Ideas about the 3-bladed VIRYA-0.65 water turbine with 20° inclined shaft coupled to the generator of the VIRYA-2.68 windmill for 12 V battery charging

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1 Introduction

In this report it is researched if it is possible to design a simple water turbine using the PM-generator of the VIRYA-2.68 windmill. The water turbine will be used at the surface of a slowly flowing river. A great advantage of a water turbine above a wind turbine is that the water speed is very constant and therefore the generator is supplying power day and night.

The turbine rotor is coupled to the generator by a 1.5 m long, 20 mm diameter stainless steel shaft. The shaft makes an angle of 20° with the water level to realise that the generator is above the water level and that the turbine rotor is below the water level. The turbine rotor is mounted behind the generator so the thrust on the turbine gives a pulling force in the shaft. It might be required to mount an extra bearing under water just in front of the turbine rotor to support the long shaft. But the 20 mm shaft is stronger than the spokes of the turbine rotor so it is worth while to test a prototype first without this extra bearing. The generator hub and the turbine hub are mounted to the shaft by a tapered hole and a central bolt. To prevent coming loose of these bolts it is necessary that the direction of rotation of the generator is right hand if seen from the shaft side. This means that the direction of rotation of the turbine rotor is left hand if seen from the front side.

The whole construction will be mounted on a little vessel made out of two pipes to keep the submersion of the turbine rotor constant for every water height. It might be necessary to mount a grid made of steel bars in front of the turbine rotor to prevent that it is damaged by branches floating in the water. A sketch of the vessel and the turbine is given in appendix 1.

The generator has been measured for different conditions and the measurements are given in report KD 78 (ref. 1). The generator generates a 3-phase current which is rectified by a 3-phase rectifier. The generator will be rectified in delta for 12 V battery charging. The average charging voltage for a 12 V battery is about 13 V. The measurements for 13 V delta are given in chapter 5 of report KD 78.

The generator is made from an asynchronous motor by replacing the short-circuit armature by a permanent magnet armature. No fan is used and the back bearing cover is closed. The generator shaft is made out of stainless steel and has a tapered shaft end. The hub is connected to the shaft by a tapered central hole and by one central inner hexagon bolt M10. An oil seal prevents the entrance of water and dust at the front bearing. This oil seal is good enough if the generator is used outside but it isn't good enough if the generator would be used under water. So the generator must be positioned above the water level.

2 Description of the water turbine rotor

The water turbine rotor looks very much the same as a wind turbine rotor and is designed using the wind turbine theory as given in report KD 35 (ref. 2). The rotor has three stainless steel blades which are mounted to a stainless steel hub plate. A blade is made out of a stainless steel strip size 2 * 100 * 250 mm. The hub plate is laser cut out of 4 mm stainless steel sheet. The hub plate has three 60 mm wide spokes with at each end a 100 mm wide and 20 mm long ear. The total spoke length from the centre of the hub plate is 95 mm. The overlap in between a blade and an ear is 20 mm. This results in a rotor diameter D = 0.65 m and so in a rotor radius R = 0.325 m. The water turbine is called the VIRYA-0.65 analogue to the names of my windmills. For the design tip speed ratio of the rotor it is chosen that $\lambda_d = 3$.

The blades are 7.14 % cambered over the whole blade length, so the ears of the hub plate have to be provided with the same camber. Because of the blade camber, the blade chord c is a little smaller than the sheet width and it is found that c = 98.7 mm = 0.0987 m. The aerodynamic characteristics of 7.14 % cambered sheet are given in report KD 398 (ref. 3). A sketch of the VIRYA-0.65 rotor is given in appendix 2.

The vessel will be designed such that the top of the rotor is 0.05 m below the water level. The distance in between the bottom of the rotor and the river bottom must be at least 0.05 m. As the rotor has a diameter of 0.65 m, the river must have a depth of at least 0.75 m.

