Development of a simple 6-pole, 2-phase axial flux permanent magnet generator for the VIRYA-1 windmill using a bicycle hub and 6 neodymium magnets size 25.4 * 25.4 * 12.7 mm

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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. An 8-pole, 3-phase axial flux generator of this kind is described in public report KD 571 (ref. 2).

The VIRYA-1.04 windmill is described in a manual (ref. 3) including the drawings of the windmill and the tools. A licence of this windmill isn't needed for production and sale. The manual can be copied for free from my page on the website of Bidnetwork. The VIRYA-1.04 is equipped with a Shimano Nexus hub dynamo type DH-2R40. This generator is supplied by the Dutch bicycle shop 't Fietshokje for a low price of only € 15 (excluding transport). However, this generator has the following disadvantages:

1. The Dutch shop needs a very long time to send some dynamos to Dutch clients and is not willing to send bicycle parts during the summer months. The dynamo might be available in other bicycle shops but probably at a much higher price. It is unsure if the specified type, or another type with similar flanges, is available in other parts of the world. I expect that it is an older type which is no longer used in current new bikes and that this is the reason why it is offered that cheap by 't Fietshokje.
2. The generator has 28 preference positions per revolution and the peak torque is rather high (0.084 Nm). Therefore a rotor is needed with a rather high starting torque coefficient otherwise the starting wind speed would be too high. A rather low design tip speed ratio λ_d = 3.5 and a rotor with three wide blades and rather large blade angles was chosen to realise a sufficient high starting torque coefficient.
3. A bicycle dynamo is normally used at an AC voltage of 6 V and then it can generate a maximum power of about 3 W. For the VIRYA-1.04, the voltage is increased up to about 13 V and the current is rectified to be able to charge a 12 V battery. The maximum power is then about 6 W. This is still rather low as the VIRYA-1.04 rotor can generate a mechanical power of about 66 W at a wind speed of 8 m/s.

For these reasons it is decided to design an alternative generator. This alternative generator must be very cheap and the construction must therefore be as simple as possible.

An axial flux generator with no iron in the coils has almost no sticking torque and therefore it isn't necessary to use a rotor with a high starting torque coefficient. In stead of the 3-bladed rotor of the VIRYA-1.04, a 2 bladed rotor with a diameter of 1 m is designed. This rotor has a design tip speed ratio λ_d = 4.25 and is made out of one aluminium strip with dimensions 125 * 1000 * 1.5 mm. The blades can be cambered using the same blade press as designed for the VIRYA-1.04 rotor. The calculation of the rotor geometry is given in chapter 5. The windmill with this rotor will be called the VIRYA-1. Although the VIRYA-1 rotor is a little smaller than the VIRYA-1.04 rotor it is expected that the same head and tower can be used. Only the vane blade thickness has to be increased from 1.5 mm up to 2 mm.

Detailed drawings of the rotor and the generator are given in the appendix chapter 10. The drawings have drawing numbers 1408-01 and 1408-02. Drawing 1408-01 gives an assembly drawing of the rotor, a list with standard parts and a detailed drawing of the rotor. Drawing 1408-02 gives detailed drawings of the armature sheet, the stator sheet, the core + coil, the distance bush and the drilling pattern for the flanges of the mountain bike hub.

2 Description of the generator (see figure 1)

In report KD 571 (ref. 2), an 8-pole generator is described for the VIRYA-1.36 which makes uses of eight magnets size 25.4 * 25.4 * 12.7 mm and a 3-phase winding with six coils. The idea is to use six identical magnets and a 2-phase winding with four coils for the VIRYA-1 rotor. The magnets have the same size 25.4 * 25.4 * 12.7 mm and the coil cores are the same as for the VIRYA-1.36 generator. Although the coil cores are the same, the coils are different because they use thinner wire and more turns per coil. It is expected that this 6-pole generator can generate a maximum power of about 25 W in combination with the VIRYA-1 rotor and the safety system of the VIRYA-1.04 windmill.

The armature consists of a dodecagonal galvanised steel sheet which is made of a square sheet 125 * 125 * 3 mm. 200 armature sheets can be made from a standard sheet size 1.25 * 2.5 m. Six 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 90 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 € 4.16 per magnet including VAT and excluding mailing costs for an order of 20 magnets, so the magnet costs for one generator are about € 25 which seems to be acceptable. The magnets are called N1, S1, N2, S2, N3 and S3.

For the bearing housing of the generator an old hub of the front wheel of a mountain bike is used. This hub has an aluminium casing with two flanges. Each flange has 18 holes for the spokes at a pitch circle of 45 mm. For both flanges, six holes at 60° are enlarged up to a diameter of 4 mm. The rotor blades are connected to the front flange by six stainless steel screws M4 * 10, six stainless steel washers for M4 and six self locking nuts M4. The armature sheet of the generator is connected to the back flange, by six stainless steel screws M4 * 10 and six self locking nuts M4.

There are hubs with smaller flanges and smaller pitch circles of the spoke holes. These hubs can also be used if the hole pattern in the rotor and the armature sheet is adjusted.

The bicycle hub has a threaded shaft with a diameter of about 9.4 mm. The 9 mm hole in the head frame has to be enlarged up to 9.5 mm. Standard, both shaft ends which are jutting out of the hub are of equal length but the bearing cones are twisted such that one shaft end is about 22 mm longer than the other. The hub is mounted such that the longest shaft end is at the side of the head frame.

The stator consists of a square galvanised steel disk size 125 * 125 * 3 mm with the corners bevelled. 200 stator sheets can be made from a standard sheet size 1.25 * 2.5 m. The stator coils are connected to the front side of the stator sheet. The stator has a 2-phase winding because for such winding only four coils are required. Two coils are of phase U and two coils are of phase V. The coils are called U1, V1, U2 and V2. The coils are positioned every 90°. Opposite coils are of the same phase.

The pitch circle of the cores is 90 mm too. A core is made of polyacetal (polyoxymethylene or POM, supplied as Delrin, Ertacetal and Hostaform). A core is connected to the stator sheet by a stainless steel screw M5 * 16 and a self locking nut M5. A core has a diameter of 36 mm and a width of 12 mm. It has a 1.3 mm wide flange at the front side with a diameter of 58 mm. It has a 0.7 mm wide flange at the back side with the same diameter. So the distance in between the flanges is 10 mm. The back flange is supported by the stator sheet so it can be thinner. The front flange must be rather thick to prevent that it bends to the front side because of the wire pressure.

The distance in between the armature sheet and the stator sheet is chosen 26 mm. The magnets have a thickness of 12.7 mm so the magnetic air gap t_2 in between a magnet and the stator sheet is 26 – 12.7 = 13.3 mm. The width of a core is 12 mm. So the real air gap in between a magnet and a core is 13.3 – 12 = 1.3 mm. The stator sheet is clamped in between the back bearing cone and the head frame. A distance bush with a certain width is mounted in between the back bearing cone and the stator sheet to realise a 1.3 mm air gap in between the magnets and the cores.

