Calculations executed for the 3-bladed rotor of the VIRYA-5B3S windmill (λ_d = 6.5, 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 791

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1 Introduction

The 2-bladed VIRYA-5 with wooden blades and $\lambda_d = 7$ is described in report KD 614 (ref. 1). The 3-bladed VIRYA-5B3 with wooden blades and $\lambda_d = 6$ is described in report KD 710 (ref. 2). The 2-bladed VIRYA-5S with stainless steel blades and $\lambda_d = 7$ is described in report KD 749 (ref. 3). The VIRYA-5B3 and the VIRYA-5S make use of the axial flux PM-generator of Hefei Top Grand type TGET450-5KW-300R (see KD 614 chapter 12). The generator characteristics are derived in chapter 6 of report KD 710.

In chapter 9 of KD 710 it is already proposed to use stainless steel blades for the VIRYA-5B3. There are two options. One is to use the same blades as used for the VIRYA-5S. Each blade is made from a 1.5 mm thick stainless steel sheet size 500 * 2000 mm. Two of those sheets can be made from a standard sheet size 1 * 2 m. Eight of those sheets can be made from a standard sheet size 2 * 4 m. The other option is to make a blade from a 1.5 mm thick stainless steel strip size 444 * 2000 mm. Nine of those sheets can be made from a standard sheet size 2 * 4 m. This means that the blades for three wind turbines can be made from one standard sheet and therefore this option is chosen. The wind turbine is called the VIRYA-5B3S to distinguish it from the VIRYA-5B3 and the VIRYA-5S. The VIRYA-5B3S has a design tip speed ratio $\lambda_d = 6.5$. The same axial flux generator type TGET450-5KW-300R is also used for the VIRYA-5B3S.

The head geometry of the VIRYA-5B3S is the same as the head geometry of the VIRYA-5, the VIRYA-5B3 and the VIRYA-5S. 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, the VIRYA-5S and the VIRYA-5B3S 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, the VIRYA-5S and the VIRYA-5B3S. 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-5B3S.

2 Description of the rotor of the VIRYA-5B3S windmill

The 3-bladed rotor of the VIRYA-5B3S windmill has a diameter D = 5 m and a design tip speed ratio $\lambda_d = 6.5$. Advantages of a 3-bladed rotor are that the 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 which are made out of a 1.5 mm thick stainless steel sheet size 444 * 2000 mm. So nine blades for three rotors can be made out of one standard 1.5 mm thick sheet size 2 * 4 m. As 9 * 444 = 3996, 4 mm has to be cut from the last sheet to make that all nine sheets have a width of 444 mm. 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 444 mm. It is assumed that c = 214 mm = 0.214 m.

The three blades are connected to each other by a stainless steel spoke assembly which is made from three strips size 665 * 150 * 10 mm which are welded together at the centre at an angle of 120°. Nine spokes for three hub assemblies can be made from a standard 6 m long strip. There is a small triangular hole in the centre of the hub assembly. The overlap in between a blade and a spoke this is 180 mm. The hub assembly is bolted to the generator by nine bolts M12 * 40 or M12 * 35 at a pitch circle of 130 mm.

A blade is connected to a spoke of the spoke assembly the by four stainless steel bolts M12, four self locking nuts M12 and several washers for M12. A spoke makes contact with the inner side of the flat front side of the blade. A 150 mm wide and 180 mm long aluminium block is placed in between the spoke 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 has shallow tapered chambers at the backside at the position of the bolts. The cambered side of the blade is pulled in these chambers by the bolt head if the bolts are tightened. The bolts are chosen that long that there is no thread at the 1.5 mm thick material of the flat front 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. A small hole is drilled in this sheet to make that water can escape. 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 58 kg which seems acceptable for a 3-bladed stainless 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. 4). This report (KD 791) has its own formula numbering. Substitution of $\lambda_d = 6.5$ and R = 2.5 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 2.6 * r \qquad (-) \qquad (1)$$

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 = 3 and c = 0.214 m in formula (5.4) of KD 35 gives:

$$C_l = 39.148 * r\,(1 - \cos\phi) \qquad (-) \qquad (4)$$

Substitution of V = 5 m/s and c = 0.214 m in formula (5.5) of KD 35 gives:

$$R_{e\,r} = 0.714 * 10^5 * \sqrt{}\,(\lambda_{r\,d}{}^2 + 4/9) \qquad (-) \qquad (5)$$

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 linearized 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. 5). But the chords are rather large and the airfoil has a rather sharp nose. Therefore I think that it is no problem for the calculation of the inner stations that only measurements for $Re = 4 * 10^5$ are available.

station	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	6.5	5.8	0.214	0.51	0.51	4.67	4	-1.9	-1.9	7.7	7.7	0.030
B	2.1	5.46	6.9	0.214	0.60	0.60	3.93	4	-0.8	-0.8	7.7	7.7	0.023
C	1.7	4.42	8.5	0.214	0.73	0.74	3.19	4	0.7	0.8	7.8	7.7	0.018
D	1.3	3.38	11.0	0.214	0.93	0.94	2.46	4	3.1	3.3	7.9	7.7	0.015
E	0.9	2.34	15.4	0.214	1.27	1.27	1.74	4	7.7	7.7	7.7	7.7	0.021
F	0.5	1.3	25.0	0.214	1.84	1.37	1.04	4	-	17.3	-	7.7	0.14

table 1 Calculation of the blade geometry of the VIRYA-5B3S 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 E and varies in between 7.7° and 7.9°. Therefore it is allowed to take a constant value of 7.7° for the whole blade. The spokes are twisted 7.7° right hand in between the hub and the position of the blade root. A picture of the rotor is given in figure 1.

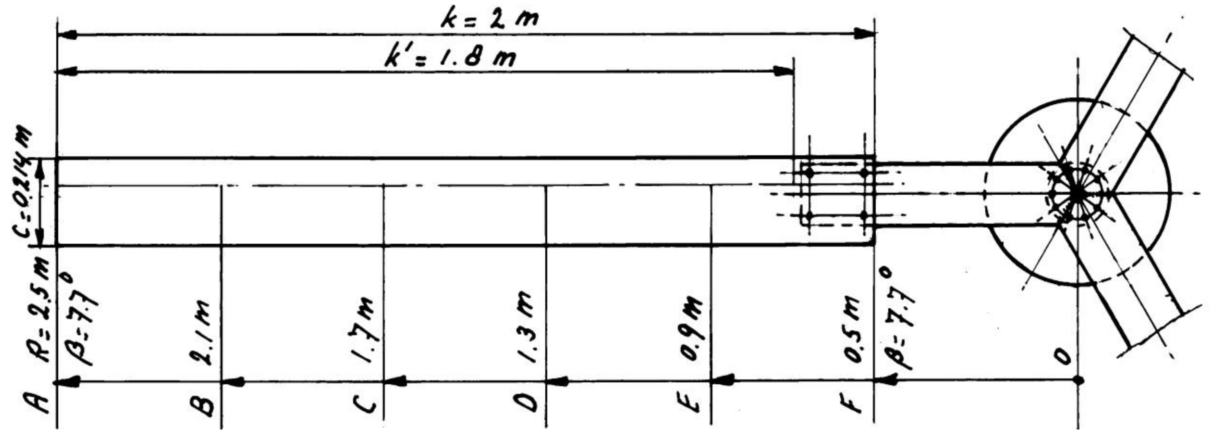

fig. 1 VIRYA-5B3S rotor for six stations A, B, C, D, E and F

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 0.022. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6.5$ and $C_d/C_l = 0.022$ gives $C_{p\ th} = 0.47$.

