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 and 24 V battery charging. Ideas about an alternative 2-bladed VIRYA-0.625.

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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.

sta-tion	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° left hand for a rotor which is rotating left 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 4.7 of KD 35 (for B = 3) 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:

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

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:

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

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.

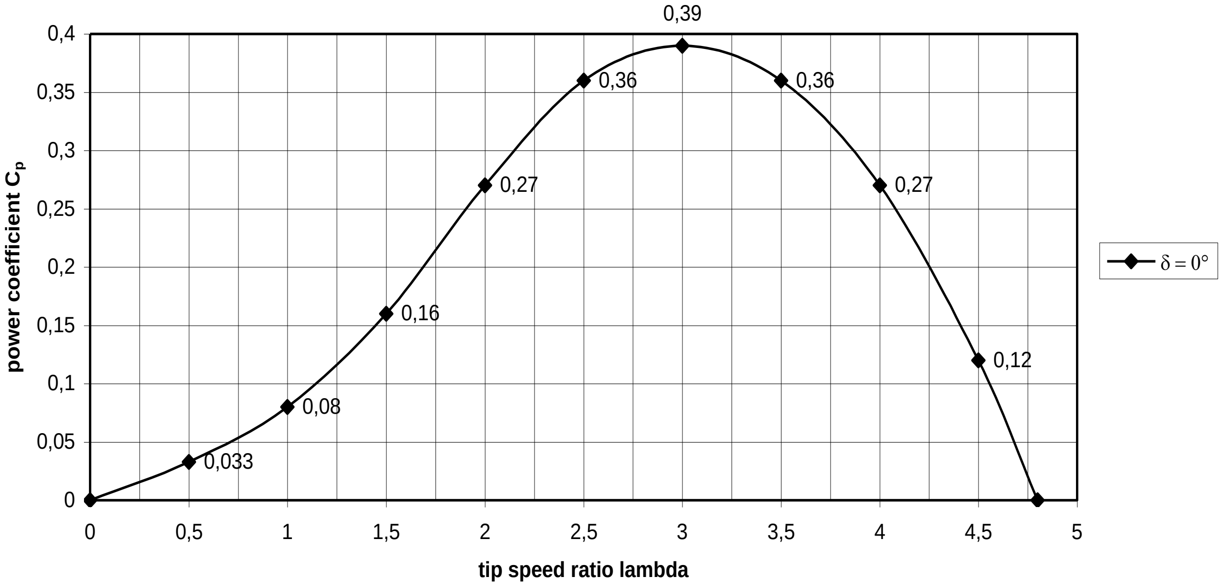

fig. 1 Estimated C_p-λ curve for the VIRYA-0.65 rotor for the water direction perpendicular to the rotor ($\delta = 0°$)

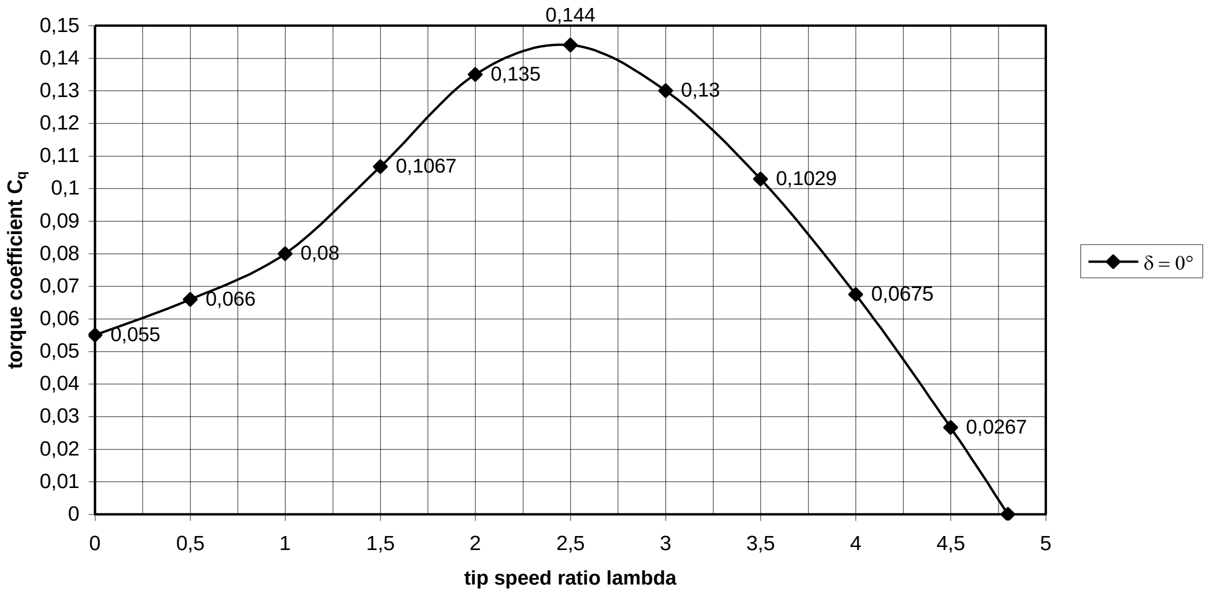

fig. 2 Estimated C_q-λ curve for the VIRYA-0.65 rotor for the water direction perpendicular to the rotor ($\delta = 0°$)

5 Determination of the P-n curves and the optimum cubic line

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a C_p-λ curve of the rotor and a δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The C_p-λ curve is given in figure 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:

$n_\delta = 27.610 * \lambda * V$ (rpm) (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:

$P_\delta = 137.67 * C_p * V^3$ (W) (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.

