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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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 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 $\lambda_d = 7$. 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.

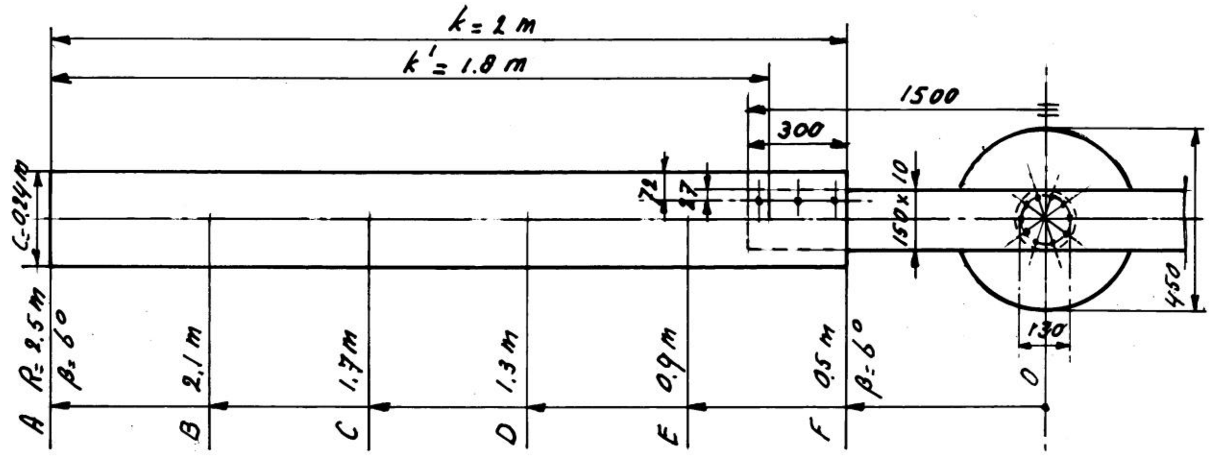

fig. 1 VIRYA-5S rotor for six stations A, B, C, D, E and F

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 $\alpha = 84°$ 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.

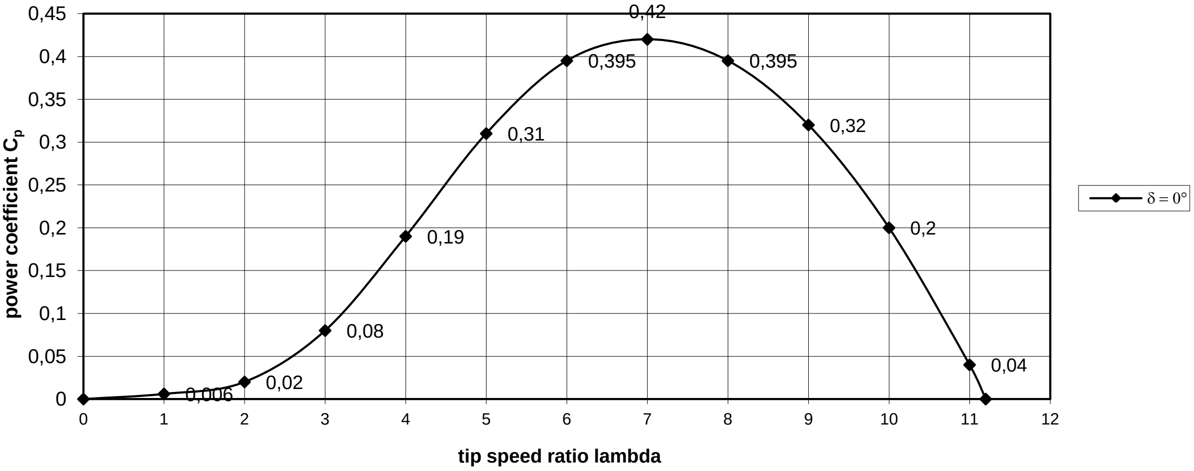

fig. 2 Estimated C_p-λ curve for the VIRYA-5 rotor for the wind direction perpendicular to the rotor (δ = 0°)

