Calculations executed for the 2-bladed rotor of the VIRYA-5S windmill (λ_d = 7, Gö 711 airfoil, stainless steel blades) meant for connection to the axial flux generator of Hefei Top Grand type TGET450-5KW-300R for grid connection or water pumping

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KD 749

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1 Introduction

The 2-bladed VIRYA-5 with wooden blades and λ_d = 7 is described in report KD 614 (ref. 1). The 3-bladed VIRYA-5B3 with wooden blades and λ_d = 6 is described in report KD 710 (ref. 2). The VIRYA-5 was originally designed for a 34-pole PM-generator but it can also be used with a PM-generator of Hefei Top Grand type TGET450-5KW-300R (see KD 614 chapter 12). The VIRYA-5B3 uses only the TGET450-5KW-300R generator. The generator characteristics are derived in chapter 6 of report KD 710.

For some countries good quality wood is difficult to obtain and therefore it is investigated if a 2-bladed rotor with stainless steel blades is possible. The wind turbine with this stainless steel rotor is called the VIRYA-5S to distinguish it from the VIRYA-5 with wooden blades. The VIRYA-5S makes also use of the TGET450-5KW-300R generator.

The head geometry of the VIRYA-5S is the same as the head geometry of the VIRYA-5 and the VIRYA-5B3. The head of the VIRYA-5 is derived from the head of the VIRYA-4.6B2 by increasing the vane dimensions. The square vane has the maximum dimensions which is possible for a standard sheet of 1.22 m * 2.44 m and so the vane height and width are both 1.22 m.

The head geometry of the VIRYA-5 is checked in chapter 10 of report KD 614 (ref. 1). The VIRYA-5 makes use of a 12 mm thick vane blade made out of okoume plywood which is rather light and the rated wind speed is therefore about 9.5 m/s. However, the VIRYA-5B3 and the VIRYA-5S make use of a 12 mm vane blade made out of meranti plywood which is heavier. This vane blade results in a rated wind speed of about 11 m/s.

The tower of the VIRYA-4.2 and the VIRYA-4.6B2 is also used for the VIRYA-5B3 and the VIRYA-5S. The tower of the VIRYA-4.6B2 is the same as the tower of the VIRYA-4.2. However, the head bearing housing has a pin diameter of 45 mm for the VIRYA-4.6B2 and a pin diameter of 40 mm for the VIRYA-4.2. A pin diameter of 45 mm is expected to be strong enough for the VIRYA-5S and the VIRYA-5B3.

2 Description of the rotor of the VIRYA-5S windmill

The 2-bladed rotor of the VIRYA-5S windmill has a diameter D = 5 m and a design tip speed ratio λ_d = 7. Advantages of a 2-bladed rotor are that no welded spoke assembly is required and that the rotor can be balanced and transported easily, even if it is mounted.

The rotor has blades which are made out of a 1.5 mm thick stainless steel sheet size 2000 * 500 mm. So the two blades of one rotor can be made out of one standard 1.5 mm thick sheet size 1 * 2 m. The sheet is bent into a Gö 711 airfoil and welded and the tailing edge. As the curved back side of the airfoil is longer than the flat front side, the chord c is a little smaller than half the sheet width of 500 mm. It is assumed that c = 240 mm = 0.24 m. So the chord is the same as the chord of the VIRYA-5 with wooden blades.

The two blades are connected to each other by a stainless steel strip size 1500 * 150 * 10 mm. The overlap in between a blade and this strip is 250 mm. The central strip is bolted to the generator by ten bolts M12 * 40 or M12 * 35 at a pitch circle of 130 mm.

The blade is connected to the central strip by three stainless steel bolts M16 and three self locking nuts M16. The holes for the bolts are milled at the place where the airfoil has its maximum thickness. This is at a distance of 72 mm from the nose. The central strip makes contact with the inner side of the flat front side of the blade. A 150 mm wide aluminium block is placed in between the central strip and the inner side of the curved back side of the blade. This aluminium block is flat at the front side but curved with the same shape as the inner back side of the airfoil. This aluminium block transfers the force in between blade and strip without stress concentration at the holes for the 16 mm bolts. The bolts are chosen that long that there is no thread at the 1.5 mm thick material of the flat lower side of the blade. So some washers have to be used below the nuts.