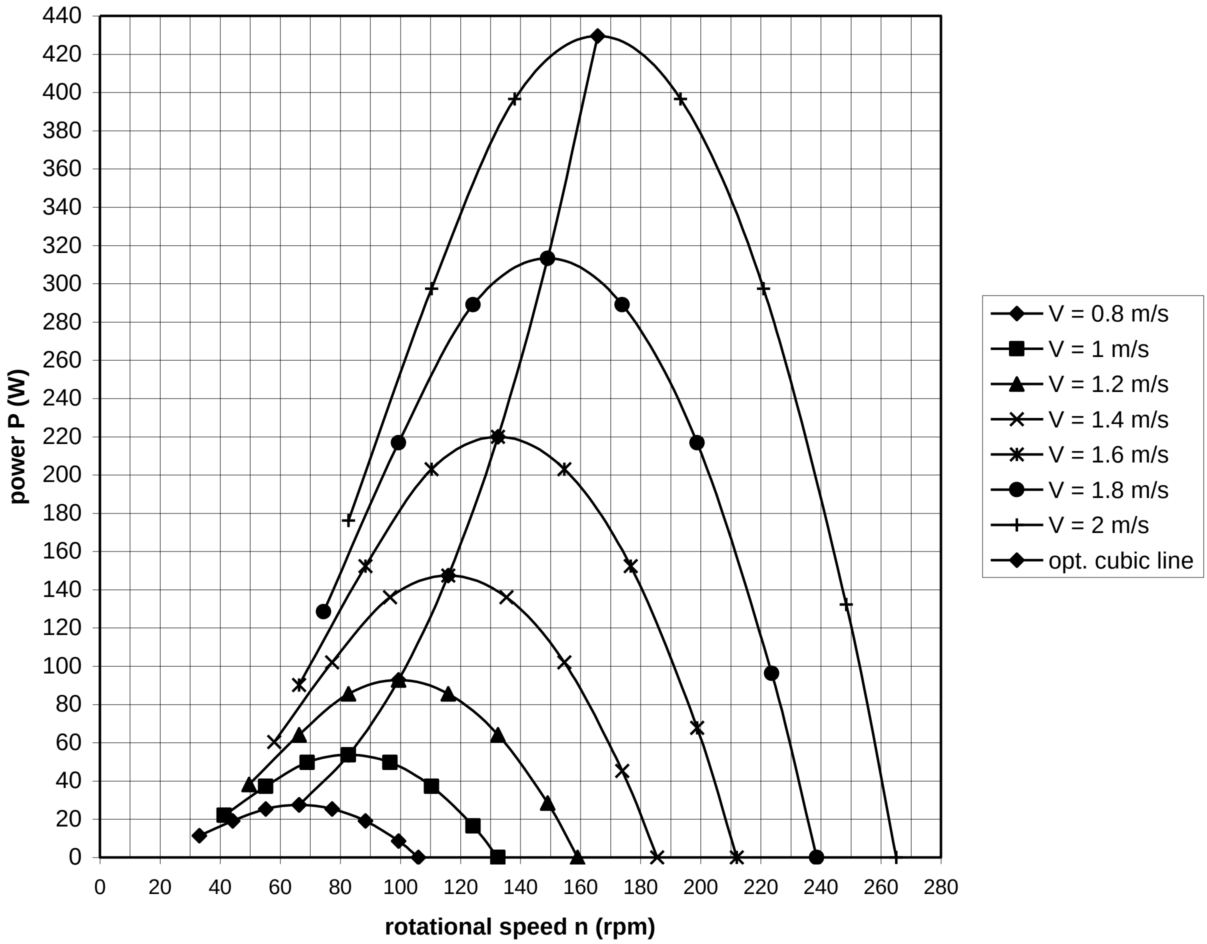

fig. 3 P-n curves of the VIRYA-0.65 rotor and optimum cubic line

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 80 % 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.

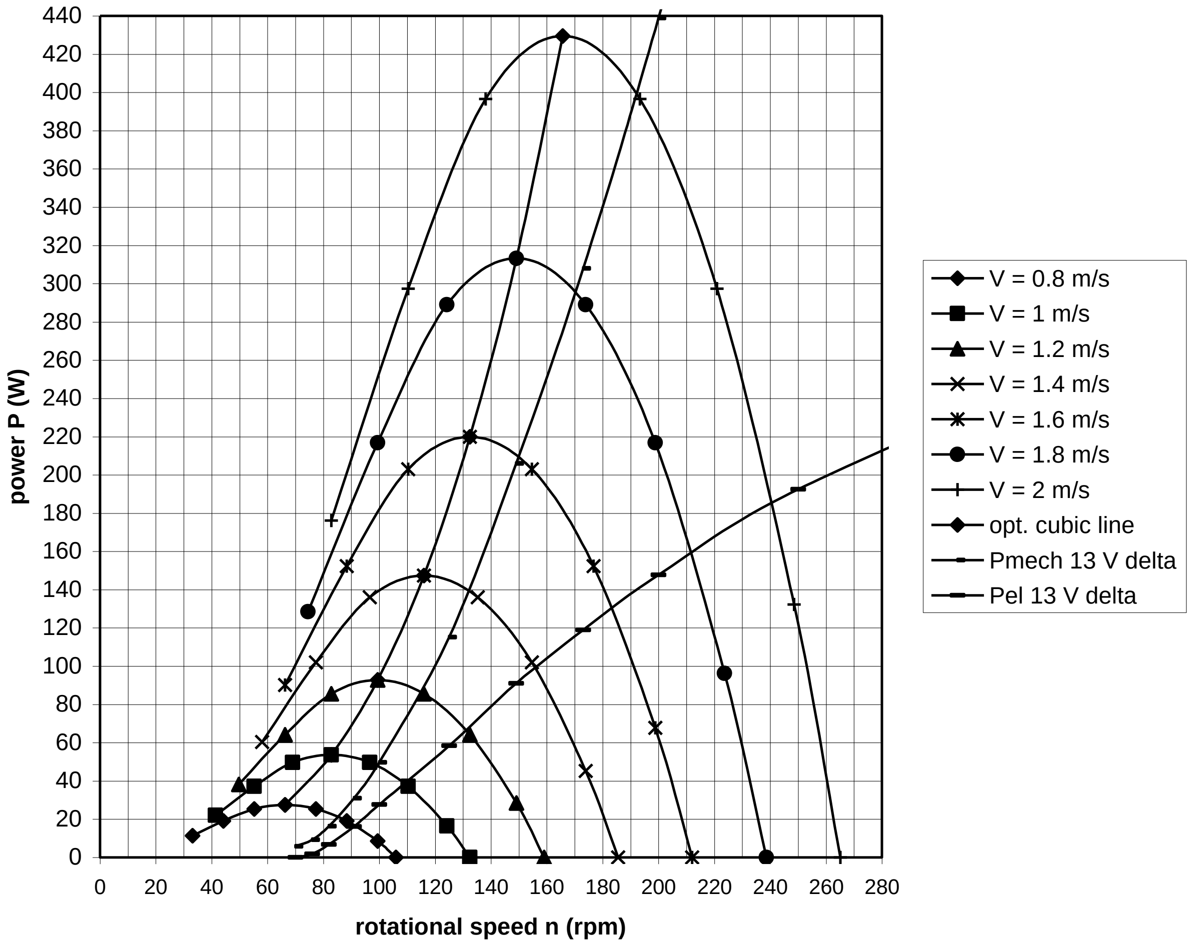

fig. 4 Calculated P-n curves of the VIRYA-0.65 rotor for δ = 20° and measured P_{mech}-n and P_{el}-n curves of the generator for 13 V delta

In figure 4 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 for higher water speeds.