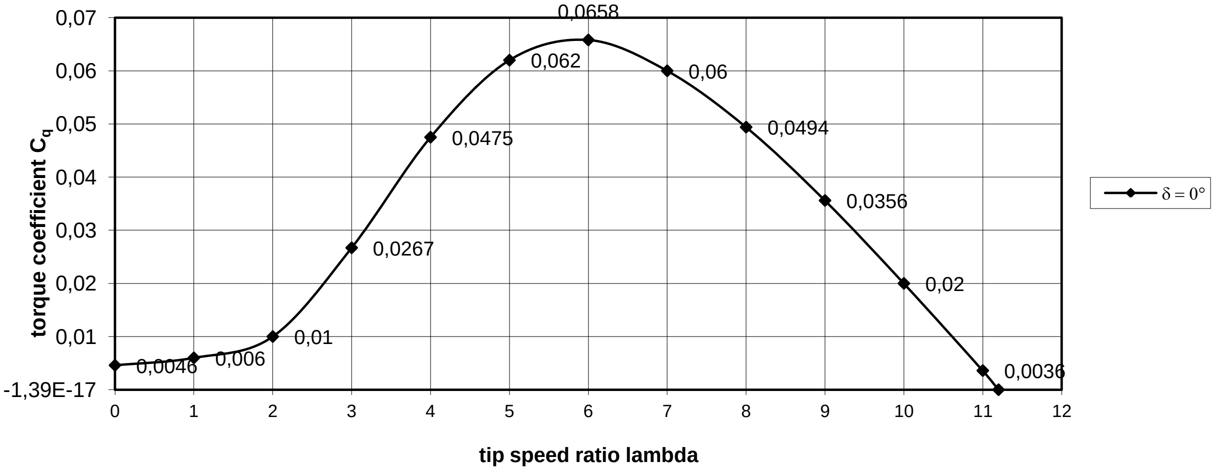

fig. 3 Estimated C_q-λ curve for the VIRYA-5 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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.

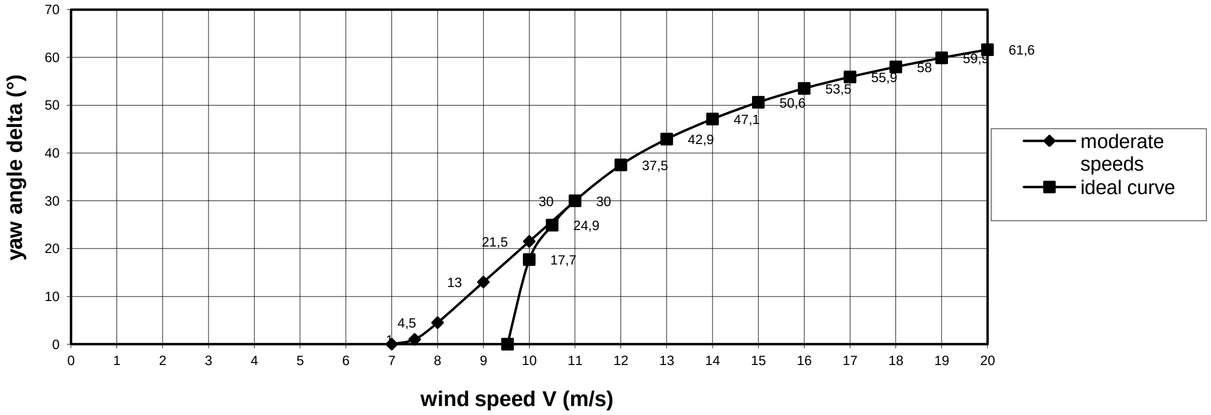

fig. 4 Estimated δ-V curve for a 12 mm meranti plywood vane blade

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.

