Development of an 8-pole, 3-phase axial flux permanent magnet generator for the VIRYA-2.2 windmill using 8 circular neodymium magnets size ϕ 45 * 15 mm. Design report of the rotor (λ_d = 4.5, B = 2, stainless steel blades).

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KD 607

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1 Introduction

The 2-bladed VIRYA-1.36 windmill and its 8-pole axial flux generator are described in report KD 571 (ref. 1). The drawings are given in the manual of the VIRYA-1.36 (ref. 2). The generator of the VIRYA-1.36 uses eight neodymium magnets size 25.4 * 25.4 * 12.7 mm.

It might be possible to design a bigger windmill and a bigger generator using most of the principles as used for the VIRYA-1.36. However, in stead of square magnets, circular magnets will be used. Advantages of circular magnets are that the variation of the magnetic field in the stator will be more sinusoidal than for square magnets and that mounting of circular magnets to the armature sheet is simpler. For this bigger windmill a rotor diameter of 2.2 m is chosen. This 2-bladed windmill will get the name VIRYA-2.2. Kragten Design has already developed a windmill with a rotor diameter of 2.2 m, the VIRYA-2.2S, but this windmill has a 3-bladed rotor and a radial flux generator made from an asynchronous motor.

The VIRYA-1.36 generator has six coils which are mounted against a steel stator sheet. Eddy currents will be generated in this sheet and this results in increase of the sheet temperature by about 6 °C at the maximum loaded rotational speed. If larger magnets are used, the eddy currents will be larger but the cooling area is also larger. But the increase of the stator temperature may still be higher than 6°. It is assumed that an increase of 15 °C is allowed at the maximum loaded rotational speed. Measurements for a prototype must prove if this limit isn’t passed.

A 3-phase one layer winding with six coils can be laid for an 8-pole armature. Star rectification of a 3-phase winding is explained in chapter 3.2.1 of report KD 340 (ref. 3). In figure 8 and 9 of KD 340 it can be seen that the DC current and the DC voltage are fluctuating only a little. However, this is only true if the AC phase voltage varies sinusoidal. This isn’t necessary the case for an axial flux generator with no iron in the coils. However, it is expected that an almost sinusoidal fluctuation of the magnetic field in the coils is realised if circular magnets are used. The advantage of little fluctuation of the DC current is that the battery lifetime is longer because the current can’t become negative if an external load is connected.

The head frame of the VIRYA-2.2 will be derived from the head frame of the VIRYA-2.2S. However, the vane blade will be made from 2 mm aluminium sheet in stead of from 1 mm stainless steel sheet to realise a rated wind speed of about 9 m/s in stead of about 11 m/s. The tower will be the same as the VIRYA-2.2S tower.

2 Description of the 8-pole axial flux generator (see figure 1 and 2)

The armature consists of a square mild steel sheet with a width and height of 248 mm and a thickness of 5 mm. If galvanised sheet of this thickness is available, galvanised sheet should be used. 72 sheets can be laser cut from a standard sheet size 1.5 * 3 m. 8 neodymium magnets size ϕ 45 * 15 mm are glued to the back side of the armature sheet at a pitch circle of 180 mm such that four north poles and four south poles are created. One may need a Teflon sheet with eight circular holes in it to get the magnets at the correct place during gluing.

A rotor blade is cut out of stainless steel strip size 2.5 * 200 * 1000 mm and 10 blades for 5 rotors can be made out of a standard sheet size 1 * 2 m with no waste material. A rotor blade is bolted to the front side of the armature sheet with four stainless steel hexagon bolts M8 * 30 which are shortened to 20, four large washers for M8 and four self locking nuts M8. The overlap in between a blade and the armature sheet is 24 mm resulting in a rotor diameter of 2 * 1000 + 248 – 2 * 24 = 2200 mm = 2.2 m.

Magnets size ϕ 45 * 15 mm are supplied by the Polish Internet company www.enesmagnets.pl. The quality is N35 with an average remanence B_r = 1.19 T. The current price is € 9.88 per magnet including VAT but excluding postage, so the total magnet costs for one generator are about € 79 excluding postage. This seems acceptable.

