Calculations executed for the 3-bladed rotor of the VIRYA-4.2B3 windmill (λ_d = 6.5, wooden constant chord blades) driving the PM-generator of Hefei Top Grand type TGET380-10KW-1200R for 24 V battery charging

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It is allowed to copy this report for private use. A prototype of the VIRYA-4.2 has been tested for three years but a prototype of the VIRYA-4.2B3 wind turbine has not yet been built and tested. The VIRYA-4.2B3 should only be built by a company which has the skills to make the final drawings, to obtain the required materials and to manufacture the required components. No responsibility is accepted by me for the use of this wind turbine.

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1 Introduction

The VIRYA-4.2B3 has a 3-bladed rotor with wooden constant chord blades with no twist. Manufacture of such blades is therefore rather easy. The generator is of the Chinese brand Hefei Top Grand with type TGET380-10KW-1200R. The head is derived from the head of the 2-bladed VIRYA-4.2 with wooden blades and λ_d = 8 by modification of the generator bracket such that the chosen generator can be mounted. For the tower one can use the 12 m high, 3-legs lattice tower of the VIRYA-4.2 or the about 8.6 m high tubular tower as described in report KD 582 (ref. 1). The VIRYA-4.2B3 has the same rotor diameter as the original VIRYA-4.2 and the head geometry of the VIRYA-4.2 can therefore be maintained. This head results in a rated wind speed of about 10 m/s.

2 Description of the rotor of the VIRYA-4.2B3 windmill

The 3-bladed rotor of the VIRYA-4.2B3 windmill has a diameter D = 4.2 m and a design tip speed ratio λ_d = 6.5. Advantages of three blades and a lower design tip speed ratio are that the gyroscopic moment in the rotor shaft isn't fluctuating, that less noise is produced, that the starting torque coefficient is higher and that a 3-bladed rotor looks better than a 2-bladed one.

The rotor has constant chord blades with a Gö 623 airfoil. Aerodynamic characteristics of this airfoil are given in report KD 463 (ref. 2). The blade length k is chosen 1900 mm = 1.9 m. The chord c is chosen 200 mm = 0.2 m. The blades of the VIRYA-4.2B3 are identical to the blades of the VIRYA-4.2. The three blades are connected to a spoke assembly which is made out of steel strip size 120 * 8 mm. The three spokes have a length of 500 mm and are welded to each other at the centre at an angle of 120°. The overlap in between a spoke and a blade is 300 mm resulting in a rotor diameter of 4.2 m and a free blade length of 1.6 m.

A blade is connected to the spoke assembly by three bolts M12 * 60 and six nuts M12. A 3 mm thick cambered stainless steel strip is mounted under the bolt heads to prevent that the wood is damaged if the nuts are tightened. The generator has an outer diameter of 380 mm which means that there is a distance of 10 mm in between the blade root and outside of the generator. The generator has a collar at the front side with a diameter of 140 mm and ten threaded holes M12 at a pitch circle of 120 mm. It is mentioned in the specification that the length of the thread is 20 mm which seems rather short for M12. So it has to be checked if it is possible to use ten bolts size M12 * 35 for connection of the spoke assembly to the generator. Locking liquid has to be used at these bolts. The rotor is balanced by balancing weights which are connected under the bolts with which a blade is connected to the spoke. A sketch of the rotor is given in figure 1.