So a blade is a hollow structure which is rather torsion stiff. This may work as organ pipe if the blade is open at the blade tip. So a 1.5 mm sheet with the shape of the airfoil is welded at the blade tip. There are two holes at the blade root at both sides of the central strip and the aluminium block but I think that it isn’t necessary to close these holes.

A press to bend the back side of the blade and to make the 90° bend at the leading edge at the front side of the blade has still to be developed. The mass of the whole rotor is about 44 kg which is acceptable for a steel rotor with a diameter of 5 m.

3 Calculation of the rotor geometry

The rotor geometry of the VIRYAS-5S is determined using the method and the formulas as given in report KD 35 (ref. 3). This report (KD 749) has its own formula numbering. Substitution of $\lambda_d = 7$ and R = 2.5 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 2.8 * r \qquad (-) \qquad (1)$$

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

$$\beta = \phi - \alpha \qquad (°) \qquad (2)$$

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

Substitution of B = 2 and c = 0.24 m in formula (5.4) of KD 35 gives:

$$C_l = 52.360 * r\,(1 - \cos\phi) \qquad (-) \qquad (4)$$

Substitution of V = 5 m/s and c = 0.24 m in formula (5.5) of KD 35 gives:

$$R_{e\,r} = 0.8 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)} \qquad (-) \qquad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.4 m of one to another. Station F corresponds to the blade root. First the theoretical values are determined for C_l, α and β. Next a constant value is chosen for β such that the linearised values correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The Reynolds values for the stations are calculated for a wind speed of 5 m/s because this is a realistic value for a windmill with a rated wind speed of 11 m/s. The aerodynamic characteristics of the Gö 711 airfoil are only available for Re = $4 * 10^5$ (see KD 285, ref. 4). But the chords are rather large and I think that it is no problem for the calculation of the inner stations that only measurements for Re = $4 * 10^5$ are available.

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	2.5	7	5.4	0.24	0.59	0.62	5.63	4	-1	-0.6	6.4	6.0	0.022
B	2.1	5.88	6.4	0.24	0.69	0.70	4.73	4	0.2	0.4	6.2	6.0	0.020
C	1.7	4.76	7.9	0.24	0.85	0.82	3.85	4	2.1	1.9	5.8	6.0	0.016
D	1.3	3.64	10.2	0.24	1.08	1.01	2.96	4	5.2	4.2	5.0	6.0	0.015
E	0.9	2.52	14.4	0.24	1.49	1.34	2.09	4	11.5	8.4	2.5	6.0	0.021
F	0.5	1.4	23.7	0.24	2.21	1.36	1.24	4	-	17.7	-	6.0	0.145

table 1 Calculation of the blade geometry of the VIRYA-5S 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 most important outer stations A up to D and varies in between 6.4° and 5.0°. Therefore it is allowed to take a constant value of 6° for the whole blade. The central strip is twisted 6° right hand in between the hub and the position of the blade root. A picture of the rotor is given in figure 1.