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 5.

The P-n curves of the rotor are given in figure 4 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.

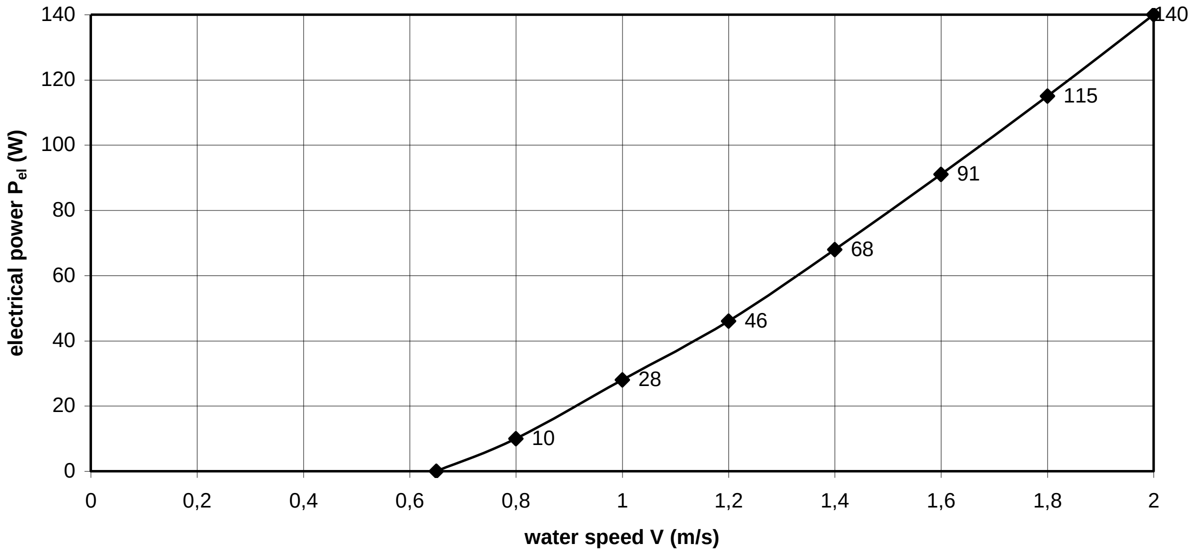

fig. 5 P_{el}-V curve VIRYA-0.65 for 12 V battery charging

In figure 5 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.

For some situations the wanted nominal battery voltage is 24 V. The generator has also been measured for 26 V star and the P_{mech}-n and P_{el}-n curves are given in figure 9 of KD 78. 26 V is the average charging voltage of a 24 V battery. Figure 4 is now copied as figure 6 but the characteristics for 13 V delta are replaced by the characteristics for 26 V star.

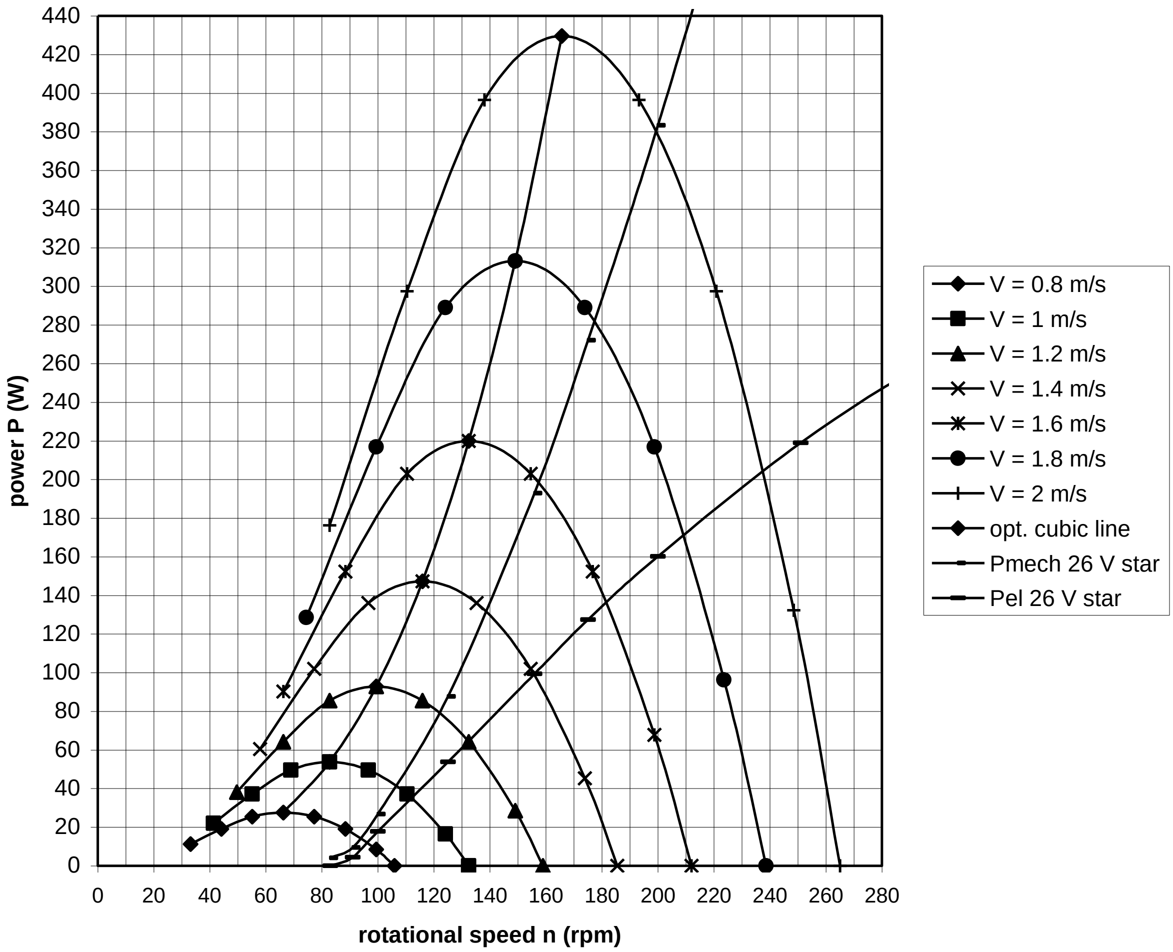

fig. 6 Calculated P-n curves of the VIRYA-0.65 rotor for δ = 20° and measured P_{mech}-n and P_{el}-n curves of the generator for 26 V star

In figure 6 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 for higher water speeds. The generator efficiency for 26 V star is higher than for 13 V delta, so a higher maximum power may be expected.