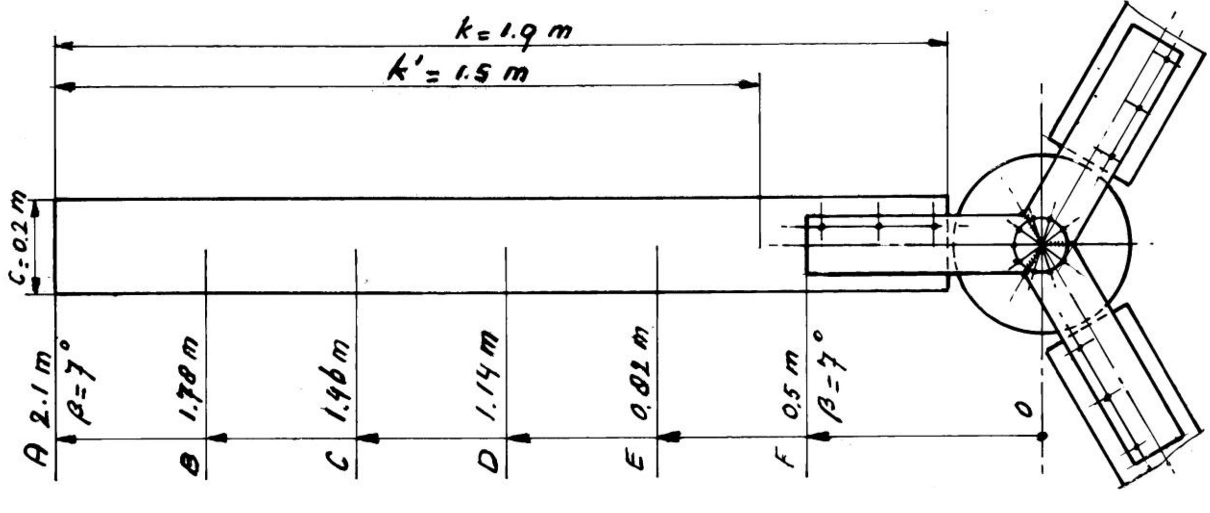

fig. 1 Front view of the VIRYA-4.2B3 rotor

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. 3). This report (KD 769) has its own formula numbering. Substitution of λ_d = 6.5 and R = 2.1 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 3.0952 * r$ (-) (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 = 0.2 m in formula (5.4) of KD 35 gives:

$C_l = 41.888 * r (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.2 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.667 * 10^5 * \sqrt{}(\lambda_{r\,d}^2 + 4/9)$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.32 m of one to another. Station F corresponds to the end of the spoke. The blade has a constant chord which means that the lift coefficient C_l is low at the blade tip and high at the blade root. This corresponds to example no. 2 as given in chapter 5.4.2 of KD 35. First the theoretical values are determined for C_l, α and β. Next the real blade angle β_{lin} is determined such that the blade twist is zero. The aerodynamic characteristics of the Gö 623 airfoil are given in report KD 463 (ref. 2) for three different Reynolds values. 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. The Reynolds value is chosen which is lying closest to the calculated value.

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 623	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	2.1	6.5	5.8	0.2	0.46	0.38	4.36	4.2	-0.5	-1.2	6.3	7.0	0.028
B	1.78	5.510	6.9	0.2	0.53	0.51	3.70	4.2	0.1	-0.1	6.8	7.0	0.024
C	1.46	4.519	8.3	0.2	0.64	0.63	3.05	2.3	1.4	1.3	6.9	7.0	0.020
D	1.14	3.529	10.5	0.2	0.81	0.81	2.40	2.3	3.5	3.5	7.0	7.0	0.027
E	0.82	2.538	14.3	0.2	1.07	1.11	1.75	2.3	6.7	7.3	7.6	7.0	0.033
F	0.5	1.548	21.9	0.2	1.51	0.81	1.12	1.1	-	14.9	-	7.0	0.31

table 1 Calculation of the blade geometry of the VIRYA-4.2B3 rotor

In table 1 it can be seen that the theoretical blade angle β_{th} varies in between 6.3° and 7.6°. If a constant blade angle β_{lin} = 7° is chosen, the linearised angle of attack α_{lin}, are lying close to the theoretical angles α_{th} for the most important outer part of the blade. The spokes of the spoke assembly are twisted 7° right hand in between the hub and the blade root to give the blade the correct blade angles. A sketch of the rotor is given in figure 1.

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 outer part of the blade is about 0.025. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6.5$ and $C_d/C_l = 0.025$ gives $C_{p\ th} = 0.46$. The airfoil is stalling at station F. Therefore not the whole blade length k = 1.9 m is taken for the calculation of the maximum C_p but only the blade length up to 0.1 m outside station F. This gives an effective blade length k' = 1.5 m.
Substitution of $C_{p\ th} = 0.46$, R = 2.1 m and effective blade length k' = 1.5 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.42$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.42 / 6.5 = 0.0646$.
Substitution of $\lambda_{opt} = \lambda_d = 6.5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 10.4$.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is copied as formula 6.