The stator consists of a circular sheet with a diameter of 270 mm and a thickness of 5 mm. 60 sheets can be laser cut from a standard sheet size 1.5 * 3 m. It might be possible to use a hexagonal steel sheet with a width of 248 mm. 72 hexagonal sheets can be laser cut from a sheet size 1.5 * 3 m if the sheets are positioned like honey combs. However, the disadvantage of using a hexagonal stator sheet is that the armature may get 24 preference positions per revolution because every 15 ° four magnets are in parallel to two sides of the stator sheet.

The VIRYA-1.36 generator uses six circular coils. Using circular coils is certainly logic for a 3-phase winding if the armature has circular magnets. A 3-phase winding for an 8-pole generator has two coils of phase U, two coils of phase V and two coils of phase W.

The distance in between the armature sheet and the stator sheet is chosen 32 mm. The magnetic air gap t_2 in between a magnet and the stator sheet is 32 – 15 = 17 mm. The coil width is chosen 15 mm, so the real air gap in between a magnet and a stator core is 2 mm.

Two opposite coils are coils of the same phase. The two coils of the same phase are connected in parallel for 12 V battery charging and are connected in series for 24 V battery charging. All six coils are made identical, so with the same winding direction. Every coil has two ends. The inner coil ends are labelled A and the outer coil ends are labelled B. So coil U1 has ends U1A and U1B, coil U2 has ends U2A and U2B, coil V1 has ends V1A and V1B, coil V2 has ends V2A and V2B, coil W1 has ends W1A and W1B and coil W2 has ends W2A and W2B. Every coil end is provided with an extra isolation tube. The stator sheet is provided with twelve 4 mm holes and every coil end of the six coils is guided through one of these holes to a 12-pole connector situated at the back side of the stator sheet.

In figure 2 it can be seen that if coil U1 is opposite a north pole, coil U2 is also opposite a north pole. So the two coils of one phase must be connected such that if the current in coil 1 is turning right hand, the current in coil 2 is also turning right hand to make that the generated voltages are strengthening each other! So if the current is flowing from A to B in coil U1, it must also flow from A to B in coil U2! The correct points of the 12-pole connector have to be connected to each other for 12 V or for 24 V battery charging. The rectifier is also positioned at the back side of the stator sheet. The correct points of the 12-pole connector have to be connected to the 3-phase rectifier for rectification of the 2-phase current.

If the generator is only used for 12 V battery charging, it is possible to cancel the 12-pole connector and to connect the coil ends labelled A directly to the tags of the rectifier. So the coil ends A of the same phase have to be connected to the same AC tag of the rectifier. In this case it isn’t necessary to drill the six 4 mm holes for the outer coil ends. All six coil ends B are connected to each other at the front side of the stator and are forming the star point.

A sketch of the winding is given in the upper picture of figure 1. Rectification for 12 V and for 24 V battery charging is given in the lower pictures of figure 1. The procedure how to determine the wire thickness and the number of turns per coil is given in chapter 7.

A coil is wound around a coil core which has a diameter of 50 mm. A core has two flanges with a diameter of 88 mm. So the maximum coil diameter is 88 mm. The front flange has a thickness of 2 mm. The back flange has a thickness of 1 mm. The back flange can be thinner because it is supported by the stator sheet. A coil core is made out of polyacetal (polyoxymethylene or POM, supplied as Delrin, Ertacetal and Hostaform). A coil core is connected to the stator sheet by a stainless steel screw M8 * 25 and a self locking stainless steel nut M8.

The average coil diameter is 69 mm. The distance in between two armature poles is 68.9 mm, so almost the same as the average coil diameter. 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. The voltage generated in the right side of a coil will therefore be in phase with the voltage generated in the right side. This results in the maximum voltage per turn and therefore in the maximum DC voltage and the maximum power.

A coil is wound on a winding thorn outside the generator. The winding thorn is made from a 20 mm shaft which can be clamped in the head stock of a lathe or in a special winding machine. The right part of the shaft is turned to a diameter of 8 mm and is provided with thread M8 at the end. The coil core is clamped in between two aluminium disks with a diameter of 88 mm and a thickness of about 6 mm by a nut M8. These disks prevent that the coil flanges bend to the outside because of the wire pressure. The right disk must have a 2 mm hole at a radius of 26 mm to make that the beginning wire can be guided to the core from the right side. If the beginning wire would be guided along the inner side of the back flange, it is hindering every new layer and the winding would become rather chaotic. The last winding has to be covered with some epoxy paint or with a piece of tape to prevent that the coil unwinds when it is removed from the winding thorn. The determination of the wire thickness and the number of turns per coil is given in chapter 7.