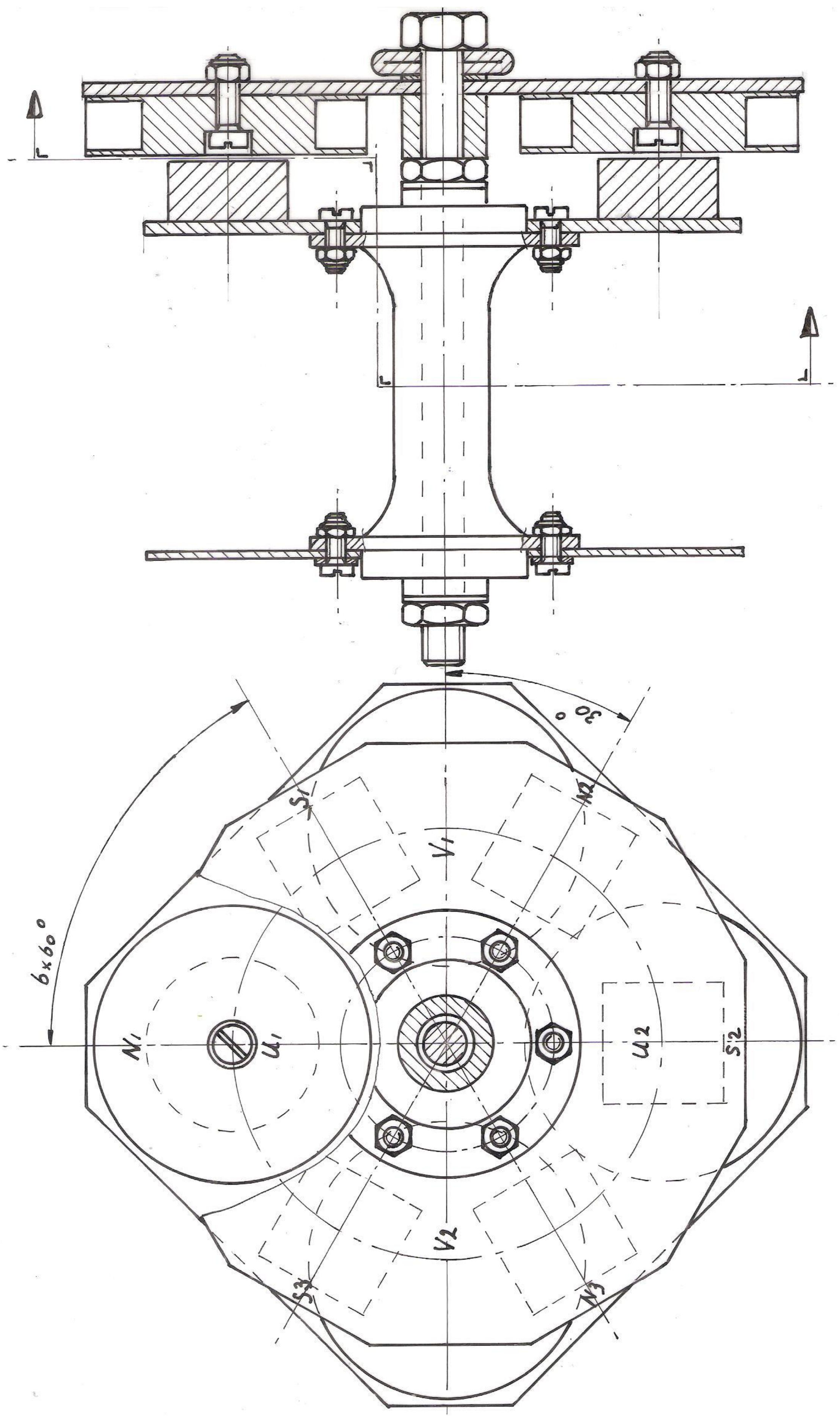

fig. 1 6-pole axial flux permanent magnet generator VIRYA-1

The two phases are connected in star. The two free coil ends and the star point are connected to the rectifier which is mounted at the back side of the stator sheet. The stator sheet has a hole through which the three wires can be guided. The coil ends are covered by an isolation tube. A 2-pole flexible cable with wires of 2 * 1.5 mm^2 connects the rectifier to a 12 V battery of minimum 30 Ah (cable and battery are not specified on the drawing).

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 8, prove that the rise in temperature caused by the eddy currents is only about 7 °C.

The calculation of the flux density in the coils and in the armature sheet is given in chapter 3. The procedure how the wire thickness and the number of turns per coil are determined, is given in chapter 8.

The 2-phase winding and the armature poles are drawn in figure 1. Figure 1 is drawn such that pole N1 is opposite to coil U1. In figure 1 it can be seen that if coil U1 is opposite to a north pole, coil U2 is opposite to a south pole. So the winding direction of coil U2 must be opposite the winding direction of coil U1 to realise that the voltage generated in U2 is strengthening the voltage generated in U1.

The winding is made in the following way. The two coils of one phase are made together on a winding thorn. It is easy if the winding direction is the same for both coils. To realise the alternating winding direction, coil U2 is flipped 180° during mounting. However, the 9 mm chamber for the screw head must be at the front side for both cores after 180° flipping of coil U2. So if the core of coil U1 is mounted on the winding thorn with the chamber to the left side, the core of coil U2 must be mounted on the winding thorn with the chamber to the right side! The two cores must be clamped in between three metal rings with a diameter of 56 mm to prevent that the flanges of the cores bend to the outside during winding.

In figure 1 it can be seen that a north pole is at the same position after 120° rotation of the armature. So a phase angle of 360° corresponds to a rotational angle of 120°. The frequency of the current will be three times higher than the rotational speed of the armature in revolutions per second. In figure 1 it can be seen that there is an angle of 30° in between north pole N2 and coil V1. So this angle corresponds with a phase angle of 90° and the winding therefore is a normal 2-phase winding. The fluctuation of the DC voltage and the DC current for a 2-phase winding is explained in chapter 6 of report KD 340 (ref 4). The fluctuation is less strong than for a 1-phase winding but stronger than for a 3-phase winding.

The average diameter of a coil is 47 mm. The pitch in between two adjacent armature poles is 45 mm, so it has about the same magnitude. This means that if a north pole is passing the left part of a coil, a south pole will just pass the right part of a coil and therefore the maximum voltage is generated.