The P_{el}-V curve for 26 V star is determined in the same way as the P_{el}-V curve for 13 V delta and is given in figure 7. In figure 7 it can be seen that the P_{el}-V curve starts at 0.7 m/s which is 0.05 m/s higher than for 13 V delta. However the maximum power at V = 2 m/s is 160 W which is 20 W higher than for 13 V delta. So use of this water turbine for 24 V battery charging is also a realistic option.

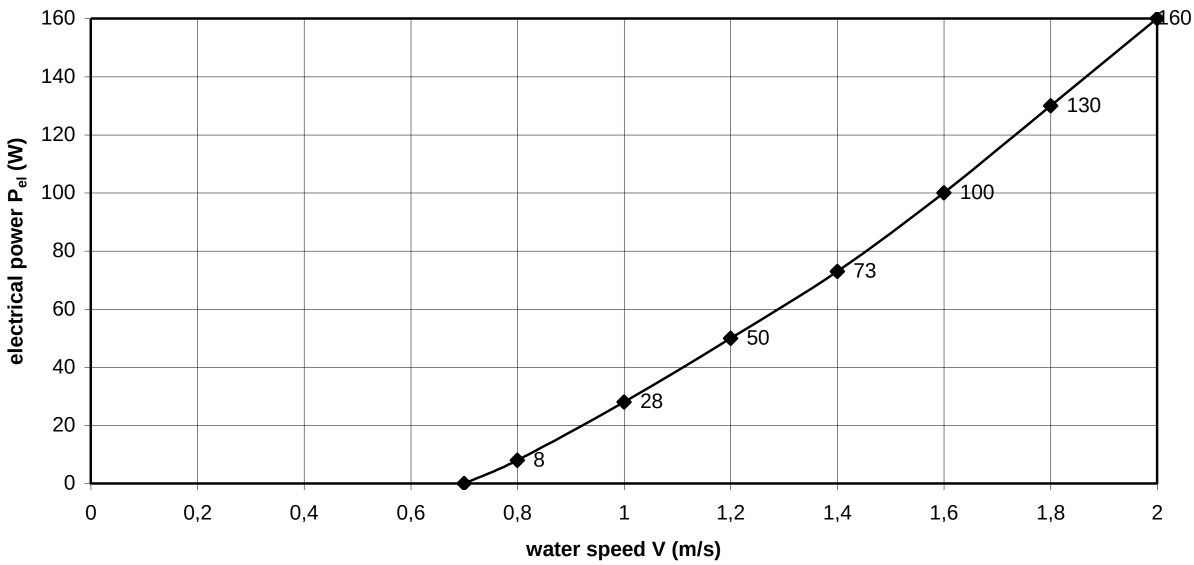

fig. 7 P_{el}-V curve VIRYA-0.65 for 24 V battery charging

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.

An alternative PM-generator using the housing of an asynchronous motor frame size 100, is described in free public report KD 503 (ref. 5). This generator will have about the same characteristics as the VIRYA-2.68 generator but it has a thicker shaft with a 28 mm shaft end with a key groove in it.

Recently I have investigated if a similar but bigger water turbine with a rotor of 0.8 m diameter can be used in combination with the VIRYA-4.2 generator for 24 V battery charging. This research is presented in report KD 655 (ref. 6). It seems possible and the maximum power is 350 W for a water speed of 2 m/s. The P_{el}-V curve starts at V = 0.78 m/s. so one needs a river with rather high water speeds. This report is not made public but someone who wants to build a prototype can receive a copy of it.

7 Ideas about the alternative 2-bladed rotor of the VIRYA-0.625

A disadvantage of the VIRYA-0.65 is that the matching in between rotor and generator isn’t good for low water speeds and this results in a rather high cut-in water speed of 0.7 m/s for 24 V battery charging. The matching is improved if the optimum cubic line of the rotor shifts to the right. This can be realised by choosing a smaller rotor diameter or a higher design tip speed ratio or by changing both. However, choosing a higher tip speed ratio results in a smaller blade chord for a 3-bladed rotor and I expect that a rotor with a smaller blade chord will be not strong enough. So it investigated if a 2-bladed rotor with the same blade chord but with λ_d = 3.5 may work.

The advantage of a 2-bladed rotor is that the whole rotor can be made out of one strip. For a windmill with a 2-bladed rotor, the connection of the blades to the hub must be elastic because other wise the fluctuating gyroscopic moment would give too large vibrations. But the rotor of a water turbine isn’t yawing and therefore there is no gyroscopic moment. So the rotor can be stiff and this means that the whole strip can be cambered. It is assumed that the strip is cut from a stainless steel sheet size 1250 * 2500 * 2 mm.

In this case a blade size 625 * 100 * 2 mm is a logic choice as 48 rotors can be made from one sheet without waste. So the rotor diameter becomes 0.625 m which means that R = 0.3125 m. The chord becomes a little smaller than the strip width resulting in c = 98.7 mm = 0.0987 m.

The hub is made from stainless steel bar size 30 * 30 mm and has a width of 100 mm. The back side of the hub is provided with a radius which is the same as the radius of the blade camber. The blade is clamped in between the hub and a clamping block which also has a radius. The rotor geometry is determined in the same way as it was done in chapter 3 for the VIRYA-0.65 rotor. Substitution of λ_d = 3.5 and R = 0.3125 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 11.2 * r$ (-) (10)

Formula's (2) and (3) for β and ϕ stay the same.