The bearing housing is derived from the bearing housing of the VIRYA-1.36 given on drawing 1407-02. It is made out of stainless steel bar ϕ 75 mm. It has a length of 120 mm. The stator sheet is bolted to the front side of the bearings housing by four hexagon screws M8 * 20 at a pitch circle of 61 mm. The stator sheet locks the front bearing. The bearing housing has four threaded holes M12 at the back side for connection to the head frame. The pitch circle of these holes is 55 mm.

The bearing housing has a 18 mm hole at the back side and a 14 mm inner hexagon spanner can be put through this hole and in the bolt head to prevent that the shaft rotates when the nut M16 is tightened.

The head frame of the VIRYA-2.2 must have a generator bracket made of strip size 70 * 6 mm which is parallel to the rotor plane. The length of this bracket must be chosen such that an eccentricity of 180 mm is realised. The vane arm item 01/01 is the same as for the VIRYA-2.2S but it has to be rotated 180° before welding it to the head pin to get the generator bracket parallel to the rotor plane! The bearing housing is connected to the front side of the generator bracket by four screws M12 * 25.

For the rotor shaft, a zinc plated steel hexagon socket head cap screw M16 * 160 is used. The cylindrical part of this screw has a diameter of about 15.85 and a bush with an inner diameter of 15.85 mm and an outer diameter of 17 mm has to be made to fill the gap in between the shaft and the bearing. Two heavy rubber sealed bearings size 17 * 47 * 14 mm are used. An extra oil seal size 25 * 35 * 5 mm is placed in the stator sheet to prevent entrance of water and dust in the bearings. The bearings are separated by a 60 mm long distance bush. A second 37 mm long distance bush separates the front bearing and the armature sheet. So both distance bushes are not identical like it is the case for the VIRYA-1.36 generator. The rotor, the two distance bushes and the bearings are clamped together by a stainless steel self locking nut M16.

A prototype has to be built and tested to prove that the generator is strong enough for the VIRYA-2.2. However, at this moment I have no plans to build a prototype so this should be done by someone else. I have made detailed drawings of the rotor and the generator and put them in a free manual (ref. 4). The drawings of the head, the tower, the dump load and the tools are not available for free and in the manual it is explained at what conditions they can be obtained.

It might be possible to test a prototype of the generator on a test rig which was developed to measure a Chinese axial flux generator. This test rig is described in report KD 595 (ref. 5). It might be possible to test a prototype of the whole windmill on top of the 12 m high tower of the VIRYA-4.2.