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 $C_{p\ th} = 0.47$, R = 2.5 m and effective blade length k' = 1.8 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.43$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.43 / 6.5 = 0.0662$.
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 given by:

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

The blade angle is 7.7° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 7.7° = 82.3°. 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. 4). For $\alpha = 82.3°$ it can be read that $C_l = 0.26$. The whole blade is stalling during starting and therefore now the whole blade length k = 2 m is taken.
Substitution of B = 3, R = 2.5 m, k = 2 m, $C_l = 0.26$ and c = 0.214 m in formula 6 gives that $C_{q\ start} = 0.0077$. For the ratio between the starting torque and the optimum torque we find that it is 0.0077 / 0.0662 = 0.116. This is acceptable for a rotor with $\lambda_d = 6.5$.

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

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

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, $C_{q\ start} = 0.0077$, $\rho = 1.2\ kg/m^3$ and R = 2.5 m in formula 7 gives that $V_{start} = 2.6$ m/s. This is acceptable for a 3-bladed rotor with a design tip speed ratio of 6.5.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for $\lambda = 0$. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 6). 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 $\lambda_d = 6$ has been measured in the wind tunnel already on 20-11-1980. It has been found that the maximum C_p was more than 0.4 and that the C_q-λ curve for low values of λ was not horizontal but somewhat rising. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-5B3S rotor are given in figure 2 and 3.

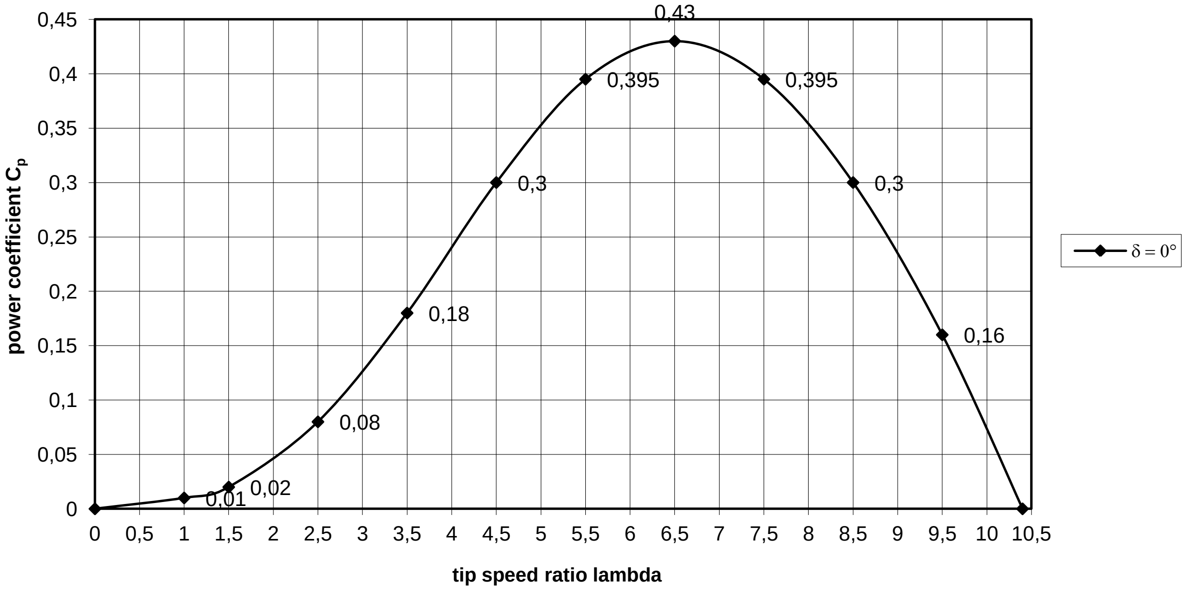

fig. 1 Estimated C_p-λ curve for the VIRYA-5R rotor for the wind direction perpendicular to the rotor (δ = 0

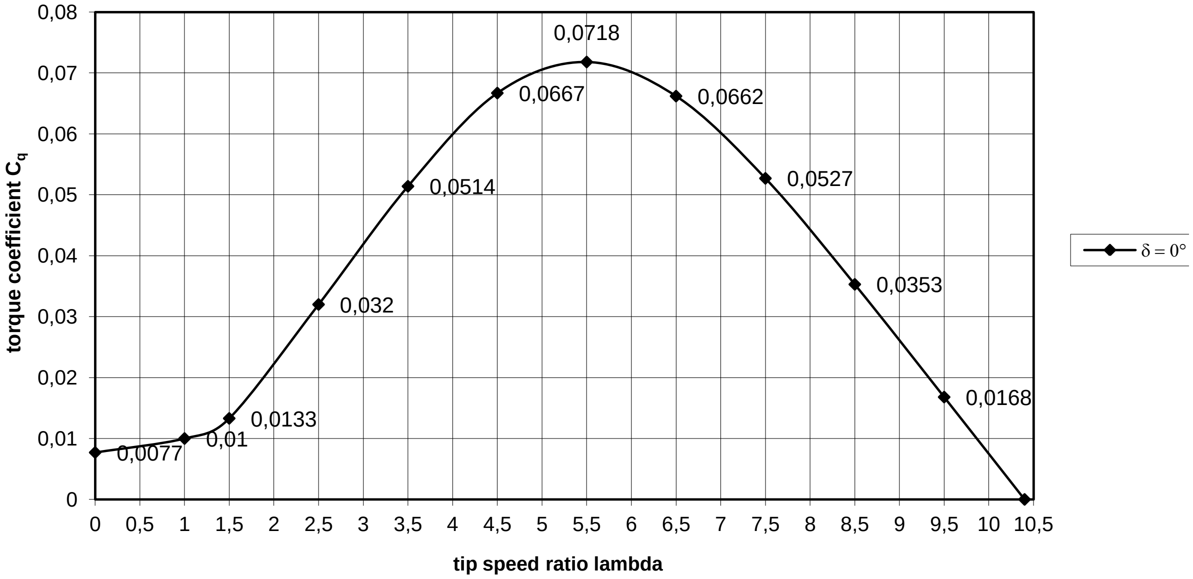

fig. 2 Estimated C_q-λ curve for the VIRYA-5R rotor for the wind direction perpendicular to the rotor (δ = 0°)

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. 7) 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.