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

The blade angle β = 7° for the whole blade. For a non rotating rotor, the angle ϕ = 90°. The angle of attack α is therefore 90° - 7° = 83°. The whole blade is stalling during starting so now the real blade length k = 1.9 m is chosen. The C_l-α curve for large angles of α is given in figure 5.10 of report KD 35 for the Gö 623 airfoil. For α = 83° it can be read that $C_l = 0.25$.

Substitution of B = 3, R = 2.1 m, k = 1.9 m, $C_l = 0.25$ and c = 0.2 m in formula 6 gives that $C_{q\ start} = 0.0084$. For the ratio in between the starting torque and the optimum torque we find that it is 0.0084 / 0.0646 = 0.13. This is rather high for a rotor with a design tip speed ratio of 6.5.

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

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

In the specification of the generator it is given that the starting torque is smaller than 0.3 Nm. However, this is the case if no seal is mounted at the generator shaft. The starting torque will be much larger is a seal is mounted. A seal is needed for horizontal positioning of the shaft to prevent that water enters the front bearing. It is assumed that the front bearing cover is already provided with a chamber for a seal. I don't know the diameter and depth of this chamber but the generator shaft has a diameter of 50 mm. Assume that the torque is 1.5 Nm with a seal. Substitution of $Q_s = 1.5$ Nm, $C_{q\ start} = 0.0084$, ρ = 1.2 kg/m^3 and R = 2.1 m in formula 7 gives that $V_{start} = 3.2$ m/s. This seems acceptable for a moderate wind regime.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for λ = 0. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 4). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a Gö 623 airfoil is used. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-4.2B3 rotor are given in figure 2 and 3.

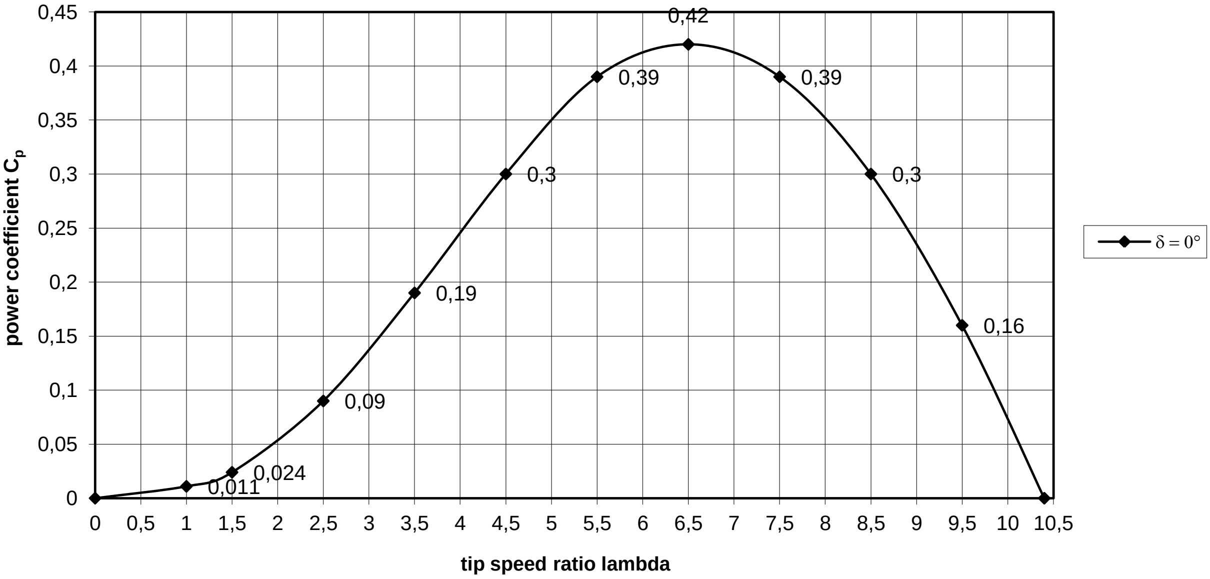

fig. 2 Estimated C_p-λ curve for the VIRYA-4.2B3 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