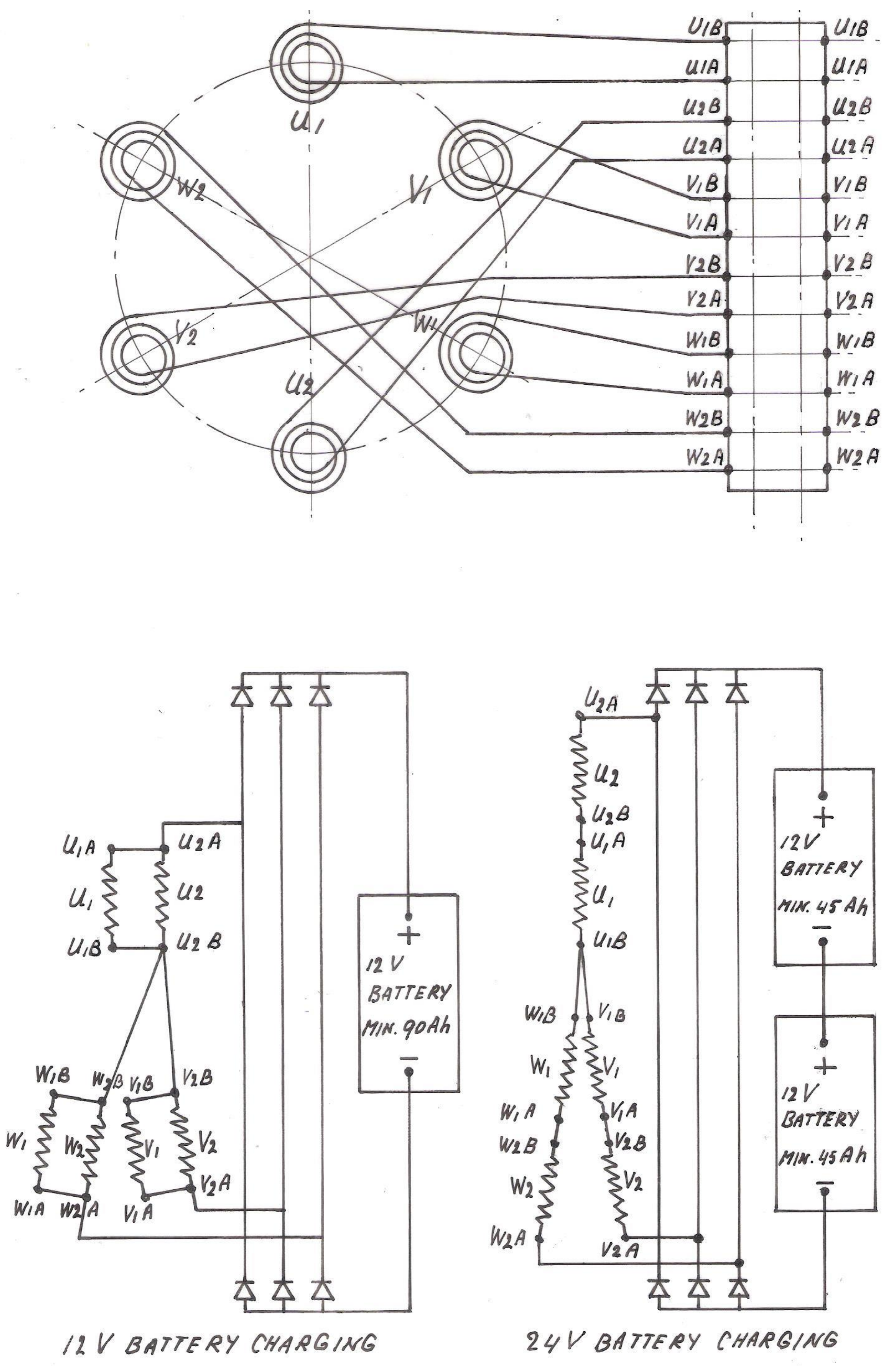

fig. 1 Sketch of the 3-phase winding. Rectification diagram for 12 V and 24 V battery charging