Substitution of B = 2 and c = 0.0987 m in formula (5.4) of KD 35 gives:

$C_l = 127.319\ r\ (1 - \cos\phi)$ (-) (11)

Formula 5 for $R_{e\,r}$ stays the same too.

The blade is calculated for six stations A till F which have a distance of 0.0465 m of one to another. 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 3.

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	0.3125	3.5	10.6	0.0987	0.68	0.71	4.20	3.4	-0.5	-0.4	11.1	11	0.041
B	0.266	2.979	12.4	0.0987	0.79	0.80	3.60	3.4	0.1	0.2	12.3	12.2	0.036
C	0.2195	2.458	14.8	0.0987	0.92	0.91	3.01	3.4	1.5	1.4	13.3	13.4	0.036
D	0.173	1.938	18.2	0.0987	1.10	1.08	2.42	2.5	3.8	3.6	14.6	14.6	0.040
E	0.1265	1.417	23.5	0.0987	1.33	1.36	1.85	1.7	7.3	7.7	16.2	15.8	0.11
F	0.08	0.896	32.1	0.0987	1.56	1.29	1.32	1.2	-	15.1	-	17	0.24

table 3 Calculation of the blade geometry of the VIRYA-0.625 rotor

The calculated lift coefficient C_l = 1.56 for station F can't be generated by the airfoil. The theoretical blade angle β_{th} for the stations A up to E varies in between 11.1° and 16.2°. If a blade angle of 11° is taken at the blade tip and of 17° is taken at the blade root, the linearised blade angles are lying close to the theoretical values. A blade is twisted 17° left hand in between station F and the hub for a rotor which is rotating left hand, to get the correct blade angle at the blade root. A sketch of the rotor is given in appendix 3.

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 0.038. Figure 4.6 of KD 35 (for B = 2) and λ_{opt} = 3.5 and C_d/C_l = 0.038 gives $C_{p\,th}$ = 0.415. The blade is stalling at station F so for the calculation of the maximum C_p only the part of the blade length up to 0.0175 m outside station F is taken into account. This gives an effective blade length k' = 0.22 m.

Substitution of $C_{p\ th}$ = 0.415, R = 0.3125 m and effective blade length k = k' = 0.22 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.38. $C_{q\ opt}$ = $C_{p\ max}$ / λ_{opt} = 0.38 / 3.5 = 0.1086. Substitution of λ_{opt} = λ_d = 3.5 in formula 6.4 of KD 35 gives λ_{unl} = 5.6.

The starting torque coefficient is calculated with formula 6. The average blade angle is 14°. For a non rotating rotor, the average angle of attack α is therefore 90° - 14° = 76°. 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 α = 76° it can be read that C_l = 0.46. During starting, the whole blade is stalling. So now the real blade length k = 0.2375 m is taken.
Substitution of B = 2, R = 0.3125 m, k = 0.2375 m, C_l = 0.46 and c = 0.0987 m in formula 6 gives that $C_{q\ start}$ = 0.033. For the ratio in between the starting torque and the optimum torque we find that it is 0.033 / 0.1086 = 0.304. This is rather high for a rotor with a design tip speed ratio of 3.5.

The starting water speed is calculated with formula 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, $C_{q\ start}$ = 0.033, ρ = ρ_w = 1000 kg/m^3 and R = 0.3125 m in formula 7 gives that V_{start} = 0.5 m/s. This is rather low which means that the rotor will even turn at rather 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 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 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-0.625 rotor are given in figure 8 and 9.

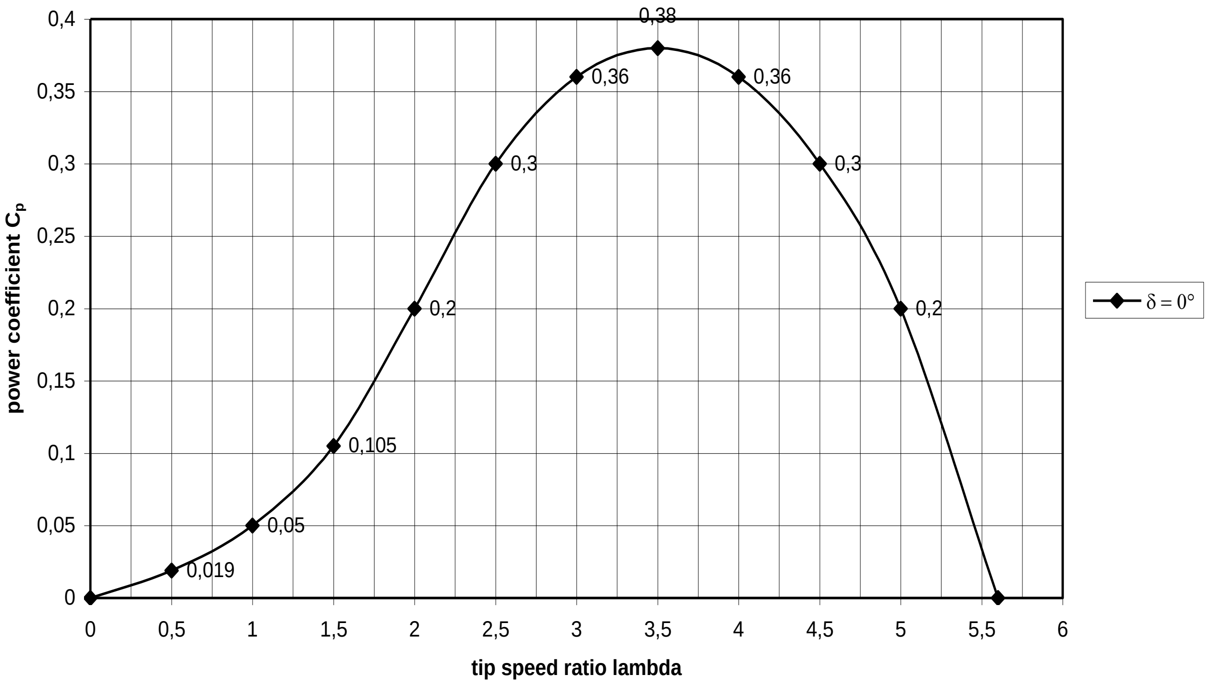

fig. 8 Estimated C_p-λ curve for the VIRYA-0.625 rotor for the water direction perpendicular to the rotor (δ = 0°)