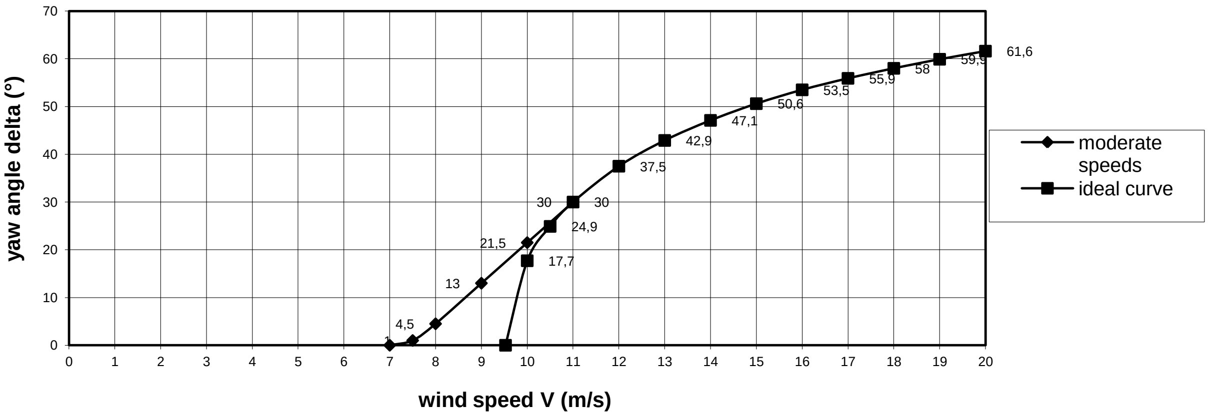

fig. 4 Estimated δ-V curve for a 12 mm meranti plywood vane blade

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 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 = 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)
3.5	0.18	40.1	57	53.5	136	66.8	265	80.2	458	93.6	727	106.6	1076	117.2	1430	124.4	1708	127.4	1833
4.5	0.3	51.6	95	68.8	226	85.9	442	103.1	763	120.3	1212	137.1	1793	150.7	2383	159.9	2847	163.7	3055
5.5	0.395	63.0	126	84.0	298	105.0	582	126.1	1005	147.1	1596	167.5	2361	184.2	3138	195.5	3748	200.1	4023
6.5	0.43	74.5	137	99.3	324	124.1	633	149.0	1094	173.8	1738	198.0	2570	217.7	3416	231.0	4080	236.5	4379
7.5	0.395	85.9	126	114.6	298	143.2	582	171.9	1005	200.5	1596	228.5	2361	251.2	3138	266.5	3748	272.9	4023
8.5	0.3	97.4	95	129.9	226	162.3	442	194.8	763	227.3	1212	258.9	1793	284.7	2383	302.1	2847	309.3	3055
9.5	0.16	108.9	51	145.1	121	181.4	236	217.7	407	254.0	647	289.4	956	318.2	1271	337.6	1518	345.7	1630
10.4	0	119.2	0	158.9	0	198.6	0	238.3	0	278.1	0	316.8	0	348.4	0	369.6	0	378.4	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-5B3S 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.

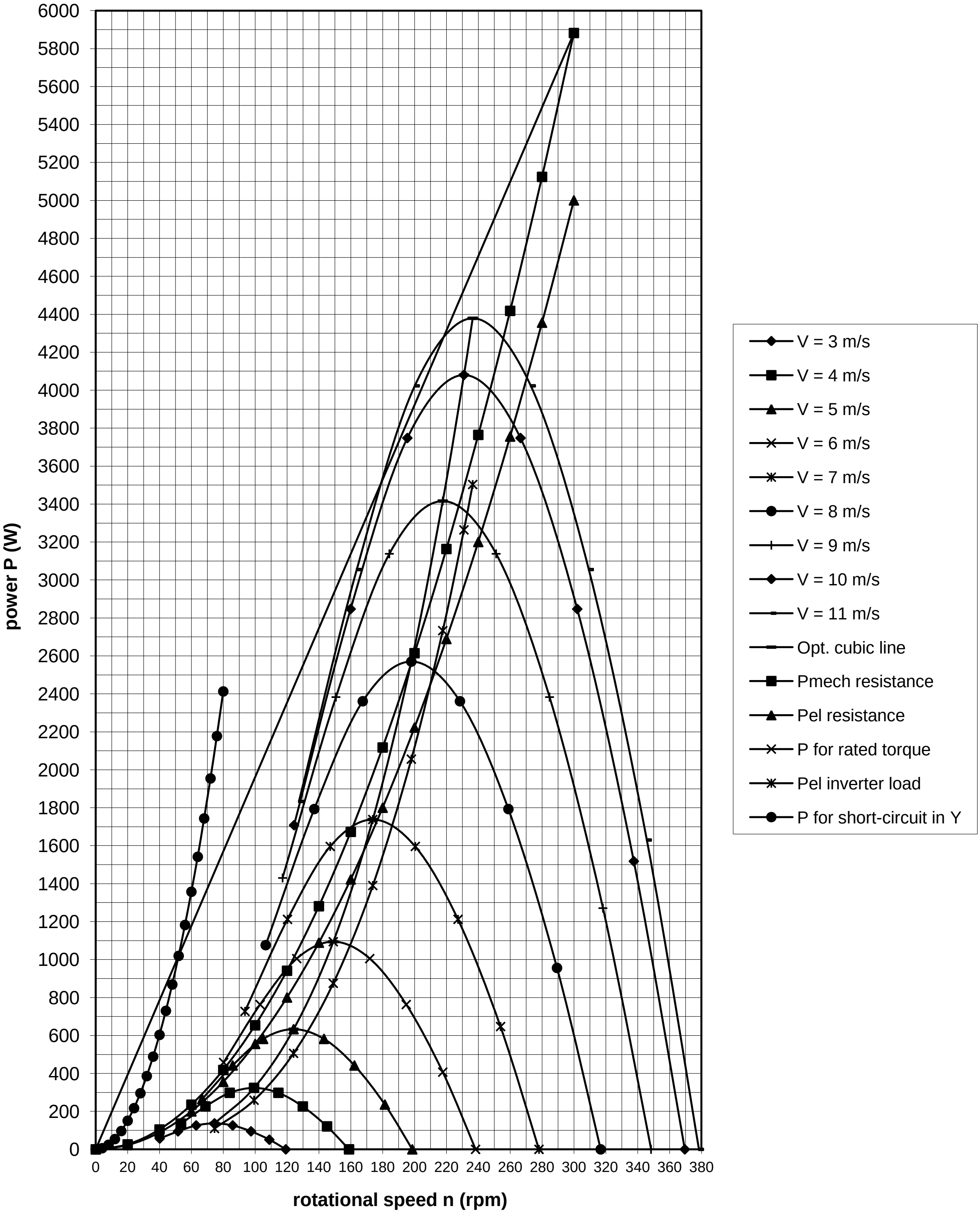

fig. 5 P-n curves and optimum cubic line of the VIRYA-5B3S rotor, P_{mech}-n and P_{el}-n curves for the generator with a resistance load such that P_{el} = 5000 W at n = 300 rpm, P-n curve for the rated torque, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

6 Use of the VIRYA-5B3S 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 given 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 rated 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.