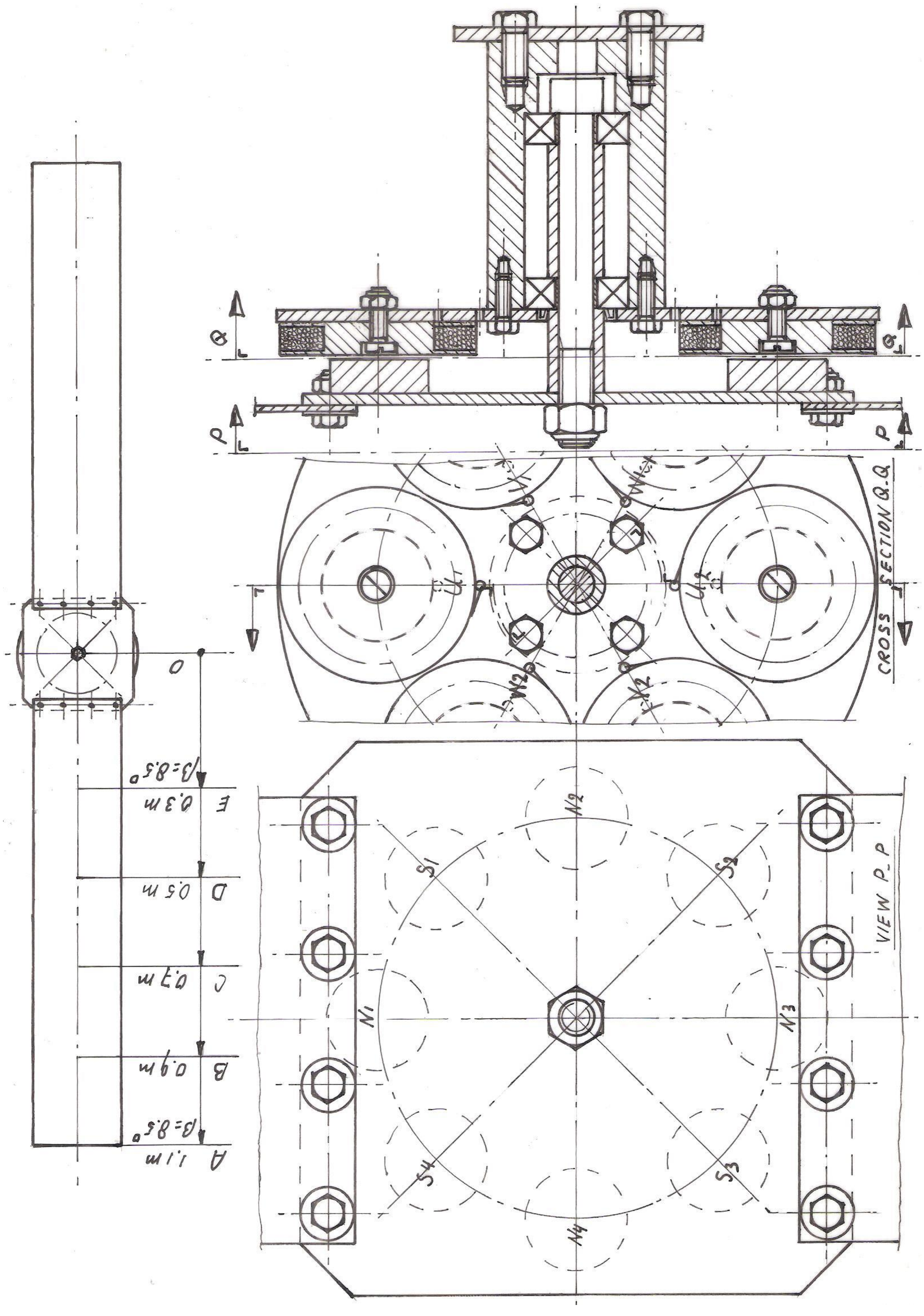

fig. 2 8-pole axial flux permanent magnet generator VIRYA-2.2

3 Calculation of the flux density in the air gap and the rotor 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. 6). 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 sheets are saturated because saturated sheets will reduce the magnetic flux in the air gap. Saturation has to be checked for the rotor sheet and for the stator sheet. The iron of a mild 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 N35 is about 1.19 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 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. For each magnet there is one air gap. The thickness of the magnetic air gap is called t_2. The magnetic air gap 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 = 1.19 T, t_1 = 15 mm and t_2 = 17 mm in formula 1 results in $B_{r\,eff}$ = 0.558 T. The real magnetic flux in the air gap in between magnet and stator sheet will be smaller than the calculated value because a part of the magnetic flux will flow directly from one magnet to its neighbour and will not pass the gap in between the magnet and the stator sheet. But the distance in between two adjacent magnets is rather large (about 24 mm) and it is expected that most of the magnetic flux will flow to the stator sheet and will therefore flow through the coils. Next it is checked if the iron of the armature sheet is not saturated. This sheet has a thickness of 5 mm. Let's look at magnet N1.

Half of the magnetic flux coming out of magnet N1 flows through the air gap. Next it bends to the left and flows through the stator sheet. Next it bends to the left and flows through the second air gap. Next it flows through half of magnet S4. Next it bends to the left and flows through the armature sheet. Next it bends to the left and flows through magnet N1. The other half flux makes a right hand loop through magnet S1. So eight magnetic loops are coming out of the eight armature poles.