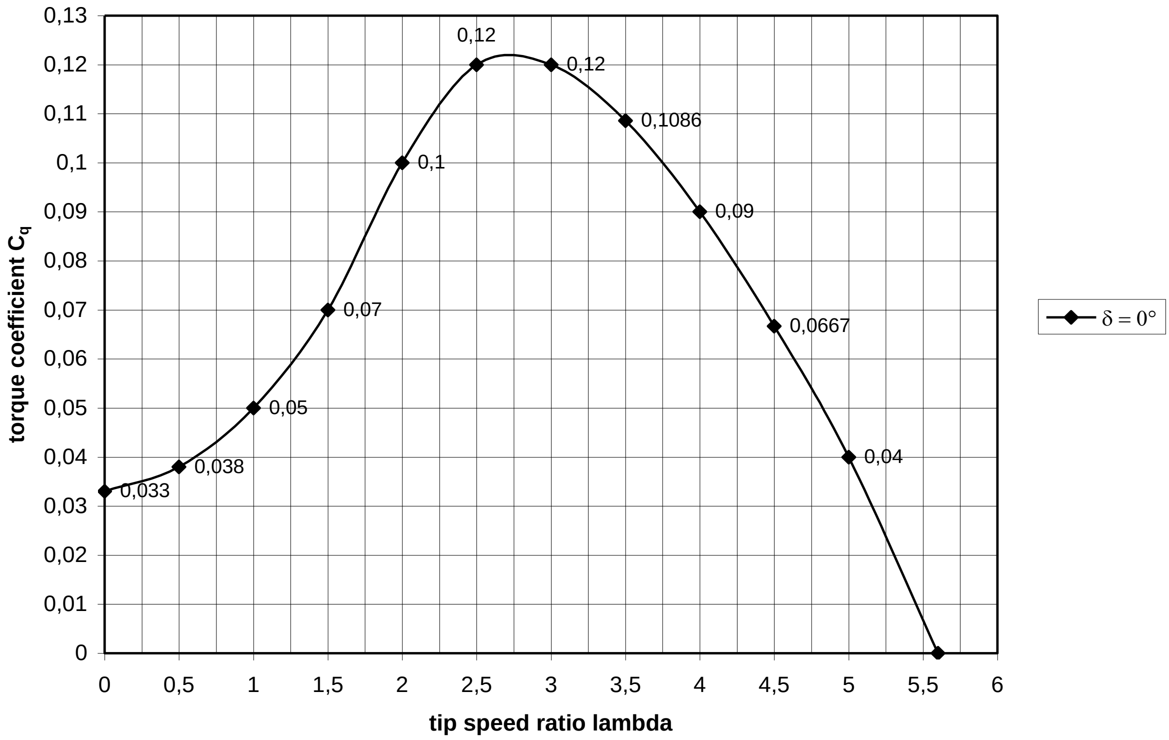

fig. 9 Estimated C_q-λ curve for the VIRYA-0.625 rotor for the water direction perpendicular to the rotor ($\delta = 0°$)

The P-n curves for the VIRYA-0.625 rotor are determined in the same way as it was done in chapter 5 for the VIRYA-0.65 rotor. 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 = 0.3125 m in formula 7.1 of KD 35 gives:

$n_\delta = 28.715 * \lambda * V$ (rpm) (12)

Substitution of δ = 20°, $\rho = \rho_w$ = 1000 kg / m^3 and R = 0.3125 m in formula 7.10 of KD 35 gives:

$P_\delta = 127.285 * C_p * V^3$ (W) (13)

The P-n curves are determined for C_p values belonging to λ = 2, 2.5, 3, 3.5, 4, 4.5, 5 and 5.6. (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 12 and 13 and this gives the P-n curve for that water speed. The result of the calculations is given in table 4.

		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)
2	0.2	45.9	13.0	57.4	25.5	68.9	44.0	80.4	69.9	91.9	104.3	103.4	148.5	114.9	203.7
2.5	0.3	57.4	19.6	71.8	38.2	86.1	66.0	100.5	104.8	114.9	156.4	129.2	222.7	143.6	305.5
3	0.36	68.9	23.5	86.1	45.8	103.4	79.2	120.6	125.7	137.8	187.7	155.1	267.2	172.3	366.6
3.5	0.38	80.4	24.8	100.5	48.4	120.6	83.6	140.7	132.7	160.8	198.1	180.9	282.1	201.0	386.9
4	0.36	91.9	23.5	114.9	45.8	137.8	79.2	160.8	125.7	183.8	187.7	206.7	267.2	229.7	366.6
4.5	0.3	103.4	19.6	129.2	38.2	155.1	66.0	180.9	104.8	206.7	156.4	232.6	222.7	258.4	305.5
5	0.2	114.9	13.0	143.6	25.5	172.3	44.0	201.0	69.9	229.7	104.3	258.4	148.5	287.2	203.7
5.6	0	128.6	0	160.8	0	193.0	0	225.1	0	257.3	0	289.4	0	321.6	0

table 4 Calculated values of n and P as a function of λ and V for the VIRYA-0.625 rotor

The calculated values for n and P are plotted in figure 10. The optimum cubic line which can be drawn through the maximum of all P-n curves is also given in figure 10. The P_{mech}-n and P_{el}-n curves for 26 V star are also given in figure 10.

In figure 10 it can be seen that the matching is much better now and is about perfect for high water speeds as the P_{mech}-n curve of the generator is lying close to the optimum cubic line. The P_{el}-V curve is determined in the same way as it was done in chapter 6 for the VIRYA-0.65 rotor and is given in figure 11.

In figure 11 it can be seen that the P_{el}-V curve starts at a water speed of 0.6 m/s. Earlier is was calculated that the starting water speed is 0.5 m/s so there is no hysteresis in the P_{el}-V curve. The maximum power at V = 2 m/s is about 160 W which is the same as for the VIRYA-0.65. So the negative effect of the slightly smaller rotor diameter is compensated by the better matching. If figure 11 is compared to figure 7 it can be seen that the P_{el}-V curve of the VIRYA-0.625 is better for water speed in between 0.6 m/s and 1.2 m/s and is the same for higher water speeds. So I think that the VIRYA-0.625 is a better choice.

