Development of an 8-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1 windmill using a bicycle hub and 8 neodymium magnets size ϕ 25 * 12 mm and a stator sheet made out of synthetic material

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KD 608

 Anyone is allowed to build the generator and the rotor described in this report. The head is described in report KD 518 and the drawings of the head are given in the manual of the VIRYA-1.04. However, at this moment only some basic measurements are performed to determine the wire thickness and the number of turns per coil. A complete windmill is not yet tested. No responsibility is accepted by Kragten Design for possible failures.

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1 Introduction

The first version of the VIRYA-1 windmill is described in report KD 574 (ref. 1). The first version has a 6-pole axial flux generator with a 2-phase winding and a steel stator sheet. The eddy currents in the stator sheet create a sticking torque which increases about proportional to the rotational speed. At this moment it is thought that an 8-pole generator with a 3-phase winding and a synthetic stator sheet is a better choice and report KD 574 is therefore cancelled. The rotor calculations out of KD 574 are now given in this new report KD 608.

The VIRYA-1 makes use of the head and tower of the VIRYA-1.04. The VIRYA-1.04 with a 3-bladed rotor is described in report KD 518 (ref. 2). The drawings of the VIRYA-1.04 are given in a separate free manual (ref. 3). The VIRYA-1.04 makes use of a Nexus hub dynamo. The advantage is that therefore it isn't necessary to build a generator. However, a hub dynamo has some disadvantages of which the most important are that the maximum power is very low (about 6 W) and that there is a large peak on the sticking torque. This requires a rotor with a high starting torque coefficient other wise the starting wind speed will be much too high. The VIRYA-1.04 has a 1.5 mm aluminium vane blade which gives a rated wind speed of about 8 m/s. However, a 2 mm aluminium vane blade is used for the VIRYA-1 resulting in a rated wind speed of about 9 m/s.

The idea is to develop an 8-pole, 3-phase axial flux generator with a synthetic stator sheet. So no eddy currents will be generated and therefore the sticking torque will be zero. However, using a synthetic stator sheet in stead of a steel stator sheet reduces the magnetic flux flowing through the coils as the magnetic air gap becomes much longer. The generated voltage per turn will therefore be lower and the maximum power will therefore be lower too. A way to compensate this is too use eight strong magnets and a 3-phase winding.

2 Description of the generator (see figure 1 and detailed drawings in appendix 1)

A Polish magnet supplier was found which supplies rather cheap circular magnets and it is chosen to use eight magnets size ϕ 25 * 12. The Internet address of this company is: www.enesmagnets.pl. The magnets have quality N38 with an average remanence B_r = 1.24 T. The price per magnet is € 2.25 including VAT and excluding mailing costs if 12 magnets are ordered. So the magnet costs per generator are € 18 excluding mailing costs which seems acceptable.

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 eighteen 3 mm holes for the spokes at a pitch angle of 20° and at a pitch circle of 45 mm. The hole pattern in the front flange is shifted 10° with respect to the hole pattern in the back flange.

For both flanges, six holes at a pitch angle of 60° are enlarged up to a diameter of 4 mm. The hole pattern of the six 4 mm holes in the front flange is shifted 30° with respect to the hole pattern of the six 4 mm holes in the back flange. A drill press has to be used for accurate drilling. The shaft has to be removed and a large ring with parallel sides has to be mounted in between the bed of the drill press and the lower flange.

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 of the VIRYA-1.04 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 armature sheet is made from a square galvanised steel sheet size 125 * 125 * 3 mm with the corners bevelled such that the sheet becomes octagonal. 200 armature sheets can be made from a standard sheet size 1.25 * 2.5 m. The eight magnets are glued by epoxy to the back side of the armature sheet such that four north and four south poles are created. The pitch circle of the magnets is chosen 95 mm.

The hexagonal stator sheet is made from 4 mm brown Phenolic Fabric. This material is flat and very stiff and is not absorbing water. It is supplied by for instance the company RS, website: www.rsonline.nl. It is supplied by RS as a sheet with size 4 * 285 * 590 mm and eight stator sheets can be made from one sheet if at least two of the corners are rounded with R = 23.5 mm. The size of the stator sheet is chosen such that the coils are lying within the sheet and this limits the possibility of damage during transport.

The stator has a 3-phase winding with totally six coils, so two coils per phase. The coils are called U1, V1, U2, V2, W1 and W2. The coils are positioned every 60°. Opposite coils are of the same phase. The pitch circle of the cores is 95 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 * 20 mm and a self locking nut M5.

A core has a diameter of 27 mm and a width of 12 mm. It has a 1.3 mm wide flange at the front side with a diameter of 45 mm. So the average coil diameter is 36 mm. This is about the same as the pitch in between the heart of a north pole and a heart of a south pole. This means that if a north pole is passing the left side of a coil, a south pole is passing the right side of a coil. So the voltage generated in the left side of a coil is in phase with the voltage generated in the right side of a coil and this means that the maximum voltage and so the maximum power is generated.

A coil core has a 0.7 mm wide flange at the back side with the same diameter as the front flange. So the distance in between the flanges is 10 mm. The back flange is supported by the stator sheet, so it can be thinner than the front flange. The front flange must be rather thick to prevent that it bends to the front side because of the wire pressure. If a coil is wound on a winding thorn, both flanges have to be supported by a 45 mm diameter aluminium disk to prevent that the flanges are bending to the outside because of the wire pressure.

