Development of an 8-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1.36 windmill using 8 neodymium magnets size 25.4 * 25.4 * 12.7 mm. Design report of the rotor (λ_d = 5, B = 2, stainless steel blades).

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KD 571

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Contains page

1 Introduction

One of the most critical parts of a small wind turbine is the generator. As far as I know, simple and cheap direct drive 3-phase permanent magnet (PM) generators are not available on the market. For my current range of VIRYA windmills, I therefore have developed a range of PM-generators. These generators are derived from standard asynchronous 4-pole, 3-phase motors by replacing the original shaft and short-circuit armature by a stainless steel shaft and a mild steel armature which is provided by neodymium magnets. These generators are described in public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking torque is not fluctuating because the armature poles are making a certain angle with the axis. This facilitates starting of the rotor at low wind speeds.

The sticking torque can almost be eliminated by using a generator with no iron in the coils. A 4-pole, 3-phase axial flux generator of this kind is described in public report KD 522 (ref. 2) for the VIRYA-1.5 rotor. However, manufacture of the stator of this generator is rather difficult because the coils have to be cast in epoxy or polyester.

The VIRYA-1.04 windmill, which makes use of a Nexus hub dynamo is described in a public manual (ref. 3) including the drawings of the windmill and the tools. The VIRYA-1.04 has a maximum power of only 6 W which is very low for a rotor diameter of 1.04 m.

The idea is to use some of the principles of the axial flux generator as described in report KD 522 but to simplify the generator by using a stator with separate coils wound around cores with flanges and by using a steel stator sheet which isn't rotating. This generator will be used for the VIRYA-1.36 rotor and it will have a maximum power of about 80 W.

The rotor of this VIRYA-1.36 windmill has a design tip speed ratio λ_d = 5 and two blades made of stainless steel sheet. The calculation of the rotor geometry is given in chapter 6. The head construction will be derived from the head construction of the VIRYA-1.25 windmill (see chapter 9). However, the VIRYA-1.36 will get a 2 mm aluminium vane blade. The rated wind speed for this vane blade will be about 9 m/s. The manufacture of the VIRYA-1.36 windmill is described in a separate manual (ref. 4).

2 Description of the generator (see figure 1)

The armature consists of a rectangular galvanised steel sheet size 156 * 156 * 3 mm. 128 sheets can be cut from a standard sheet size 1.25 * 2.5 m. Eight neodymium magnets size 25.4 * 25.4 * 12.7 mm are glued to the back side of the armature sheet at a pitch circle of 125 mm such that four north poles and four south poles are created.

A rotor blade is cut out of stainless steel strip size 1.5 * 125 * 625 mm and 40 blades for 20 rotors can be made out of a standard sheet size 1.25 * 2.5 m. A rotor blade is bolted to the front side of the armature sheet with three stainless steel bolts M6 * 12, three large washers for M6 and three self locking nuts M6. The overlap in between a blade and the armature sheet is 23 mm resulting in a rotor diameter of 2 * 625 + 156 – 2 * 23 = 1360 mm.

The magnets are supplied by the Internet company www.supermagnete.de . These magnets have quality N40 and a remanence B_r in between 1.26 T and 1.29 T. The current price is € 4.17 per magnet including VAT and excluding mailing costs for an order of 20 magnets, so the magnet costs for one generator are about € 34 which seems to be acceptable.

The stator consists of a dodecagonal galvanised steel which can be made from a square sheet size 178 * 178 * 3 mm. 98 sheets can be cut from a standard sheet size 1.25 * 2.5 m. In stead of a dodecagonal sheet, it is also allowed to use a circular sheet with a diameter of 184 mm. Six coils are bolted to the front side of the sheet by six stainless steel screws M5 * 16 and six self locking nuts M5. The stator sheet has three holes through which the three coil ends are guided to the backside. A 3-phase rectifier is connected to the back side of the stator sheet. An oil seal size 18 * 26 * 4 mm is pressed in the stator sheet and gives extra prevention against the penetration of water or dust in the bearings.

As the stator sheet is not rotating, the magnetic flux through this sheet varies and this creates eddy currents in the sheet. Tests with a prototype which are described in chapter 10, prove that the rise in temperature caused by the eddy currents is only about 6 °C.

A coil is wound around a polyacetal (polyoxymethylene or POM, supplied as Delrin, Ertacetal and Hostaform) core. The pitch circle of the coils is also 125 mm. A core has a width of 12 mm and a diameter of 36 mm. A core has a central 5 mm hole and a 9 mm chamber for the screw head. A core has two flanges with a diameter of 58 mm. The front flange has a thickness of 1.3 mm. The back flange has a thickness of 0.7 mm so the width in between the flanges is 10 mm. The back flange can be thinner because it is supported by the stator sheet.

The average coil diameter is (58 + 36) / 2 = 47 mm. The pitch in between a north and a south pole is about 47 mm. So if a north pole is passing the left side of a coil, a south pole is passing the right side of a coil. This means that the voltage generated in the left side is in phase to the voltage generated in the right side and for this condition the maximum total voltage will be generated in a coil.

The distance in between the armature sheet and the stator sheet is chosen 26 mm. The magnet has a thickness of 12.7 mm, so the magnetic air gap t_2 in between the magnet and the stator sheet is 26 – 12.7 = 13.3 mm. The core has a width of 12 mm, so the real air gap in between a magnet and a core is 13.3 – 12 = 1.3 mm.

The six coils all have the same dimensions and the same winding direction. Two coils are of phase U, two coils are of phase V and two coils are of phase W. The armature pole pitch is 45° for an armature with eight poles. The stator coil pitch is 60° for a stator with six coils. The positioning of the armature poles with respect to the coils is drawn in figure 1 such that north pole N1 is just opposite coil U1. In chapter 3 it will be proven that a 3-phase current is generated if the armature rotates. The calculation of the flux density in the coils and in the armature sheet is given in chapter 4. The procedure how the wire thickness and the number of turns per coil is determined, is given in chapter 10.

The bearing housing is made out of stainless steel bar ϕ 50 mm. It has a length of 70 mm. The stator sheet is bolted to the front side of the bearings housing by four bolts M5 * 10 at a pitch circle of 41 mm. The stator sheet locks the front bearing. The bearing housing has four threaded holes M8 at the back side for connection to the head frame. The pitch circle of these holes is 38 mm.

The bearing housing has a 13 mm hole at the back side and a 10 mm inner hexagon spanner can be put through this hole and in the bolt head to prevent that the shaft rotates when the nut M12 is tightened. The head frame of the VIRYA-1.36 has a generator bracket size 50 * 100 * 4 mm which is in parallel to the rotor plane. The bearing housing is connected to the front side of the generator bracket by four bolts M8 * 16.

For the rotor shaft, a stainless steel inner hexagon bolt M12 * 100 is used. The cylindrical part of this bolt has a diameter of about 11.9 mm so some epoxy glue has to be used in between the bolt and the 12 mm inside of the bearings to fill the gap. Two sealed bearings size 12 * 32 * 10 mm are used. The bearings are separated by a 29 mm long distance bush. A second 29 mm long distance bush separates the front bearing and the armature sheet. So both distance bushes are identical. The rotor, the two distance bushes and the bearings are clamped together by a stainless steel self locking nut M12.