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 2). This report (KD 598) has its own formula numbering. Substitution of λ_d = 3 and R = 0.35 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 8.5714 * r$ (-) (1)

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

$\beta = \phi - \alpha$ (°) (2)

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

Substitution of B = 3 and c = 0.0987 m in formula (5.4) of KD 35 gives:

$C_l = 84.879\ r\ (1 - \cos\phi)$ (-) (4)

Formula 5.5 out of KD 35 gives the Reynolds value at a certain radius if the rotor is used in air. Formula 5.13 out of KD 35 has to be used for water in combination with the kinematic viscosity of water. For water with a temperature of 20 °C it is valid that $\gamma = 1.004 * 10^{-6}$ m^2/s. It is assumed that the water speed of the river V = 1.2 m/s. The chord c = 0.0987 m. Substitution of these values in formula 5.13 of KD 35 gives:

$R_{e\,r} = 1.18 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.046 m of one to another. Station F corresponds with the end of the hub plate. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root. First the theoretical values are determined for C_l, α and β and next β is linearised such that the twist is linear and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of the 7.14 % cambered airfoil are given in report KD 398 (ref. 3). The Reynolds values for the stations are calculated for a water speed of 1.2 m/s because this seems a reasonable water speed for slow flowing river. Those airfoil Reynolds numbers are used which are lying closest to the calculated values. The calculated Reynolds values are rather high, even for a low water speed of 1.2 m/s. This is because the kinematic viscosity of water is about a factor 15 lower than for air. A sketch of the VIRYA-0.65 rotor is given in appendix 2.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 1.2 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	0.325	3	12.3	0.0987	0.63	0.63	3.63	3.4	-0.7	-0.7	13.0	13	0.049
B	0.279	2.575	14.1	0.0987	0.72	0.69	3.14	3.4	-0.3	-0.5	14.4	14.6	0.042
C	0.233	2.151	16.6	0.0987	0.83	0.78	2.66	2.5	0.8	0.4	15.8	16.2	0.035
D	0.187	1.726	20.1	0.0987	0.96	0.95	2.18	2.5	2.4	2.3	17.7	17.8	0.032
E	0.141	1.302	25.0	0.0987	1.12	1.19	1.73	1.7	4.7	5.6	20.3	19.4	0.050
F	0.095	0.877	32.5	0.0987	1.26	1.43	1.30	1.2	6.2	11.5	26.3	21.0	0.150

table 1 Calculation of the blade geometry of the VIRYA-0.65 rotor

The theoretical blade angle β_{th} varies in between 13.0° and 26.3°. If a blade angle of 13° is taken at the blade tip and of 21° is taken at the blade root, the linearised blade angles are lying close to the theoretical values. The spokes of the hub plate are twisted 21° right hand to get the correct blade angle at the blade root.

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

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the most important outer part of the blade is about 0.04. Figure 4.8 of KD 35 (for B = 4) and $\lambda_{opt} = 3$ and $C_d/C_l = 0.04$ gives $C_{p\ th} = 0.43$. The blade is just stalling at station F so only the part of the blade until 0.01 m outside station F is taken for the calculation of C_p. This gives an effective blade length k' = 0.22 m.
Substitution of $C_{p\ th} = 0.43$, R = 0.325 m and blade length k = k' = 0.22 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.39$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.39 / 3 = 0.13$.
Substitution of $\lambda_{opt} = \lambda_d = 3$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 4.8$.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

The average blade angle is 17°. For a non rotating rotor, the average angle of attack α is therefore 90° - 17° = 73°. The C_l-α curve for large values of α is given as figure 5 of KD 398 for the 10 % cambered airfoil. As the whole airfoil is stalling during starting, it is assumed that this curve can also be used for a 7.14 % cambered airfoil. For $\alpha = 73°$ it can be read that $C_l = 0.56$. During starting, the whole blade is stalling. So now the real blade length k = 0.25 m is taken.
Substitution of B = 3, R = 0.325 m, k = 0.25 m, $C_l = 0.56$ and c = 0.0987 m in formula 6 gives that $C_{q\ start} = 0.058$. The real starting torque coefficient is a little lower than the calculated value because the average blade angle is used. Assume $C_{q\ start} = 0.055$. For the ratio in between the starting torque and the optimum torque we find that it is 0.055 / 0.13 = 0.423. This is rather high for a rotor with a design tip speed ratio of 3.