The VIRYA-0.625 can also be used for 12 V battery charging if the original 230/400 V winding is rectified in delta, but then the maximum power will be lower. Another option is to modify the 230/400 V winding to a 115/200 V winding by connecting the first and the second layer in parallel in stead of in series. In this case the same characteristics will be obtained for 13 V star as for the original winding for 26 V star. So the P_{el}-V curve will also be the same.

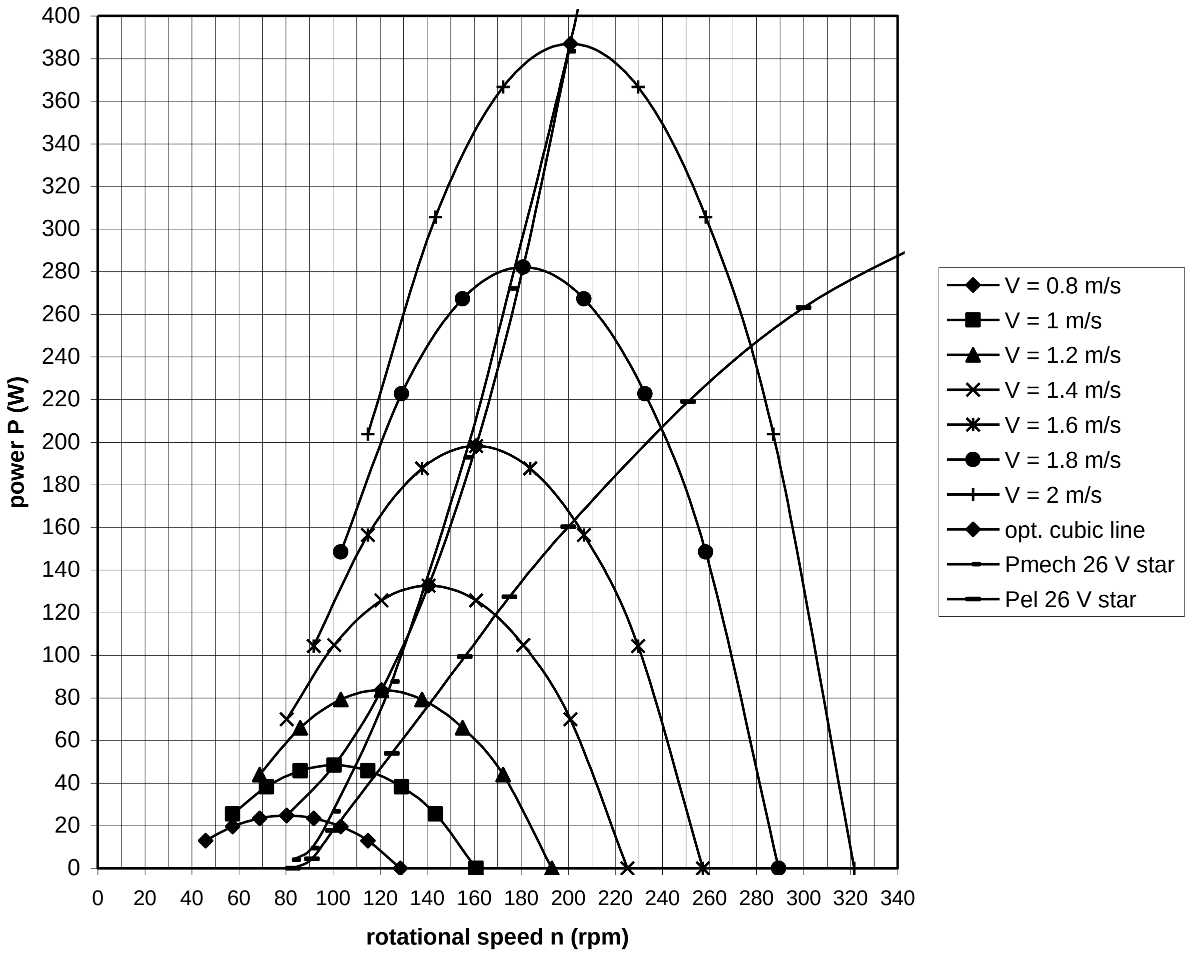