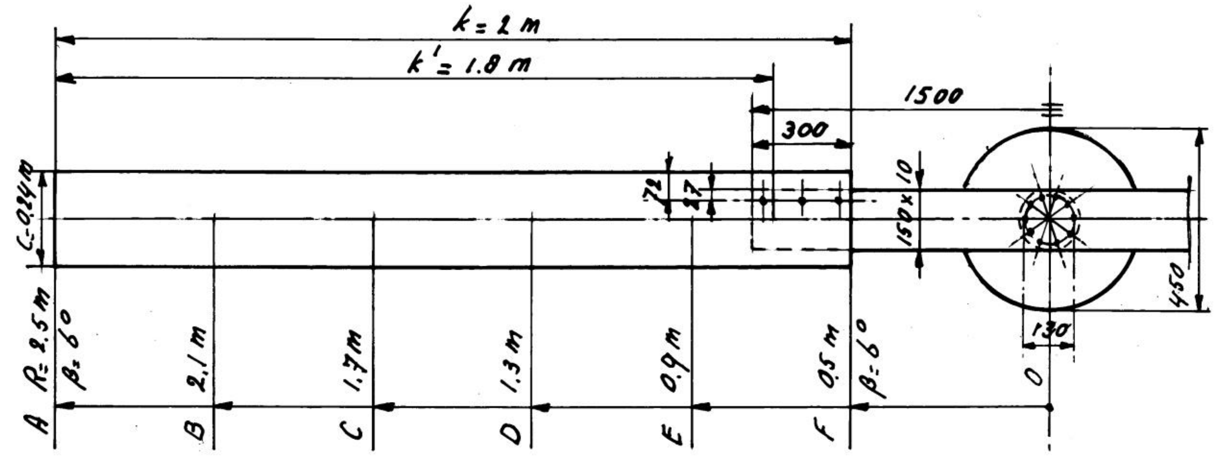

fig. 1 VIRYA-5S rotor for six stations A, B, C, D, E and F

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

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the most important outer part of the blade is about 0.02. Figure 4.6 of KD 35 (for B = 2) and $\lambda_{opt} = 7$ and $C_d/C_l = 0.02$ gives $C_{p\ th} = 0.46$.

The blade is stalling at station F and the airfoil is disturbed by the bolt heads and nuts. For the calculation of the maximum C_p therefore not the whole blade length k = 2 m is taken into account but only the part up to half way station E and F. This gives an effective blade length k' = 1.8 m.

Substitution of $C_{p\ th} = 0.46$, R = 2.5 m and effective blade length k' = 1.8 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.42$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.42 / 7 = 0.06$.

Substitution of $\lambda_{opt} = \lambda_d = 7$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 11.2$.

The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

The blade angle is 6° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 6° = 84°. The aerodynamic characteristics for the Gö 711 aren't given for large angles of α. However, it is assumed that the characteristics of the Gö 623 airfoil can be used for large angles of α. The estimated C_l-α curve for large values of α is given as figure 5.10 of KD 35 (ref. 3). For α = 84° it can be read that $C_l = 0.21$. The whole blade is stalling during starting and therefore now the whole blade length k = 2 m is taken.

Substitution of B = 2, R = 2.5 m, k = 2 m, $C_l = 0.21$ and c = 0.24 m in formula 6 gives that $C_{q\ start} = 0.0046$. For the ratio between the starting torque and the optimum torque we find that it is 0.0046 / 0.06 = 0.077. This is acceptable for a rotor with $\lambda_d = 7$.

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

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

For the generator it is specified that the sticking torque is less than 0.3 Nm. However, this is if no oil seal on the generator shaft is mounted. For use with the shaft horizontal, a seal is needed. Assume that the sticking torque with a seal is 1.5 Nm. Substitution of Q_s = 1.5 Nm, $C_{q\ start}$ = 0.0046, ρ = 1.2 kg/m^3 and R = 2.5 m in formula 7 gives that V_{start} = 3.3 m/s. This is acceptable for a 2-bladed rotor with a design tip speed ratio of 7.

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. 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 623 or a Gö 711 airfoil is used. A scale model of a three bladed rotor with constant chord and blade angle and with a design tip speed ratio λ_d = 6 has been measured in the wind tunnel already on 20-11-1980. It has been found that the maximum C_p was more than 0.4 and that the C_q-λ curve for low values of λ was not horizontal but somewhat rising. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-5S rotor are given in figure 2 and 3.