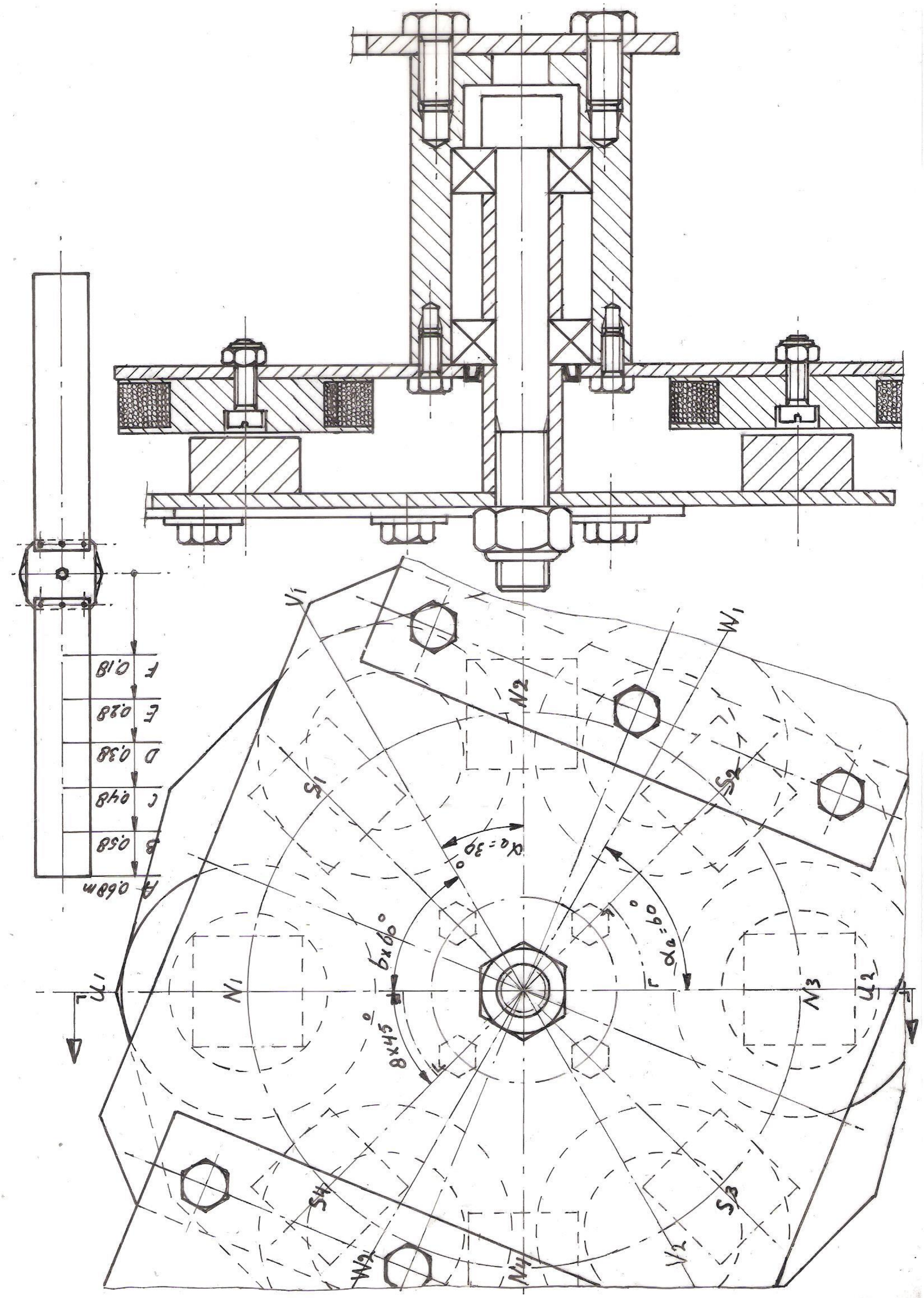

fig. 1 8-pole axial flux permanent magnet generator VIRYA-1.36

3 Checking if a 3-phase current is generated

A 3-phase current has three phases called U, V and W. Normally the voltage U of each phase varies sinusoidal and the angle α in between the phases is 120°. The formulas for the voltage of each phase are:

$$U_u = U_{max} * \sin\alpha \quad (V) \qquad (1)$$

$$U_v = U_{max} * \sin(\alpha - 120°) \quad (V) \qquad (2)$$

$$U_w = U_{max} * \sin(\alpha - 240°) \quad (V) \qquad (3)$$

The three curves are shown in figure 2.

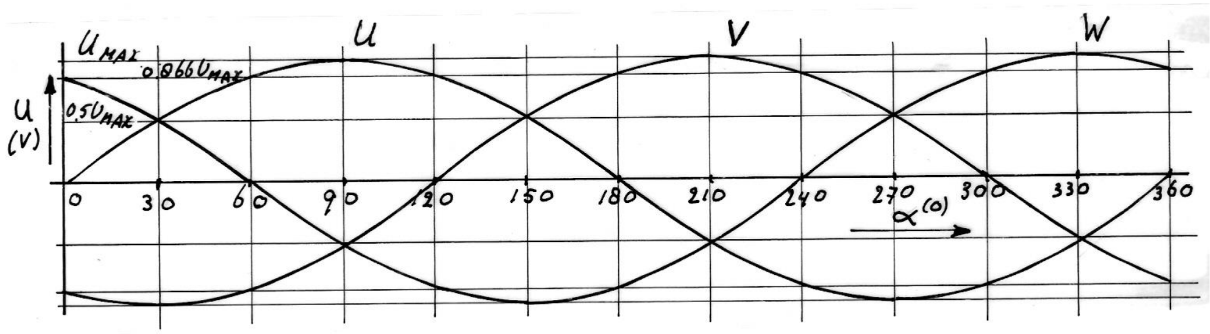

fig. 2 Three phases U, V and W

A pure sine wave is generated if a coil is rotating in a constant magnetic field because the magnetic field through the coil varies sinusoidal. If a permanent magnet is moving along a coil, the generated voltage may not be a pure sine wave, especially if the distance in between the magnets is large. But for the chosen generator configuration it is assumed that the generated voltage varies about sinusoidal. If the armature has two poles, the position of the armature with respect to the stator will be the same if the armature has rotated 360°. So the phase angle α is the same as the rotational angle α_a of the armature. If the armature has eight poles, this will be the case for 360 * 2 / 8 = 90° rotation of the armature. This results in the formula:

$$\alpha = \alpha_a * p_a / 2 \quad (-) \qquad (4)$$

α is the phase angle. α_a is rotational angle of the armature. p_a is the number of armature poles.

In figure 1 it can be seen that α_a = 0° in between N1 and U1, that α_a = 30° in between N2 and V1 and that α_a = 60° in between N3 and W1. Substitution of α_a = 30° and p_a = 8 in formula 4 gives α = 120°. Substitution of α_a = 60° and p_a = 8 in formula 4 gives α = 240°. So a 3-phase voltage is created in between the coils U1, V1 and W1.

In figure 1 it can be seen that coil U1 is opposite to north pole N1 and that coil U2 is opposite north pole N3. This means that if coil U1 is wound right hand, coil U2 must also be wound right hand to make that the voltages of both coils strengthen each other.

The two coils of one phase are wound together on a two steps winding thorn. The winding direction of both coils is the same so both coils have to be mounted on the winding thorn such that the chamber for the screw is pointing in the same direction. The two coils are clamped in between three metal disks with a diameter of about 56 mm to prevent that the flanges bend to the outside during winding due to the pressure of the wires.

A bundle of two coils U has two wire ends which are labelled U_A and U_B. The two coils V have wire ends V_A and V_B. The two coils W have wire ends W_A and W_B. The wire ends U_B, V_B and W_B are connected to each other and are forming the star point. The wire ends U_A, V_A and V_A are connected to the 3-phase rectifier.

4 Calculation of the flux density in the air gap and the armature sheet

A calculation of the flux density in the air gap for the current VIRYA generators is given in chapter 5 of KD 341 (ref. 1). However, the magnet configuration of this new type PM-generator is completely different and so the formulas out of KD 341 can't be used.