The winding direction of all six coils is identical. Every coil has two wire ends. The beginning wire end is labelled A. The ending wire end is labelled B. The back core flange has a 2 mm hole at a radius of 14.5 mm and the beginning wire end is guided through this hole. The right aluminium disk of the winding thorn must have a hole at the same place. The stator sheet has two 3 mm holes for every coil and both coil ends are guided to the back side of the stator sheet through these holes. This gives the option to connect both coils of the same phase in parallel for a low voltage and in series for a high voltage. At this moment it is chosen that the low voltage corresponds to 6 V battery charging and that the high voltage corresponds to 12 V battery charging. However, one may also chose a winding which is good for 12 V and 24 V battery charging. This winding must have the double number of turns per coil and a wire thickness which is a factor 0.71 smaller.

The distance in between the armature sheet and the stator sheet is chosen 25 mm. The magnets have a thickness of 12 mm and the width of a core is 12 mm. So the real air gap in between a magnet and a core is 25 – 12 – 12 = 1 mm. The stator sheet is clamped in between two shaft washers and two shaft nuts. The nuts are adjusted such that the air gap in between the magnets and the cores is just 1 mm. The flattened front part of the head frame may be not fully flat and therefore one washer must always be mounted in between the stator sheet and the head frame.

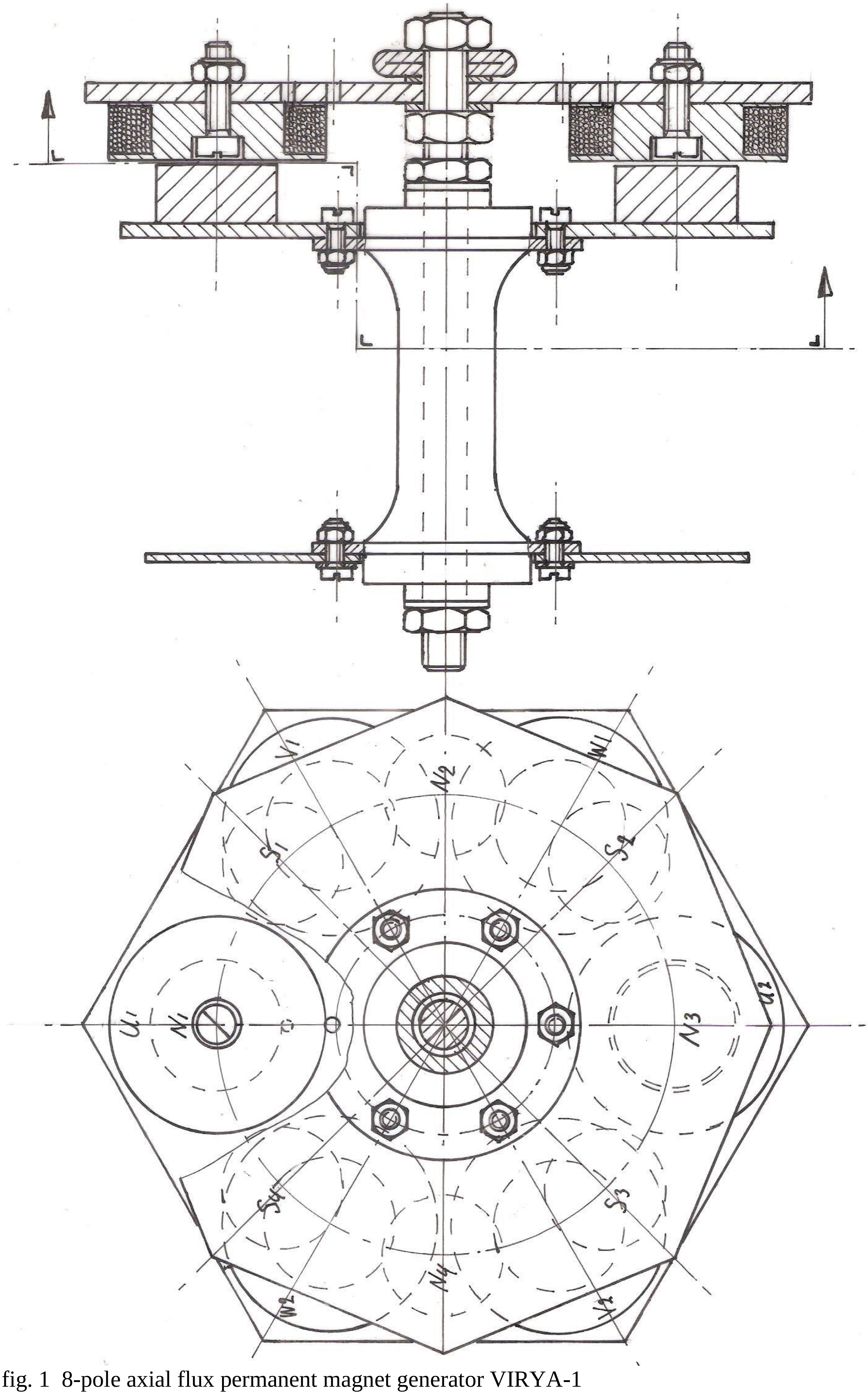


fig. 1 8-pole axial flux permanent magnet generator VIRYA-1

The three phases are connected in star. Assume the 12 V option is chosen for a 6 V / 12 V winding. So both coils of one phase have to be connected in series in the correct way. This means that coil end U1B has to be connected to coil end U2A, that coil end V1B has to be connected to coil end V2A and that coil end W1B has to be connected to coil end W2A .

The three coil ends U2B, V2B and W2B are connected to each other and are forming the star point. The three coil ends U1A, V1A and W1A are connected to the three AC point of a 3-phase rectifier which is mounted to the back side of the stator sheet. The coil ends are covered by an extra 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.

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 3-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 also opposite to a north pole. So the winding direction of coil U2 must be the same as the winding direction of coil U1 to realise that the voltage generated in U2 is strengthening the voltage generated in U1.