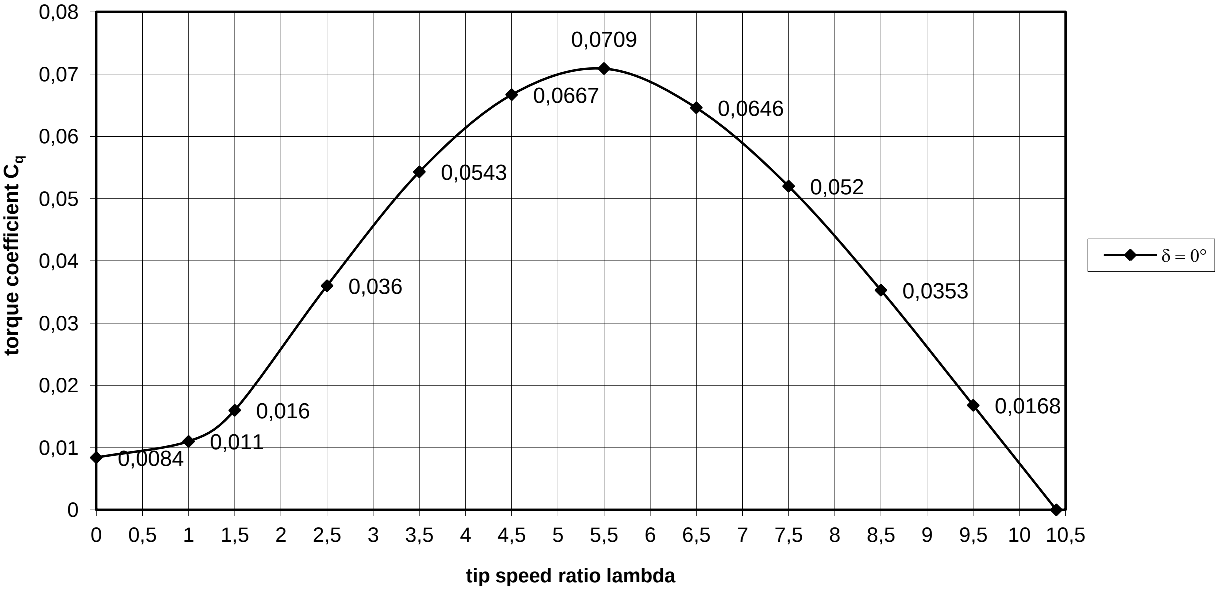

fig. 3 Estimated C_q-λ curve for the VIRYA-4.2B3 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

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 2. 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 waterproof plywood with a density of about $0.6 * 10^3$ kg/m^3. This vane blade gives a rated wind speed V_{rated} of about 10 m/s. In report KD 213 (ref. 5) 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. This windmill also has a vane blade made of 9 mm plywood. So the δ-V curve of the VIRYA-4.2 will be about the same as for the VIRYA-4.2B3. The estimated and calculated curves appear to lie very close to each other so it is allowed to use the estimated curve. The estimated 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.

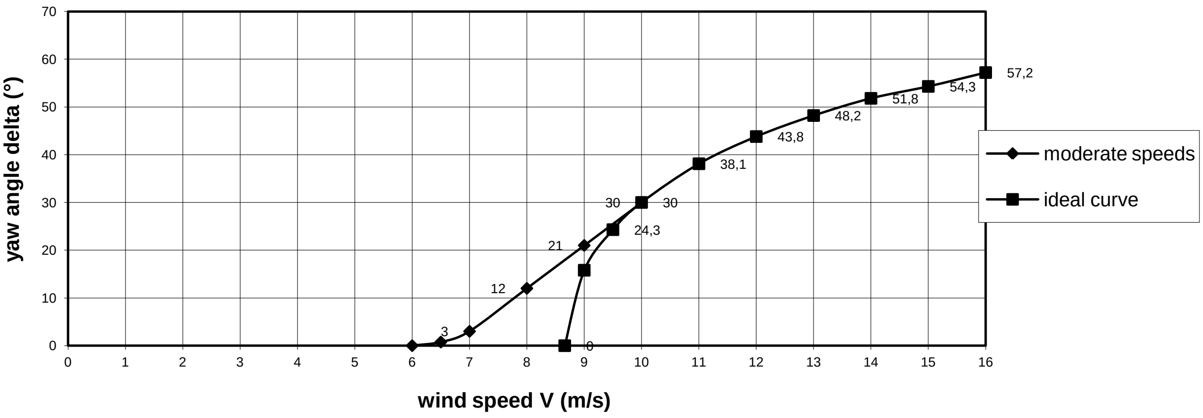

fig. 4 Estimated δ-V curve for a 9 mm meranti plywood vane blade

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 = 2.1 m in formula 7.1 of KD 35 gives:

$$n_\delta = 4.5473 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 2.1 m in formula 7.10 of KD 35 gives:

$$P_\delta = 8.3127 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ is 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5 and 10.4 (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°	
3.5	0.19	47.7	43	63.7	101	79.6	197	95.5	341	111.3	540	124.5	757	133.7	937	137.8	1026
4.5	0.3	61.4	67	81.9	160	102.3	312	122.8	539	143.0	852	160.1	1195	171.9	1479	177.2	1620
5.5	0.39	75.0	88	100.0	207	125.1	405	150.1	700	174.8	1107	195.7	1553	210.1	1923	216.6	2106
6.5	0.42	88.7	94	118.2	223	147.8	436	177.3	754	206.6	1193	231.3	1673	248.3	2071	256.0	2268
7.5	0.39	102.3	88	136.4	207	170.5	405	204.6	700	238.4	1107	266.9	1553	286.6	1923	295.4	2106
8.5	0.3	116.0	67	154.6	160	193.3	312	231.9	539	270.2	852	302.5	1195	324.8	1479	334.7	1620
9.5	0.16	129.6	36	172.8	85	216.0	166	259.2	287	302.0	454	338.0	637	363.0	789	374.1	864
10.4	0	141.9	0	189.2	0	236.5	0	283.8	0	330.6	0	370.1	0	397.4	0	409.6	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-4.2B3 rotor