A radial flux PM-generator with a laminated stator is normally designed such that the magnetic field in the stator is just saturated. For this condition, the generator has its maximum torque level and this means that it can supply the maximum electrical power for a certain rotational speed. However, for this new axial flux generator it is not allowed that the armature sheet or the stator sheet are saturated because a saturated sheet will reduce the magnetic flux in the air gap. The iron of a steel sheet is saturated at a flux density of about 1.6 Tesla (T).

The remanence B_r (magnetic flux) in a neodymium magnet with quality N 40 is about 1.275 T if the magnet is short-circuited with a mild steel arc which is not saturated. However, an air gap in the arc reduces the magnetic flux because it has a certain magnetic resistance. The resistance to a magnetic flux for the magnet itself is about the same as for air. The magnet thickness is called t_1. The magnetic resistance of the iron of the armature sheet and the stator sheet can be neglected if there is no saturation. So the total magnetic resistance is only caused by the magnet itself and by the air gap.

Let's follow the magnetic flux coming out of north pole N1. This flux passes the 13.3 mm wide magnetic air gap in between the magnet and the steel stator sheet. Halve of this flux bends to the right and flows through the steel stator sheet. Then it bends to the right again and passes the second air gap. Then it passes through halve of magnet S1. Then it bends to the right again and flows through the steel armature sheet. Then it bends to the right again and flows through halve of magnet N1. So this flux is turning right hand. The other half flux bends to the left and flows through the stator sheet, halve the south pole S4, the armature sheet and half the north pole N1. This flux is turning left hand. So eight magnetic loops are coming out of the eight armature poles.

One complete magnetic loop flows through two magnets and two air gaps, so there is one air gap for one magnet. The thickness of a magnet is called t_1. The magnetic air gap is called t_2. The air gap t_2 results in an increase of the magnetic resistance by a factor $(t_1 + t_2) / t_1$. This results in decrease of the remanence B_r to the effective remanence $B_{r\ eff}$. $B_{r\ eff}$ is given by:

$$B_{r\ eff} = B_r * t_1 / (t_1 + t_2) \qquad \text{(T)} \qquad (5)$$

Substitution of B_r = 1.275 T, t_1 = 12.7 mm and t_2 = 13.3 mm in formula 5 results in $B_{r\ eff}$ = 0.623 T.

Next it is checked if the iron of the armature sheet isn't saturated. The sheet has a thickness of 3 mm. Let's look at magnet S1. Half of the magnetic flux entering magnet S1 will be a part of a right hand turning loop and the other halve will be a part of a left hand turning loop. As there is a large distance in between the outer side of a magnet and the outside of the armature sheet, the magnetic flux coming out of magnet S1 can flow in all directions of the armature sheet. So in the steel sheet, the magnet flux has to pass an area with a circumference of four times the width of a magnet and a height identical to the thickness of the sheet. This area has a sheet area A_{sh} which is given by: $A_{sh} = 4 * 25.4 * 3 = 304.8\ mm^2$. A_{mag} is called the magnet area and i_1 is called the concentration ratio in between A_{mag} and A_{sh}.

$i_1 = A_{mag} / A_{sh}$ (-) (6)

Substitution of A_{mag} = 25.4 * 25.4 = 645.2 mm^2 and A_{sh} = 304.8 mm^2 in formula 6 gives i_1 = 2.12. The fact that A_{mag} is larger than A_{sh} results in concentration of the magnetic flux in the sheet $B_{r\,sh}$ with a factor i_1. So $B_{r\,sh}$ is given by:

$B_{r\,sh} = B_{r\,eff} * i_1$ (T) (7)

Substitution of $B_{r\,eff}$ = 0.623 T and i_1 = 2.12 in formula 7 gives $B_{r\,sh}$ = 1.32 T. This is smaller than 1.6 T, so the armature sheet is not saturated. The stator sheet is larger than the armature sheet, so the stator sheet is not saturated too.

5 Mounting sequence of the generator and the rotor

1 Clean the shaft and the inside of the bearings with acetone or alcohol.
2 The back bearing is shifted over the shaft. Use some anaerobe or epoxy glue.
3 The 29 mm long distance bush is shifted over the shaft.
4 The front bearing is shifted over the shaft. Use some glue. The bearings have to be pressed together during hardening of the glue. This can be done by the second distance bush and the nut M12. The second bush shouldn't be glued to the shaft.
5 The nut and the second bush are removed after hardening of the glue.
6 The assembly of shaft and bearings is pushed in the bearing housing.
7 The oil seal is pressed in the stator sheet.
8 The six coils are mounted against the stator sheet. The three cable ends U_B, V_B an W_B are soldered to each other thus forming the star point. The star point is isolated with a piece of isolation tube. The three cable ends U_A, U_B and U_C are isolated by an isolation tube and pushed through the three holes in the stator sheet. It is advised to paint the winding with epoxy lacquer for better protection against corrosion.
9 A 3-phase rectifier is mounted to the back side of the stator sheet and the three isolated cables are connected to the rectifier by three tags.
10 The stator is bolted to the bearing housing using four bolts M5 * 10.
11 The second 29 mm long distance bush is pushed over the shaft.
12 The 8 magnets are glued to the back side of the rectangular armature sheet such that four north and four south poles are created. To prevent corrosion, the assembly of sheet and magnets has to be painted by epoxy lacquer.
13 The assembly of the armature sheet and the magnets and is shifted over the shaft and locked with the central M12 nut.
14 The two blades are bolted to the front side of the armature sheet using six stainless steel bolts M6 * 12, six stainless steel self locking nuts M6 and six large stainless steel washers.
15 The rotor is balanced on a frictionless shaft at a windless place.
16 The assembly of generator and rotor is bolted to the generator bracket of the head frame using four bolts M8 * 16 mm.

6 Calculation of the geometry of the VIRYA-1.36 rotor

The 2-bladed rotor of the VIRYA-1.36 windmill has a diameter D = 1.36 m and a design tip speed ratio λ_d = 5. Advantages of a 2-bladed rotor are that no welded spoke assembly is required and that the rotor can be balanced easily and can be transported even mounted.

The rotor has blades with a constant chord and is provided with a 7.14 % cambered airfoil. A rotor blade is made out of a stainless strip with dimensions of 1.5 * 125 * 625 mm and 40 strips can be made out of a standard sheet of 1.25 * 2.5 m. Because the blade is cambered, the chord c is a little less than the blade width, resulting in c = 123.3 mm = 0.1233 m. For cambering the blades, it is possible to use a blade press which is derived from the blade press of the VIRYA-1.04 blades but the blade press should have a length of 500 mm in stead of 400 mm. For twisting one can also use the VIRYA-1.04 tools but one has to use a 3° jig to measure the correct twisting angle of the cambered part and a 11° jig to measure the correct blade angle at the blade root.

The camber is only made in the outer 500 mm of the blade. This part of the blade is twisted linear. The inner 23 mm, where the blade is connected to the armature sheet, is flat. The 102 mm long transition part in between the flat inner part and the outer cambered part is twisted 11° to get the correct blade angle at the blade root. It is assumed that the outer 62 mm of this 102 mm long part is used for the transition of camber to flat. So the inner 40 mm is not cambered. This non cambered part makes the blade rather flexible which is necessary to prevent vibrations due to the gyroscopic moment.