In figure 1 it can be seen that a north pole is at the same position after 90° rotation of the armature. So a phase angle of 360° corresponds to a rotational angle of 90°. The frequency of the AC voltage will be four 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 120°. In figure 1 it can be seen that there is an angle of 60° in between north pole N3 and coil W1. So this angle corresponds with a phase angle of 240°. The winding therefore is a normal 3-phase winding.

The fluctuation of the DC voltage and the DC current for a 3-phase winding is explained in chapter 3.2.1 of report KD 340 (ref. 4). The fluctuation is only little if the variation of the magnetic flux is sinusoidal. The variation of the magnetic flux is not sinusoidal for an axial flux generator, especially if rectangular magnets are used but for circular magnets it is assumed that the variation is about sinusoidal and that so the fluctuation of the DC voltage and current is only little. This has as advantage that the battery is not loaded and unloaded with a high frequency if the battery is charged by the windmill and simultaneously discharged by a load. Charging and discharging with a high frequency has an unfavourable influence on the lifetime of the battery.

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. 5). 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 is 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 N38 is about 1.24 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 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 half the north pole N1. This flux makes a 180° right hand bend and then flows into half the south pole S1. Then it flows through the armature sheet and enters half the north pole N1.

The other half of the magnetic flux coming out of north pole N1 makes a 180° left hand magnetic loop and then flows into half the south pole S4. So eight magnetic loops are coming out of the eight armature poles.

One complete magnetic loop flows through two magnets and one air gap. The thickness of a magnet is called t_1. The length of the magnetic air gap is called t_2. The length of t_2 is difficult to determine because for a 180° bend, it differs for all field lines. The distance in between the heart of a north pole and the heart of a south pole is 36.4 mm. Half a pole has a centre of gravity which lies at about a distance of 5 mm from the magnet heart. So the distance in between the centres of gravity of half a north pole and halve a south pole is about 26 mm. The shape of a magnetic filed line in the air gap is about halve an ellipse. It is assumed that the length of the ellipse which connects the centres of gravity is about 36 mm and that this length is representative for the average air gap. So t_2 = 36 mm.

The air gap results in an increase of the magnetic resistance by a factor $(2\ t_1 + t_2) / 2\ t_1$. This results in decrease of the remanence B_r to the effective remanence $B_{r\ eff}$. $B_{r\ eff}$ is given by:

$$B_{r\ eff} = B_r * 2\ t_1 / (2\ t_1 + t_2) \qquad \text{(T)} \qquad (1)$$

Substitution of B_r = 1.24 T, t_1 = 12 mm and t_2 = 36 mm in formula 1 results in $B_{r\ eff}$ = 0.496 T. This is lower than the value $B_{r\ eff}$ = 0.623 T which was calculated in report KD 574 for the VIRYA-1 generator with six magnets size 25.4 * 25.4 * 12.7 and a 3 mm steel stator sheet but this is the consequence of using a synthetic stator sheet. So $B_{r\ eff}$ is a factor 0.496 / 0.623 = 0.796 lower. However, it is expected that the 3-phase winding of the 8-pole generator is more effective than the 2-phase winding of the 6-pole generator and that this compensates the lower flux density in the air gap. To be sure if this alternative 8-pole generator has an acceptable maximum power and an acceptable efficiency, it is necessary to build and measure a prototype.

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 rather large distance of about 6 mm in between 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 a circular area with the circumference 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: $A_{sh} = \pi * 25 * 3 = 236\ mm^2$. A_{mag} is called the magnet area and i_1 is called the concentration ratio in between A_{mag} and A_{sh}.

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

Substitution of $A_{mag} = \pi/4 * 25^2 = 491\ mm^2$ and $A_{sh} = 236\ mm^2$ in formula 2 gives i_1 = 2.08. 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:

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

Substitution of $B_{r\ eff}$ = 0.496 T and i_1 = 2.08 in formula 3 gives $B_{r\ sh}$ = 1.03 T. This is much 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 magnetic loop in the stator sheet which has to pass the bridge in between the outside of the armature sheet and the central 36 mm hole. This bridge has a width of (125 – 36) / 2 = 44.5 mm. So the bridge area $A_{br} = 44.5 * 3 = 133.5\ mm^2$. This is larger than halve A_{sh} as halve $A_{sh} = 118\ mm^2$. So there is also no saturation in other parts of the armature sheet.

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 eight magnets are glued to the armature sheet with epoxy glue such that four north and four south poles are created. It is advised to make a square Teflon sheet with eight 25 mm circular holes 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 coil ends are pushed through the corresponding 3 mm holes in the stator sheet and the six coils are mounted against the stator sheet. The coil ends are isolated by an isolation tube. The 3-phase rectifier is connected to the back side of the stator sheet. It is assumed that the winding is a 6 V / 12 V winding which is used for 12 V battery charging. So both coils of the same phase are connected in series. The coil ends U1A, V1A and W1A are connected to the AC terminals of the rectifier. All coil ends U2B, V2B and W2B are connected to each other and are forming the star point. It is advised to wrap a piece of isolation tape around each coil to prevent unwinding and to protect the wires 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 shaft nut and a shaft washer is placed at the long end of the generator shaft. Next the stator sheet is placed. Next one washer is placed and the second shaft nut is tightened. The nuts are adjusted such that the distance in between a magnet and the front core flange is just 1 mm. The generator is ready now.
6 The head is mounted and connected to the tower pipe.
7 The back shaft nut is removed when the generator is connected to the head frame and tightened again if the generator is mounted.
8 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.