The starting water speed is calculated with formula 8.6 of KD 35 which is given by:

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

The sticking torque Q_s of the VIRYA-2.68 generator has been measured at stand still position and Q_s = 0.4 Nm. Substitution of Q_s = 0.4 Nm, $C_{q\ start} = 0.055$, ρ_w= 1000 kg/m^3 and R = 0.325 m in formula 7 gives that V_{start} = 0.37 m/s. This is very low which means that the rotor will even turn at very low water speeds.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing a S-shaped line which is horizontal for $\lambda = 0$. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 4). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a 7.14 % cambered airfoil is used. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-0.65 rotor are given in figure 1 and 2.

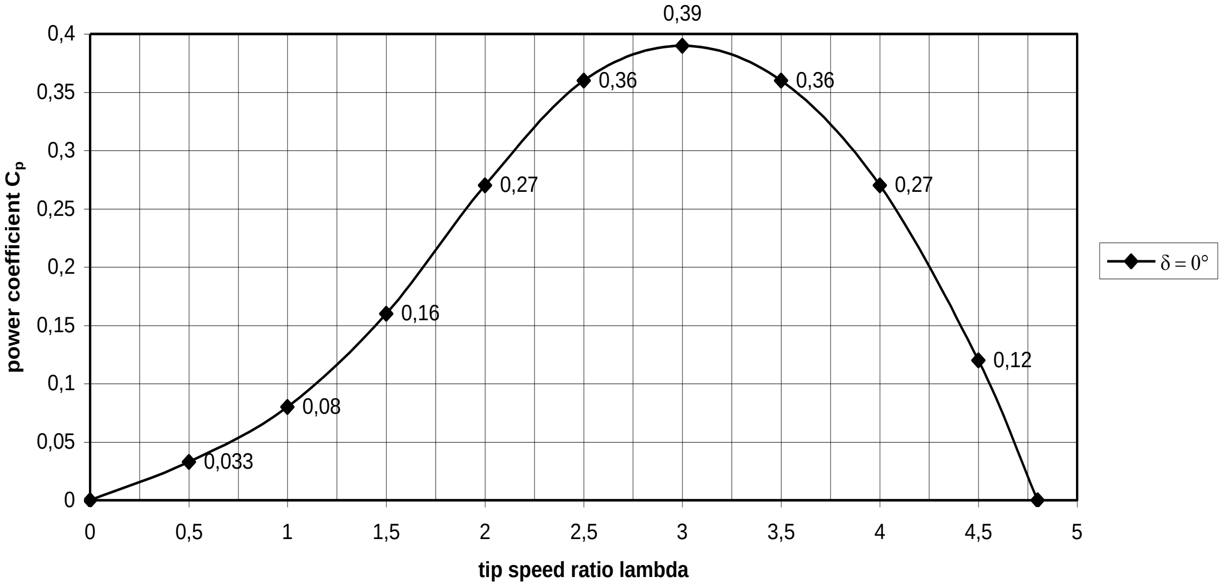

fig. 1 Estimated C_p-λ curve for the VIRYA-0.65 rotor for the water direction perpendicular to the rotor (δ = 0°)