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 5). This report (KD 571) has its own formula numbering. Substitution of λ_d = 5 and R = 0.68 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 7.353 * r \qquad (-) \qquad (8)$$

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

$$\beta = \phi - \alpha \qquad (°) \qquad (9)$$

$$\phi = 2/3 \text{ arc tan } 1 / \lambda_{r\,d} \qquad (°) \qquad (10)$$

Substitution of B = 2 and c = 0.1233 m in formula (5.4) of KD 35 gives:

$$C_l = 101.917 \, r \, (1 - \cos\phi) \qquad (-) \qquad (11)$$

Substitution of V = 5.5 m/s and c = 0.1233 m in formula (5.5) of KD 35 gives:

$$R_{e\,r} = 0.452 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)} \qquad (-) \qquad (12)$$

The blade is calculated for six stations A till F which have a distance of 0.1 m of one to another (see figure 1). 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 constant 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 a 7.14 % cambered airfoil are given in report KD 398 (ref. 6). The Reynolds values for the stations are calculated for a wind speed of 5.5 m/s because this is a reasonable wind speed for a windmill which is designed for a rated wind speed of 9 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\ th}$ (-)	$C_{l\ lin}$ (-)	$R_{e\ r} * 10^{-5}$ V = 5.5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\ lin}$ (-)
A	0.68	5	7.5	0.1233	0.60	0.64	2.28	2.5	-0.7	-0.5	8.2	8	0.050
B	0.58	4.265	8.8	0.1233	0.70	0.64	1.95	1.7	0.6	0.2	8.2	8.6	0.057
C	0.48	3.529	10.5	0.1233	0.83	0.78	1.62	1.7	1.7	1.3	8.8	9.2	0.043
D	0.38	2.794	13.1	0.1233	1.01	1.02	1.30	1.2	3.2	3.3	9.9	9.8	0.030
E	0.28	2.059	17.3	0.1233	1.29	1.30	0.98	1.2	6.7	6.9	10.6	10.4	0.050
F	0.18	1.324	24.7	0.1233	1.68	1.33	0.67	1.2	-	13.7	-	11.0	0.2

table 1 Calculation of the blade geometry of the VIRYA-1.36 rotor

No value for α_{th} and therefore for β_{th} is found for station F because the required C_l value can not be generated. The theoretical blade angle β_{th} varies in between 8.2° and 10.6°. If a blade angle of 8° taken at the blade tip and of 11° at the blade root, the linearised blade angles are lying close to the theoretical values. So the blade twist is 11° - 8° = 3°. The transition part of the strip is twisted 11° to get the correct blade angle at the blade root.

7 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 0.045. Figure 4.6 of KD 35 (for B = 2) en λ_{opt} = 5 and C_d/C_l = 0.045 gives $C_{p\ th}$ = 0.4. The blade is stalling in between station E and F so only the part of the blade till 0.04 m outside station F is taken for the calculation of C_p. This gives an effective blade length k' = 0.46 m.
Substitution of $C_{p\ th}$ = 0.4, R = 0.68 m and blade length k = k' = 0.46 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.36. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.36 / 5 = 0.072.
Substitution of $\lambda_{opt} = \lambda_d$ = 5 in formula 6.4 of KD 35 gives λ_{unl} = 8.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \quad (-) \qquad (13)$$

The average blade angle is 9.5° for the whole blade. For a non rotating rotor, the average angle of attack α is therefore 90° - 9.5° = 80.5°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 80.5° it can be read that C_l = 0.31. During starting, the whole blade is stalling. So now the real blade length k = 0.5 m is taken.
Substitution of B = 2, R = 0.68 m, k = 0.5 m, C_l = 0.31 en c = 0.1233 m in formula 13 gives that $C_{q\ start}$ = 0.0125. The real coefficient will be somewhat lower because we have used the average blade angle. Assume $C_{q\ start}$ = 0.012. For the ratio in between the starting torque and the optimum torque we find that it is 0.012 / 0.072 = 0.167. This is acceptable for a rotor with a design tip speed ratio λ_d = 5.

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

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3}\right)} \quad (m/s) \qquad (14)$$

The sticking torque Q_s of the VIRYA-1.36 generator will be very low because there is no iron in the coils. Only the bearing friction and the eddy currents in the stator sheet will cause some small sticking torque. It is estimated for Q_s that Q_s = 0.04 Nm. Substitution of Q_s = 0.04 Nm, $C_{q\ start}$ = 0.012, ρ = 1.2 kg/m^3 and R = 0.68 m in formula 15 gives that V_{start} = 2.4 m/s. This is acceptable for a 2-bladed rotor with a design tip speed ratio λ_d = 5 and a rated wind speed V_{rated} = 9 m/s.

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. 7). 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 sheet airfoil is used. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-1.36 rotor are given in figure 3 and 4.

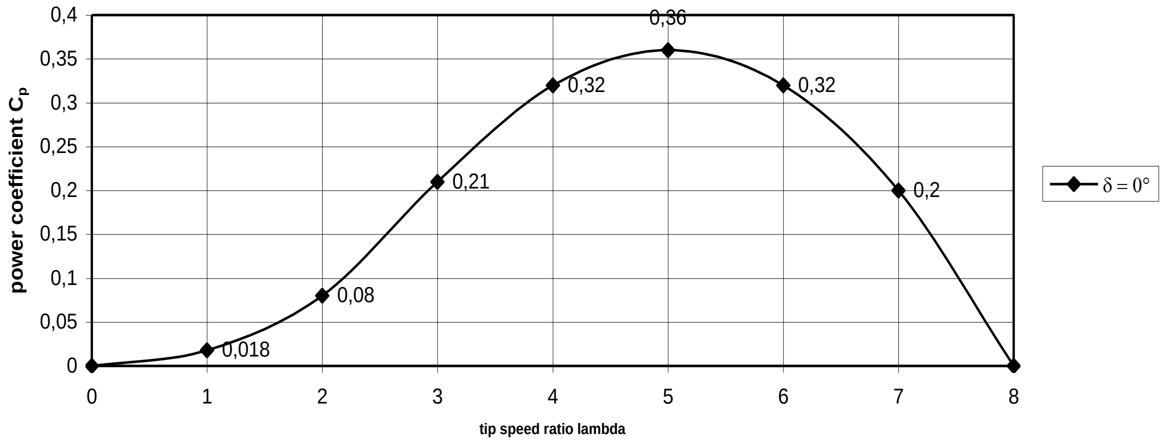

fig. 3 Estimated C_p-λ curve for the VIRYA-1.36 rotor for the wind direction perpendicular to the rotor (δ = 0°)

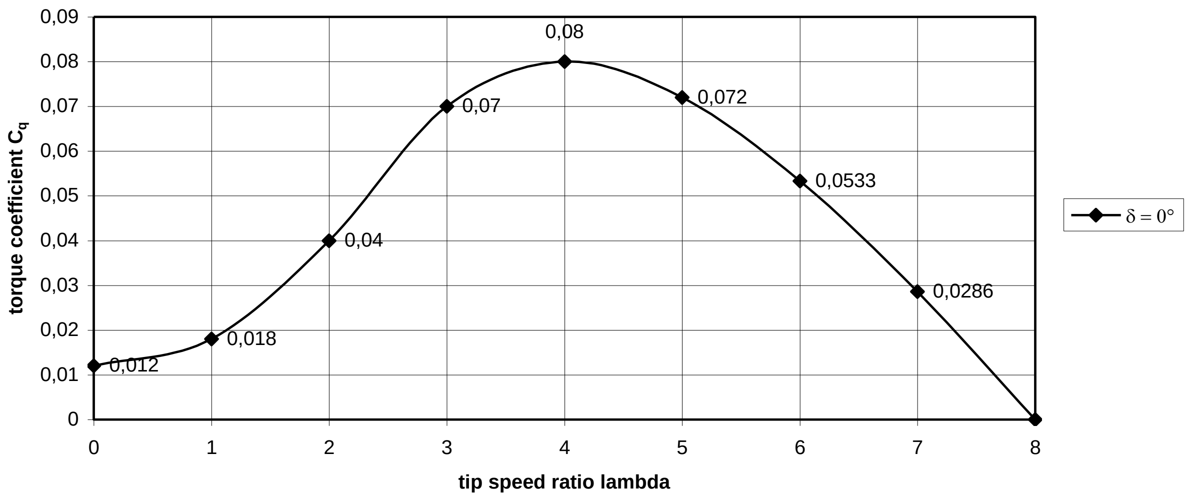

fig. 4 Estimated C_q-λ curve for the VIRYA-1.36 rotor for the wind direction perpendicular to the rotor (δ = 0°)

8 Determination of the P-n curves, the optimum cubic line and the P_{el}-V curve

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 3. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 2 mm aluminium. The rated wind speed for this vane blade is about 9 m/s. The estimated δ-V curve is given in figure 5.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 9 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 9 m/s will therefore also be valid for wind speeds higher than 9 m/s.