To prevent entrance of water and dust at the front bearing, it might be possible to cover the front side of the generator by a metal or synthetic cap (not specified). Sealing of the back bearing isn’t possible so it is required the renew the grease in the bearings regularly if a long lifetime is wanted. Mounting of the remaining parts of the VIRYA-1 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 $\lambda_d = 4.25$. 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 608) 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)

$\phi = 2/3 \text{ arc tan } 1 / \lambda_{r\,d}$ (°) (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 9 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 9 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.

sta-tion	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ 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:

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

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:

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

The sticking torque Q_s of the VIRYA-1 generator will be very low because there is no iron in the coils and in the stator sheet. Only the bearings 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} = 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 rotor are given in figure 2 and 3.

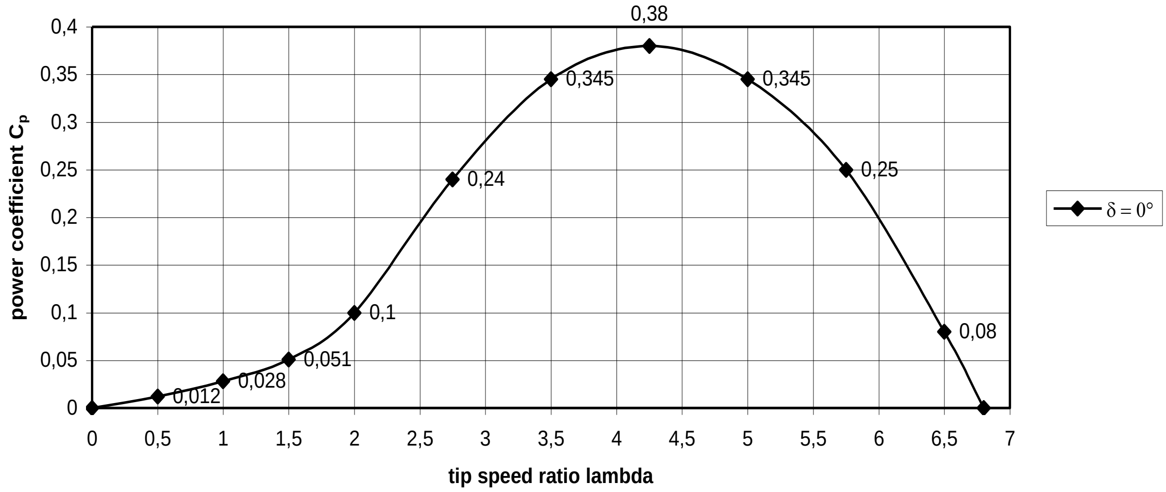


fig. 2 Estimated C_p-λ curve for the VIRYA-1 rotor for the wind direction perpendicular to the rotor (δ = 0°)

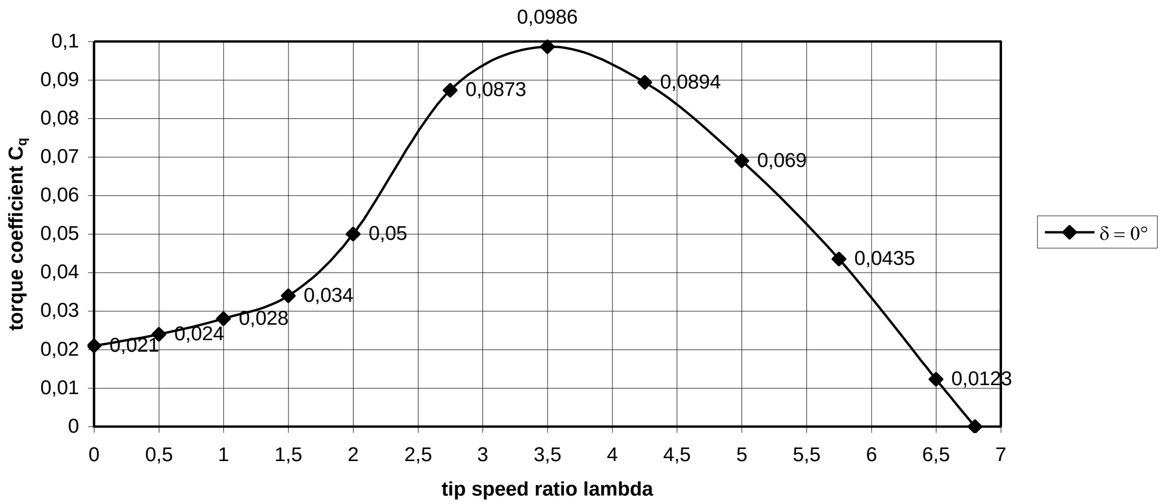


fig. 3 Estimated C_q-λ curve for the VIRYA-1 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 9 m/s. The estimated δ-V curve is given in figure 4.

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.