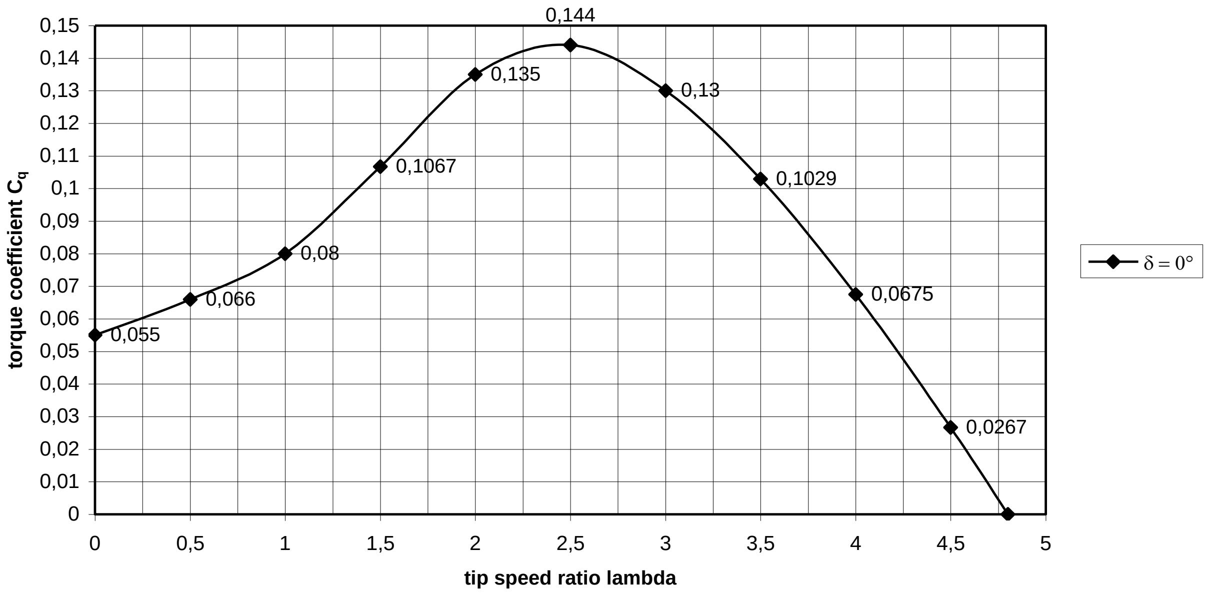

fig. 2 Estimated C_q-λ curve for the VIRYA-0.65 rotor for the water direction perpendicular to the rotor (δ = 0°)

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 1. The VIRYA-0.65 water turbine has no safety system because it is assumed that the maximum possible water speed is low enough to prevent too high forces working on the rotor and the generator shaft. So the rotor makes always the same angel of 20° with the water speed.

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator for a certain gear ratio i (the VIRYA-0.65 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves for low values of λ appear to lie very close to each other, the P-n curves are not determined for low values of λ. The P-n curves are determined for water speeds V = 0.8, 1, 1.2, 1.4, 1.6, 1.8 and 2 m/s.

Substitution of δ = 20° and R = 0.325 m in formula 7.1 of KD 35 gives:

$$n_\delta = 27.610 * \lambda * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of δ = 20°, $\rho = \rho_w$ = 1000 kg / m^3 and R = 0.325 m in formula 7.10 of KD 35 gives:

$$P_\delta = 137.67 * C_p * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for C_p values belonging to λ = 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 4.8. (see figure 1). For a certain water speed, for instance V = 0.8 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 water speed. The result of the calculations is given in table 2.

		V = 0.8 m/s δ = 20°		V = 1 m/s δ = 20°		V = 1.2 m/s δ = 20°		V = 1.4 m/s δ = 20°		V = 1.6 m/s δ = 20°		V = 1.8 m/s δ = 20°		V = 2 m/s δ = 20°	
λ (-)	C_p (-)	n_δ (rpm)	P_δ (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)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
1.5	0.16	33.1	11.3	41.4	22.0	49.7	38.1	58.0	60.4	66.3	90.2	74.5	128.5	82.8	176.2
2	0.27	44.2	19.0	55.2	37.2	66.3	64.2	77.3	102.0	88.4	152.3	99.4	216.8	110.4	297.4
2.5	0.36	55.2	25.4	69.0	49.6	82.8	85.6	96.6	136.0	110.4	203.0	124.2	289.0	138.1	396.5
3	0.39	66.3	27.5	82.8	53.7	99.4	92.8	116.0	147.3	132.5	219.9	149.1	313.1	165.7	429.5
3.5	0.36	77.3	25.4	96.6	49.6	116.0	85.6	135.3	136.0	154.6	203.0	173.9	289.0	193.3	396.5
4	0.27	88.4	19.0	110.4	37.2	132.5	64.2	154.6	102.0	176.7	152.3	198.8	216.8	220.9	297.4
4.5	0.12	99.4	8.5	124.2	16.5	149.1	28.5	173.9	45.3	198.8	67.7	223.6	96.3	248.5	132.2
4.8	0	106.0	0	132.5	0	159.0	0	185.5	0	212.0	0	238.6	0	265.1	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-0.65 rotor

The calculated values for n and P are plotted in figure 3. The optimum cubic line which can be drawn through the maximum of all P-n curves is also given in figure 3.