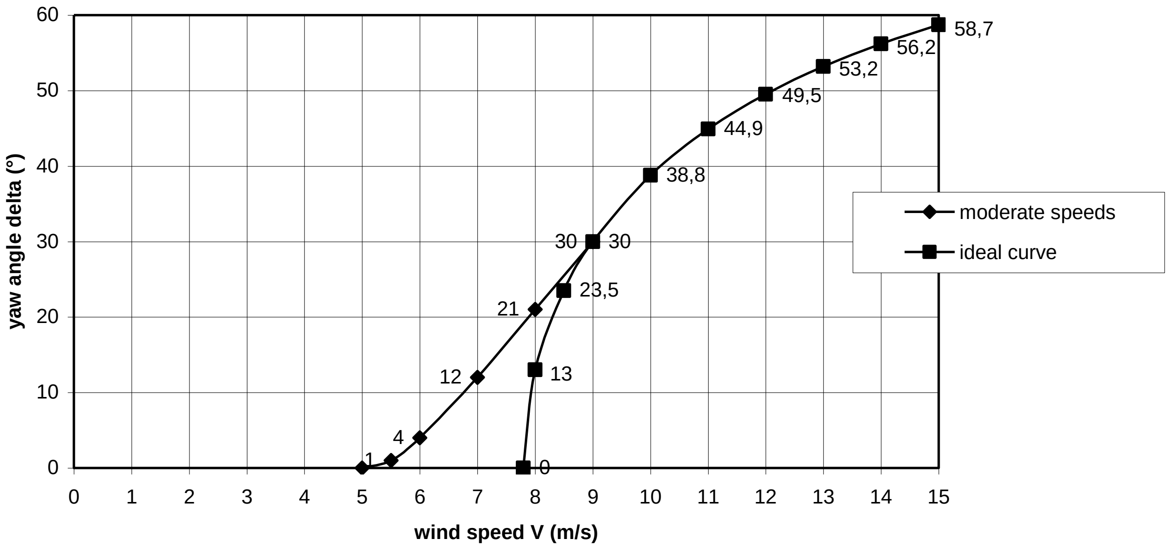

fig. 5 Estimated δ-V curve VIRYA-1.36 for a 2 mm aluminium vane blade

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-1.36 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 wind the speeds 3, 4, 5, 6, 7, 8 and 9 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 = 0.68 m in formula 7.1 of KD 35 gives:

$$n_\delta = 14.0431 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (15)$$

Substitution of ρ = 1.2 kg / m^3 and R = 0.68 m in formula 7.10 of KD 35 gives:

$$P_\delta = 0.8716 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (16)$$

The P-n curves are determined for C_p values belonging to λ = 2, 3, 4, 5, 6, 7 and 8. (see figure 3). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 15 and 16 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 5, 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 = 4°		V = 7 m/s δ = 12°		V = 8 m/s δ = 21°		V = 9 m/s δ = 30°	
λ	C_p	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)
2	0.08	84.3	1.88	112.3	4.46	140.5	8.72	168.1	14.95	192.3	22.38	209.8	29.05	218.9	33.02
3	0.21	126.4	4.94	168.5	11.71	210.8	22.88	252.2	39.25	288.5	58.75	314.6	76.25	328.4	86.67
4	0.32	168.5	7.53	224.7	17.85	281.1	34.86	336.2	59.81	384.6	89.53	419.5	116.20	437.8	132.06
5	0.36	210.6	8.47	280.9	20.08	351.3	39.22	420.3	67.28	480.8	100.72	524.4	130.72	547.3	148.57
6	0.32	252.8	7.53	337.0	17.85	421.6	34.86	504.3	59.81	576.9	89.53	629.3	116.20	656.7	132.06
7	0.2	294.9	4.71	393.2	11.16	491.9	21.79	588.4	37.38	673.1	55.96	734.2	72.62	766.2	82.54
8	0	337.0	0	449.4	0	562.1	0	672.4	0	769.2	0	839.1	0	875.6	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-1.36 rotor

The calculated values for n and P are plotted in figure 6. The optimum cubic line which can be drawn through the maximum of all P-n curves is also given in figure 6.

The axial flux generator has not yet been built and measured so P_{mech}-n and P_{el}-n curves are not yet available. The P_{mech}-n curve is therefore estimated. Using a realistic η-n curve, the P_{el}-n curve is derived from the P_{mech}-n curve. The maximum efficiency η is estimated to be 0.75 for n = 300 rpm. The efficiency is estimated to be 0.48 for the maximum power at n = 560 rpm. The average charging voltage for a 12 V battery is about 13 V, so the P_{el}-n curve is given for 13 V. The estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging are also given in figure 6. It is necessary to measure the curves if a prototype is available and to check if the estimated curves are about correct.

The point of intersection of the P_{mech}-n curve for 13 V of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The working point for V = 9 m/s is lying at about P = 149 W and n = 560 rpm. The electrical power P_{el} for the working point of a certain wind speed is found by going down vertically from that working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 7).

The matching of rotor and generator is good for wind speeds in between 3 and 9 m/s because the P_{mech}-n curve of the generator is lying close to the optimum cubic line.

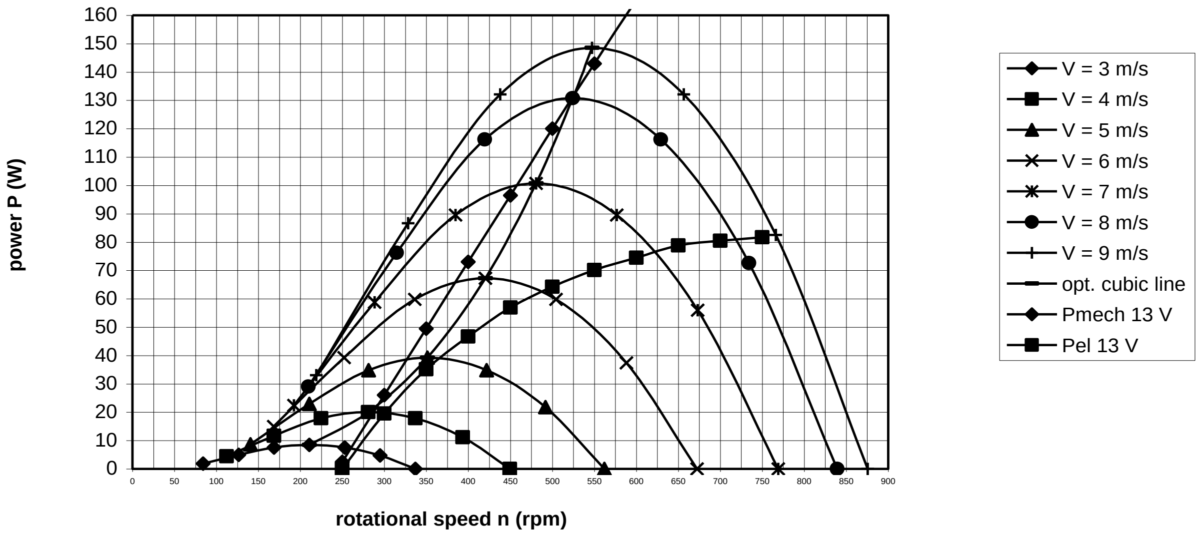

fig. 6 P-n curves of the VIRYA-1.36 rotor, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging for the chosen winding

The supply of power starts already at a wind speed of 2.5 m/s ($V_{cut\ in}$ = 2.5 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. In chapter 7 it was calculated that V_{start} = 2.4 m/s, so there is no hysteresis in the P_{el}-V curve.