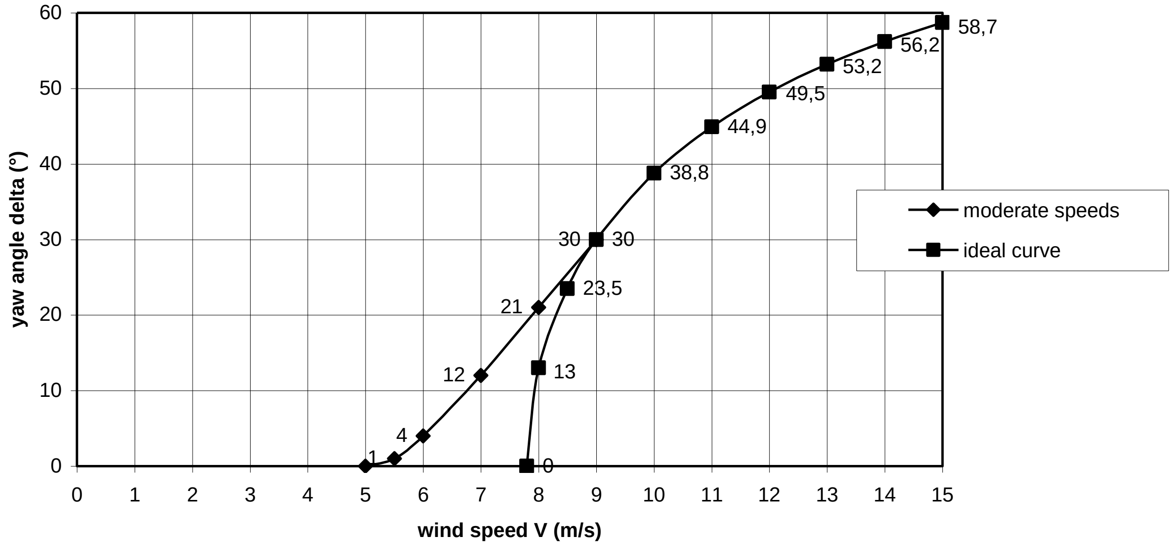


fig. 4 Estimated δ-V curve VIRYA-1 for a 2 mm aluminium vane blade

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 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 = 0.5 m in formula 7.1 of KD 35 gives:

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

Substitution of $\rho = 1.2$ 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 = 3 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 = 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	0.1	114.6	1.27	152.8	3.02	191.0	5.89	228.6	10.10	261.5	15.13	285.3	19.63	297.7	22.31
2.75	0.24	154.7	3.05	210.1	7.24	262.6	14.14	314.4	24.25	359.6	36.30	392.3	47.11	409.4	53.55
3.5	0.345	200.5	4.39	267.4	10.40	334.2	20.32	400.1	34.86	457.7	52.18	499.2	67.73	521.0	76.97
4.25	0.38	243.5	4.83	324.7	11.46	405.8	22.38	485.8	38.39	555.8	57.48	606.2	74.60	632.7	84.78
5	0.345	286.5	4.39	382.0	10.40	477.5	20.32	571.6	34.86	653.8	52.18	713.2	67.73	744.3	76.97
5.75	0.25	329.5	3.18	439.3	7.54	549.1	14.73	657.3	25.26	751.9	37.81	820.2	49.08	855.9	55.78
6.5	0.08	372.4	1.02	496.6	2.41	620.7	4.71	743.0	8.08	850.0	12.10	927.2	15.70	967.6	17.85
6.8	0	389.6	0	519.5	0	649.4	0	777.3	0	889.2	0	970.0	0	1012	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 0.8 for n = 350 rpm. The efficiency is estimated to be 0.4 for n = 700 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 9 m/s because the P_{mech}-n curve of the generator is lying close to the optimum cubic line.

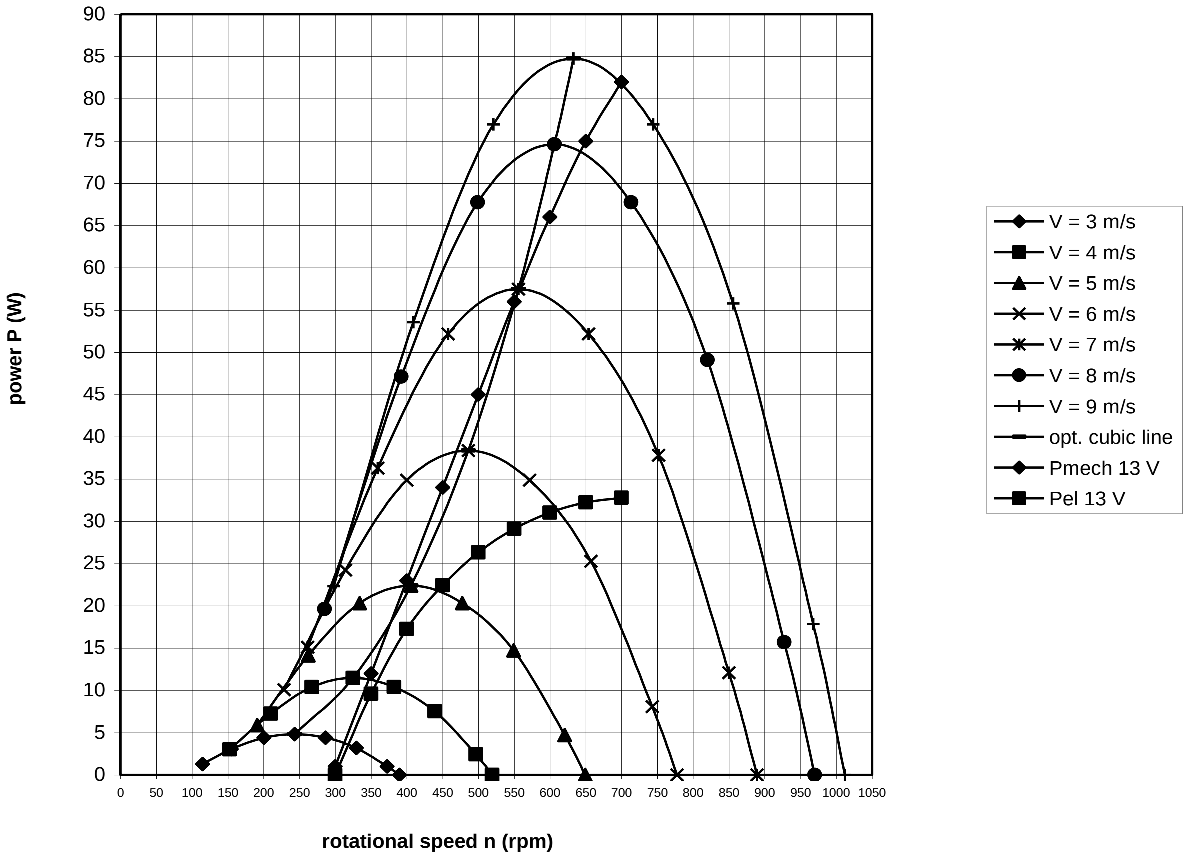


fig. 5 P-n curves of the VIRYA-1 rotor and a 2 mm aluminium vane blade, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging for the chosen 6 V /12 V winding