fig. 10 P-n curves of the VIRYA-0.625 rotor and optimum cubic line

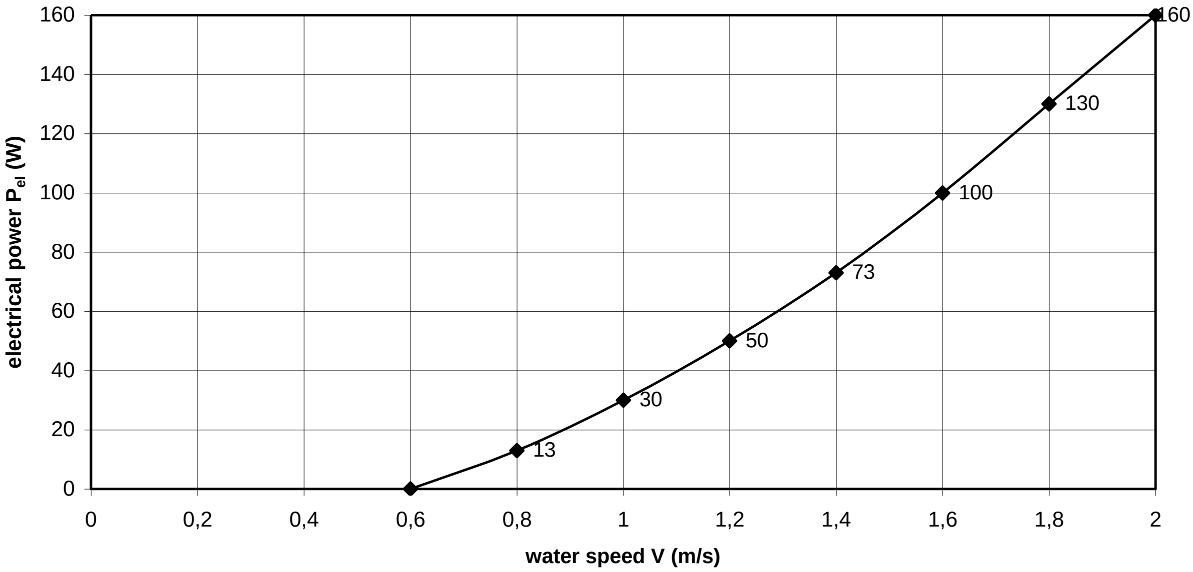

fig. 11 P_{el}-V curve VIRYA-0.625 for 24 V battery charging

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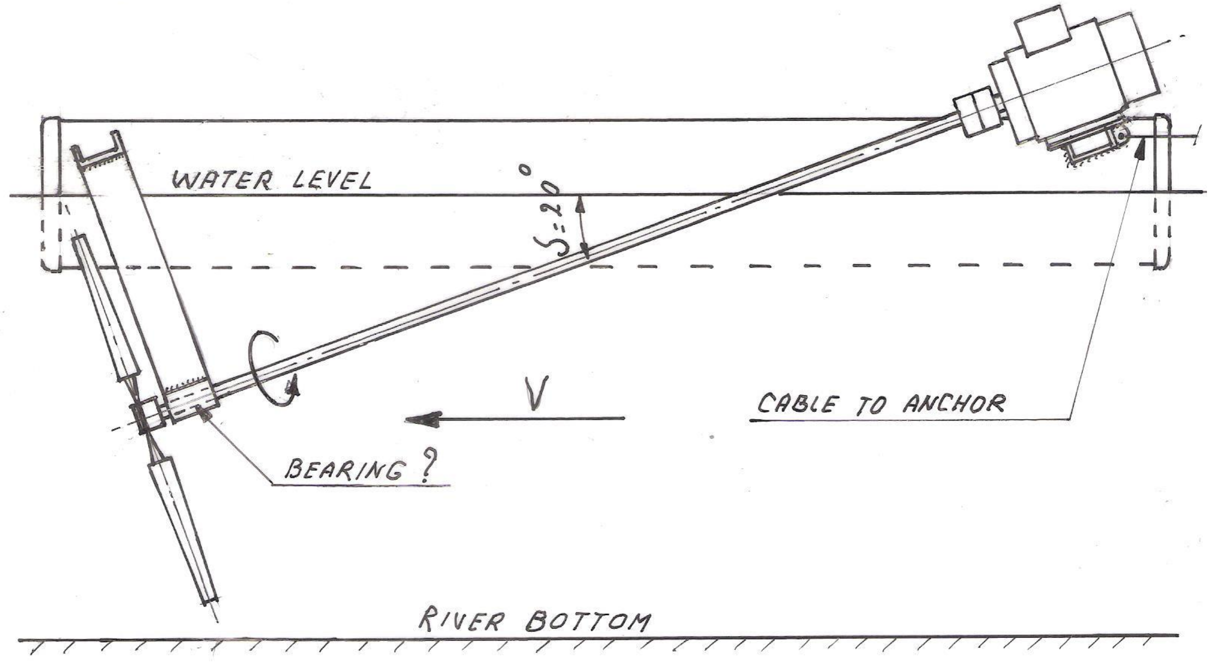
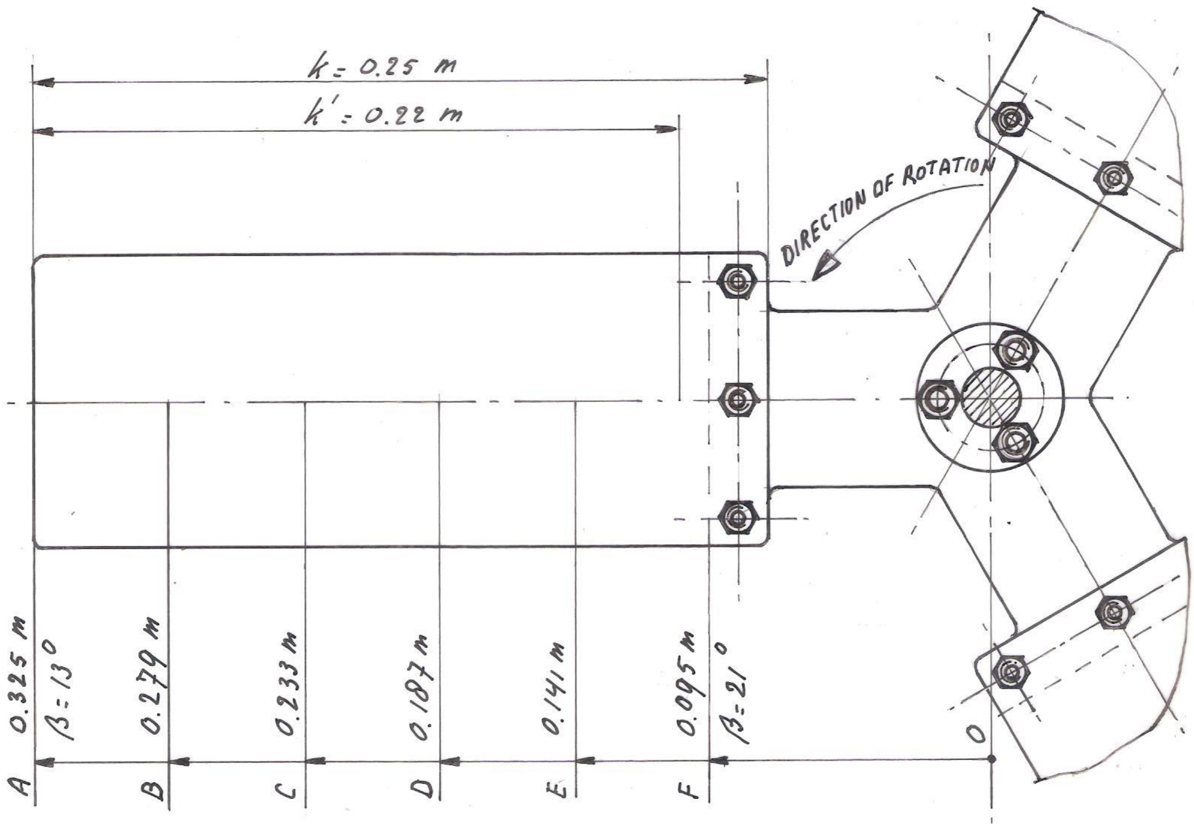
Appendix 1
Sketch of the vessel and the water turbine



Appendix 2
Sketch of the VIRYA-0.65 water turbine rotor



Appendix 3
Sketch of the VIRYA-0.625 water turbine rotor