The maximum power is about 71 W which is acceptable for a 1.36 m diameter rotor. This means that the maximum charging current is 5.07 A for a maximum charging voltage of 14 V. It is expected that a 60 Ah battery can have this current for a certain time even if it's full. So a voltage controller might not be necessary. The mechanical power at V = 9 m/s is 149 W. This means that the heat losses in the winding, the stator iron and the rectifier are 149 – 71 = 78 W.

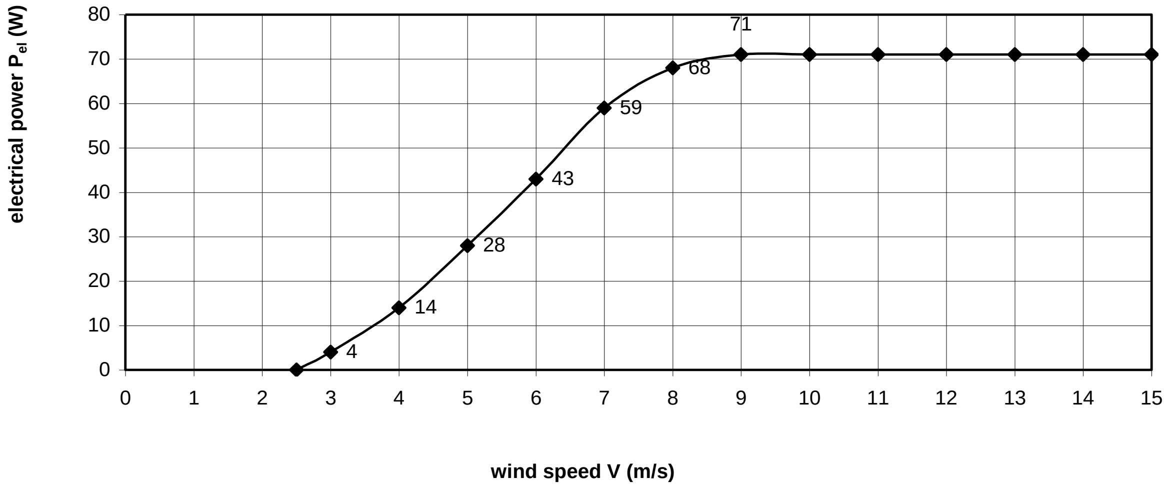

fig. 7 P_{el}-V curve of the VIRYA-1.36 windmill with V_{rated} = 9 m/s for 12 V battery charging

9 Checking of the head geometry (see figure 8)

The hinged side vane safety system is described in report KD 223 (ref. 8) for a rotor with cambered blades. The vane and rotor geometry have to be chosen such that the rotor is about perpendicular to the wind at very low wind speeds. This means that the rotor moment is the same as the vane moment around the tower axis. The moment equation for this situation is given by formula 48 or 49 of KD 223. Formula 49 is copied as formula 17.

$$C_n = \pi R^2 * C_t * e / \{h * w * (R_v + i_1)\} \quad (-) \qquad (17)$$

C_n is the normal coefficient of a square flat plate. The C_n-α curve of a square flat plate is given as figure 6 of report KD 223 (ref. 8) or as figure 2 of report KD 551 (ref. 9). R is the rotor radius and R = 0.68 m. C_t is the thrust coefficient of the rotor and C_t = 0.75. e is the eccentricity in between the rotor axis and the tower axis and it is chosen that e = 0.12 m. h is the vane height and h = 0.3125 m. w is the vane width and w = 0.3125 m. So 32 vane blades can be made out of a sheet of 1.25 * 2.5 m. R_v is the distance in between the leading edge of the vane blade and the tower axis measured in the direction of the vane hinge axis. A composite drawing of the head has been made for a vane arm length of 1 m. From this composite drawing it was found that R_v = 0.88 m. i_1 is the distance in between the normal force N acting on the vane blade and the leading edge of the vane blade. For the balance of moments around the tower axis one has to take the horizontal component N cosθ of the normal force but for very low wind speeds the vane is hanging almost vertical and cosθ can be taken 1. The distance i_1 depends on the angle of attack α in between the wind direction and the vane blade. The angle α is 30° if the rotor is perpendicular to the wind. The ratio i_1/w is given in figure 7 of KD 223. For α = 30° it can be read that i_1 = 0.37 * w = 0.37 * 0.3125 = 0.116 m. So $R_v + i_1$ = 0.88 + 0.116 = 0.996 m. Substitution of these values in formula 17 gives C_n = 1.34. In figure of report KD 551 it can be read that α = 29° for C_n = 1.34. This means that the yaw angle δ is -1° for very low wind speeds. This shows that the chosen head geometry is OK.