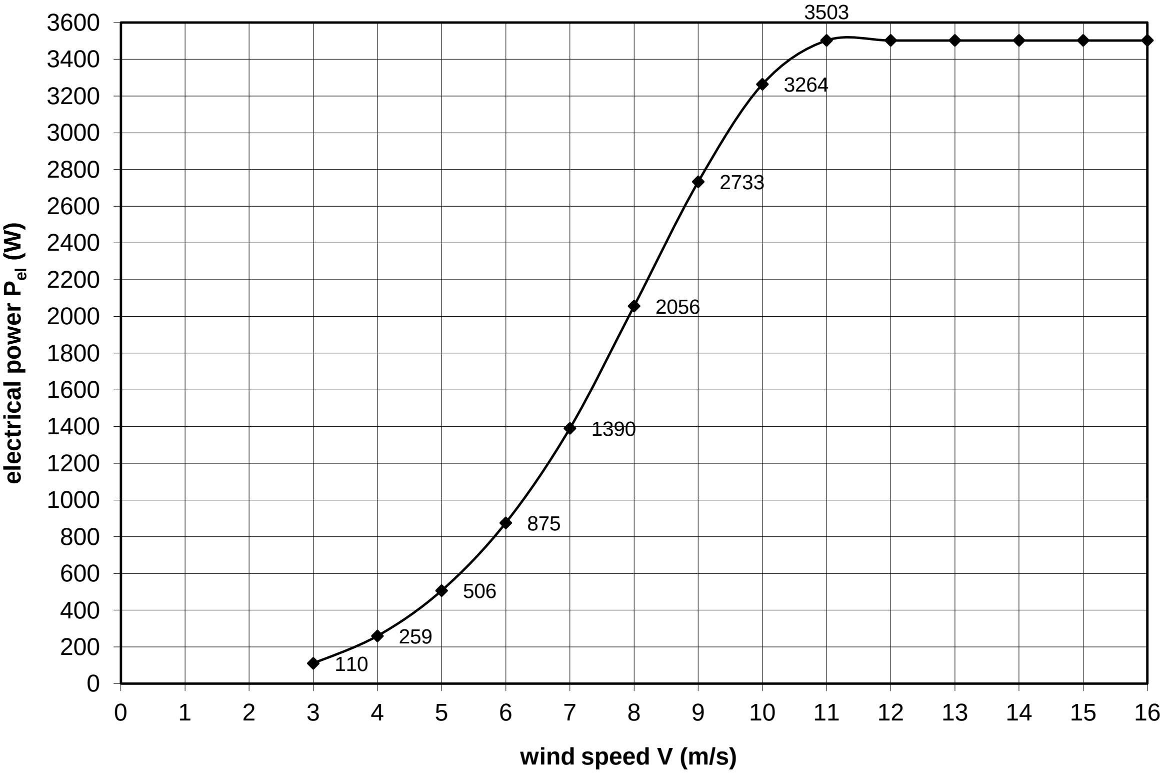

fig. 6 P_{el}-V curve VIRYA-5B3S for a load such that the optimum cubic line is followed.

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} = 110 W at V = 3 m/s. In chapter 4 it was calculated that the starting wind speed is 2.6 m/s and so there is no hysteresis in the P_{el}-V curve. 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 also given in figure 5. This curve is laying far 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. The straight P-n line for the rated torque is also given in figure 5. This line starts at the short-circuit curve. Only a small part of the P-n curve of the rotor for V = 11 m/s is lying to the left side of this line and so normally, the generator torque won’t be higher than the rated torque. But the generator torque can be much higher than the rated torque.

Instead of the generator of Hefei Top Grand, it might also be possible to use a generator which is made from a 6-pole asynchronous 3-phase motor frame size 160. This generator is described in chapter 7 of report KD 747 (ref. 8).

7 Use of the VIRYA-5B3S for 144 V battery charging

The VIRYA-5B3S with the generator type TGET450-5KW-300R is primary meant for grid connection. However, there are many places on earth where no grid is available and it would be nice if the VIRYA-5B3S could also be used to charge batteries. As the generator supplies a rather high DC voltage after rectification, the battery voltage must be rather high to get an acceptable matching at moderate wind speeds. 120 V battery charging is described in chapter 7 of KD 710 (ref. 2) for the VIRYA-5B3. The VIRYA-5B3S has a higher design tip speed ratio than the VIRYA-5B3 (6.5 instead of 6) and the optimum cubic line is therefore lying more to the right. This would result in bad matching for high wind speeds if 120 V battery charging would also been chosen for the VIRYA-5B3S. So 144 V battery charging is chosen for the VIRYA-5B3S. It is assumed that 12 V lead acid batteries are used, so twelve 12 V batteries (each minimal 100 Ah) have to be connected in series to get a nominal battery voltage of 144 V. Information about 12 V lead acid batteries is given in chapter 3 of report KD 378 (ref. 9).

The open voltage of a 12 V lead acid battery is about 12 V if the battery is 10 % full and about 12.6 V if the battery is 90 % full. The open voltage should be measured only after at least 15 minutes no charging or discharging. The loaded voltage of a 12 V battery depends on the charging state and on the current. The minimum loaded voltage is about 12.6 V for an almost empty battery at low currents. The maximum loaded voltage is normally limited up to 13.8 V to prevent gassing. So the average charging voltage of a 12 V battery is about 13.2 V. So the average charging voltage of a 144 V battery is about 12 * 13.2 = 158.4 V. The Q-n and the P_{mech}-n curves are now determined for a charging voltage of 158.4 V in the same way as it was done in KD 710 for charging voltage of 132 V. It is checked if the matching is acceptable for this average charging voltage.

In KD 710 it was found that an open voltage of 132 V is obtained at a rotational speed of 110 rpm. So an open voltage of 158.4 V will be obtained at a rotational speed of 110 * 158.4 / 132 = 132 rpm. Figure 9 out of KD 710 is now copied as figure 7 and the curve for 132 V DC is replaced by the curve for 158.4 V DC. This means that the curve for 158.4 V DC is a straight line which is going through the point n = 132 rpm and Q = 0 Nm and the point n = 184 rpm and Q = 187.2 Nm.

To determine the P_{mech}-n curve for U = 132 V DC, several points have to be chosen on the Q-n curve for U = 158.4 V DC. This was done for every 4 rpm. P_{mech} is then calculated for every point using formula 10.

$$P_{mech} = Q * n * \pi / 30 \quad (W) \qquad (10)$$

The result of this procedure is given in table 3. It is assumed that the Q-n curve is about straight for rotational speeds up to 208 rpm and the Q-n and P-n curves are extended up to this rotational speed. For higher rotational speeds than about 208 rpm, the Q-n curve for 158.4 V DC will bend to the right and will have a maximum value at a certain rotational speed. This part of the curve can only be determined by measuring. So the P_{mech}-n curve for 158.4 V DC can’t be determined for rotational speeds higher than about 208 rpm.

Figure 5 is now copied as figure 8 but only the optimum cubic line, the curve “P for rated torque” and the curve “P_{mech} resistance” are maintained. The P_{mech}-n curve for 158.4 V DC is added in figure 8. For the determination of the P_{el}-n curve for 158.4 V DC, it is necessary to estimate an efficiency curve. It is not allowed to take a constant efficiency as it was done for an inverter load as for a battery load, the voltage is almost constant and the power is only increasing by increase of the current. So the copper losses are increasing at increasing current and so at increasing rotational speed and this means that the generator efficiency η_{gen} is decreasing at increasing rotational speed. The estimated η_{gen}-n curve is given in figure 9. It is assumed that the peak efficiency is 0.9 for n = 144 rpm.