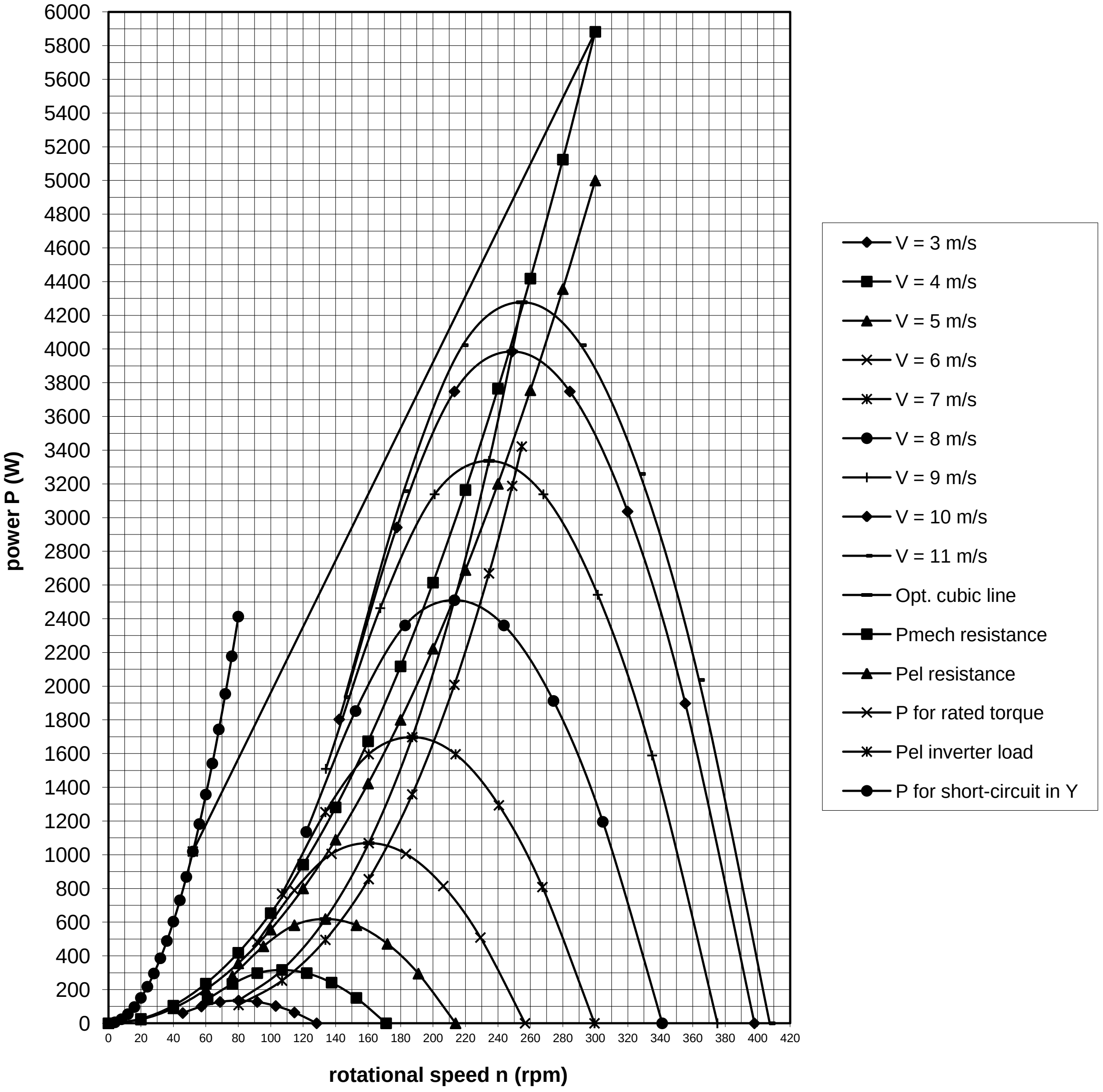

fig. 5 P-n curves and optimum cubic line of the VIRYA-5S rotor, P_{mech}-n and P_{el}-n curves for the generator with a resistance load such that P_{el} = 5000 W at n = 300 rpm, P-n curve for the rated torque, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

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.