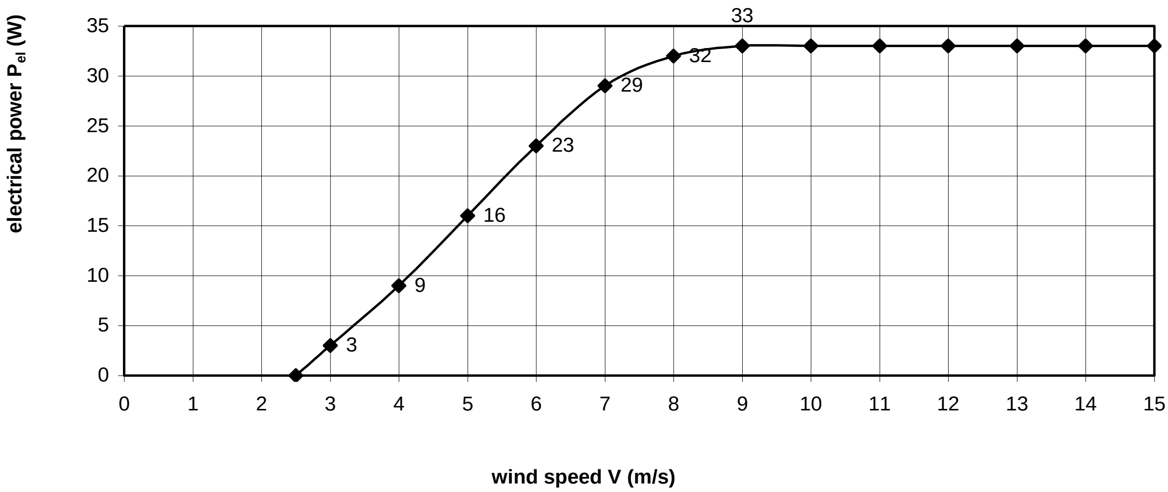


fig. 6 P_{el}-V curve of the VIRYA-1 windmill with V_{rated} = 9 m/s for 12 V battery charging

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 33 W which is acceptable for a rotor with 1 m diameter and for a rated wind speed of 9 m/s. A power of 33 W is more than a factor five 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 82 W for V = 9 m/s. The electrical power is 33 W so the heat dissipation in in the copper of the winding and in the rectifier is 82 – 33 = 49 W. The current for an electrical power of 33 W and a voltage of 13 V is 2.54 A. If it is assumed that the voltage drop over the rectifier is 1.4 V, this means that the power dissipation in the rectifier is about 3.5 W. So the heat loss in the copper winding is 45.5 W. This seams acceptable as the generator is cooled well by the wind when the maximum power is generated.

8 Determination of 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. Star rectification of a 3-phase current is explained in chapter 3.2.1 of report KD 340 (ref. 4). 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 13.

$$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff} \quad \text{(V)} \quad \text{(star rectification)} \qquad (13)$$

U_{eff} is the effective AC voltage of one complete phase. One complete phase has two coils in series for the chosen winding and for 12 V battery charging. So the effective AC voltage of one coil, $U_{eff\ 1\text{-}coil}$ is half U_{eff}. This gives:

$U_{DCeff} = 1.91 * \sqrt{2} * \sqrt{3} * U_{eff\ 1\text{-}coil}$ (V) (star rectification) (14)

Formula 13 can be written as:

$U_{eff\ 1\text{-}coil} = 0.214 * U_{DCeff}$ (V) (star rectification) (15)

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 the power loss in the rectifier.

Recently I have developed a test rig to measure a Chinese axial flux generator. This test rig is described in report KD 595 (ref. 6). This test rig is meant for a generator with a rather high maximum torque level and therefore it is provided with a reducing chain transmission. The VIRYA-1 generator has a rather low maximum torque level and therefore it can be used directly on the motor shaft. A special coupling is designed to couple the front generator flange to the motor shaft. This also allows a rather high rotational speed. The torque Q is measured by a reaction arm on the generator shaft which is coupled by a thin rope to a balance. The rotational speed n is measured by a laser rpm meter. At this moment it is uncertain if I will make a complete generator and measure the P_{mech}-n and the P_{el}-n curves for 12 V battery charging. But I have performed the measurements which are required to determine the wire thickness and the number of turns per coil (see chapter 9).

Substitution of U_{DCeff} = 12.5 V in formula 15 gives that U_{eff} = 2.68 V. So the effective AC voltage of one coil must be 2.68 V at n = 300 rpm.

9 Determination of the wire thickness and the number of turns per coil

An aluminium coupling was made with which the front flange of the generator could be coupled to the driving motor. A steel armature sheet has been made and eight magnets are glued to this sheet. A synthetic stator sheet was made and one coil core was connected to the stator sheet. Enamelled copper wire with a thickness of 0.8 mm was available. It appeared to be possible to lie 110 turns by hand on the coil core for an outside coil diameter of 45 mm. The stator sheet was connected to the generator shaft. The effective open AC voltage was measured for a rotational speed of 300 rpm. It was measured that U_{eff} = 1.3 V. So this means that the number of turns per coil has to be increased by a factor 2.68 / 1.3 = 2.06 and becomes 2.06 * 110 = 227.