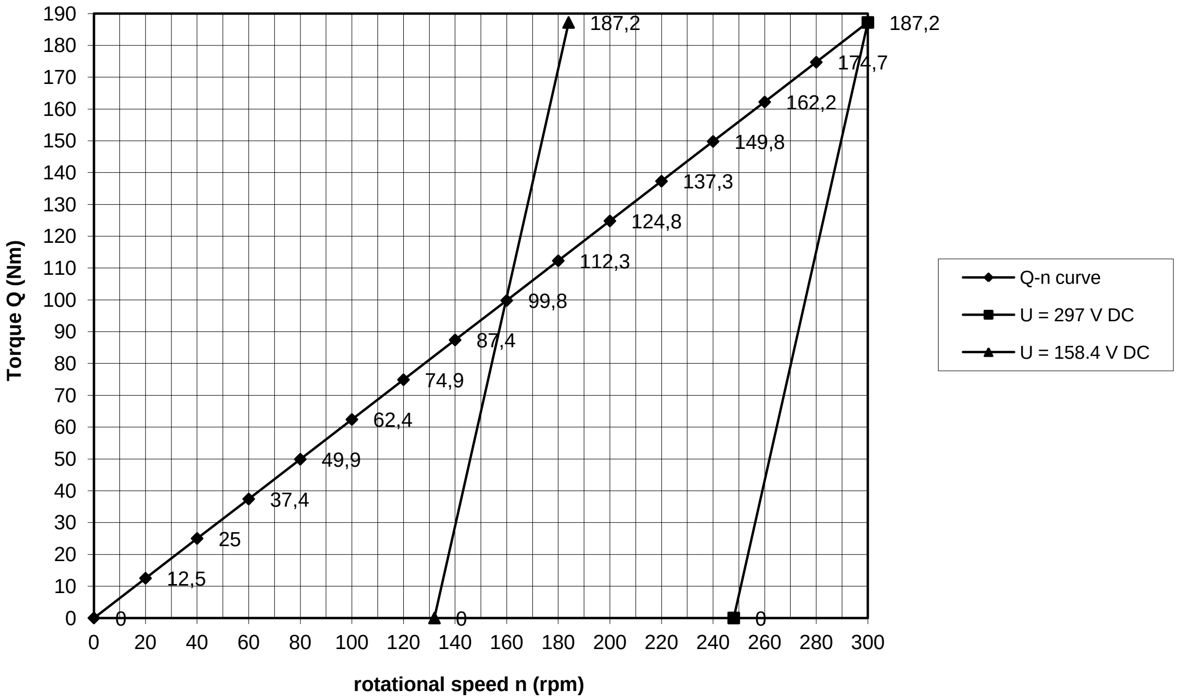

fig. 7 Loaded torque Q as a function of n for a resistance load, Q-n curves for 297 V DC and for 158.4 V DC

n (rpm)	Q (Nm)	P_{mech} (W)	η_{gen} (-)	P_{el} (W)	P_{heat} (W)
132	0	0	0	0	0
136	14.4	192	0.72	138	54
140	28.8	396	0.86	341	55
144	43.2	611	0.9	550	61
148	57.6	837	0.89	745	92
152	72	1146	0.875	1003	143
156	86.4	1411	0.85	1199	212
160	100.8	1689	0.825	1393	296
164	115.2	1978	0.8	1582	396
168	129.6	2280	0.775	1767	513
172	144	2594	0.75	1946	648
176	158.4	2919	0.73	2131	788
180	172.8	3257	0.71	2312	945
184	187.2	3607	0.69	2489	1118
188	201.6	3969	0.67	2659	1310
192	216.0	4343	0.655	2845	1498
196	230.4	4729	0.64	3027	1702
200	244.8	5127	0.625	3204	1923
204	259.2	5537	0.61	3378	2159
208	273.6	5959	0.595	3546	2413

table 3 Calculated values of Q and P_{mech}, P_{el} and P_{heat} as a function of n and η_{gen} for 158.4 V DC

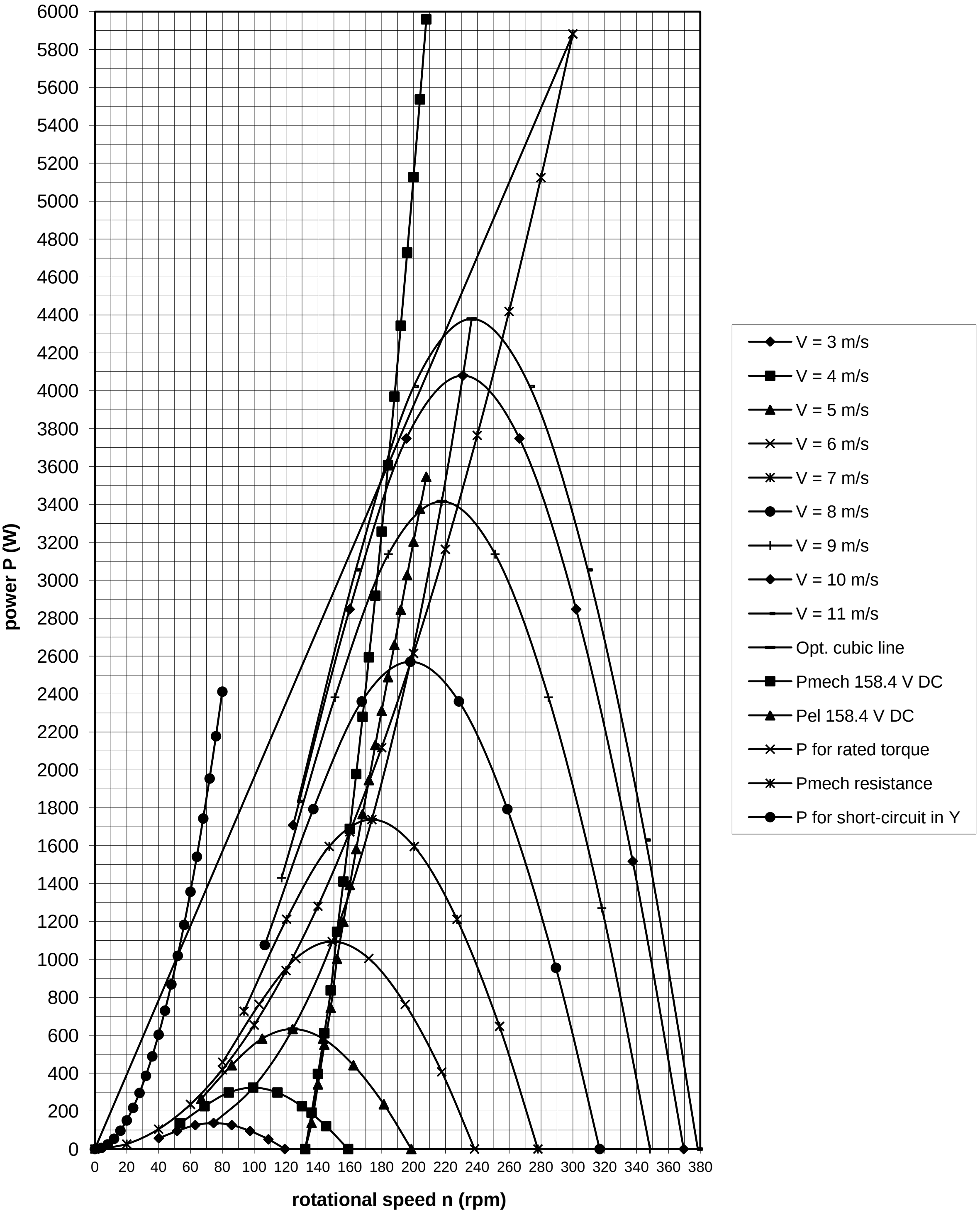

fig. 8 P-n curves of the VIRYA-5B3 rotor, optimum cubic line, P_{mech}-n curve for the generator with a resistance load such that P_{el} = 5000 W at n = 300 rpm, P-n curve for the rated torque, P_{mech}-n and P_{el}-n curves for 158.4 V DC, P-n curve for short-circuit in star

In figure 8 it can be seen that the P_{mech}-n curve for 158.4 V DC is intersecting with the optimum cubic line at a rotational speed of about 152 rpm. This rotational speed belongs to a wind speed of about 6.1 m/s. This wind speed is called the design wind speed V_d for a 144 V battery load. The values of η_{gen} are taken from figure 9 and put in the fourth column of table 3. Next P_{el} is calculated for the given values of η_{gen}. The P_{el}-n curve is then derived from table 3 and is also given in figure 8.