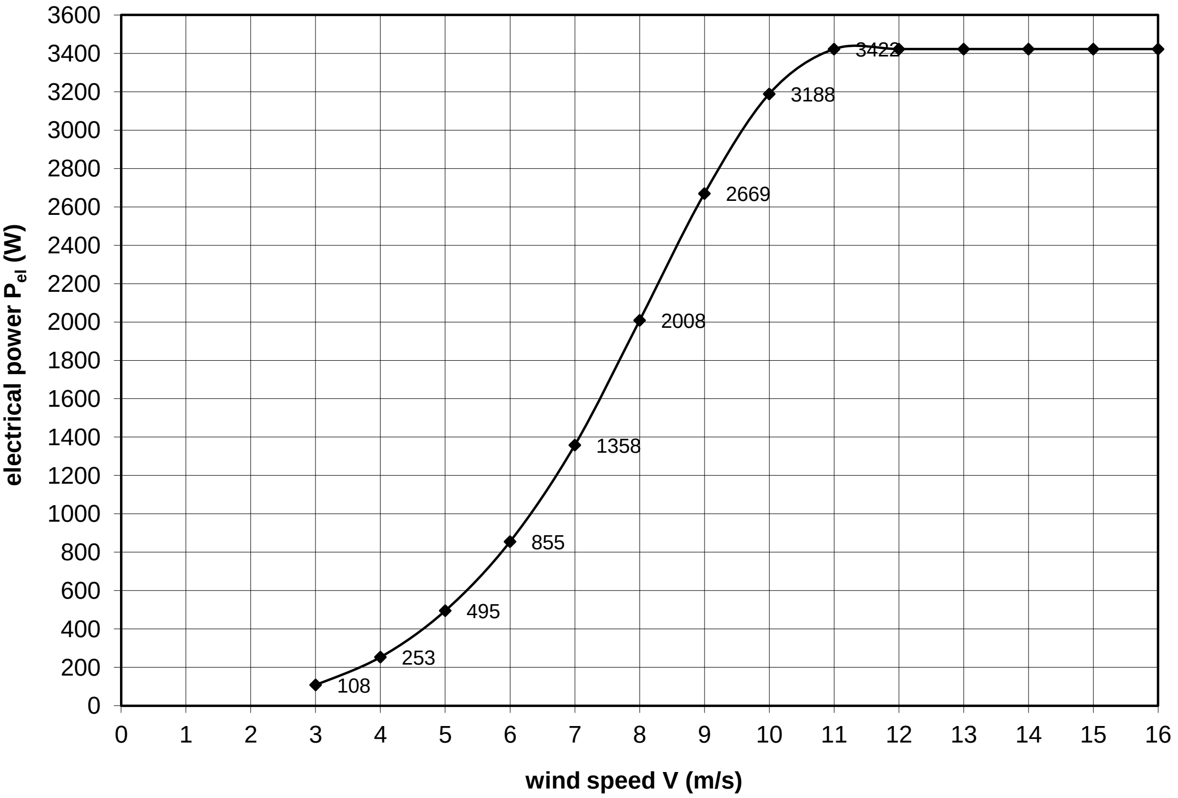

fig. 6 P_{el}-V curve VIRYA-5S for a load such that the optimum cubic line is followed.

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 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. The P-n curve of the rotor for V = 11 m/s is laying to the right side of this line and so the generator torque will never be higher than the rated torque.

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

If the VIRYA-5S 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.

However, a grid isn't always available and a 3-phase inverter requires 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 7 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, 50 Hz and 55 Hz. These frequencies correspond to rotational speeds n of 90 rpm, 120 rpm, 150 rpm, 180 rpm, 210 rpm, 240 rpm, 270 rpm, 300 rpm and 330 rpm. In figure 7 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 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 8.4. 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 at half of its nominal rotational speed and therefore it can be used at a factor $(½)^2 = ¼ = 0.25$ 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 7 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 890 W. This power can be supplied at a wind speed of about 5.65 m/s which seems a reasonable wind speed for the VIRYA-5B3S if it is used for water pumping. So the point P = 890 W and n = 150 rpm is taken as design point and a wind speed of 5.65 m/s is the design wind speed V_d. The electrical power P_{el} for $V_d = 5.65$ m/s depends on the generator efficiency η_{gen}. Assume $\eta_{gen} = 0.85$. This gives that $P_{el} = 0.85 * 890 = 757$ W for $V_d = 5.65$ m/s. To find the working points for other rotational speeds, a P-n curve for a pump load has to be estimated.