3 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 sheets 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:

$$B_{r\,eff} = B_r * t_1 / (t_1 + t_2) \qquad (T) \qquad (1)$$

Substitution of B_r = 1.275 T, t_1 = 12.7 mm and t_2 = 13.3 mm in formula 1 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. 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}.

$$i_1 = A_{mag} / A_{sh} \qquad (-) \qquad (2)$$

Substitution of $A_{mag} = 25.4 * 25.4 = 645.2$ mm^2 and $A_{sh} = 304.8$ mm^2 in formula 2 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:

$$B_{r\,sh} = B_{r\,eff} * i_1 \qquad (T) \qquad (3)$$

Substitution of $B_{r\,eff}$ = 0.623 T and i_1 = 2.12 in formula 3 gives $B_{r\,sh}$ = 1.32 T. This is smaller than 1.6 T, so the armature sheet isn't saturated.

Half of the magnetic flux coming out of a magnet is a part of a loop in the stator sheet which has to pass the bridge in between the 125 mm wide outside of the stator sheet and the central 36 mm hole. This bridge has a width of 44.5 mm. So the bridge area $A_{br} = 44.5 * 3 = 133.5$ mm^2. This is a somewhat smaller than halve A_{sh} as halve A_{sh} = 152.4 mm^2. So the magnetic flux in the bridge is concentrated by the ratio in between both areas. This gives $B_{r\,br}$ = 1.32 * 152.4 / 133.5 = 1.51 T which is lower than 1.6 T. So the bridge is also not saturated. The stator sheet has a much smaller central hole (9.5 mm) and so a much larger bridge area. So the stator sheet is certainly not saturated.

4 Mounting sequence of the generator and the rotor

1 The hub of the bicycle wheel is modified according to the description in chapter 2.
2 The six magnets are glued to the armature sheet with epoxy glue such that three north and three south poles are created. It is advised to make a square Teflon sheet with six square holes size 25.5 * 25.5 mm in it to get the magnets on the right position. The Teflon sheet should have at least three 4 mm holes at a pitch circle of 45 mm to connect the Teflon sheet to the armature sheet. To prevent corrosion of the magnets, it is advised to paint the whole armature with epoxy lacquer.
3 The four coils are mounted against the stator sheet. The three cables are isolated by an isolation tube and pushed through the hole in the stator sheet. The 3-phase rectifier is connected to the back side of the stator sheet and the three wires connected to the rectifier by three tags. It is advised to paint the winding with epoxy lacquer for better protection against corrosion.
4 The armature sheet is mounted against the back flange of the hub using six stainless steel screws M4 * 10 and six stainless steel nuts M4.
5 A distance bush is made with a thickness such that the distance in between the magnets and the coil cores is 1.3 mm.
6 The distance ring and the stator sheet are shifted over the back shaft. A standard washer is mounted at the back side of the stator sheet. The assembly is tightened with the nut which belongs to the bicycle shaft. The generator is ready now.
7 The head is mounted and connected to the tower pipe.
8 The standard nut is removed when the generator is connected to the head frame and tightened again if the generator is mounted.
9 The windmill rotor is mounted to the front flange of the hub using six stainless steel screws M4 * 10, six washers for M4 and six stainless steel nuts M4.

Mounting of the complete windmill is described in the manual of the VIRYA-1.04.

5 Calculation of the geometry of the VIRYA-1 rotor

The 2-bladed rotor of the VIRYA-1 windmill has a diameter D = 1 m and a design tip speed ratio λ_d = 4.25. Advantages of a 2-bladed rotor are that no spoke assembly is required and that the rotor can be balanced easily.

The rotor has blades with a constant chord and is provided with a 7.14 % cambered airfoil. The rotor is made of one aluminium strip with dimensions of 125 * 1000 * 1.5 mm and 16 strips can be made out of a standard sheet of 1 * 2 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 the same blade press which is also used for the blades of the VIRYA-1.04. For twisting one can also use the VIRYA-1.04 tools but one has to use a 8° jig to measure the correct twisting angle of the cambered part and a 16° jig to measure the correct blade angle at the blade root.

The camber is only made in the outer 400 mm of the blade. This part of the blade is twisted linear. The central 60 mm, where the blade is connected to the front flange of the hub, is flat. The 70 mm long transition part in between the flat central part and the outer cambered part is twisted 16° to get the correct blade angle at the blade root. It is assumed that the outer 50 mm of this 70 mm long part is used for the transition of camber to flat. So the inner 20 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 574) has its own formula numbering. Substitution of λ_d = 4.25 and R = 0.5 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 8.5 * r$ (-) (4)

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

$\beta = \phi - \alpha$ (°) (5)

$\phi = 2/3 \arctan 1 / \lambda_{r\,d}$ (°) (6)

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

$C_l = 101.917\, r\, (1 - \cos\phi)$ (-) (7)

Substitution of V = 5 m/s and c = 0.1233 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.411 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (8)

The blade is calculated for five stations A till E which have a distance of 0.1 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 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 rated wind speed for a 2 mm aluminium vane blade is about 10 m/s. 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 m/s because this is a reasonable wind speed for a windmill which is designed for a rated wind speed of 10 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values. The calculated Reynolds values for V = 5 m/s are rather low and so the lowest available Reynolds value Re = 1.2 * 10^5 has to be used for stations B up to E.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	0.5	4.25	8.8	0.1233	0.60	0.72	1.77	1.7	0	0.8	8.8	8.0	0.048
B	0.4	3.4	10.9	0.1233	0.74	0.69	1.42	1.2	1.2	0.9	9.7	10.0	0.041
C	0.3	2.55	14.3	0.1233	0.94	0.90	1.08	1.2	2.6	2.3	11.7	12.0	0.032
D	0.2	1.7	20.3	0.1233	1.27	1.27	0.75	1.2	6.3	6.3	14.0	14.0	0.050
E	0.1	0.85	33.1	0.1233	1.65	1.27	0.44	1.2	-	17.1	-	16.0	0.29

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

No value for α_{th} and therefore for β_{th} is found for station E because the required C_l value can not be generated. The theoretical blade angle β_{th} varies in between 8.8° and 14.0°. If a blade angle of 8° taken at the blade tip and of 16° at the blade root, the linearised blade angles are lying close to the theoretical values. So the blade twist is 16° - 8° = 8°. The transition part of the strip is twisted 16° to get the correct blade angle at the blade root.