The dissipated heat P_{heat} is given in the last column of table 5. The generated heat for a resistance load at n = 300 rpm is 882 W. So for about the same dissipated heat, the generator should not be driven faster than about 160 rpm for a 158.4 V DC load.

In figure 8 it can be seen that the P_{mech}-n curve for 158.4 V DC is intersecting with the P-n curve of the rotor for V = 11 m/s at a power of about 3600 W and at a rotational speed of about 184 rpm. This is higher than 160 rpm and the dissipated heat for this rotational speed is about 1118 W which is higher than 882 W. But at high wind speeds, the generator is cooled very well and I think that this dissipated heat is acceptable.

The point of intersection of the P_{mech}-n curve for 158.4 V DC and the P-n curve of the rotor for a certain wind speed is called the working point for that wind speed. The electrical power for that wind speed is found by going down vertically from the working point until the P_{el}-n curve is crossed. The P_{el}-V curve found this way for every wind speed is given in figure 10.

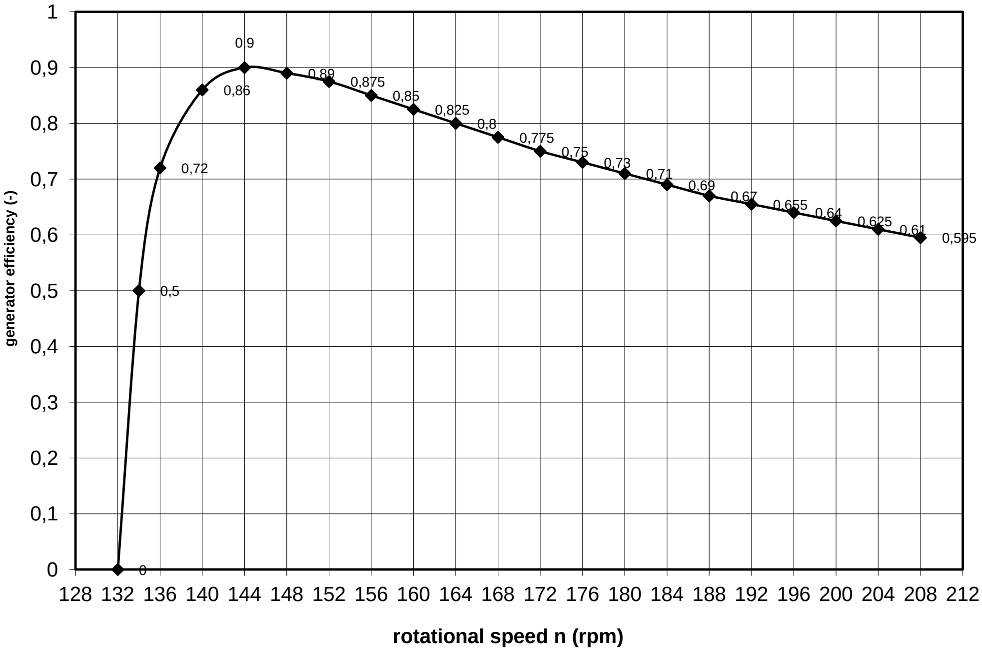

fig. 9 Estimated η_{gen}-n curve for 158.4 V DC for the generator type TGET450-5KW-300R

In figure 8 it can be seen that the rotational speed at V = 11 m/s is about 184 rpm. So only the part of the η_{gen}-n curve for 132 < n < 184 rpm is used. The average efficiency for 136 < n < 184 rpm is about 0.8 which is rather good for battery charging.

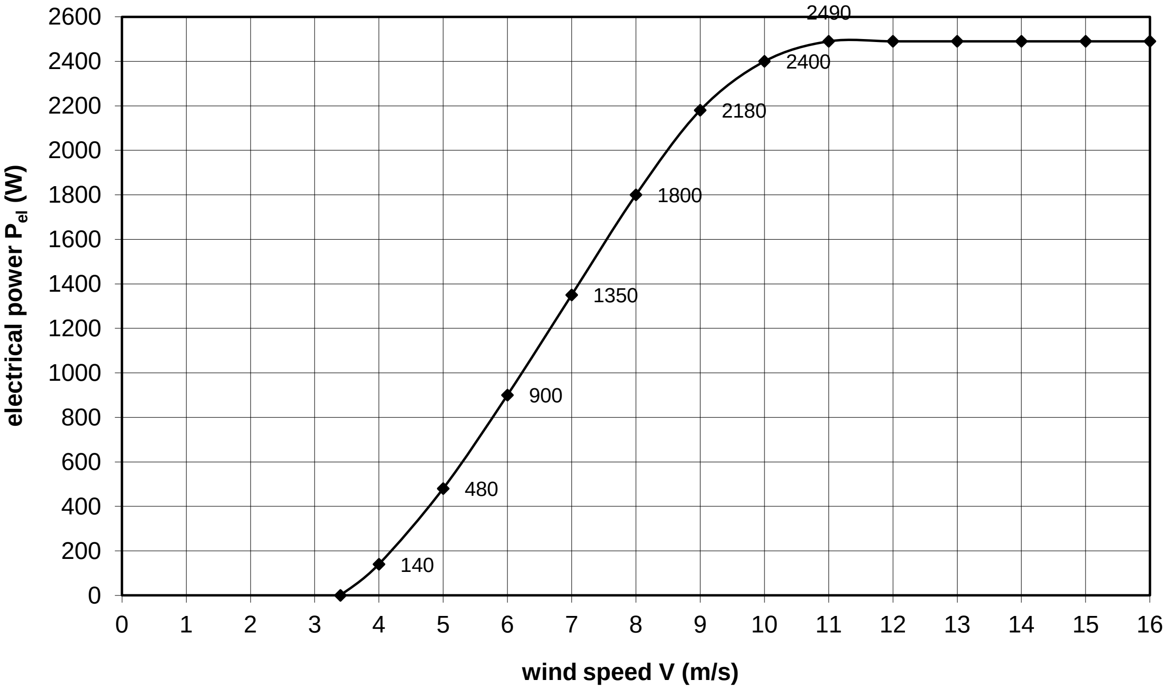

fig. 10 P_{el}-V curve for 158.4 V DC (144 V battery charging)

In figure 10 it can be seen that the cut-in wind speed is about 3.4 m/s and that the maximum power is about 2490 W so about 2.5 kW. This maximum power is much lower than for grid connection for which the maximum power is about 3.5 kW. The cut-in wind speed for grid connection was estimated to be about 3 m/s but it isn't known which minimum voltage is accepted by the inverter. So the power for an inverter load is higher at very low wind speeds and at high wind speeds but at wind speeds in between 5 m/s and 8 m/s it is about the same. The lower power for battery charging is because of bad matching at high wind speeds and because of a lower generator efficiency at high powers.

So the maximum power for 144 V battery charging is about 2490 W. The real charging voltage at this power is 165.6 V if a battery charge controller is used. So the charging current is about 15 A which isn't very high. A battery charge controller is needed to limit the maximum charging voltage up to 165.6 V or to 27.6 V for a set of two 12 V batteries connected in series. A 27.6 V, 200 W battery charge controller is described in a manual which can be found on my website at the bottom of the menu KD reports. The power can be increased up to 400 W by using a cooling plate size 500 * 500 mm with two transistor and four resistors on each plate. So six 400 W battery charge controllers connected in series can dissipate about 2400 W which seems enough as even a full battery, will absorb some power. All six cooling plates and all six voltage controllers must be electrically isolated from each other! Another option is to design a new 165.6 V battery charge controller which can dissipate at least 2400 W but I can't do that.