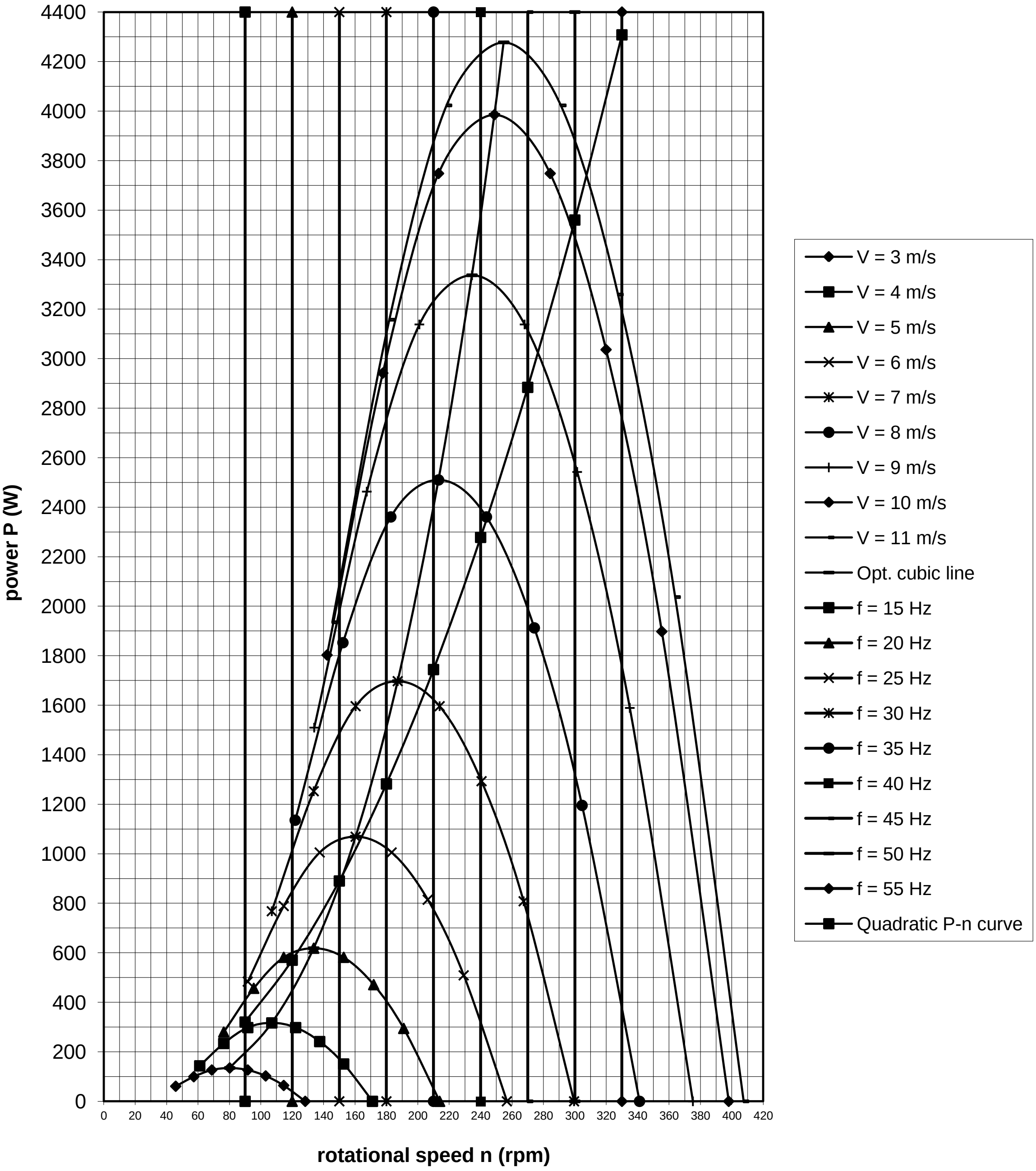

fig. 7 P-n curves and optimum cubic line of the VIRYA-5S rotor, lines for frequencies f of 15 Hz, 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz and 50 Hz and quadratic P-n curve

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

$$C = P / n^2 \tag{10}$$

Substitution of P = 890 W and n = 150 rpm in formula 10 gives that C = 0.03956. So the formula for the expected P-n curve is:

$$P = 0.03956 * n^2 \quad \text{(W)} \tag{11}$$

P is now calculated for the rotational speeds belonging to the nine chosen frequencies. The result of the calculation is given in table 3.

f (Hz)	n (rpm)	P (W)
15	90	320
20	120	570
25	150	890
30	180	1282
35	210	1744
40	240	2278
45	270	2884
50	300	3560
55	330	4308

table 3 Calculated values of the quadratic P-n curve

The P-n curve found this way is also given in figure 7. In figure 7 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 of about 52 Hz. It is assumed that this frequency and the corresponding rotational speed is no problem for the centrifugal pump and the asynchronous motor.

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 7 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 2.8 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 570 W but this power can’t be supplied at a wind speed of 2.8 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 2.8 m/s or higher.

In figure 7 and table 3 it can be seen that the required power at n = 90 rpm is 320 W. A wind speed of about 4.9 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 4.9 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 √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 maximum electrical power which can be generated will be reduced by a factor 0.5 * 0.5 = 0.25 and so it will be about 0.25 * 5000 = 1250 W. This is more than the electrical power of 757 W at the design point and so the generator will certainly be strong enough.

Next it is supposed that the VIRYA-5S 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 = 890 W at n = 150 rpm belonging to V_d = 5.65 m/s. Earlier is was calculated that P_{el} = 757 W for V_d = 5.65 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 * 757 = 568 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 8 * 568 = 4544 W = 4.544 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 = 5.65 m/s. Earlier it was calculated that P_{el} = 757 W for V_d = 5.65 m/s. The hydraulic power P_{hyd} is given by:

$$P_{hyd} = \rho_w * g * H * q \qquad \text{(W)} \qquad (12)$$

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:

$$P_{el} = \rho_w * g * H * q / (\eta_p * \eta_m) \qquad \text{(W)} \qquad (13)$$

Formula 13 can be written as:

$$q = \eta_p * \eta_m * P_{el} / (\rho_w * g * H) \qquad (\text{m}^3/\text{s}) \qquad (14)$$

Assume η_p = 0.6, η_m = 0.75, P_{el} = 757 W, ρ_w = 1000 kg/m^3, g = 9.81 m/s^2 and H = 1 m. Substitution of these values in formula 14 gives that q = 0.0347 m^3/s = 125 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 5.65 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-5S 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-5S 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.

8 References

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