6 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 4.6 of KD 35 (for B = 2) en λ_{opt} = 4.25 and C_d/C_l = 0.04 gives $C_{p\ th}$ = 0.415. The blade is stalling in between station D and E so only the part of the blade till 0.05 m outside station E is taken for the calculation of C_p. This gives an effective blade length k' = 0.35 m.
Substitution of $C_{p\ th}$ = 0.415, R = 0.5 m and blade length k = k' = 0.35 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.38. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.38 / 4.25 = 0.0894.
Substitution of $\lambda_{opt} = \lambda_d$ = 4.25 in formula 6.4 of KD 35 gives λ_{unl} = 6.8.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (9)$$

The average blade angle is 12° for the whole blade. For a non rotating rotor, the average angle of attack α is therefore 90° - 12° = 78°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 78° it can be read that C_l = 0.4. During starting, the whole blade is stalling. So now the real blade length k = 0.4 m is taken.
Substitution of B = 2, R = 0.5 m, k = 0.4 m, C_l = 0.4 en c = 0.1233 m in formula 9 gives that $C_{q\ start}$ = 0.0226. The real coefficient will be somewhat lower because we have used the average blade angle. Assume $C_{q\ start}$ = 0.021. For the ratio in between the starting torque and the optimum torque we find that it is 0.021 / 0.0894 = 0.235. This is acceptable for a rotor with a design tip speed ratio λ_d = 4.25.

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

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3} \right)} \qquad (m/s) \qquad (10)$$

The sticking torque Q_s of the VIRYA-1 generator will be very low because there is no iron in the coils. Only the bearings and the eddy currents in the stator will give some little friction. It is estimated for Q_s that Q_s = 0.03 Nm. Substitution of Q_s = 0.03 Nm, $C_{q\ start}$ = 0.021, ρ = 1.2 kg/m^3 and R = 0.5 m in formula 10 gives that V_{start} = 2.5 m/s. This is acceptable for a 2-bladed rotor with a design tip speed ratio λ_d = 4.25 and a rated wind speed V_{rated} = 10 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 rotor are given in figure 2 and 3.

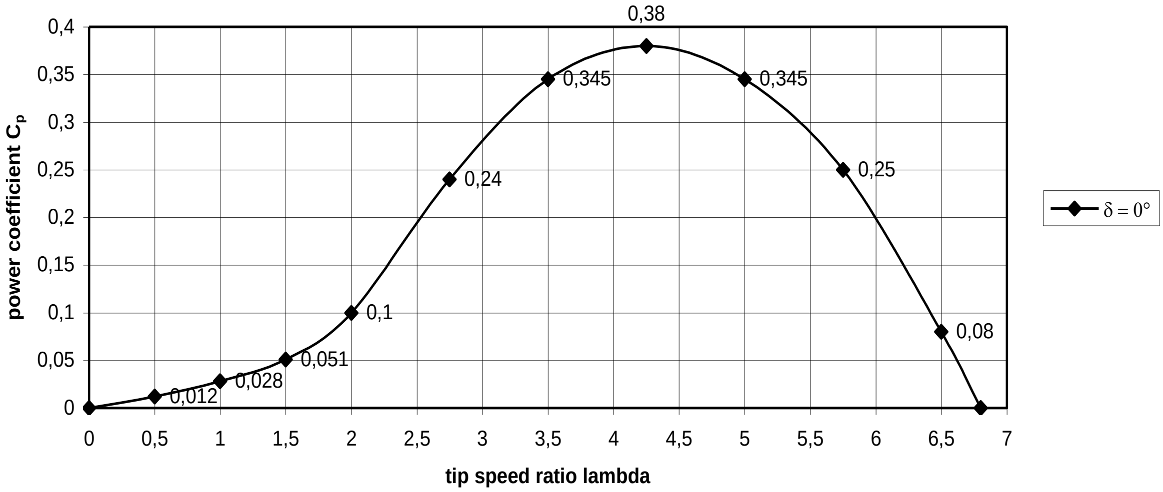

fig. 2 Estimated C_p-λ curve for the VIRYA-1 rotor for the wind direction perpendicular to the rotor (δ = 0°)

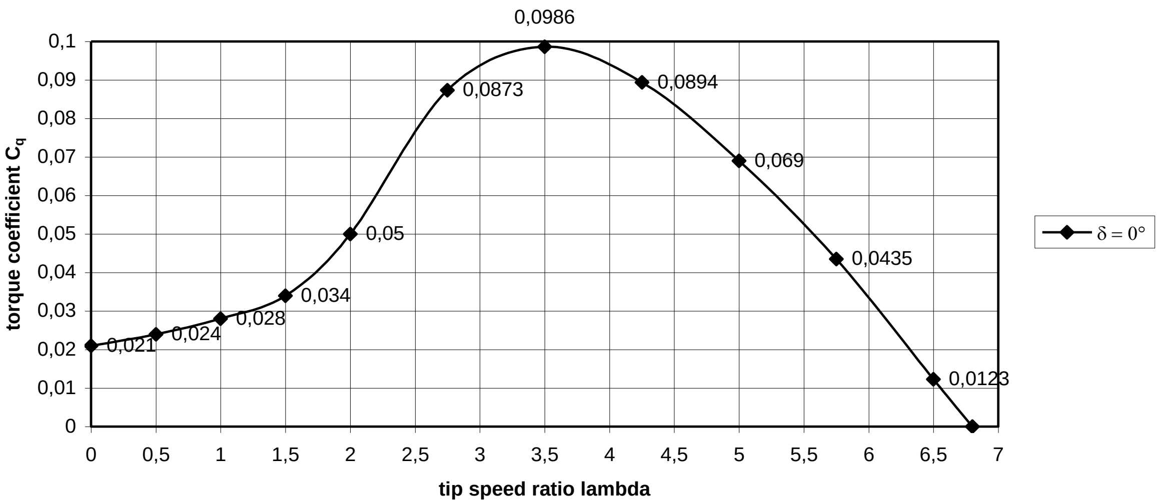

fig. 3 Estimated C_q-λ curve for the VIRYA-1 rotor for the wind direction perpendicular to the rotor (δ = 0°)

7 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 2. 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 10 m/s. The estimated δ-V curve is given in figure 4.

The head starts to turn away at a wind speed of about 6 m/s. For wind speeds above 10 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 10 m/s will therefore also be valid for wind speeds higher than 10 m/s.