The rather high generator voltage has as advantage that rather thin wires can be used in between the windmill and the batteries. It is assumed that the rectifier and the short-circuit switch are mounted at the tower foot. So a cable with only two copper wires size 2.5 mm^2 seems enough to prevent large cable losses if the cables aren't very long. For a large distance, one can use wire size 4 mm^2 or two 2.5 mm^2 wires in parallel.

The disadvantage of the high voltage is that it is dangerous. So the batteries must be placed in a closed room which is only accessible by qualified people. The battery voltage can be transferred into an AC voltage of 230 V and 50 Hz with an inverter. Selection of the correct inverter is out of the scope of this report.

8 Use of the VIRYA-5B3S for water pumping

If the VIRYA-5B3S is grid connected by a 3-phase inverter, adding a pump to the system is easy. The size of the pump and the 3-phase asynchronous pump motor isn't important as the required electrical power can always be supplied by the wind turbine or by the grid.

The VIRYA-5B3S with λ_d = 6.5, can be used for 144 V battery charging. This is described in chapter 7. If one has a 144 V battery of enough capacity, there are two options to drive a pump. One option is that one uses a pump with a 144 V DC motor. The other option is that one uses an inverter which transforms the battery voltage into a 3-phase current connected in star with a frequency of 50 Hz and a phase voltage of 230 V. Then one can use the same pump and asynchronous pump motor as if the wind turbine was grid connected.

However, a battery and a 3-phase inverter require a rather large investment. So 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. But 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. Other frequencies can be found easily because the frequency is proportional to the rotational speed.

Next figure 5 is copied as figure 11 but the generator characteristics are removed and replaced by the vertical lines for constant frequencies f of 15 Hz, 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz and 50 Hz. These frequencies correspond to rotational speeds n of 90 rpm, 120 rpm, 150 rpm, 180 rpm, 210 rpm, 240 rpm, 270 rpm and 300 rpm. In figure 11 it can be seen that a frequency of 50 Hz, corresponding to a rotational speed of 300 rpm is only reached for an unloaded rotor at a wind speed of about 6.75 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 7.4. So the use of a pump at 50 Hz is impossible for the normal rotational speed of the pump motor.

The static head H for which a centrifugal pump is designed, depends on the rotational speed n. Water starts only flowing out of the pump above a certain critical rotational speed n_{crit}. Below n_{crit}, the water is only rising in the pressure pipe up to a certain height which is smaller than H. The allowed static head H increases quadratic with n. So a pump designed for a certain head H at a certain rotational speed n can be used at a rotational speed ½ n for a static height of ¼ H.

Assume that a centrifugal pump is used with a 3-phase asynchronous motor. Assume that the pump motor is used at a nominal frequency of 25 Hz. This means that the pump rotates only at half of its nominal rotational speed and therefore it can be used at a quart of its nominal head H. Assume that the critical rotational speed n_{crit} is then reached for a frequency of 15 Hz belonging to a rotational speed of 90 rpm.

In figure 11 it can be seen that the line for f = 25 Hz or n = 150 rpm intersects with the optimum cubic line at a power of about 1100 W. This power can be supplied at a wind speed of about 6 m/s which seems a reasonable wind speed for the VIRYA-5B3S if it is used for water pumping. So the point P = 1100 W and n = 150 rpm is taken as design point and a wind speed of 6 m/s is the design wind speed V_d. The electrical power P_{el} for V_d = 6 m/s depends on the generator efficiency η_{gen}. Assume η_{gen} = 0.85. This gives that $P_{el} = 0.85 * 1100$ = 935 W for V_d = 6 m/s. To find the working points for other rotational speeds, a P-n curve for a pump load has to be estimated.

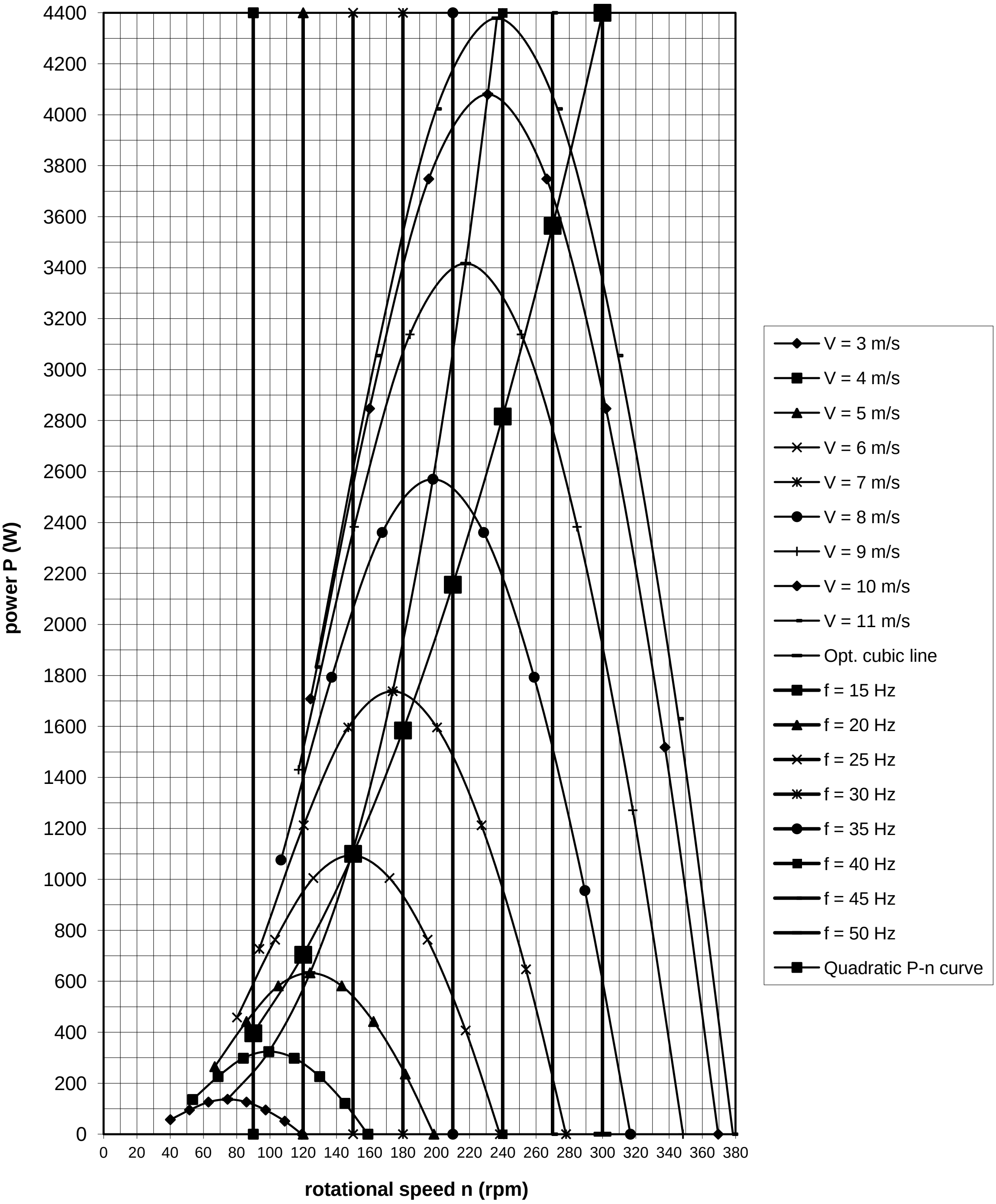

fig. 11 P-n curves and optimum cubic line of the VIRYA-5B3S rotor, lines for frequencies f of 15 Hz, 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz and 50 Hz and quadratic P-n curve