The magnets are mounted at a rather large distance of 11.5 mm from the sides of the armature sheet so it is assumed that the magnet flux can flow in all directions of the sheet. So the sheet area A_{sh} through which the magnetic flux has to pass is given by: $A_{sh} = \pi * 45 * 5$ = 707 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 $A_{mag} = \pi/4 * 45^2$ = 1590 mm^2 and A_{sh} = 707 mm^2 in formula 2 gives i_1 = 2.249. 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 $B_{r\ eff}$ = 0.558 T and i_1 = 2.249 in formula 3 gives $B_{r\ sh}$ = 1.255 T. This is smaller than 1.6 T, so the armature sheet isn't saturated at the edges of the magnets.

Half of the magnetic flux flows through the armature sheet from one magnet to the adjacent magnet. This flux has to pass the area in between the side of the armature sheet and the 16 mm central hole. This area is 116 * 5 = 580 mm^2. This is much larger than halve A_{sh}, so the armature sheet is also not saturated at this point. The round stator sheet has a diameter of 270 mm. The stator sheet has a 35 mm central hole so the magnet flux has to pass an area of 117.5 * 5 = 587.5 mm^2. This is also much larger than half A_{sh} so the stator sheet is therefore not saturated too.

As there is no iron in the coils, the generator will have no fluctuation of the sticking torque. Some sticking torque will be caused because of the eddy currents in the stator but it is hoped that this torque is rather low and that the generated heat because of the eddy currents is acceptable. This should be checked first before building a complete prototype! One can use a hexagonal sheet with a width of 248 mm and a thickness of 5 mm which is connected to the shaft of an electric motor which is driven at a rotational speed of 310 rpm. Eight magnets are glued to this sheet at the correct position. A steel disk with a diameter of 270 mm and a thickness of 5 mm is kept stationary at a distance of 32 mm from the rotating disk. The temperature of this disk is measured at the start and after at least 15 minutes of rotation. The temperature rise should not be more than about 15 C°! If the temperature rise is more, it is doubtful if the generator wouldn't become too hot at high wind speeds.

A positive point is that the eddy currents for a loaded generator will probably be less than for an unloaded generator because the current in the stator winding causes a counter acting magnetic field which reduces the magnetic field in the stator. There will also be heat losses in the winding because of the resistance of the copper wires and the winding may not become hotter than about 80 °C at maximum power, so at n = 310 rpm (see figure 6).

4 Calculation of the geometry of the VIRYA-2.2 rotor

The 2-bladed rotor of the VIRYA-2.2 windmill has a diameter D = 2.2 m and a design tip speed ratio λ_d = 4.5. Advantages of a 2-bladed rotor are that manufacture and balancing of the rotor is easy and that it is possible to transport a completely mounted rotor. The gyroscopic moment in the rotor shaft of a 2-bladed rotor is fluctuating but this is almost completely neutralised because the rotor blades are very flexible.

The rotor has blades with a constant chord and is provided with a 7.14 % cambered airfoil. A rotor blade is made out of a stainless strip with dimensions of 2.5 * 200 * 1000 mm and 10 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 = 197.3 mm = 0.1973 m. For cambering the blades, it is possible to use an hydraulic blade press which is derived from the blade press of the VIRYA-4.1 blades which also have a chord of 197.3 mm. However the press can be much shorter as the camber should be made only in the outer 800 mm of the blade. One also has to develop tools for twisting and measuring of the correct blade angles. One may also use tools similar to the tools as described in the manual of the VIRYA-1.36.

The camber is only made in the outer 800 mm of the blade. This part of the blade is twisted linear. The inner 24 mm, where the blade is connected to the armature sheet, is flat. The 176 mm long transition part in between the flat inner part and the outer cambered part is twisted to get the correct blade angle at the blade root. It is assumed that the outer 100 mm of this 176 mm long part is used for the transition of camber to flat. So the inner 76 mm is not cambered. This non cambered part makes the blade rather flexible which prevents vibrations due to the gyroscopic moment and due to wind gusts.

