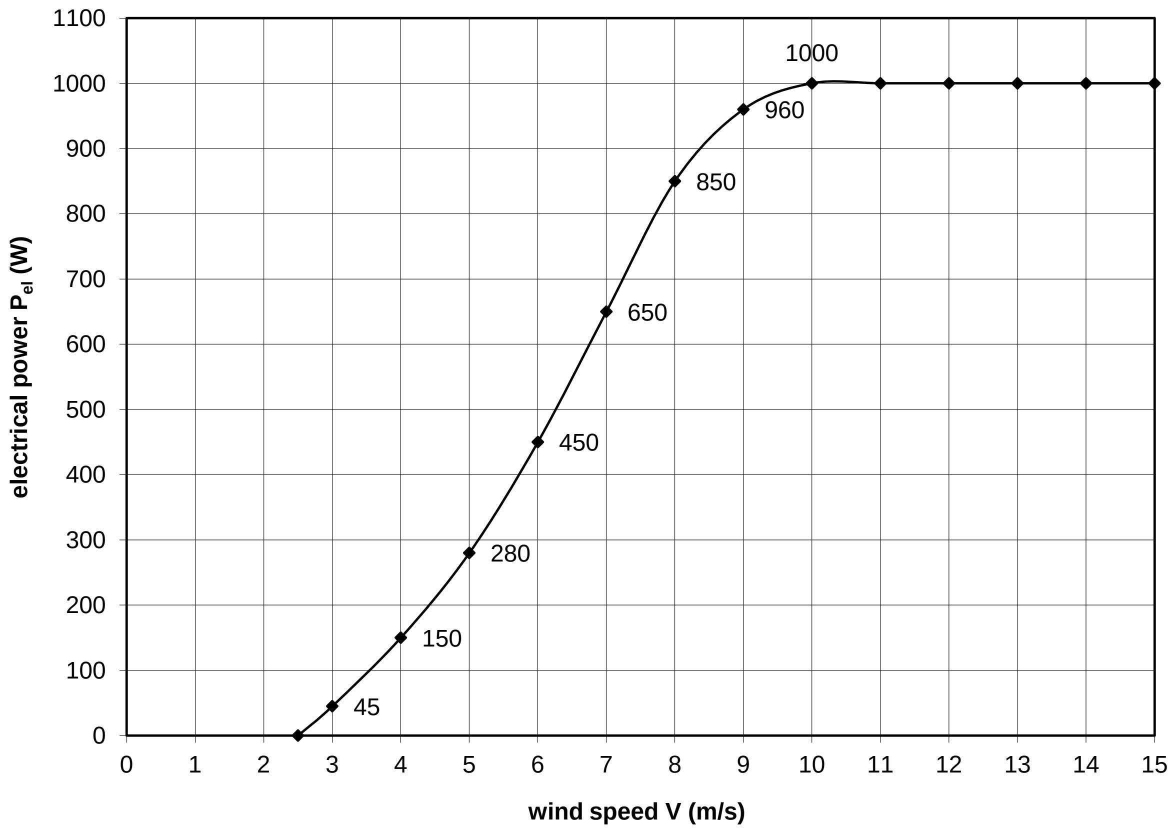

fig. 11 P_{el}-V curve for 52 V star

A 27.6 V, 200 W battery charge controller with dump load is described in a free manual (ref. 7). If three dump loads are connected in parallel, 600 W can be dissipated for 27.6 V. If two of these 600 W units are connected in series, totally 1200 W can be dissipated which is certainly enough for the VIRYA-4S. The two 600 W units have to be isolated from each other.

The P_{mech}-n, the P_{el}-n curves as given in figure 5 and the P_{el}-V as given in figure 11 are estimated and not measured like it was done for the generator of the VIRYA-4.2. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the generator of Hefei Top Grand, it is necessary to buy one and to test it at a large test rig with which it is possible to also measure the torque Q.

If such a test rig isn't available, at least one has to measure the open DC voltage as a function of the rotational speed and check if the real U_{open}-n curve is about the same as the estimated U_{open}-n curve as given in figure 6. It is also advised to connect the generator to a large almost empty 48 V lead acid battery and check if the measured P_{el}-n curve is about the same as the estimated P_{el}-n curve given in figure 5. If this is the case, one may assume that the P_{mech}-n curve is also almost the same and so the matching will be acceptable.