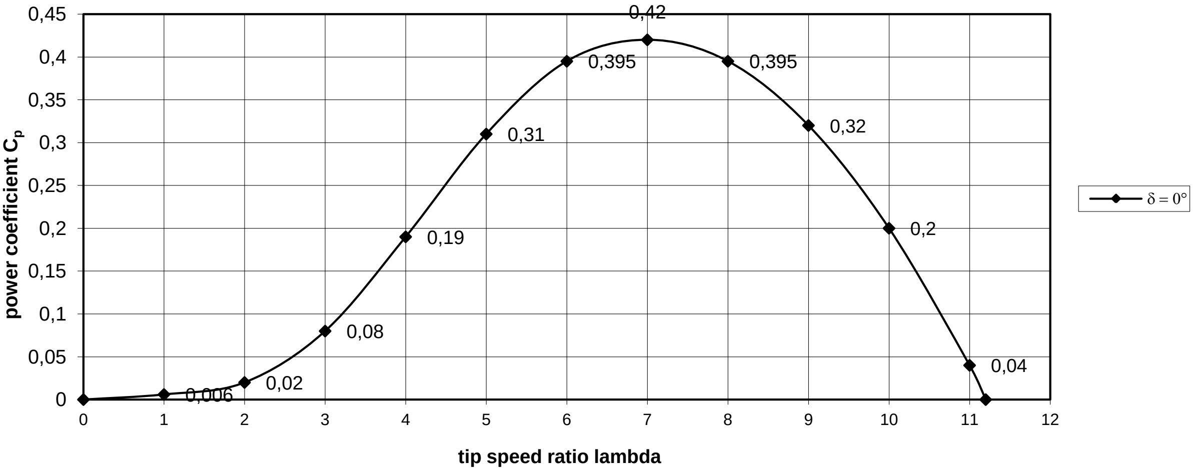

fig. 2 Estimated C_p-λ curve for the VIRYA-5 rotor for the wind direction perpendicular to the rotor (δ = 0°)

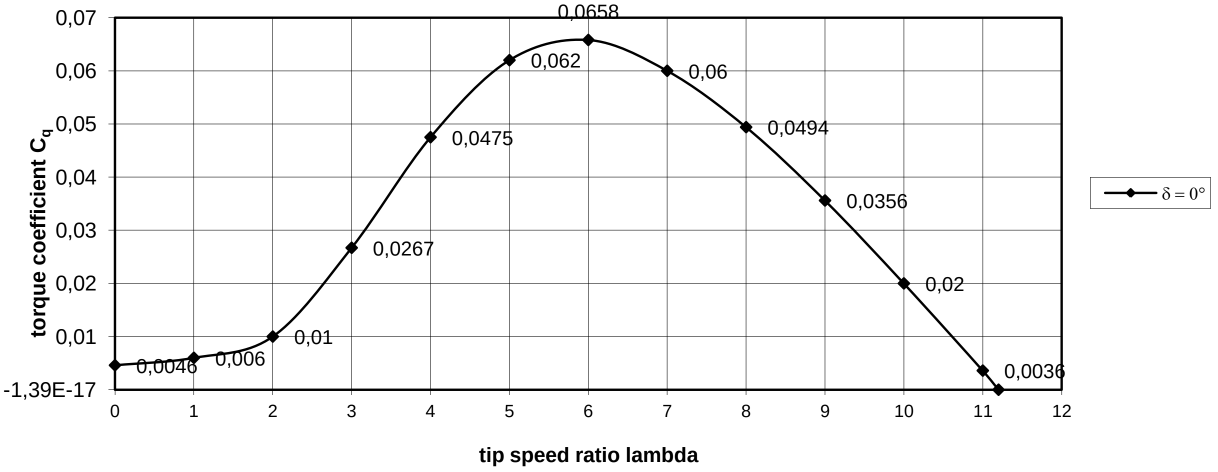

fig. 3 Estimated C_q-λ curve for the VIRYA-5 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 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 12 mm meranti waterproof plywood with a density of about $0.45 * 10^3$ kg/m^3. This vane blade gives a rated wind speed V_{rated} of about 11 m/s. In report KD 213 (ref. 6) 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 meranti plywood and a rated wind speed of about 9.5 m/s. Increase of the thickness from 9 mm up to 12 mm results in a rated wind speed of about 11 m/s. The estimated curve is given in figure 4.

The head starts to turn away at a wind speed of about 7 m/s. For wind speeds above 11 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 11 m/s will therefore also be valid for wind speeds higher than 11 m/s.