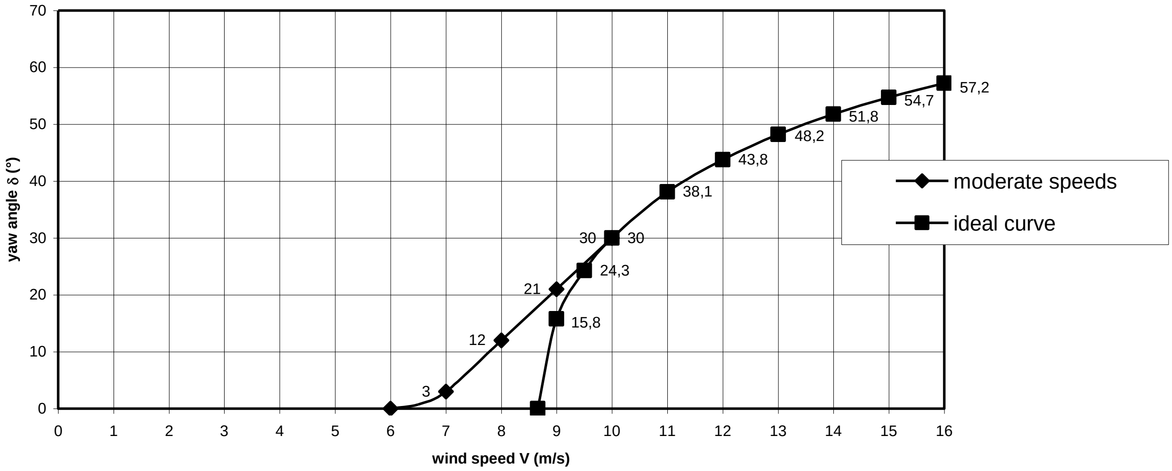

fig. 4 Estimated δ-V curve VIRYA-1 for a 2 mm aluminium vane blade

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 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, 9 and 10 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 = 0.5 m in formula 7.1 of KD 35 gives:

$n_\delta = 19.0986 * \lambda * \cos\delta * V$ (rpm)   (11)

Substitution of $\rho = 1.2 \text{ kg / m}^3$ en R = 0.5 m in formula 7.10 of KD 35 gives:

$P_\delta = 0.4712 * C_p * \cos^3\delta * V^3$ (W)   (12)

The P-n curves are determined for C_p values belonging to λ = 2, 2.75, 3.5, 4.25, 5, 5.75, 6.5 and 6.8. (see figure 3). For a certain wind speed, for instance V = 2 m/s, related values of C_p and λ are substituted in formula 11 and 12 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 4, is taken into account. The result of the calculations is given in table 2.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 0°		V = 7 m/s δ = 3°		V = 8 m/s δ = 12°		V = 9 m/s δ = 21°		V = 10 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2	0.1	114.6	1.27	152.8	3.02	191.0	5.89	229.2	10.2	267.0	16.1	298.9	22.6	320.9	28.0	330.8	30.6
2.75	0.24	154.7	3.05	210.1	7.24	262.6	14.14	315.1	24.4	367.1	38.6	411.0	54.2	441.3	67.1	454.8	73.5
3.5	0.345	200.5	4.39	267.4	10.40	334.2	20.32	401.1	35.1	467.3	55.5	523.1	77.9	561.6	96.4	578.9	107.1
4.25	0.38	243.5	4.83	324.7	11.46	405.8	22.38	487.0	38.7	567.4	61.2	635.2	85.8	682.0	106.2	702.9	116.3
5	0.345	286.5	4.39	382.0	10.40	477.5	20.32	573.0	35.1	667.5	55.5	747.2	77.9	802.4	96.4	827.0	107.1
5.75	0.25	329.5	3.18	439.3	7.54	549.1	14.73	658.9	25.4	767.7	40.2	859.3	56.4	922.7	69.9	951.0	76.5
6.5	0.08	372.4	1.02	496.6	2.41	620.7	4.71	744.8	8.1	867.8	12.9	971.4	18.1	1043	22.4	1075	24.5
6.8	0	389.6	0	519.5	0	649.4	0	779.2	0	907.8	0	1016	0	1091	0	1125	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-1 rotor

The calculated values for n and P are plotted in figure 5. The optimum cubic line which can be drawn through the maximum of all P-n curves is also given in figure 5.

The axial flux generator is not yet 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 = 350 rpm. The efficiency is estimated to be 0.3 at the maximum power at n = 750 rpm. The average charging voltage for a 12 V battery is about 13 V. So the estimated P_{mech}-n and P_{el}-n curves are given for 13 V in figure 5. It is necessary to measure the curves for 13 V 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 electrical power P_{el} for that wind speed is found by going down vertically from the 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 6).

The matching of rotor and generator is good for wind speeds in between 3 and 10 m/s because the P_{mech}-n curve of the generator is lying close to the optimum cubic line.

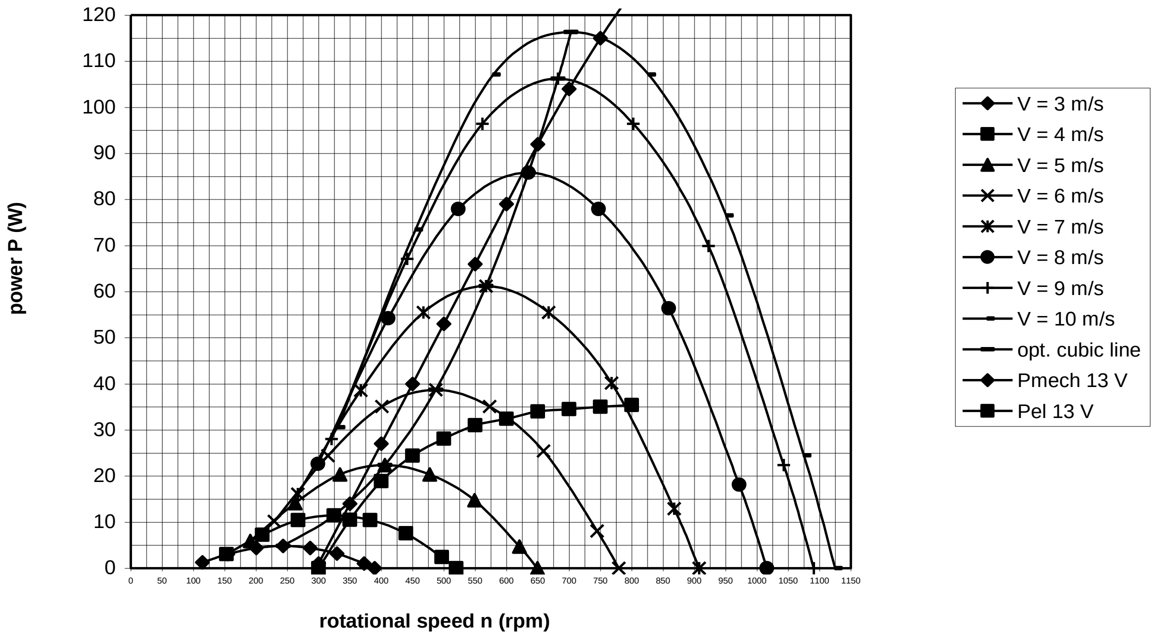

fig. 5 P-n curves of the VIRYA-1 rotor and 2 mm aluminium vane blade, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging for the chosen winding