The rated torque Q = 112.3 Nm can also be supplied at lower rotational speeds. A constant torque is a straight line through the origin in the P-n graph. This line is also given in figure 5. The line starts at the end of the P-n curve for short-circuit in star because at rotational speeds below 90 rpm, the short-circuit torque is the highest possible torque. The whole P-n curve of the rotor for V = 10 m/s is lying to the right side of this line and so the generator isn't overloaded if short-circuit is made at a wind speed of 10 m/s.

8 Checking of the rotor strength

A rotor blade contains the cambered blade and the spoke. The blade must have a certain minimum thickness to prevent flutter at high tip speeds. I have tested a 2-bladed rotor with a design tip speed ratio of 6 in the wind tunnel already in 1978 and found that a 2 mm thick blade can have a maximum free blade length of 800 mm. A blade of the VIRYA-4S rotor has a free blade length of 1200 mm and so a blade thickness of 3 mm is large enough, especially because the design tip speed ratio of the VIRYA-4S is a lot lower which results in a lower tip speed at very high wind speeds. Flutter is mainly caused by a too low torsion stiffness. So a thickness of 3 mm makes the torsion stiffness high enough. However, the bending stiffness represented by the moment of inertia I and the strength represented by the moment of resistance W are much higher than needed.

I and W can be calculated for the chosen 7.14% cambered airfoil and the chosen sheet geometry using formula 11 and 12 as given in report KD 398 (ref. 2). The airfoil geometry is also given in KD 398 for a strip width of 100 mm. For a strip width of 250 mm, all values have to be multiplied by a factor 2.5. This gives a bending radius r_c = 176 * 2.5 = 440 mm. The blade thickness is called t and t = 3 mm. Formula 11 and 12 out of KD 398 are copied as formula 15 and 16.

$$I = 0.000081301\ r_c^3 * t \quad (mm^4) \tag{15}$$

$$W = 0.0030466\ r_c^2 * t \quad (mm^3) \tag{16}$$

Substitution of r_c = 440 mm and t = 3 mm in formula 15 gives: I = 20777 mm^4.
Substitution of r_c = 440 mm and t = 3 mm in formula 16 gives: W = 1769 mm^3.

The width and thickness of the spokes are chosen that large that it is expected that a spoke is strong enough. However, the spoke is rather thin and this results in bending of the blade backwards. The centrifugal force in the blade gives a compensating moment in the forwards direction which reduces the bending stress. But at this moment, this effect is neglected. The moment of inertia I and the moment of resistance W of a strip with a width b and a thickness h are given by:

$$I = 1/12 * b * h^3 \quad (mm^4) \tag{17}$$

$$W = 1/6 * b * h^2 \quad (mm^3) \tag{18}$$

Substitution of b = 100 mm and h = 8 mm in formula 17 gives: I = 4267 mm^4.
Substitution of d = 100 mm and h = 8 mm in formula 18 gives: W = 1067 mm^3.

So the moment of inertia I of the spoke is a factor 4267 / 20777 = 0.205 of that of the blade. The moment on resistance W of the spoke is a factor 1067 / 1769 = 0.603 of that of the blade.

The bending stiffness is determined by the moment of inertia. The fact that the blade is so much stiffer than the spoke is caused by the camber. If the blade would not be cambered, the moment of inertia can be determined by formula 17. Substitution of b = 250 mm and h = 3 mm in formula 17 gives that I = 562.5 mm^4. So now the blade stiffness is only a factor 562.5 / 4267 = 0.132 of the stiffness of the spoke! According to this calculation it seems that the blade is much too strong. However, the blade thickness must be chosen that large to prevent flutter in the blade at high tip speeds. Flutter is mainly caused by a too low torsion stiffness. However, the camber has no influence on the torsion stiffness. The torsion stiffness of the spoke is much higher than the torsion stiffness of the blade because the torsion stiffness increases about with b * h^3 if b is large with respect to h.

So the torsion stiffness of the spoke is a factor 100 * 8^3 / (250 * 3^3) = 7.585 larger than that of the blade outside the welded strip. This factor is large enough to prevent that flutter is caused by torsion of the spoke.