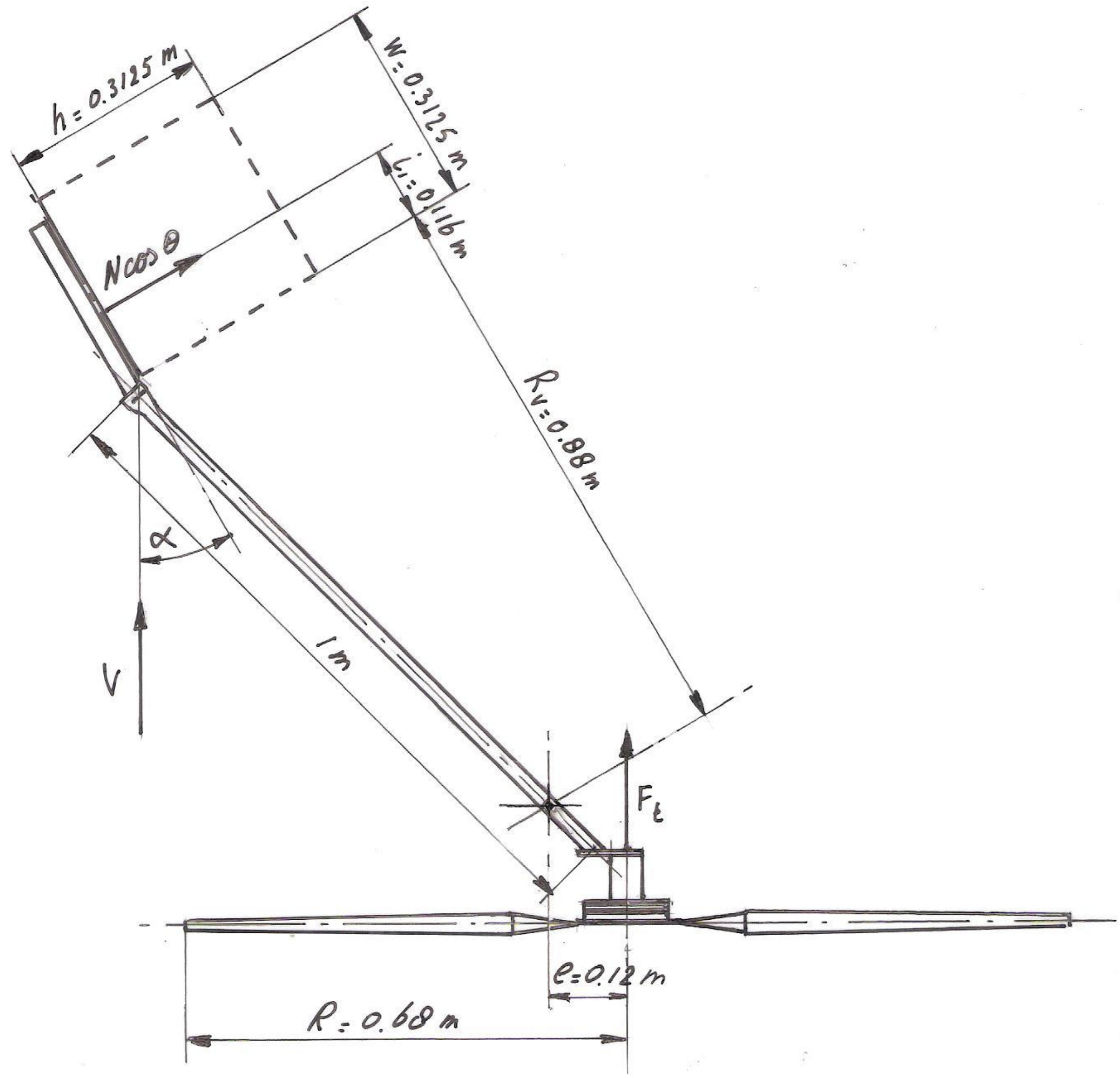

fig. 8 Head geometry VIRYA-1.36

10 Tests performed to determine the winding

The estimated P_{el}-n curve given in figure 6 starts at a rotational speed of 250 rpm. This means that the generated unloaded DC voltage must be equal to the open battery voltage at this rotational speed. It is assumed that the open battery voltage is 12.5 V. So the winding must be such that the open DC voltage is 12.5 V for n = 250 rpm. In this case the starting point of the real P_{el}-n curve will be the same as for the estimated P_{el}-n curve. However, the remaining part of the real P_{el}-n curve can only be found by building and measuring of a generator prototype.

The generated effective AC voltage U_{eff} of one phase for a certain stator and armature geometry is proportional to the rotational speed n and proportional to the number of turns per coil. Rectification of a 3-phase current is explained in report KD 340 (ref. 10). The winding is rectified in star. The relation in between the effective DC voltage U_{DCeff} and the effective AC voltage U_{eff} is given by formula 13 of KD 340 if the voltage drop over the rectifier U_{rect} is neglected. Formula 13 of KD 340 is copied as formula 18.

$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff}$ (V) (star rectification) (18)

The voltage drop over the rectifier U_{rect} depends on the current. It can be neglected for the very small current flowing through a digital volt meter if the open DC voltage is measured.

But for medium up to large currents, the voltage drop U_{rect} is about 1.4 V for a 3-phase rectifier with silicon diodes and the value of U_{DCeff} has to be reduced by 1.4 V to find the loaded voltage. The voltage drop over the rectifier can be reduced up to about 0.4 V if a rectifier is used which is provided with so called Schottky diodes. However, I could not find a 3-phase bridge rectifier provided with these diodes of enough power and therefore a rectifier with normal diodes is specified on the drawings. But one can make a rectifier with six separate Schottky diodes and this will reduce power loss in the rectifier.

The voltage U_{eff} is the effective AC voltage of one complete phase winding containing two coils. The effective voltage of two coils is a factor 2 larger than the effective voltage of one coil $U_{eff\ 1}$. This gives:

$$U_{eff} = 2 * U_{eff\ 1} \quad \text{(V)} \qquad (19)$$

(18) + (19) gives:

$$U_{DCeff} = 1.91 * \sqrt{2} * \sqrt{3} * U_{eff\ 1} \quad \text{(V)} \quad \text{(star rectification)} \qquad (20)$$

All drawings of the VIRYA-1.36 windmill are ready and are given in the manual (ref. 4). The following tests were performed to determine the heat dissipation in the stator iron and to determine the optimum number of turns per coil.

A square armature sheet and a round stator disk were made. Eight magnets were glued to the armature sheet. The armature sheet was mounted to the flange of a permanent magnet DC motor which could be driven at variable speed. The motor current and voltage were measured, so the absorbed electrical motor power could be calculated. The rotational speed was measured by a laser rpm meter pointing to a white dot on the motor flange.

The maximum rotational speed is reached for the point of intersection of the P_{mech}-n curve with the P-n curve of the rotor for V = 9 m/s. In figure 6 it can be seen that this point is lying at a rotational speed of about 560 rpm. To have some reserve, the motor was measured at higher rotational speed of 670 rpm without the stator sheet mounted and the absorbed electrical motor power P_{elm} then was about 4 W (to overcome the internal motor losses).

Next the stator sheet was mounted such that the distance in between the stator sheet and the armature sheet is 26 mm. This corresponds to a distance between a magnet and a coil core of 1.3 mm. The absorbed electrical motor power was measured again and now it was found that P_{elm} = 33 W. So the absorbed electrical power is increased by 33 – 4 = 29 W by placing of the stator sheet. It is assumed that the motor has an efficiency of about 0.75 so the supplied mechanical motor power P_{mechm} = 22 W. This mechanical power is used to overcome the sticking torque caused by the eddy currents. 22 W is a power which seems acceptable low for the maximum rotational speed of 670 rpm. At 560 rpm, the heat loss will be about 16 W.

The motor was running for 15 minutes at n = 670 rpm. The stator temperature was measured by a thermometer. The temperature at the beginning was 18 °C and the temperature after 15 minutes was 24 °C. So the rise in temperature was 6 °C which is acceptable. The back side of the stator sheet was covered by the wooden structure. For the real generator, both sides of the sheet are free so the cooling is even better and the rise of the temperature due to the eddy currents will be less. For maximum power, the coils will produce a magnetic field opposed to the magnetic field of the magnets and this may result in reduction of the eddy currents in the stator but it is assumed that the iron losses in the stator are about 16 W for every load.

Next one test coil was made using 0.8 mm enamelled copper wire. The core of this test coil has a width of 12 mm, a 1.3 mm wide flange at the front side and a 0.7 mm flange at the back side. So the width in between the flanges is 10 mm. The flanges have a diameter of 58 mm. For the test winding 16 layers could be laid until the coil diameter was also about 58 mm but the number of turns per layer varied in between 10 and 7.

It appeared to be that in the beginning the wires could be laid very close to each other but that the winding becomes more chaotic if more layers are laid. The reason is that the beginning wire end runs along the side of the inner flange and that this wire end is disturbing every new layer because there is more space at the opposite side of the core. The winding was laid by turning the wire around the core by hand. If the coil is wound on a winding thorn, it is easier to lie all wires close to each other but the problem of the beginning wire end will also be there if the coil is wound on a winding thorn. The coil was provided with 132 turns of 0.8 mm wire. The core was connected to the stator disk at the correct position. The motor was clamped in the vice such that the hart of the motor coincides about to the hart of the stator sheet.

The open AC voltage was measured for different rotational speeds and from these measurements it was determined that the AC voltage $U_{eff\ 1}$ = 2.72 V for n = 250 rpm. Substitution of $U_{eff\ 1}$ = 2.72 V in formula 20 gives U_{DCeff} = 12.73 V. The open voltage at 250 rpm must be 12.5 V, so the number of turns per coil must be reduced to 132 * 12.5 / 12.73 = 130. So it appeared that by lucky chance, the test winding was very close to the final winding. The wire thickness for the final winding is chosen 0.8 mm and the number of turns per coil is chosen 130.