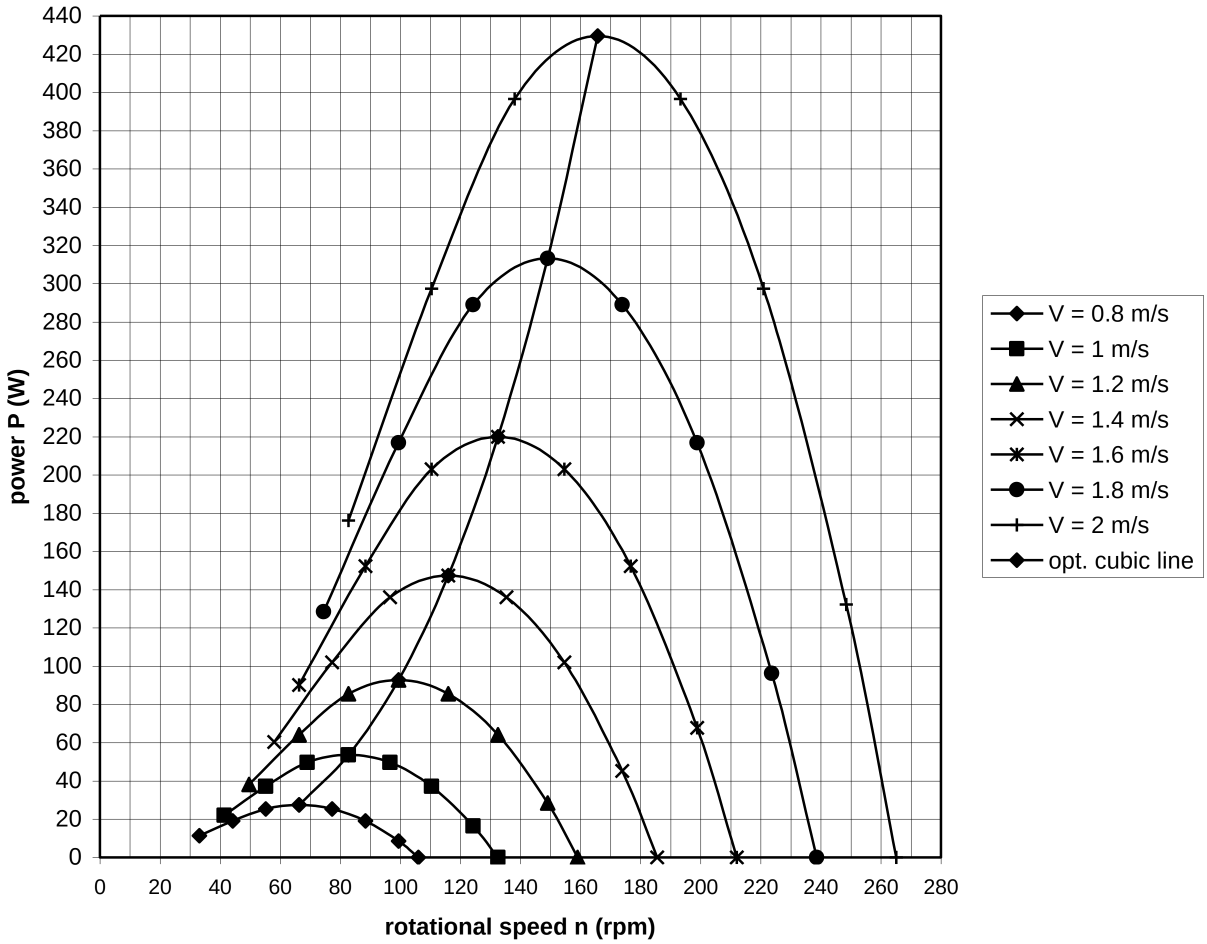

fig. 3 P-n curves of the VIRYA-0.65 rotor and optimum cubic line

6 Checking of the rotor curves with the measured generator curves

The generator has been measured on a test rig of the University of Technology Eindhoven. The measurements are given in report KD 78 (ref. 1). The measurements for rectification in delta are given in chapter 5 of KD 78. The P_{mech}-n and P_{el}-n curves for 13 V delta are given in figure 14. Figure 3 is now copied as figure 4 and the measured P_{mech}-n and P_{el}-n curves of the generator for a 13 V delta are copied in figure 4.