The bending moment due to the rotor thrust is maximal in the spoke just outside the hub. So if the spoke is strong enough, the blade is certainly strong enough. The rotor thrust for a yawing rotor $F_{t\delta}$ is given by formula 7.7 of KD 35 (ref. 1). This gives the rotor thrust on the whole rotor. The rotor thrust on only one blade of a 3-blade rotor is 1/3. So the rotor thrust on one blade of a 3-bladed rotor $F_{t\delta\ bl}$ = given by:

$$F_{t\delta\ bl} = 1/3 * C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 \qquad \text{(N)} \qquad (19)$$

It is assumed that the thrust is maximal for a wind speed V = 10 m/s and that δ = 30°. The thrust coefficient C_t is about 0.7 for a rotor with a cambered sheet airfoil and with a large central part of the rotor for which no airfoil is available. Substitution of C_t = 0.7, δ = 30°, ρ = 1.2 kg/m^3, V = 10 m/s and R = 2 m in formula 19 gives: $F_{t\delta\ bl}$ = 132 N.

The thrust is a triangular load which is maximal at the blade tip. A triangular load give the same bending moment at the hub as a point load which exerts at 2/3 R. However, the load isn't really a triangular load because there is no airfoil at the spokes. This makes that the point load is at exerting at a somewhat larger radius than 2/3 R. Assume this radius r = 1.4 m. So for the bending moment M at the hub it is valid that M = $F_{t\delta\ bl}$ * r = 132 * 1.4 = 184.8 Nm = 184800 Nmm. The bending stress σ is given by:

$$\sigma = M / W \qquad (\text{N/mm}^2) \qquad (20)$$

Substitution of M = 184800 Nmm and W = 1067 mm^3 in formula 20 gives: σ = 173 N/mm^2. The spoke is made from cold rolled mild steel St 37-2 K with tolerance h9. The stress belonging to a 0.2 % deformation limit is 355 N/mm^2 for a thickness of 8 mm. However, this is for a pulling force. The allowable stress for a bending moment is higher and it is assumed that it is about 400 N/mm^2. The calculated bending stress is far below the allowable stress and so the spoke is strong enough. The breaking stress for this material is in between 470-770 N/mm^2 and so the spoke has a very large reserve for breaking. As the bending moment in the blade at cross section E is much smaller than at the root of the spoke and as the moment of resistance of the blade is much larger than the moment of resistance of the spoke, the blade is no critical component for the bending stress.

Building of the VIRYA-4S with this axial flux generator of Hefei Top Grand is only possible if the drawings are available. The drawings of the head and tower of the VIRYA-4.2 are made on A1 format and therefore it is difficult to make them digital but I can make a photo of them if needed.

New detailed drawings of the rotor of the VIRYA-4S must also be made. The generator bracket at the drawing of the head has to be modified such that the axial flux generator can be mounted. From 1-1-2018 Kragten Design is no longer a commercial company and licences of the bigger VIRYA windmills are no longer supplied. Building of the VIRYA-4S is only possible for a commercial company which has the skills to make the missing drawings and which has the equipment to build and test a prototype. Serial production should only be started if the prototype has survived a heavy storm.

9 Use of the VIRYA-4S for water pumping

There are several ways how the VIRYA-4S can be used for water pumping. The first option is to maintain the 48 V lead acid battery and to use a pump with a 48 VDC motor. However, the pump motor can't be connected permanently because this would empty the battery too much if there is only little wind. So connection of the pump motor must be steered. The first steering signal must come from the wish to pump water. The second steering signal must come from the battery voltage. If the battery voltage becomes lower than about 46 V, pumping must be stopped. The battery charge controller prevents than the voltage of the pump motor becomes too high if the batteries are full.

The second option is to use a pump with a 48 VDC motor without a battery. However, one still needs a battery charge controller to prevent a too high voltage at high wind speeds. If the pump motor can be connected permanently to the 3-phase rectifier of the generator, depends on the type of pump. If the pump is a centrifugal pump, the needed electrical power of the pump motor will be low at low rotational speeds of the pump. The VIRYA-4S has a rather large starting torque coefficient (see figure 3) and so the rotor will start even if the generator supplies some power at low rotational speeds. However, if the pump is a positive displacement pump, a high starting torque of the pump motor is required and this requires a high current at low rotational speeds. This might give starting problems for the rotor if a big pump is used. In this case the connection in between the rectifier and the pump motor can be made only at a certain rotational speed of the rotor and must be broken at a lower rotational speed.