A positive displacement pump requires about a constant torque for any rotational speed. This means that the P-n curve is a straight line through the origin. A centrifugal pump with only a dynamic head formed by the resistance of the pump fan and the tubing, needs a pressure which is increasing quadratic with the flow and so with the rotational speed. The torque then increases quadratic with n and this means that the P-n curve then will be a cubic line. For a centrifugal pump which is used for a static head H, a part of the required pressure is used to overcome the pressure drop of the static head but another part of the pressure drop is used to overcome the dynamic head which is caused by the friction of the water when it passes the pump fan and the tubing. These friction losses makes that a centrifugal pump normally has a much lower efficiency than a positive displacement pump. Assume that the pump has a quadratic P-n curve as the result of both pressure drops.

A quadratic curve through the origin has a formula:

$P = C * n^2$ which can be written as

$$C = P / n^2 \tag{11}$$

Substitution of $P = 1100$ W and $n = 150$ rpm in formula 11 gives that $C = 0.04889$. So the formula for the expected P-n curve is:

$$P = 0.04889 * n^2 \quad \text{(W)} \tag{12}$$

P is now calculated for the rotational speeds belonging to the eight chosen frequencies. The result of the calculation is given in table 4.

f (Hz)	n (rpm)	P (W)
15	90	396
20	120	704
25	150	1100
30	180	1584
35	210	2156
40	240	2816
45	270	3564
50	300	4400

table 4 Calculated values of the quadratic P-n curve

The P-n curve found this way is also given in figure 11. In figure 11 it can be seen that the P-n curve of the rotor for $V = 11$ m/s is intersecting with the P-n curve for a quadratic pump load at a frequency in between 45 Hz and 50 Hz. So a frequency of 50 Hz will never be reached. This means that the pump or the pump motor can never be over loaded.

It was assumed that $n_{crit} = 90$ rpm belonging to a frequency of 15 Hz. So for lower rotational speeds, no water will be pumped. The water will rise in the pressure pipe but only up to a level lower than the static head H. So it is useless to connect the generator to the pump motor for frequencies lower than 15 Hz. Assume that the connection is broken if the frequency becomes 15 Hz. So then the rotor turns unloaded. In figure 11 it can be seen that an unloaded rotor has a rotational speed of about 120 rpm belonging to a frequency of 20 Hz for a wind speed of about 3 m/s. Assume that the connection is made again at this frequency. The required power at this frequency is the point of intersection of the line $f = 20$ Hz with the quadratic P-n curve for a pump load. This power is 704 W but this power can’t be supplied at a wind speed of 3 m/s. So the rotor slows down until the frequency has been reduced to 15 Hz and then the connection is broken again. But this means that some water is pumped at a wind speed of 3 m/s or higher.

In figure 11 and table 4 it can be seen that the required power at $n = 90$ rpm is 396 W. A wind speed of about 4.5 m/s is required so supply this power at a constant rotational speed. So the procedure of connecting and disconnecting is stopped for wind speeds higher than about 4.5 m/s.

Up to now, only the frequency has been taken into account. However, also the AC voltage must be correct. The European 3-phase grid has a frequency of 50 Hz and is connected in star. The nominal AC voltage in between the star point and one of the phases is 230 V. The AC voltage in between two of the phases is a factor $\sqrt{3}$ higher and so 398 V, mostly rounded to 400 V. Most asynchronous pump motors are connected in star and so this means that that the nominal voltage in between the phases is 398 V_{AC}.

For the generator of Hefei Top Grand type TGET450-5KW-300R, it is specified that the loaded AC voltage in between two phases is 220 V_{AC} at n = 300 rpm and that the loaded AC line current is 13.1 A. This voltage is much too low if the pump motor is connected in star. However, this voltage is about right for n = 300 rpm if the pump motor is connected in delta. So it is assumed that a centrifugal pump with a asynchronous pump motor is chosen for which the pump motor can be connected in delta.

The voltage is about proportional to the rotational speed. So the loaded AC voltage of the generator at 150 rpm will be about 110 V_{AC}. The current is proportional to the voltage and so the current will be 0.5 * 13.1 = 6.55 A. So the maximal electrical power which can be generated will be reduced by a factor 0.5 * 0.5 = 0.25 and so the generated power will be about 0.25 * 5000 = 1250 W. This is more than the electrical power of 935 W at the design point and so the generator will certainly be strong enough.

Next it is supposed that the VIRYA-5B3S is used for drainage in The Netherlands and that the static head H = 1 m. This means that one has to chose a pump which is designed for a static head H = 4 m. Assume the pump dimensions are such that the working point is lying at P = 1100 W at n = 150 rpm belonging to V_d = 6 m/s.

Assume that the efficiency of the pump motor at a frequency f = 25 Hz is 0.75. This means that the mechanical power supplied by the pump motor is 0.75 * 935 = 701 W. The nominal motor power at a frequency of 50 Hz must be a factor 4 higher because of the higher head and a factor 2 higher because of the higher flow. So it must be a factor 8 higher and so about 5600 W = 5.6 kW which is rather large. I think that a nominal motor power of 4 kW at 50 Hz is large enough. The pump must be designed for a static head of 4 m. The next question is how much water can be pumped for the design wind speed V_d = 6 m/s. Earlier it was calculated that P_{el} = 935 W for V_d = 6 m/s. The hydraulic power P_{hyd} is given by:

$$P_{hyd} = \rho_w * g * H * q \qquad (W) \qquad (13)$$

In this formula P_{hyd} is the hydraulic power in W, ρ_w is the density of water in kg/m^3 and ρ_w = 1000 kg/m^3, g is the acceleration of gravity and g = 9.81 m/s^2. H is the static head in m and q is the flow in m^3/s. The required electrical power of the pump motor P_{el} depends of the pump efficiency η_p and on the motor efficiency η_m. The efficiencies aren't given as a percentage but as a factor of 1. This results in:

$$P_{el} = \rho_w * g * H * q / (\eta_p * \eta_m) \qquad (W) \qquad (14)$$

Formula 14 can be written as:

$$q = \eta_p * \eta_m * P_{el} / (\rho_w * g * H) \qquad (m^3/s) \qquad (15)$$

Assume η_p = 0.6, η_m = 0.75, P_{el} = 935 W, ρ_w = 1000 kg/m^3, g = 9.81 m/s^2 and H = 1 m. Substitution of these values in formula 15 gives that q = 0.0429 m^3/s = 154.4 m^3/hour. So this is the flow which belongs to the design point at a frequency of 25 Hz and a design wind speed of 6 m/s. At higher wind speeds and so at higher rotational speeds and higher frequencies, the flow will be a lot higher. I think that the VIRYA-5B3S can very well be used for drainage using the generator type TGET450-5KW-300R if the correct pump with the correct pump motor can be found. But it can also be used for other heights H if a pump is used which is designed for four times the height H.

A big advantage of the VIRYA-5B3S is that it isn't necessary to place the wind turbine close to the pump. As a rather high voltage is used, the wind turbine can be placed at a large distance from the pump without getting too much copper losses in the cables in between the generator and the pump motor.

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