The maximum efficiency for 13 V delta is 56 % at n = 100 rpm. This is rather low and this generator can have efficiencies of more that 8o % if it is used at higher voltages and higher rotational speeds. But the P_{mech}-n curve for 13 V delta is lying very much to the left and only this curve gives an acceptable matching with the chosen direct drive water turbine. So the rather low efficiency is accepted as direct drive results in a very simple design.

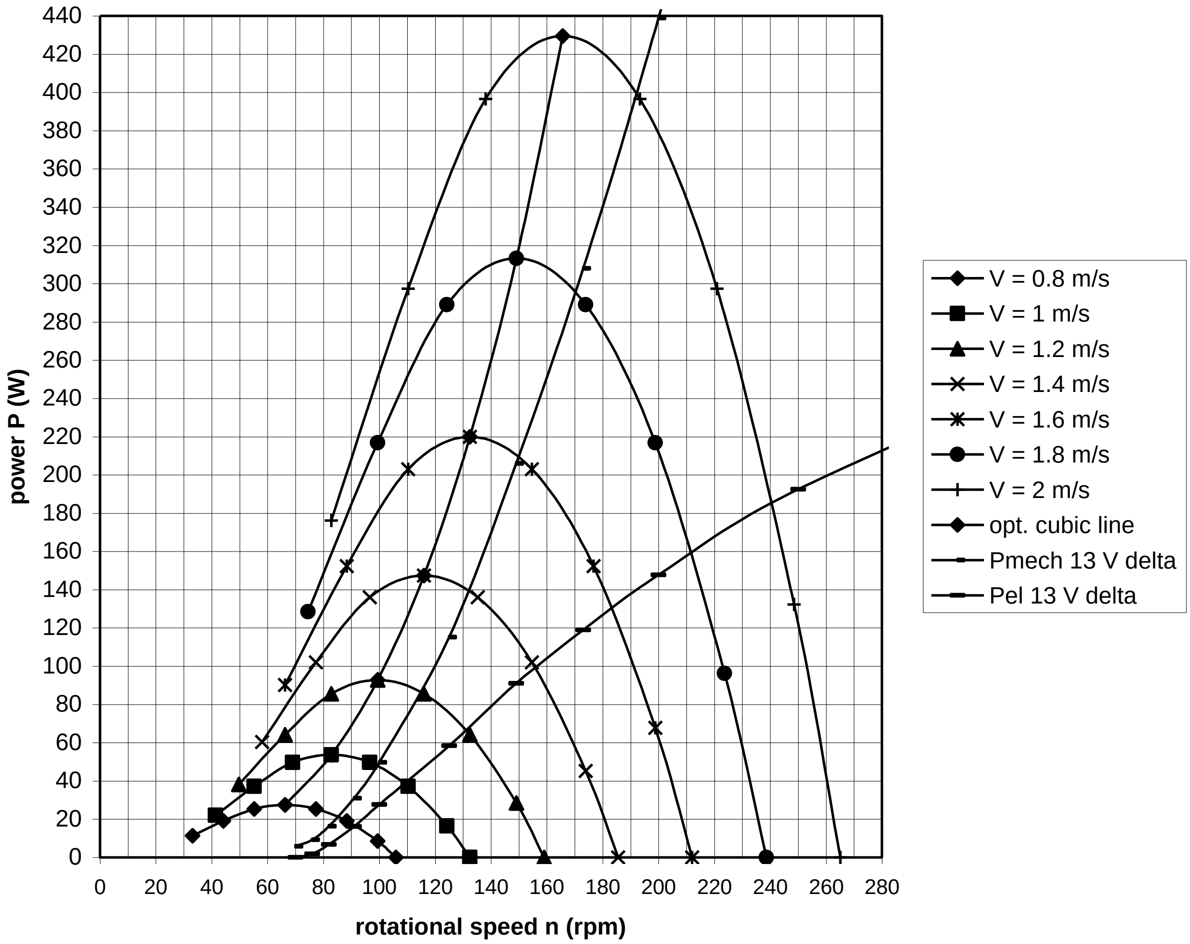

fig. 5 Calculated P-n curves of the VIRYA-0.65 rotor for $\delta = 20°$ and measured P_{mech}-n and P_{el}-n curves of the generator for 13 V delta

In figure 5 it can be seen that the matching isn't optimal because the P_{mech}-n curve of the generator is lying at a certain distance to the right side of the optimum cubic line of the rotor. This means that the rotor will turn at a higher tip speed ratio than the optimum value of 3. But the matching is certainly acceptable.