The wire must be thinner for 227 turns per coil. It is assumed that at least the same total cross sectional area of all wires together can be realised for the thinner wire. So the wire thickness has to be reduced by a factor $\sqrt{(1 / 2.06)}$ = 0.697. So it should become 0.697 * 0.8 = 0.557 mm. The available closest standard wire diameter is 0.56 mm so this wired diameter is chosen. The final number of turns per coil is chosen 230.

Detailed drawings of the generator and the rotor are given in appendix 1. For manufacture of the head + tower pipe one also needs some of the drawings as given in the manual of the VIRYA-1.04.

10 References

1 Kragten A. 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. December 2014, report KD 574, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-1.04 windmill (λ_d = 3.5, 7.14 % cambered, aluminium blades) meant to be coupled to a Nexus hub dynamo (with free manual), January 2013, reviewed May 2013, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

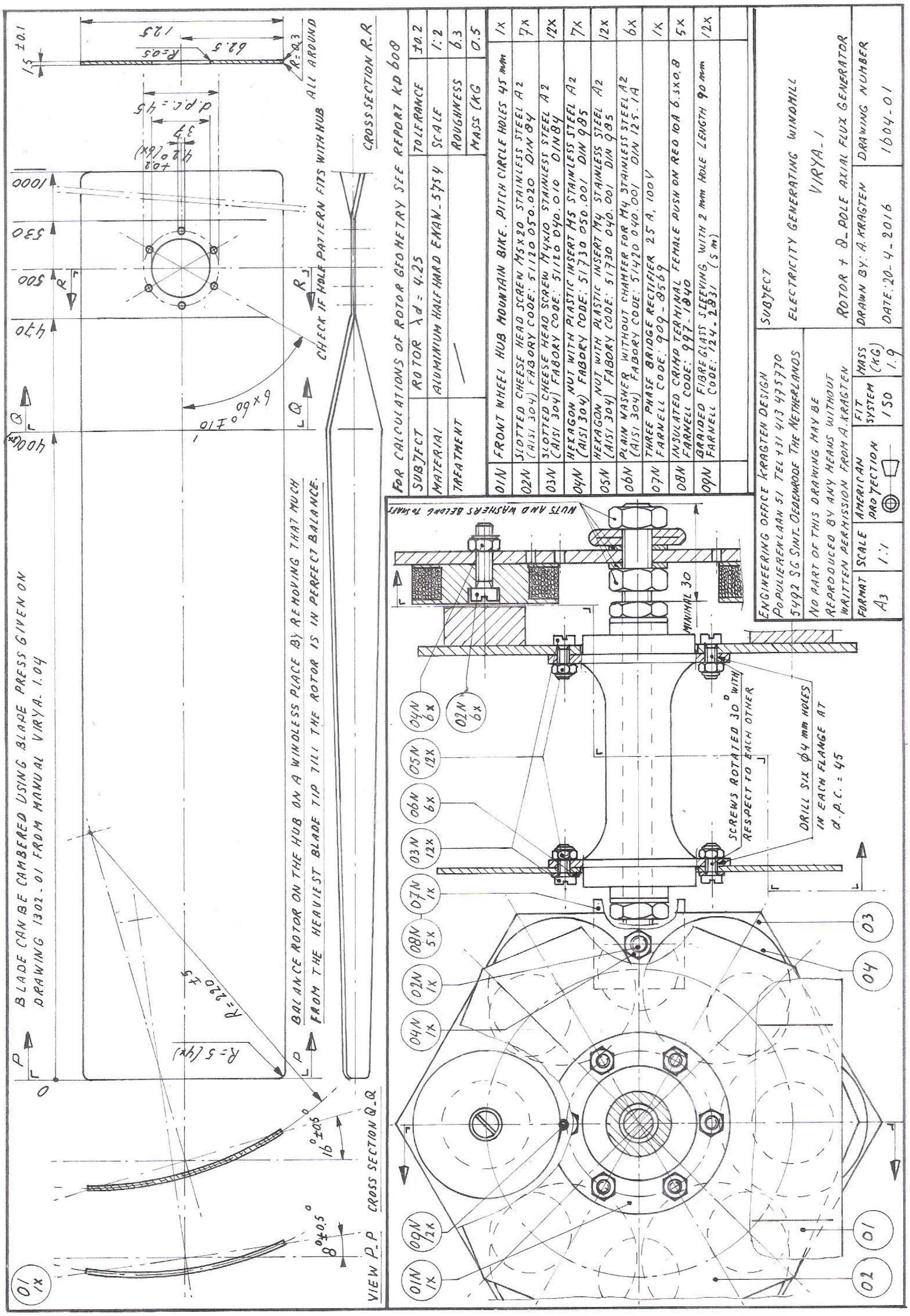
3 Kragten A. Manual of electricity generating windmill VIRYA-1.04, February 2013, reviewed May 2013, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands, can be copied for free from my website.