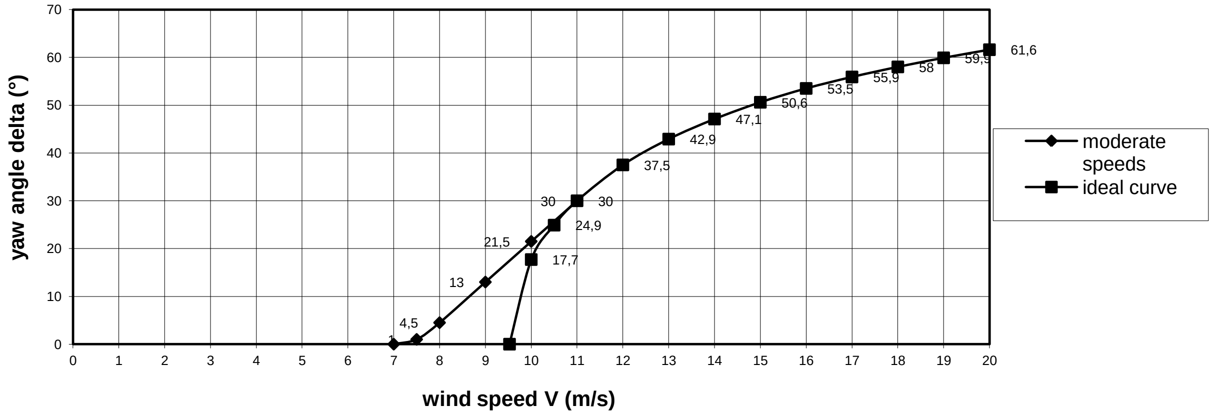

fig. 4 Estimated δ-V curve for a 12 mm meranti plywood vane blade

The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10, and 11 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 = 2.5 m in formula 7.1 of KD 35 gives:

$$n_\delta = 3.8197 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 2.5 m in formula 7.10 of KD 35 gives:

$$P_\delta = 11.781 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ is 4, 5, 6, 7, 8, 9, 10 and 11.2 (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 = 0°		V = 8 m/s δ = 4.5°		V = 9 m/s δ = 13°		V = 10 m/s δ = 21.5°		V = 11 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_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
4	0.19	45.8	60.9	61.1	143.3	76.4	279.8	91.7	483.5	107.0	767.8	121.9	1135.5	134.0	1509.5	142.2	1802.9	145.6	1935.1
5	0.31	57.3	99.4	76.4	233.7	95.5	456.5	114.6	788.9	133.7	1252.7	152.3	1852.6	167.5	2462.9	177.7	2941.6	181.9	3157.3
6	0.395	68.8	126.6	91.7	297.8	114.6	581.7	137.5	1005.2	160.4	1596.1	182.8	2360.6	201.0	3138.2	213.2	3748.1	218.3	4023.0
7	0.42	80.2	134.6	107.0	316.7	133.7	618.5	160.4	1068.8	187.2	1697.2	213.2	2510.0	234.5	3336.8	248.8	3985.3	254.7	4277.6
8	0.395	91.7	126.6	122.2	297.8	152.8	581.7	183.3	1005.2	213.9	1596.1	243.7	2360.6	268.0	3138.2	284.3	3748.1	291.1	4023.0
9	0.32	103.1	102.6	137.5	241.3	171.9	471.2	206.3	814.3	240.6	1293.1	274.2	1912.4	301.5	2542.3	319.9	3036.4	327.5	3259.1
10	0.2	114.6	64.1	152.8	150.8	191.0	294.5	229.2	508.9	267.4	808.2	304.6	1195.3	335.0	1589.0	355.4	1897.8	363.9	2037.0
11.2	0	128.3	0	171.1	0	213.9	0	256.7	0	299.5	0	341.2	0	375.2	0	398.0	0	407.5	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-5S 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.