The working point for a certain water speed is the point of intersection of the P-n curve of the rotor for that water speed and the P_{mech}-n curve of the generator. The electrical power P_{el} for a certain working point is found by going down from that working point till the P_{el}-n curve is intersected. P_{el} has been determined for each water speed and is given in the P_{el}-V curve of figure 6.

The P-n curves of the rotor are given in figure 5 up to a water speed of 2 m/s which is a rather high water speed for a low land river. The mechanical power at the working point for V = 2 m/s is 400 W. The electrical power is 140 W which means that 260 W has to be dissipated in the winding and the stator iron. The generator is made from a 2.5 kW or 2500 W motor frame size 90 with lengthened stator stamping. The efficiency of this motor is about 80 % which means that the supplied electrical power is 3125 W. So the dissipated heat is 625 W which is much more than 260 W. However, as a motor it is running at a speed of 1450 rpm and it has a fan which causes extra cooling of the housing. But I expect that 260 W can be dissipated without a fan for a long time without being over heated.

The thrust on the rotor blades increases proportional to the square of the water speed. The blades have a width of 100 mm and thickness of 2 mm but a blade is cambered and the moment of resistance therefore increases substantial (see chapter 6 report KD 398).

The spokes of the hub plate have a width of 60 mm and a thickness of 4 mm but the moment of resistance is less than that of the blades. The hub plate is therefore the weakest component. The width of the spokes is reduced to 60 mm other wise it isn't possible to twist the spokes by 21°. The hub plate is clamped in between the hub and a clamping sheet by three stainless steel bolts M8. A blade is connected to the ear of the hub plate by three stainless steel bolts M6. A clamping sheet is used to prevent stress concentration at the three holes in the hub plate. It is expected that the blades and the hub plate are strong enough up to water speeds of 2 m/s but the water turbine should not be used in rivers with higher water speeds.

If a rotor is used in water, cavitation may exist at positions of the blade where the pressure becomes too low. Cavitation means that the water is transferred in to water vapour but that later it is becoming water again. This transformation of vapour into water may cause a water jet which can damage the stainless steel of the blade. However, the rotor is designed with rather low lift coefficients at the blade tip and it is therefore expected that the negative pressure at the back side of the airfoil is not becoming that low that cavitation will become a problem. But this has to be checked in practice.