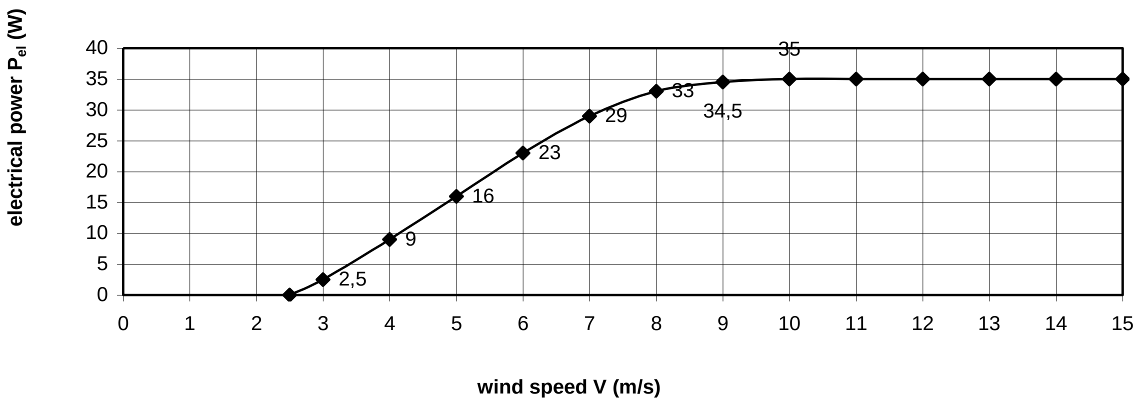

fig. 6 P_{el}-V curve of the VIRYA-1 windmill with V_{rated} = 10 m/s for 12 V battery charging

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 4 it was calculated that V_{start} = 2.5 m/s so there is no hysteresis in the P_{el}-V curve.

The maximum power is about 35 W which is good for a rotor with 1 m diameter. This is about a factor six higher than the 6 W of the Nexus hub dynamo of the VIRYA-1.04. So even if the VIRYA-1 generator would be more expensive than the hub dynamo, the investment will be paid back much sooner.

In figure 5 it can be seen that the mechanical power is about 115 W for V = 10 m/s. The electrical power is 35 W so the heat dissipation in the stator iron, in the copper of the winding and in the rectifier is 115 – 35 = 69 W.

8 Tests performed to determine the winding

The estimated P_{el}-n curve given in figure 5 starts at a rotational speed of 300 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 = 300 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 2-phase current is explained in chapter 6 of report KD 340 (ref. 4). 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 17 of KD 340 if the voltage drop over the rectifier U_{rect} is neglected. Formula 17 of KD 340 is copied as formula 13.

$U_{DCeff} = 1.1 * \sqrt{2} * U_{eff}$ (V) (star rectification) (13)

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 has 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:

$U_{DCeff} = 2.2 * \sqrt{2} * U_{eff\ 1}$ (V) (14)

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 dodecagonal armature sheet and a square stator sheet were made. The armature sheet with six magnets glued to it was connected to the hub 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 = 10 m/s. In figure 5 it can be seen that this point is lying at a rotational speed of about 750 rpm. The motor was measured at 750 rpm without the stator sheet mounted and the absorbed electrical motor power P_{elm} then was about 4.3 W (to overcome the internal motor losses).

A wooden structure with a vertical plank was clamped to the workbench by two glue clamps. One core was made out of POM. This core was connected to the stator sheet by a stainless steel screw M5. The assembly of stator sheet and coil was connected to the vertical plank by some stainless steel screws. 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} = 18 W. So the absorbed electrical power is increased by 18 – 4.3 = 13.7 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} = 10 W. This mechanical power is used to overcome the sticking torque caused by the eddy currents. 10 W is a power which seems acceptable low for the maximum rotational speed of 750 rpm.

The motor was running for 15 minutes at n = 750 rpm. The stator temperature was measured by a thermometer. The temperature at the beginning was 11 °C and the temperature after 15 minutes was 18 °C. So the rise in temperature was 7 °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 10 W at n = 750 rpm 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.

If a rectified 2-phase current is used to charge a 12 V battery, charging will not start when the effective DC voltage is equal to the open battery voltage but when the peak DC voltage is equal to the open battery voltage. The peak voltage is somewhat higher than the effective DC voltage. For the determination of the number of turns per coil, the effective voltage will be used. This means that the cut-in rotational speed and so the cut-in wind speed will lie somewhat lower than the calculated value.

The open AC voltage was measured for different rotational speeds and from these measurements it was determined that the AC voltage $U_{eff\ 1}$ = 2.37 V for n = 300 rpm. Substitution of $U_{eff\ 1}$ = 2.37 V in formula 14 gives U_{DCeff} = 7.37 V. The open voltage at 300 rpm must be 12.5 V, so the number of turns per coil must be increased to 132 * 12.5 / 7.37 = 224. The wire thickness for the final winding is chosen 0.6 mm and the number of turns per coil is chosen 230.

This wire has about the same total cross sectional copper area as for the test winding. It should be tested if it is possible to wind a final winding on a winding thorn with 230 turns per coil of wire thickness 0.6 mm.

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 or in parallel. 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 a digital universal meter with a maximum current of 10 A. The resistance of 0.705 Ω was gained by connecting two bundles of three serial resistors in parallel. The measured and calculated values for different loads are given in table 3.

R (Ω)	U (V)	I (A)	P (W)
0.47	2.47	4.34	10.7
0.705	2.98	3.68	11.0
0.94	3.36	3.22	10.8
1.41	3.92	2.57	10.1

table 3 Power generated in one coil for different load resistances for n = 625 rpm

So the maximum power is 11 W for a load resistance of 0.705 Ω. The maximum DC power generated by four coils is less than four times the maximum AC power of one coil because not the whole sinus is used for a rectified current. Figure 13 from KD 340 gives the voltage variation for the three phases U, V and W. Phase W contains no coils and therefore generates a voltage which is always zero. 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°. A current is only flowing through those coils which have the highest or the lowest voltage. Phase U has the highest voltage for $0° > \alpha > 135°$. Phase V has the highest voltage and phase W has the lowest voltage for $135° > \alpha > 180°$. So this means that no current is flowing through phase U for $135° > \alpha > 180°$. 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 $0° > \alpha > 135°$. It is estimated that about a factor 0.91 of the power of half a sinus is generated for $0° > \alpha > 135°$. For the other half sinus the same factor will be found. So the maximum power of four coils is 0.91 * 4 * 11 = 40 W. About 3.5 W will be lost in the rectifier so about 36.5 W can be generated at 750 rpm if the load has the optimum resistance. Probably this optimum resistance isn’t realised if the load is a 12 V battery. But in table 3 it can be seen that the generated power is not very different for load resistances in between 0.47 Ω and 1.41 Ω. So a maximum DC power of 35 W at 750 rpm is a realistic estimation.

It was chosen for the final winding to take a wire thickness of 0.6 mm and to lie 230 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 a wire thickness of 0.8 mm.