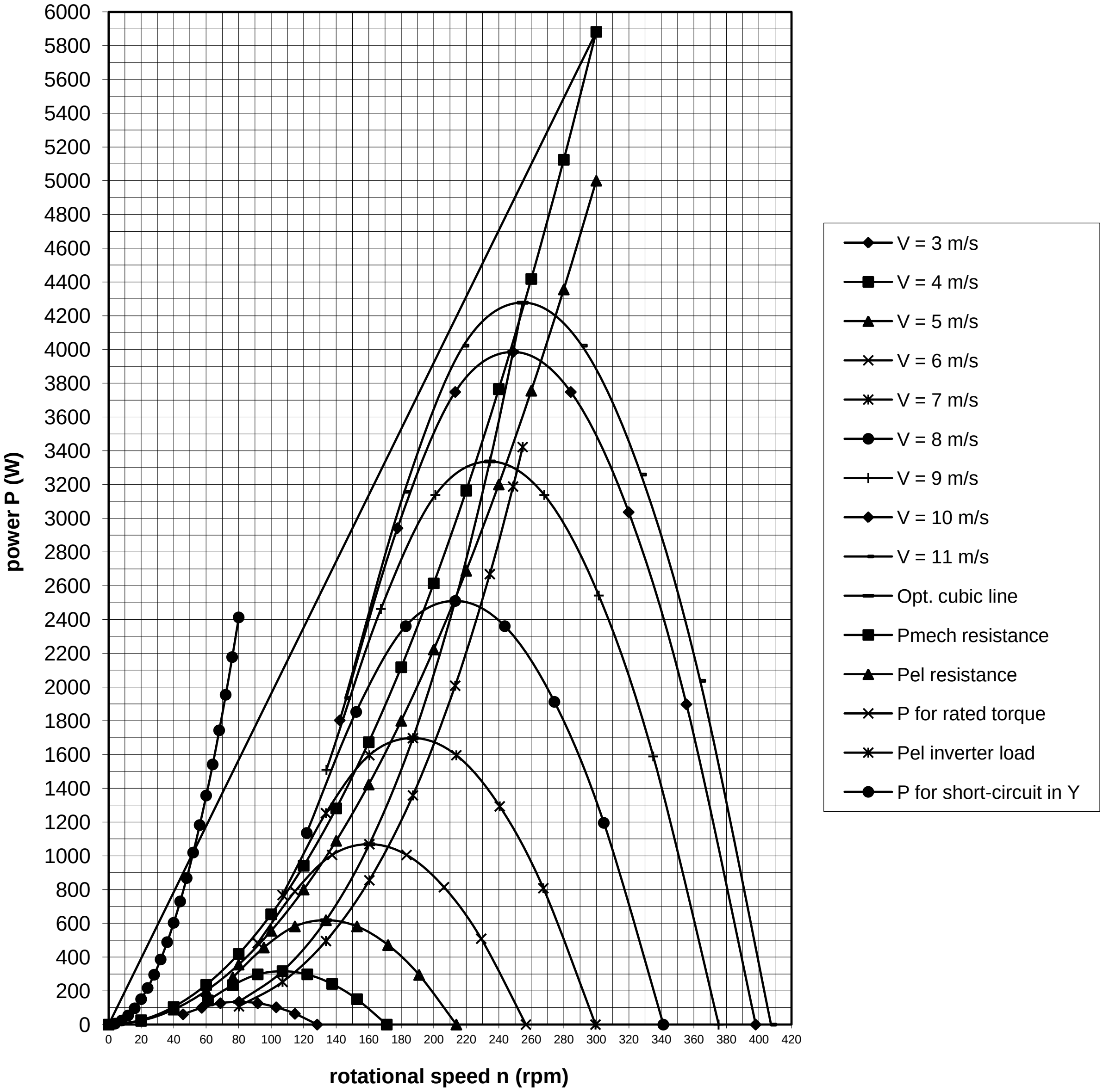

fig. 5 P-n curves and optimum cubic line of the VIRYA-5S rotor, P_{mech}-n and P_{el}-n curves for the generator with a resistance load such that P_{el} = 5000 W at n = 300 rpm, P-n curve for the rated torque, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

6 Use of the VIRYA-5S rotor with the axial flux generator TGET450-5KW-300R

The characteristics of the generator of Hefei Top Grand type TGET450-5KW-300R are derived in chapter 6 of KD 710 (ref. 2) for a resistance load with a value of the resistance such that the electrical power is 5 KW at a rotational speed of 300 rpm. The P_{mech}-n and P_{el}-n curve for this condition are copied in figure 5. It can be seen that the P_{mech}-n curve is intersecting with the optimum cubic line at a wind speed of about 8 m/s.

The P_{el}-n curve for an inverter load such that the optimum cubic line is followed is also copied in figure 5. It is assumed that the total efficiency of generator, rectifier and inverter is 0.8. The P_{el}-V curve for the working points is derived from figure 5 and is given in figure 6.

The torque for a resistance load is maximal for n = 300 rpm. This torque can also be supplied at lower rotational speeds. A constant torque results in a power curve which increases linear. The P-n line for the rated torque and the line for short-circuit in star are also given in figure 5.