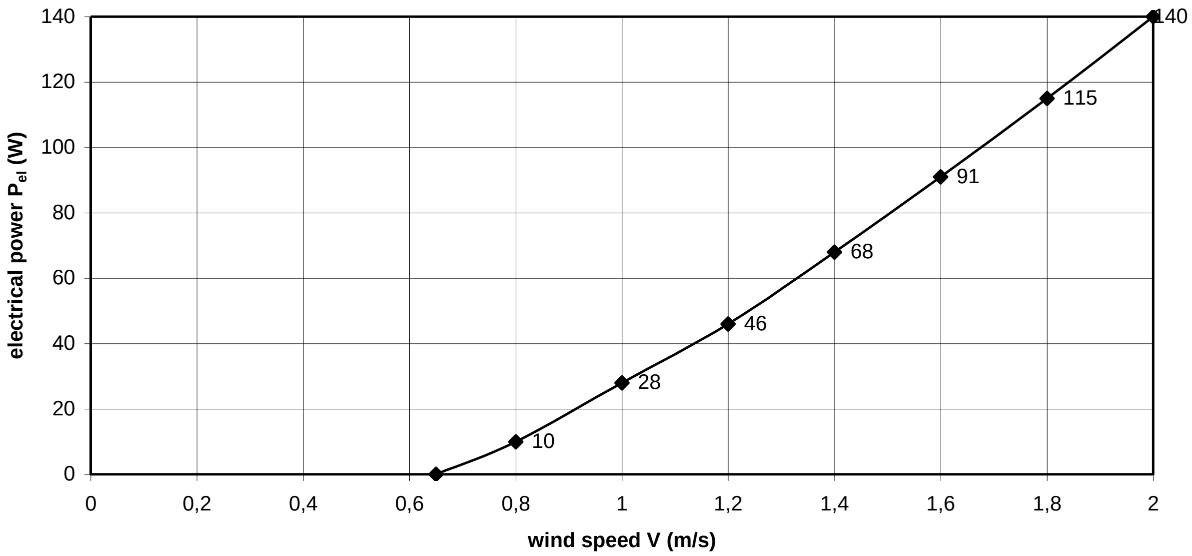

fig. 6 P_{el}-V curve VIRYA-0.65 for 12 V battery charging

In figure 6 it can be seen that the P_{el}-V curve starts at about at V = 0.65 m/s. In chapter 4 it was calculated that the starting water speed is 0.37 m/s, so there is no hysteresis in the P_{el}-V curve. The maximum power is 140 W which is acceptable for a water turbine with a rotor diameter of 0.65 m.

It seems worth while to build and test a prototype of this water turbine. However, I won't do this. If someone has interest to test it, I can make detailed drawings of the turbine rotor and the shaft. A new prototype of the generator is available which can be bought at a reasonable price but the generator can't be borrowed. The generator drawing is available at a reasonable licence fee.

7 References

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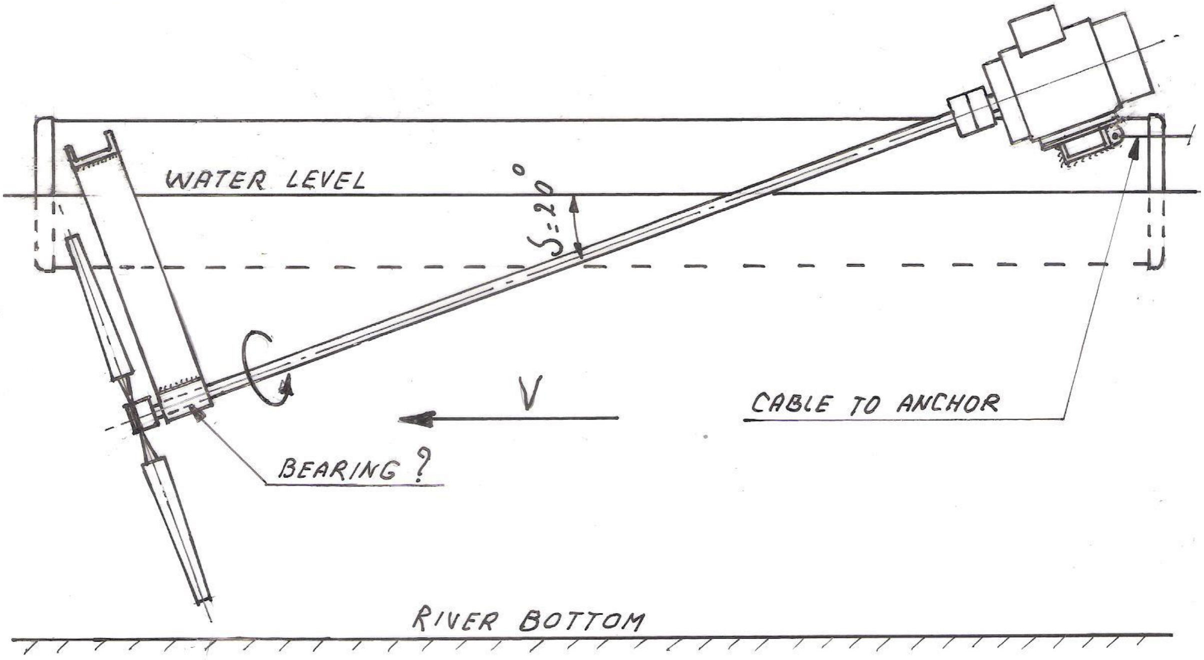
4 Kragten A. Determination of C_q for low values of λ. Deriving the C_p-λ and C_q-λ curves of the VIRYA-1.8D rotor, July 2002, free public report KD 97, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1
Sketch of the vessel and the water turbine



Appendix 2
Sketch of the VIRYA-0.65 water turbine rotor