The third option is to directly use the 3-phase current coming from the generator for a pump with a 3-phase asynchronous motor. However, this is only possible if the generator has the correct frequency and voltage range. The frequency at a certain rotational speed depends on the number of armature poles of the generator. The number of armature poles isn't specified by Hefei Top Grand. However, if "TGET380 generator" is typed in the website of Alibaba, one finds a page about the TGET380 and the PMG380. If one scrolls down at this page, one finds several photo's. One photo shows the armature and it can be counted that 20 poles are used. But if this is really the case for the PMG380, has still to be verified. Assume that the armature has 20 poles and so 10 north poles and 10 south poles. The frequency is 50 Hz for a 2-pole armature at 3000 rpm. So the frequency is 50 Hz for a 20-pole armature at 300 rpm. In figure 5 it can be seen that a rotational speed of 300 rpm is never reached, even not for an unloaded rotor at a wind speed of about 10 m/s. So the use of a pump with a 50 Hz asynchronous motor is impossible for the normal rotational speed of the pump motor.

However, it is possible to use a standard pump at a much lower frequency than 50 Hz if the pump head H is also much lower than the nominal head. But not only the frequency is important. The voltage must also be right. The chosen generator PMG380-I-5KW-500R has a loaded voltage in between two of the three phases of 220 VAC at 500 rpm. This voltage is too low for direct connection to the asynchronous motor of a centrifugal pump. It is better to use the generator PMG380-I-3KW-300R which has a loaded voltage of 380 VAC at 300 rpm.

Assume that the pump motor is used for a frequency which is a factor 2.5 lower than 50 Hz so the frequency is 20 Hz. This corresponds to a rotational speed of 120 rpm. In figure 5 it can be seen that this rotational speed belongs to the maximum of the P-n curve for V = 6 m/s. The mechanical power is 619 W. Assume that the generator efficiency is 0.85. So the electrical power is 526 W. Assume that the pump is used for drainage with a static height H = 2 m. The height of a centrifugal pump increases quadratic to the rotational speed. So one has to chose a pump which is designed for a height of $2 * 2.5^2 = 12.5$ m. The required nominal power of the pump motor increases to the cube of the rotational speed and so the pump motor must have a nominal electric power of $526 * 2.5^3 = 8219$ W. The mechanic power of the pump motor depends on the motor efficiency. Assume that this efficiency is 0.8. So the mechanical power of the pump motor is 0.8 * 8219 = 6575 W. This is rather large and may be a pump with a smaller nominal motor power of 5.5 kW or 4 kW is also acceptable.

The use of the VIRYA-4S for water pumping with a standard centrifugal pump at a low frequency needs more study and testing of the pump and pump motor at low frequencies.

It is possible to use the VIRYA-4S for grid connection if the right inverter can be found. For grid connection it is also better to use the generator PMG380-I-3KW-300R.

It might be possible to replace the axial flux PM-generator of Hefei Top Grand by a 32-pole radial flux PM-generator which is made from a 7.5 kW, 4-pole asynchronous motor frame size 132. This generator makes use of the original housing, winding and motor shaft. This generator is described in chapter 7 of report KD 718 (ref. 8).

10 References

1 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.

2 Kragten A. The 7.14 %, 10 % and 12.5 % cambered plate as airfoil for windmill rotor blades. Aerodynamic characteristics, geometry, moment of inertia I and moment of resistance W. November 2008, reviewed April 2018, free public report KD 398, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 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 report KD 97, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode.

4 Kragten A. Method to check the estimated δ-V curve of the hinged side vane safety system and checking of the δ-V curve of the VIRYA-4.2 windmill, December 2004, free public report KD 213, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Measurements performed on a generator with housing 5RN90L04V and a 4-pole armature equipped with neodymium magnets, March 2001, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Ideas about the use of the 3-bladed VIRYA-3B3 rotor (λ_d = 6) 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.

7 Kragten A. Manual of a 27.6 V, 200 W battery charge controller, March 2006, reviewed February 2022, free manual, available at my website at the bottom of the menu KD-reports. Engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Ideas about a 16-pole, 28-pole, 32-pole or 40-pole, 3-phase permanent magnet generator using the housing and winding of a 4-pole asynchronous motor. May 2021, reviewed April 2025, free public report KD 718, Engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.