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

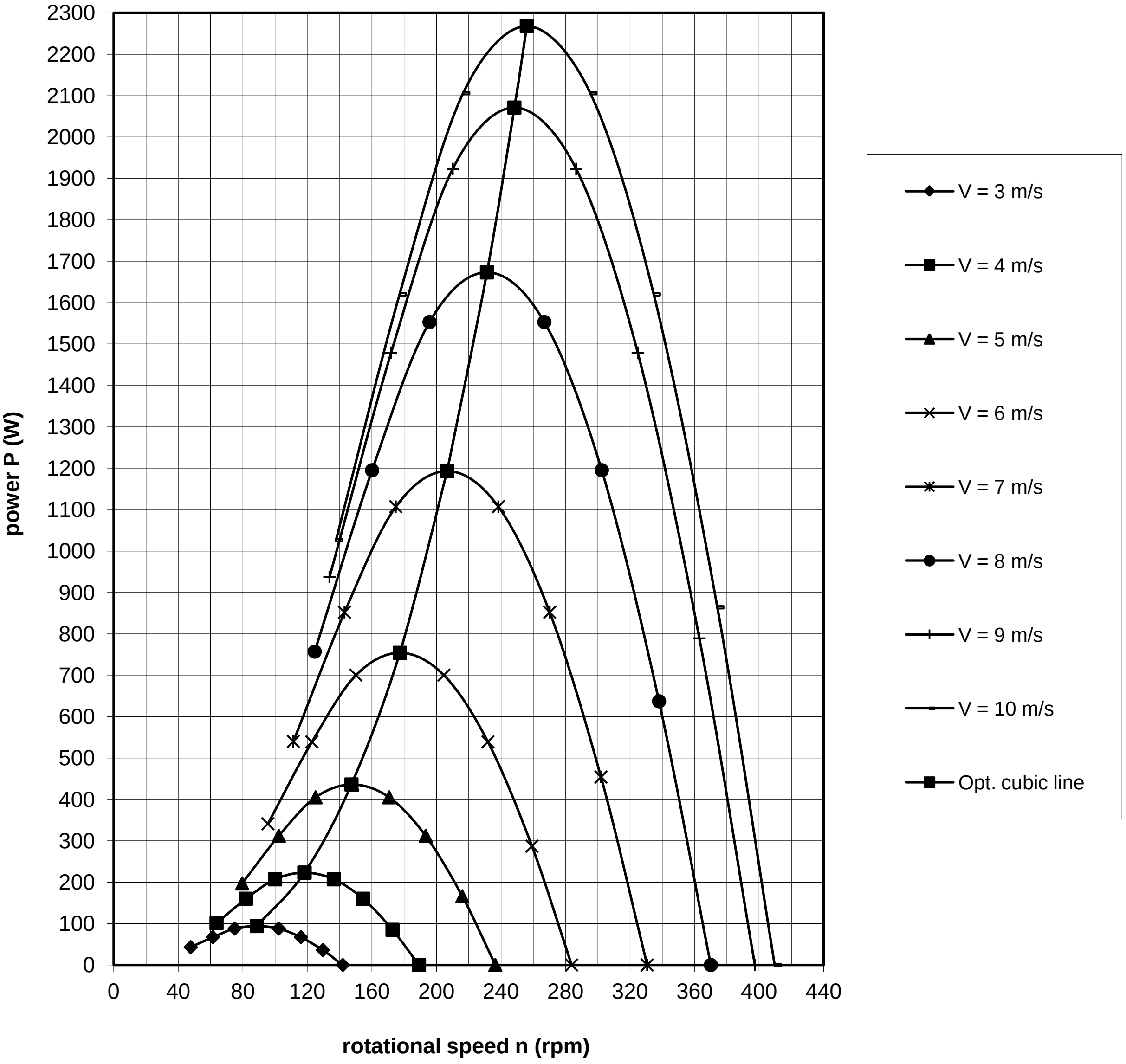

fig. 5 P-n curves and optimum cubic line of the VIRYA-4.2B3 rotor

6 Determination of the generator characteristics for 24 V battery charging

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 24 V battery load are needed. A 24 V battery is charged at an average charging voltage of about 26 V and 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 10 kW = 10000 W at a rotational speed of 1200 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 26 V have to be estimated to check the matching in between rotor and generator. This is done in chapter 10 of report KD 733 (ref. 6). Figure 5 is now copied as figure 6 and the P_{mech}-n and P_{el}-n curves for 26 V star are copied in figure 6.