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 7). This report (KD 607) has its own formula numbering. Substitution of $\lambda_d = 4.5$ and R = 1.1 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 4.0909 * r$ (-) (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 = 0.1973 m in formula (5.4) of KD 35 gives:

$C_l = 63.692\ r\ (1 - \cos\phi)$ (-) (7)

Substitution of V = 5.5 m/s and c = 0.1973 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.724 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (8)

The blade is calculated for five stations A till E which have a distance of 0.2 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 aerodynamic characteristics of a 7.14 % cambered airfoil are given in report KD 398 (ref. 8). The Reynolds values for the stations are calculated for a wind speed of 5.5 m/s because this is a reasonable wind speed for a good wind regime. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5.5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	1.1	4.5	8.4	0.1973	0.74	0.75	3.29	3.4	-0.2	-0.1	8.6	8.5	0.038
B	0.9	3.682	10.1	0.1973	0.89	0.89	2.71	2.5	1.6	1.6	8.5	8.5	0.031
C	0.7	2.864	12.8	0.1973	1.11	1.15	2.13	2.5	3.9	4.3	8.9	8.5	0.042
D	0.5	2.045	17.4	0.1973	1.45	1.42	1.56	1.7	10	8.9	7.4	8.5	0.115
E	0.3	1.227	26.1	0.1973	1.95	1.27	1.01	1.2	-	17.6	-	8.5	0.29

table 1 Calculation of the blade geometry of the VIRYA-2.2 rotor

The theoretical blade angle β_{th} varies in between 7.4° and 8.9°. If a constant blade angle of 8.5° is taken, the linearised blade angles are lying close to the theoretical values. The advantage of taking a constant blade angle is that it isn't necessary to twist the blade in between station A and E and this simplifies manufacture of a blade. The transition part of the blade is twisted 8.5° right hand to get the correct blade angle at the blade root.

5 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) and $\lambda_{opt} = 4.5$ and $C_d/C_l = 0.04$ gives $C_{p\ th} = 0.415$. The blade is stalling at station E only so only the part of the blade till 0.06 m outside station E is taken for the calculation of C_p. This gives an effective blade length k' = 0.74 m.
Substitution of $C_{p\ th} = 0.415$, R = 1.1 m and blade length k = k' = 0.74 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.37$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.37 / 4.5 = 0.0822$.
Substitution of $\lambda_{opt} = \lambda_d = 4.5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 7.2$.
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 blade angle is 8.5° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 8.5° = 81.5°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 81.5° it can be read that $C_l = 0.29$.

During starting, the whole blade is stalling. About 50 mm of the transition part also contributes to the starting torque. So now a blade length k = 0.85 m is taken.
Substitution of B = 2, R = 1.1 m, k = 0.85 m, $C_l = 0.29$ and c = 0.1973 m in formula 9 gives that $C_{q\ start} = 0.012$. For the ratio in between the starting torque and the optimum torque we find that it is 0.012 / 0.0822 = 0.146. This is acceptable for a rotor with a design tip speed ratio $\lambda_d = 4.5$. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

The sticking torque Q_s of the VIRYA-2.2 generator will be very low at stand still position because there is no iron in the coils which cause preference positions. Only the bearing friction and the oil seal will cause some small sticking torque. It is estimated for Q_s that $Q_s = 0.2$ Nm. The sticking torque will increase at increasing rotational speeds because of the eddy currents but it is assumed that the rotor torque increases faster than the generator torque.

Substitution of $Q_s = 0.2$ Nm, $C_{q\ start} = 0.012$, $\rho = 1.2$ kg/m^3 and R = 1.1 m in formula 10 gives that $V_{start} = 2.6$ m/s. This is low for a 2-bladed rotor with a design tip speed ratio $\lambda_d = 4.5$ and a rated wind speed $V_{rated} = 9$ m/s. So the rotor will start very easily.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing a S-shaped line which is horizontal for $\lambda = 0$.

Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 9). 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-2.2 rotor are given in figure 3 and 4.