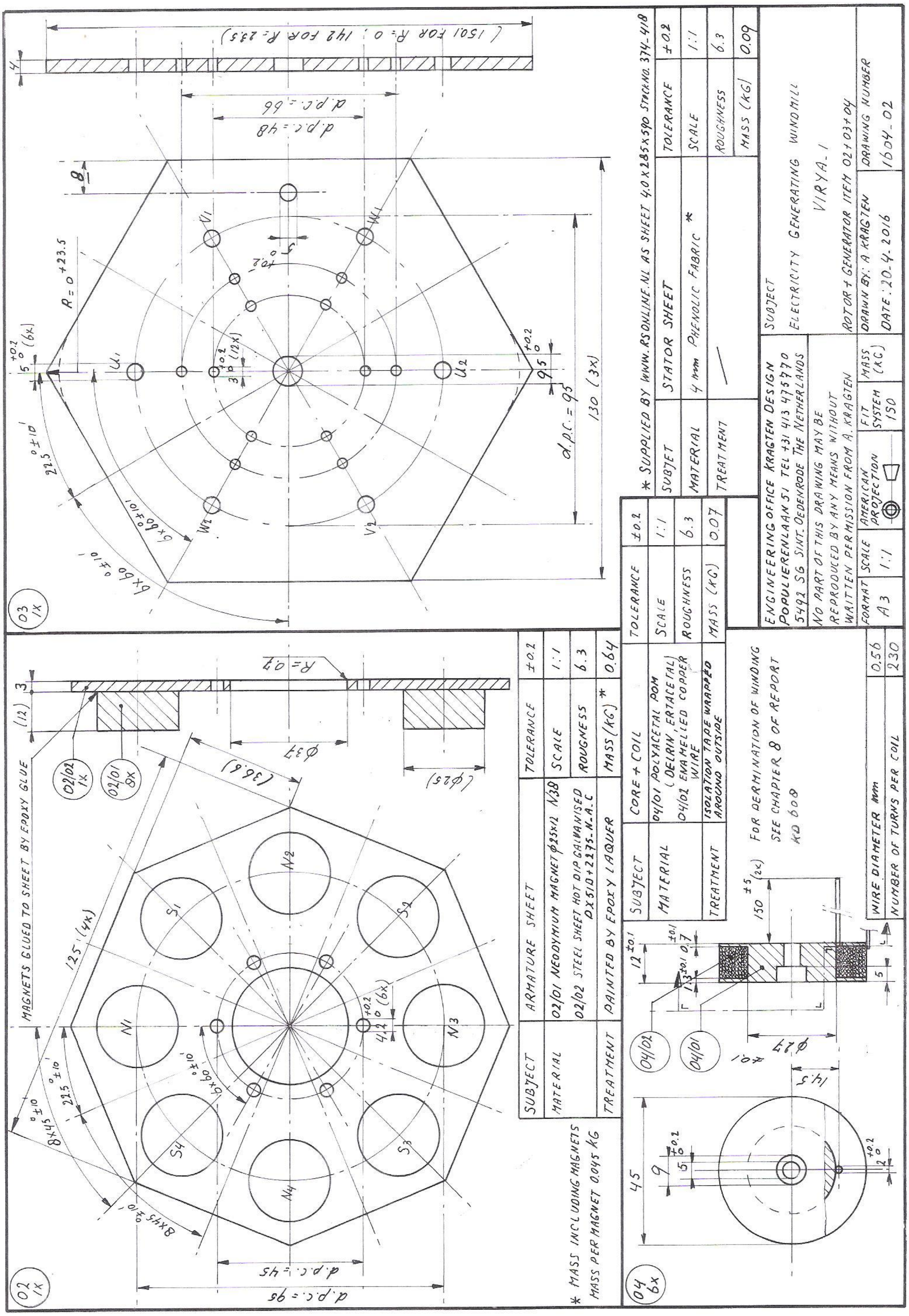
4 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed October 2014, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Measurements performed on a Chinese axial flux generator of Hefei Top Grand model TGET165-0.15kW-500R for a 12 V battery load, September 2015, free public report KD 595, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1 Detailed drawings of the rotor and the generator




ENGINEERING OFFICE KRAGTEN DESIGN
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5491 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 ITEM 02+03+04
DRAWN BY: A. KRAGTEN
DATE: 20-4-2016
DRAWING NUMBER
1604-02
FORMAT A3
SCALE 1:1
AMERICAN PROJECTION
FIT SYSTEM ISO
MASS (KG)
* SUPPLIED BY WWW.RSONLINE.NL AS SHEET 4.0 X 285 X 590 STOCKNO. 374-418
SUBJECT STATOR SHEET
MATERIAL 4 mm PHENOLIC FABRIC *
TREATMENT
TOLERANCE ±0.2
SCALE 1:1
ROUGHNESS 6.3
MASS (KG) 0.09
SUBJECT ARMATURE SHEET
MATERIAL 02/01 NEODYMIUM MAGNET Ø25x12 N38
02/02 STEEL SHEET HOT DIP GALVANISED DX51D+Z275-N.A.C
TREATMENT PAINTED BY EPOXY LAQUER
TOLERANCE ±0.2
SCALE 1:1
ROUGNESS 6.3
MASS (KG) * 0.64
* MASS INCLUDING MAGNETS
MASS PER MAGNET 0.045 KG
MAGNETS GLUED TO SHEET BY EPOXY GLUE
SUBJECT CORE + COIL
MATERIAL 04/01 POLYACETAL POM (DELRIN, ERTACETAL)
04/02 ENAMELLED COPPER WIRE
TREATMENT ISOLATION TAPE WRAPPED AROUND OUTSIDE
TOLERANCE ±0.2
SCALE 1:1
ROUGHNESS 6.3
MASS (KG) 0.07
FOR DERMINATION OF WINDING SEE CHAPTER 8 OF REPORT KD 608
WIRE DIAMETER mm 0.56
NUMBER OF TURNS PER COIL 230
02 1X
03 1X
04 6X
d.p.c. = 95
d.p.c. = 45
d.p.c. = 66
d.p.c. = 48
130 (3x)
(150 FOR R=0 ; 142 FOR R=23.5)