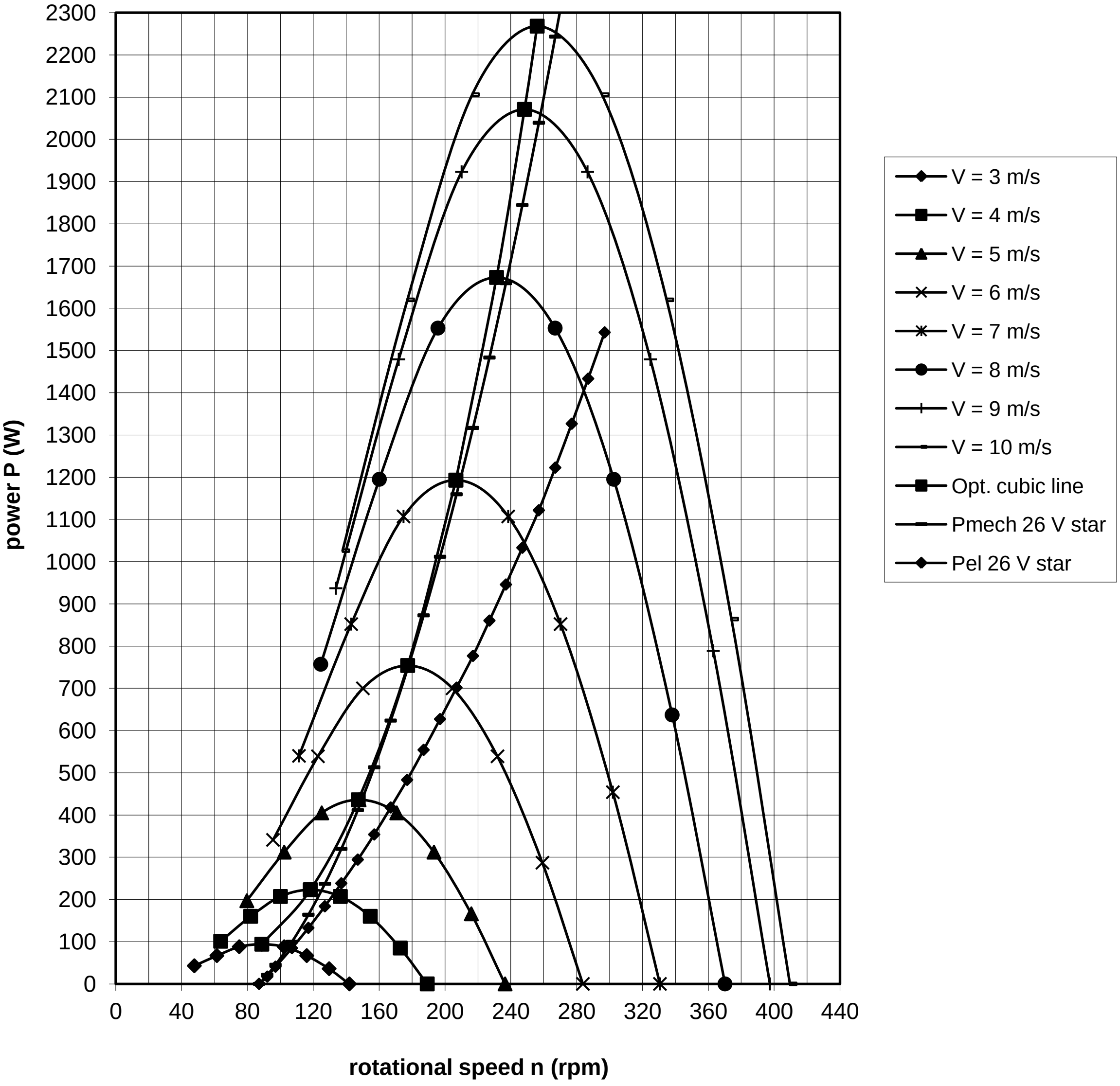

fig. 6 P-n curves and optimum cubic line of the VIRYA-4.2B3 rotor, estimated P_{mech}-n and P_{el}-n curves of the generator type TGET380-10KW-1200R for 26 V star

In figure 6 it can be seen that the matching in between rotor and generator is very good because the P_{mech}-n curve of the generator for 26 V star is lying close to the optimum cubic line of the rotor.

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 7.

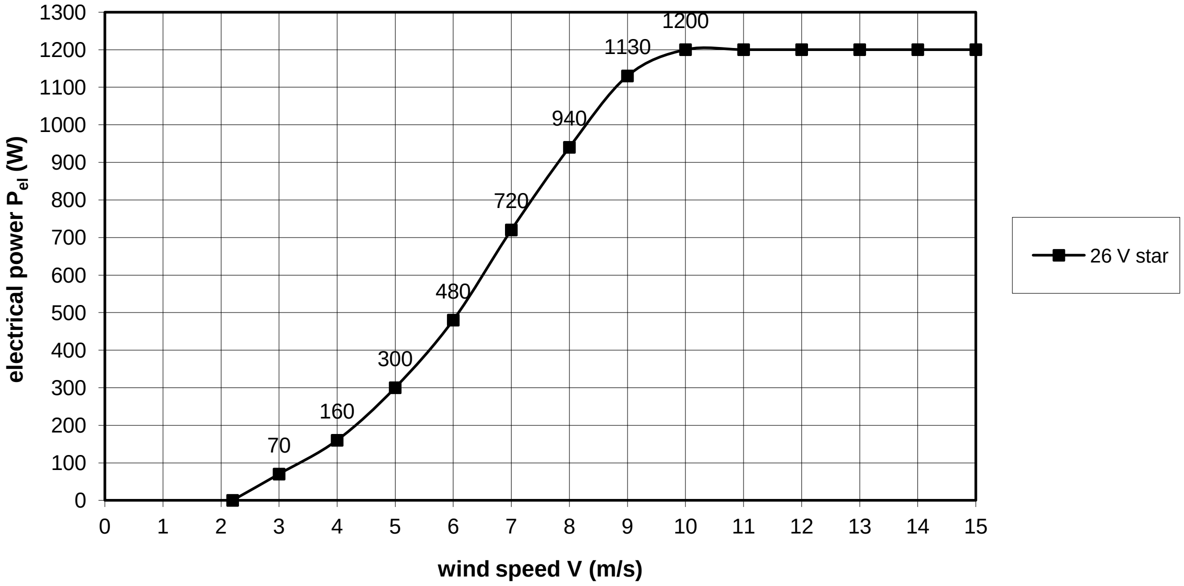

fig. 7 Estimated P_{el}-V curve for 26 V star

The P_{el}-V curve starts at a wind speed of about 2.2 m/s so the $V_{cut\ in}$ = 2.2 m/s which is very low. This means that the VIRYA-4.2B3 can be used in regions with low wind speeds.