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 $\pi * 47 = 147.7$ mm. So the total wire length of a coil is 230 * 147.7 = 33971 mm = 34 m. For star rectification of a 2-phase winding with four coils, the current is flowing through four coils during half the time and through two coils during the other half the time (see description 2-phase current chapter 6 report KD 340). So the average number of coils through which a current is flowing is three. The total wire length of three coils is 3 * 34 = 102 m. The cross sectional area A of a wire with a diameter of 0.6 mm is $\pi/4 * 0.6^2 = 0.283$ mm^2.

The wire resistance R is given by:

$R = \rho_c * l / A$ (Ω) (15)

The specific resistance of copper ρ_c = 0.0175 Ωmm^2/m. Substitution of this value and l = 102 m and A = 0.283 mm^2 in formula 15 gives R = 6.31 Ω. The heat dissipation or copper loss in the copper winding P_c is given by:

$P_c = I^2 * R$ (W) (16)

The current for a maximum power of 35 W and a charging voltage of 14 V is 2.5 A. Substitution of I = 2.5 A and R = 6.31 Ω in formula 16 gives that P_c = 39.4 W. In chapter 8 it was calculated that the total heat loss in the copper wire, the stator iron and the rectifier is 69 W for the maximum power. The heat loss in the stator iron is about 9 W and the loss in the rectifier is about 3.5 W so the estimated heat loss in the copper wire is 69 – 9 – 3.5 = 56.5 W. So the real copper loss of 39.4 W at a current of 2.5 A for a 0.6 mm wire is less than the loss for the estimated P_{el}-n and P_{mech}-n curves of figure 5. This means that the estimated curves will deviate from the real measured curves.

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 lie lower than the estimated curve. This means that the rotor will run at a higher tip speed ratio but this isn't a problem. If the measured P_{el}-n curve is lying higher than the estimated curve, the maximum power will be higher than 35 W. The real P_{mech}-n curve can still have about the same shape as the estimated P_{mech}-n curve if the generator has a higher efficiency than as assumed for the estimated curves.

Next a complete generator can be made using a wire thickness of 0.6 mm and 230 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 5. One has to check the temperature of the winding if the generator is running loaded for a long time at a rotational speed of 750 rpm. The rise in temperature should not be more than 50 °C to prevent that the wire isolation burns.

The housing of the bicycle hub should be driven for these tests. It might be possible to drive the housing by a flat belt which is running in between the flanges. But a driving motor with a high torque level is required if the belt transmission has an accelerating gear ratio.

Another option is to use a similar test rig as which was used to determine the winding but now the stator has to be provided with four coils and a rectifier. However, I expect that the maximum torque level of the permanent magnet DC motor which was used for the tests, is too low for a complete stator. This motor originates from a Philips washing machine. So a bigger motor is needed and this requires the design of a new test rig.

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 but this is rather difficult for a generator housing which is made of a bicycle hub.

9 Refeneces

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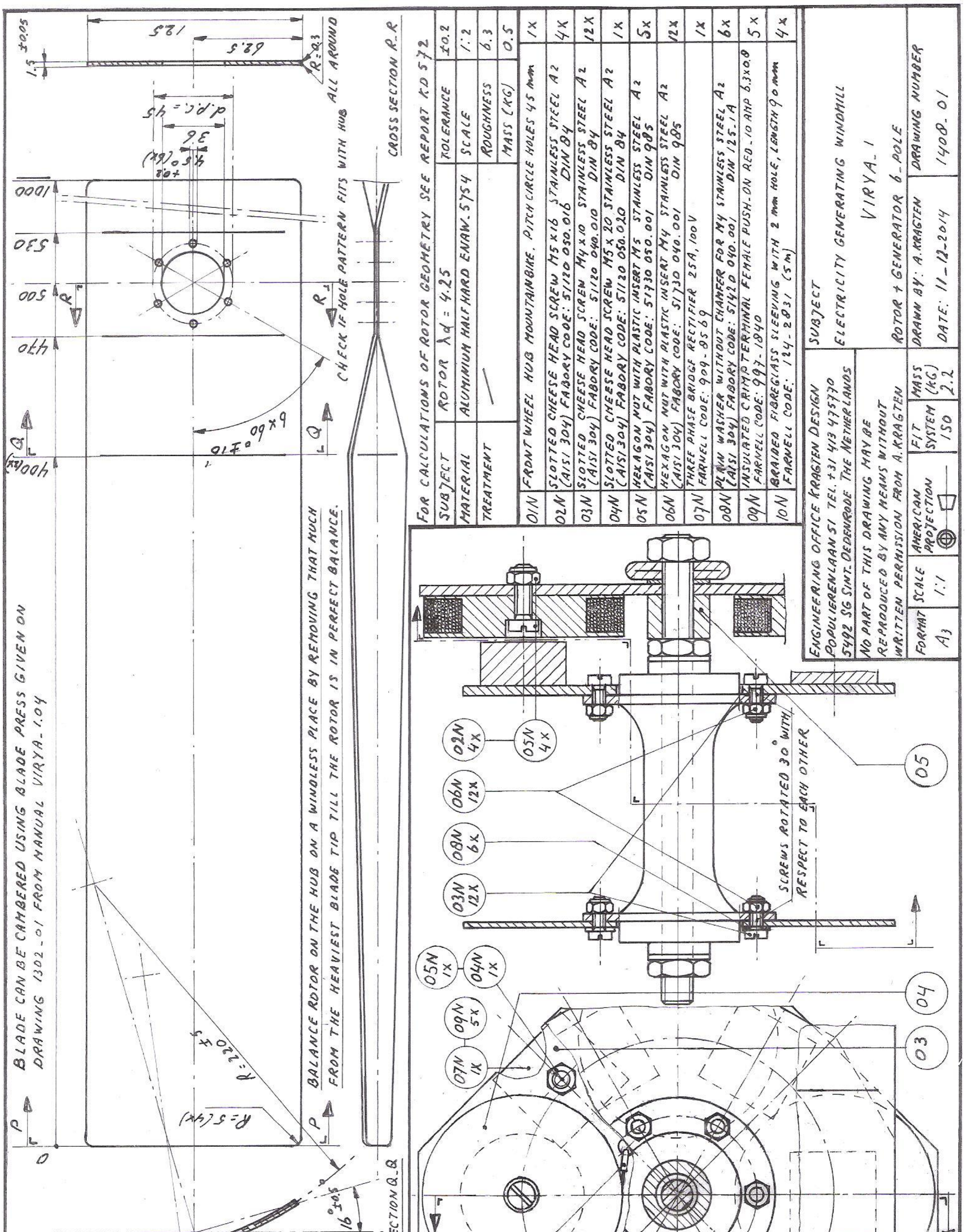
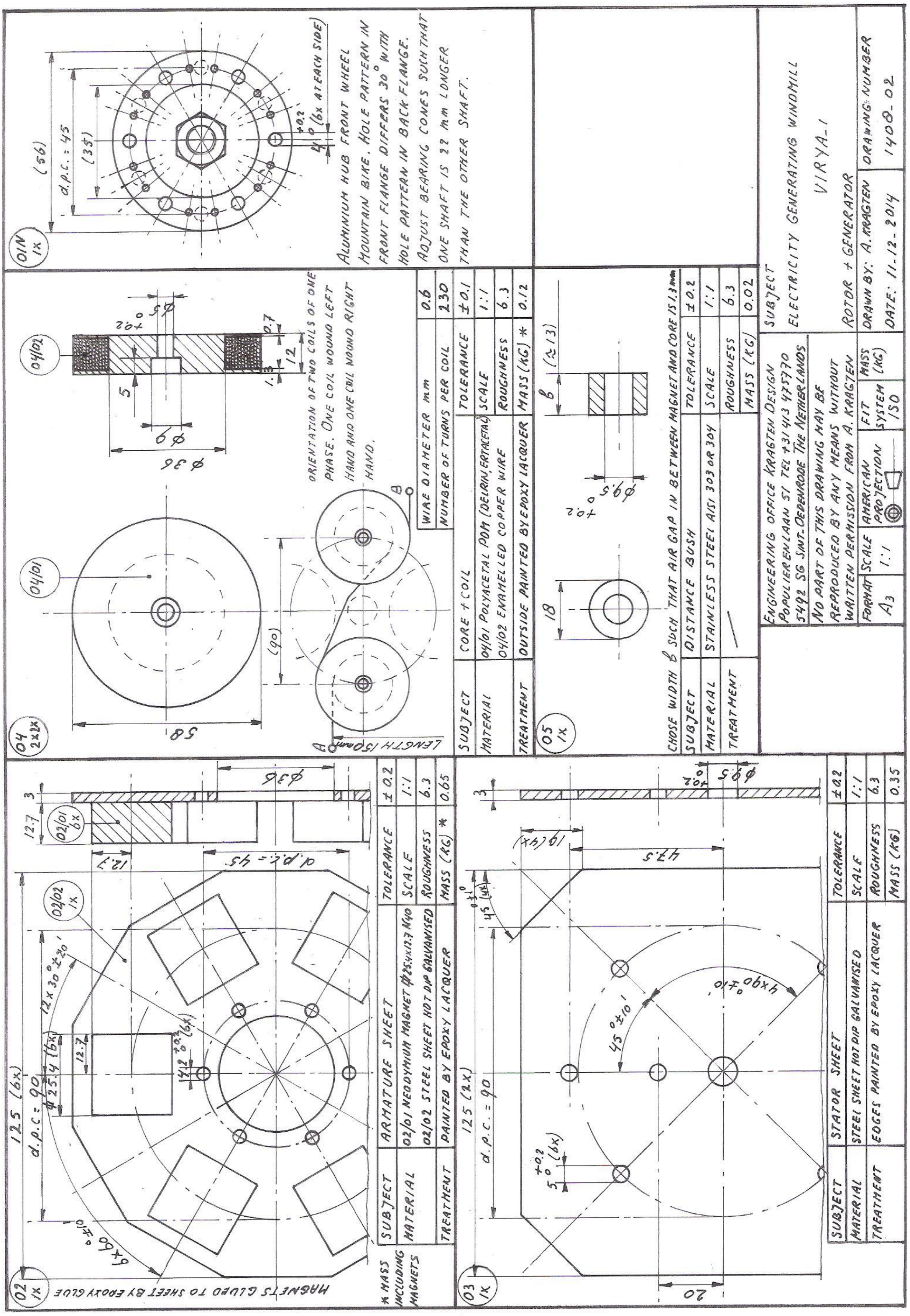
10 Appendix: Detailed drawings of the rotor and the generator