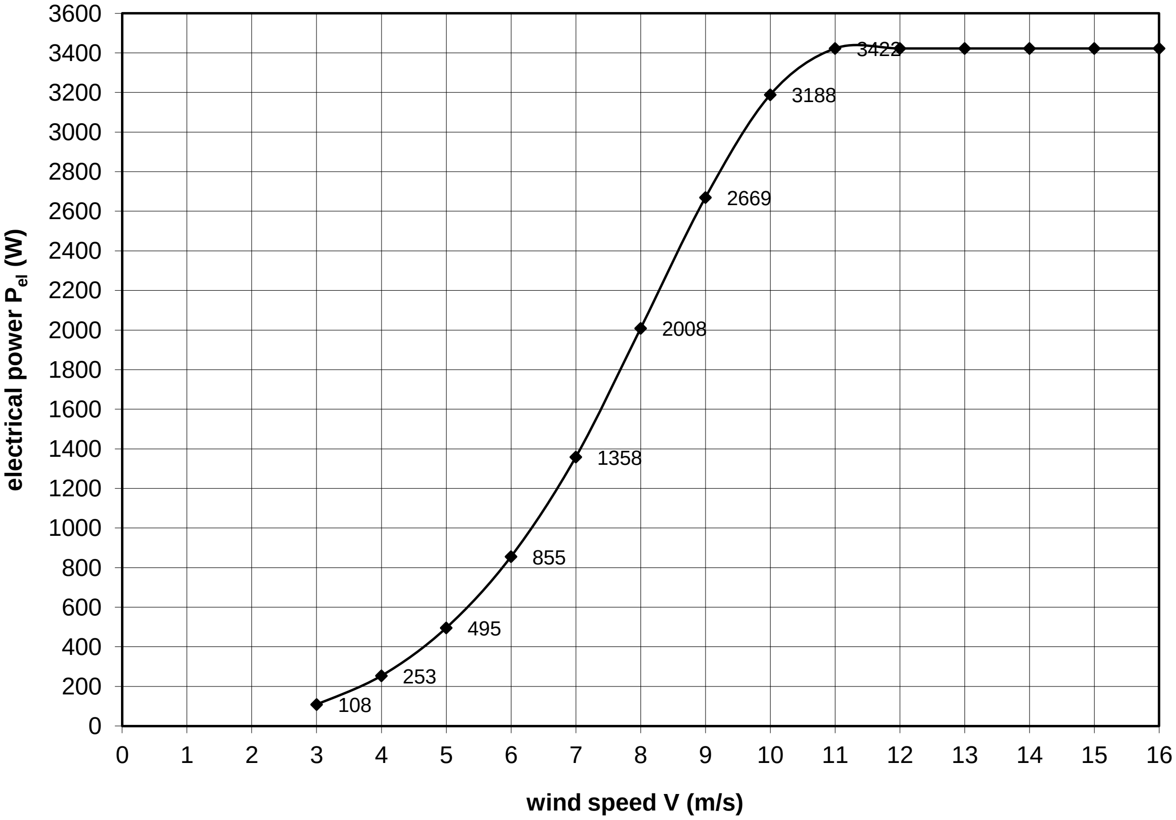

fig. 6 P_{el}-V curve VIRYA-5S for a load such that the optimum cubic line is followed.

The inverter needs a minimum voltage to start functioning. It is assumed that this voltage is generated at V = 3 m/s. This is the reason why the P_{el}-V curve starts suddenly with P_{el} = 108 W at V = 3 m/s. In chapter 4 it was calculated that the starting wind speed is 3.3 m/s and so there is hysteresis in the P_{el}-V curve for $3 < V < 3.3$ m/s. The maximum power is about 3.5 kW at a wind speed of 11 m/s or higher which is very good for a wind turbine with a rotor diameter of 5 m and a rated wind speed of 11 m/s. The P-n curve for short-circuit in star is lying for to the left side of the P-n curve of the rotor for V = 11 m/s. So it is possible to slow down the rotor till almost stand still at any wind speed by making short-circuit.

Just as it is the case for the VIRYA-5B3, it is also possible to use the VIRYA-5S for 120 V battery charging or for heating by a resistance load (see KD 710 chapter 7 and 8).

7 Use of the VIRYA-5S for water pumping

The most elegant option for water pumping 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 "TGET450 generator" is typed in the website of Alibaba, one finds a page about the TGET450 and the PMG450. If one scrolls down at this page, one finds several photos. One photo shows the magnet configuration and it can be counted that 20 poles are used. But if this is really the case for the TGET450, has still to be verified. Assume that the generator 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 only reached for an unloaded rotor at a wind speed of about 7 m/s. For a loaded rotor and a wind speed of 11 m/s, this rotational speed is reached at a tip speed ratio of about 8.25. So the use of a pump at 50 Hz is impossible for the normal rotational speed of the pump motor.