In chapter 4 it has been calculated that the starting wind speed V_{start} = 3.2 m/s if the sticking torque of the generator is 1.5 Nm. This means that there is hysteresis in the P_{el}-V curve for $2.2 < V < 3.2$ m/s.

The maximum power is about 1200 W. This is 100 W higher than for the original VIRYA-4.2. But the whole P_{el}-V curve is better especially at low wind speeds. This is because the generator has no iron in the coils and the efficiency at low powers is therefore higher.

The mechanical power at V = 10 m/s is about 2250 W at n = 268 rpm. The corresponding electrical power is about 1200 W. So this gives for the heat losses that P_{heat} = 2250 – 1200 = 1050 W. If the generator is used with a resistance load at n = 1200 rpm, the electrical power is 10000 W. If the efficiency is 0.85, it means that the mechanical power is 10000 / 0.85 = 11765 W and so the heat losses are 1765 W. So although the efficiency at 26 VDC and a maximum rotational speed of about 268 rpm is rather low (about 0.53), the generated heat is certainly acceptable. So the generator type TGET380-10KW-1200R can be used in combination with the VIRYA-4.2B3 rotor for 24 V battery charging.

The P_{mech}-n, the P_{el}-n curves as given in figure 6 and the P_{el}-V as given in figure 7 are estimated using an estimated η-n curve and not measured like it was done for the original VIRYA-4.2 generator. 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 large test rig with which it is possible to measure the torque Q and the rotational speed n.

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 of KD 733 (ref. 6).

It is also advised to connect the generator to a large almost empty 24 V lead acid battery and check if the measured P_{el}-n curve is about the same as the estimated P_{el}-n curve as given in figure 6. 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.

Building of the VIRYA-4.2B3 with this generator type TGET380-10KW-1200R is only possible if the drawings of the rotor, the head and the tower are available. The VIRYA-4.2 drawings of rotor, head and tower are made by pencil on sheet with A1 format and therefore it is difficult to make them digital. Figure 1 gives an impression of the rotor but detailed drawings have to be made.

For 24 V battery charging one needs a voltage controller plus dump load to limit the maximum charging voltage up to 27.6 V to prevent over charging when the battery is full. A 27.6 V, 200 W controller is described in a free public manual which is available at my website at the bottom of the menu KD-reports (ref. 7). As the VIRYA-4.2B3 can produce a maximum power of about 1200 W, at least six 200 W dump loads have to be connected in parallel. Only one voltage controller is needed. Two identical 12 V lead acid batteries of at least 200 Ah have to be connected in series.

From 1-1-2018 Kragten Design is no longer a commercial company and licences and drawings of the bigger VIRYA windmills are no longer supplied. The final drawings of the VIRYA-4.2B3 have to be made by the company which is interested to build this VIRYA-4.2B3 wind turbine in series. If a certain company is interested, I can make photos of the original drawings of the rotor, the head and the tower of the VIRYA-4.2. Copies of the original printed drawings on A1 format are not available.

The head has to be modified such that generator of Hefei Top Grand can be mounted. The construction must be such that the 50 mm generator shaft is clamped at two places, that the eccentricity $e = 0.42$ m and that the generator shaft makes a tilt angle of 5° upwards with the horizon to get enough space in between the blade tips and the tower.

Instead of the 12 m high, 3-legs VIRYA-4.2 tower, it seems also possible to use the 8.6 m high tubular tower which is described in report KD 582 (ref. 1). But also for this tower, final drawings have to be made.

Instead of using the axial flux generator of Hefei Top Grand TGET380-10KW-1200R it might also be possible to use the radial flux generator which is described in chapter 11 of report KD 710 (ref. 8). This generator makes use of an asynchronous motor frame size 132 M with a shaft diameter of 38 mm. The standard winding and the original shaft and armature are used. Inclined magnet grooves are made in between the aluminium short-circuit bars and magnets size 40 * 10 * 10 mm are only used for the north poles. It is necessary to make a prototype and measure it to prove that the winding can be used for 24 V or 48 V battery charging.

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