01N 1x
ALUMINIUM HUB FRONT WHEEL MOUNTAIN BIKE. HOLE PATTERN IN FRONT FLANGE DIFFERS 30° WITH HOLE PATTERN IN BACK FLANGE.
ADJUST BEARING CONES SUCH THAT ONE SHAFT IS 22 mm LONGER THAN THE OTHER SHAFT.
04 2x2x
ORIENTATION OF TWO COILS OF ONE PHASE. ONE COIL WOUND LEFT HAND AND ONE COIL WOUND RIGHT HAND.
LENGTH 150mm
WIRE DIAMETER mm 0.6
NUMBER OF TURNS PER COIL 230
SUBJECT CORE + COIL
MATERIAL 04/01 POLYACETAL POM (DELRIN, ERTACETAL) 04/02 ENAMELLED COPPER WIRE
TREATMENT OUTSIDE PAINTED BY EPOXY LACQUER
TOLERANCE ±0.1 SCALE 1:1 ROUGHNESS 6.3 MASS (KG) * 0.12
05 1x
CHOSE WIDTH B SUCH THAT AIR GAP IN BETWEEN MAGNET AND CORE IS 1.3mm
SUBJECT DISTANCE BUSH
MATERIAL STAINLESS STEEL AISI 303 OR 304
TOLERANCE ±0.2 SCALE 1:1 ROUGHNESS 6.3 MASS (KG) 0.02
02 1x
MAGNETS GLUED TO SHEET BY EPOXY GLUE
SUBJECT ARMATURE SHEET
MATERIAL 02/01 NEODYMIUM MAGNET ∅25.4x12.7 N40 02/02 STEEL SHEET HOT DIP GALVANISED
TREATMENT PAINTED BY EPOXY LACQUER
TOLERANCE ±0.2 SCALE 1:1 ROUGHNESS 6.3 MASS (KG) * 0.65
* MASS INCLUDING MAGNETS
03 1x
SUBJECT STATOR SHEET
MATERIAL STEEL SHEET HOT DIP GALVANISED
TREATMENT EDGES PAINTED BY EPOXY LACQUER
TOLERANCE ±0.2 SCALE 1:1 ROUGHNESS 6.3 MASS (KG) 0.35
ENGINEERING OFFICE KRAGTEN DESIGN
POPULIERENLAAN 51 TEL +31 413 475770
5492 SG SINT-OEDENRODE THE NETHERLANDS
NO PART OF THIS DRAWING MAY BE REPRODUCED BY ANY MEANS WITHOUT WRITTEN PERMISSION FROM A. KRAGTEN
SUBJECT ELECTRICITY GENERATING WINDMILL
VIRYA-1
ROTOR + GENERATOR
FORMAT A3 SCALE 1:1 AMERICAN PROJECTION FIT SYSTEM ISO MASS (KG)
DRAWN BY: A. KRAGTEN
DATE: 11.12-2014
DRAWING NUMBER 1408-02