To get an impression of the power which can be generated, the test winding was loaded by a resistor with different resistances. Available were several 100 W resistors of 0.47 Ω which could be connected in series. The AC voltage U and AC current I were measured over the resistor and the power is the product of U times I. The AC voltage was measured by a digital universal meter. The AC current was measured by another digital universal meter with a current range of 10 A. All measurement were performed at n = 670 rpm. The open voltage was also measured for n = 670 rpm and it was found that U = 7.32 V. The measured and calculated values for different loads are given in table 3.

R (Ω)	U (V)	I (A)	P (W)
0.47	3.15	5.05	15.9
0.94	4.31	3.83	16.5
1.41	5.11	3.04	15.5
infinite	7.32	0	0

table 3 Power generated in one coil for different load resistances for n = 670 rpm

From earlier measurements it was found that the power is maximal if the voltage is reduced up to about 2/3 of the open value, so up to 2/3 * 7.32 = 4.88 V. So the power will be maximal for a resistance in between 0.94 Ω and 1.41 Ω. It is expected that the maximum power is about 17 W at 670 rpm.

The maximum DC power generated by six coils is less than six times the maximum AC power of one coil because not the whole sinus is used for a rectified current. Figure 3 from KD 340 gives the voltage variation for the three phases U, V and W. The three phases are rectified in star. Lets look at phase U for halve a sinus, so for the part of the curve in between 0° and 180°. Only the part for 30° > α > 150° is used for rectification in star. So the part for 0° > α > 30° and the part for 150° > α > 180° isn't used. The power variation of one phase is given in figure 2 of KD 340. In this figure it can be seen that the majority of the power is generated for 30° > α > 150°. It is estimated that about a factor 0.93 of the power of half a sinus is generated for 30° > α > 150°. So the maximum power of six coils is 0.93 * 6 * 17 = 95 W. About 8 W will be lost in the rectifier so about 87 W can be generated at 670 rpm if the load has the optimum resistance. Probably this optimum resistance isn't realised if the load is a 12 V battery but a maximum power of 71 W at 560 rpm seems a realistic estimation.

It was chosen for the final winding to take a wire thickness of 0.8 mm and to lie 130 turns per coil. This is certainly possible if the coil is made on a winding thorn because 132 turns per coil could be laid for the test winding with this wire thickness.

Next it is checked if the copper loss for the chosen wire thickness and the chosen number of turns per coil isn't too big. The average diameter of a turn is (58 + 36) / 2 = 47 mm. So the average length of a turn is π * 47 = 147.7 mm. So the total wire length of a coil is 130 * 147.7 = 19195 mm = 19.2 m. For rectification in star, the current is always flowing through four of the six coils (see report KD 340). So the total wire length of four coils is 4 * 19.2 = 76.8 m. The cross sectional area A of a wire with a diameter of 0.8 mm is $\pi/4 * 0.8^2 = 0.503\ mm^2$. The wire resistance R is given by:

$$R = \rho_c * l / A \quad (\Omega) \qquad (21)$$

The specific resistance of copper ρ_c = 0.0175 $\Omega mm^2/m$. Substitution of this value and l = 76.8 m and A = 0.503 mm^2 in formula 21 gives R = 2.67 Ω. The heat dissipation or copper loss in the copper winding P_c is given by:

$$P_c = I^2 * R \quad (W) \qquad (22)$$

The current for a maximum power of 71 W and a charging voltage of 14 V is 5.07 A. Substitution of I = 5.07 A and R = 2.67 Ω in formula 22 gives that P_c = 69 W. In chapter 8 it was calculated that the total heat loss in the copper wire, the stator iron and the rectifier is 78 W for the maximum power. The heat loss in the stator iron is about 16 W and the loss in the rectifier is about 7 W so the estimated heat loss in the copper wire is 78 – 16 – 7 = 55 W. So the real copper loss of 69 W at a current of 5.07 A for a 0.8 mm wire is somewhat higher than for the estimated P_{el}-n and P_{mech}-n curves of figure 6.

To find the real characteristics, a complete generator has to be made and tested but I won't do this. If the measured P_{el}-n curve is about the same as the estimated one, it can be expected that the P_{mech}-n curve will also be about the same as the estimated curve because a realistic efficiency curve has been used.

Next a complete generator can be made using a wire thickness of 0.8 mm and 130 turns per coil. This complete generator has to be measured for a constant DC voltage of 13 V or for a real 12 V battery as load. One should measure the DC voltage and the DC current at increasing rotational speed. Multiplying voltage and current gives the electrical power P_{el}. The measured P_{el}-n curve can now be compared to the estimated P_{el}-n curve of figure 6. One has to check the temperature of the winding if the generator is running loaded for a long time at a rotational speed of 560 rpm. The rise in temperature should not be more than 50 °C to prevent that the wire isolation burns.

For verification of the matching in between rotor and generator it is required to measure the P_{mech}-n curve. This requires measurement of the torque Q and this requires a special test rig. It might be possible to make a 20 mm shaft with M12 thread in one end and to use this shaft in stead of the M12 nut. The shaft can be clamped in the head stock of a lath and so the whole generator is hanging on the shaft. The reaction torque can be measured if a lever is connected to the stator sheet and if the end of the lever is connected to a balance by a thin chord. The balance has to be loaded by weights up to its maximum level. The pulling force in the chord is reducing the weight and so the torque is proportional to the reduction of the measured weight. If the generator works well, a complete VIRYA-1.36 windmill can be built and tested. I won't do this but I hope that someone else will do this and will give me feedback.

11 Alternative with circular magnets size ϕ 33 * 10 mm

It might be possible to use circular magnets size ϕ 33 * 10 mm with quality N42 instead of square magnets size 25.4 * 25.4 * 12.7 with quality N40. The armature sheet isn't changed and the circular magnets are mounted at the same position and at the same pitch circle as for the square magnets. The circular magnets are supplied by the Polish company Enes, website: www.enesmagnets.pl. The current magnet price including VAT but excluding costs of transport is € 3.17 per magnet if at least 25 magnets are ordered. The use of circular magnets has the following advantages:

1 The total magnet costs for one generator are about € 8 lower.
2 Circular magnets make that the variation of the magnetic flux in a circular coil is more fluent than for square magnets and the generated AC voltage will therefore look more like a sine wave. This will reduce the fluctuation of the rectified DC voltage and this increases the lifetime of the battery.
3 Gluing of circular magnets to the armature sheet is easier than for square magnets. Only the position and the pitch circle must be correct but no rotation is required.

As the circular magnets are thinner than the original square magnets (t_1 = 10 mm instead of t_1 = 12.7 mm), the front distance bush must be shortened from 29 mm up to 26.5 mm to get an acceptable air gap of 1.5 mm in between a magnet and a coil. This means that the magnetic air gap t_2 in between a magnet and the steel stator disk is 26.5 – 10 – 3 = 13.5 mm. As the circular magnets have a higher quality than the square magnets, the average remanence B_r is a little higher than for the square magnets. This gives that B_r = 1.305 T.

Substitution of B_r = 1.305 T, t_1 = 10 mm and t_2 = 13.5 mm in formula 5 results in $B_{r\,eff}$ = 0.555 T. This is a factor 0.89 lower than the value $B_{r\,eff}$ = 0.623 T which was calculated in chapter 4 for the square magnets. But the magnet area of a circular magnet is larger than for a square magnet. The magnet area of a circular magnet is $\pi/4 * 33^2 = 855$ mm^2 and that of a square magnet is 25.4 * 25.4 = 645 mm^2. So the magnet area of a circular magnet is a factor 1.33 higher than for a square magnet and this will certainly compensate the lower flux density in the air gap. This may even result in a somewhat stronger variation of the total magnetic flux in a coil but in the first instance it is expected that the same coils can be used.

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