Assume that a centrifugal pump is used with a 3-phase asynchronous motor. Assume that the pump motor is used at a frequency of 31 Hz. This means that the pump rotates only at 31/50 of its nominal rotational speed. A 20-pole PM-generator will have this frequency at a rotational speed of 31/50 * 300 = 186 rpm. In figure 5 it can be seen that this rotational speed is found for the optimum cubic line at a wind speed of 7 m/s. This wind speed is now called the design wind speed V_d. The mechanical power is about 1700 W. Assume that the generator efficiency is 0.85. So the electrical power of the generator at V_d = 7 m/s is 0.85 * 1700 = 1445 W. Assume that the efficiency of the pump motor is 0.8. So the supplied mechanical power of the pump motor is 0.8 * 1445 = 1156 W.

The static height H of a centrifugal pump decreases with the square of the rotational speed. The static height H is the height in between the low and the high water level. The flow q decreases linear with the rotational speed. Assume that the VIRYA-5S is used for drainage and that the height H = 1 m. So one has to choose a pump which is designed for a height H which is a factor $(50/31)^2$ = 2.6 higher and so the nominal height must be 2.6 * 1 = 2.6 m. This pump must have a 3-phase asynchronous motor meant for a 3-phase grid with a frequency of 50 Hz and a phase voltage of 230 V as standard used in Europe. Such a grid is connected in star and so it has a voltage in between the phases of 230 * √3 = 398 V. This value is mostly rounded to 400V.

The generator type TGET450-5KW-300R has a voltage in between the phases of 220 VAC at a rotational speed of 300 rpm. This voltage is much too low if the pump motor is connected in star. But it is about right if the pump motor is connected in delta. So it is assumed that the pump is provided with a motor with a 230/400 V winding which can be connected in delta or star and that delta connection is chosen.

If the pump is used at a frequency of 31 Hz, the flow q is 31/50 of the nominal flow. The height H is $(31/50)^2$ of the nominal height H. The needed power is proportional with H *q and at 31 Hz, it is therefore $(31/50)^3$ = 0.238 of the needed nominal power at 50 Hz. This means that the original pump motor must have a nominal motor power of about 1156 / 0.238 = 4857 W = 4.857 kW. The pump must have a nominal height of 2.6 m if it is used for a real height of 1 m at 31 Hz. If the real height H is larger, for instance 2 m, one has to chose a pump with a nominal height which is also a factor 2.6 higher, so which is 5.2 m for H = 2 m.

So a wind speed V_d = 7 m/s is chosen as the design wind speed for the chosen combination of wind turbine and centrifugal pump. At lower wind speeds, the frequency will be lower and the pump motor will therefore turn slower. There is a critical rotational speed of the pump motor for which only just the static water level H can be supplied but for which the flow q is zero.

So the supply of water starts only if the rotational speed is higher than this critical value. It is expected that this critical rotational speed is reached at a wind speed of about 4 m/s. So no water is pumped for lower wind speeds. This means that use of the VIRYA-5S with a centrifugal pump with a 3-phase motor is only possible for areas with rather high wind speeds.

At higher wind speeds than V_d = 7 m/s, the generator will run at a higher rotational speed than 186 rpm and so at a higher frequency than 31 Hz. The needed mechanical power of the pump will increase at increasing rotational speed but, as the static water height is constant, the needed power will increase less than according to a cubic line. This means that the needed electrical power will also increase less than according to a cubic line. This means that the mechanical power which has to be supplied by the rotor of the wind turbine will increase less than according to a cubic line and so the tip speed ratio of the rotor will increase for wind speeds above V_d = 7 m/s. Assume that at V = 11 m/s, the tip speed ratio has increased up to $\lambda = 9$. In figure 5 and table 2 it can be seen that the rotational speed is 327.5 rpm for this wind speed and this tip speed ratio. The frequency at 300 rpm is 50 Hz and so the frequency at 327.5 rpm is 50 * 327.5/ 300 = 54.6 Hz. So at a wind speed of 11 m/s or higher, the pump motor will turn at a slightly higher rotational speed than the nominal rotational speed for which it is designed. I think that this isn’t a problem. So use of the VIRYA-5S for water pumping seems possible but it must be checked in practice.

8 References

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