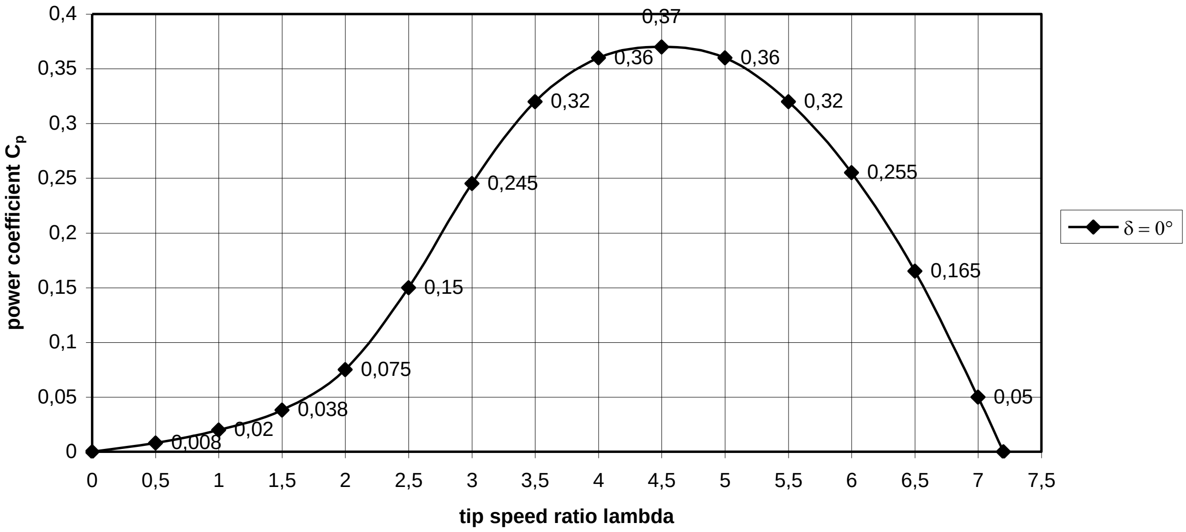

fig. 3 Estimated C_p-λ curve for the VIRYA-2.2 rotor for the wind direction perpendicular to the rotor (δ = 0°)

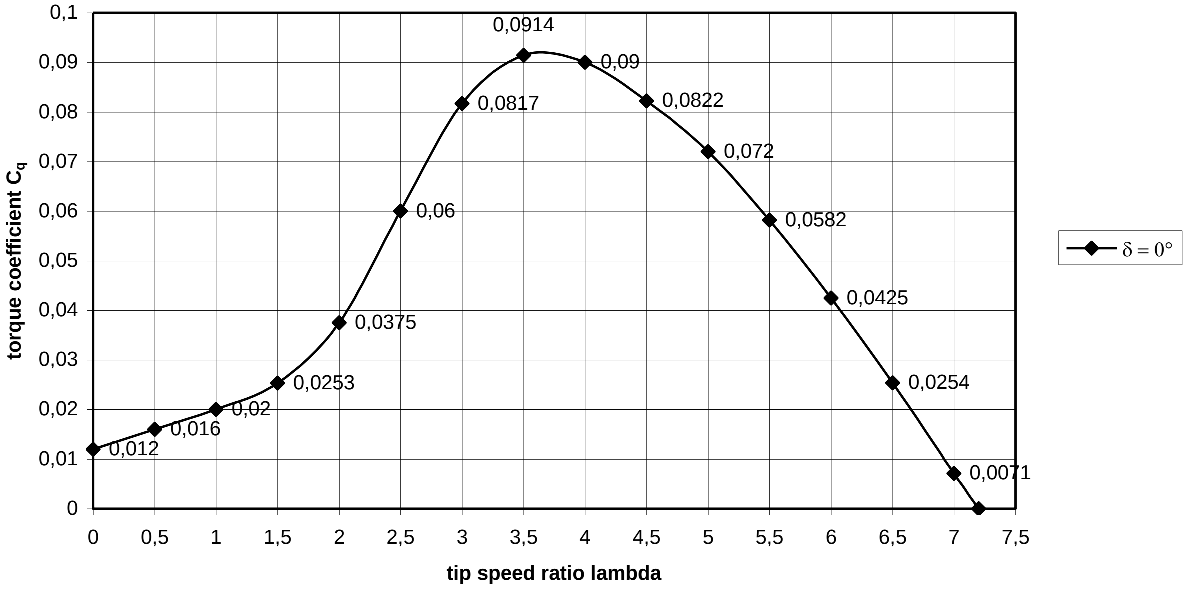

fig. 4 Estimated C_q-λ curve for the VIRYA-2.2 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a C_p-λ curve of the rotor and a δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The C_p-λ curve is given in figure 3. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 2 mm aluminium sheet. The rated wind speed for this vane blade is about 9 m/s. The estimated δ-V curve is given in figure 5.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 9 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 9 m/s will therefore also be valid for wind speeds higher than 9 m/s.

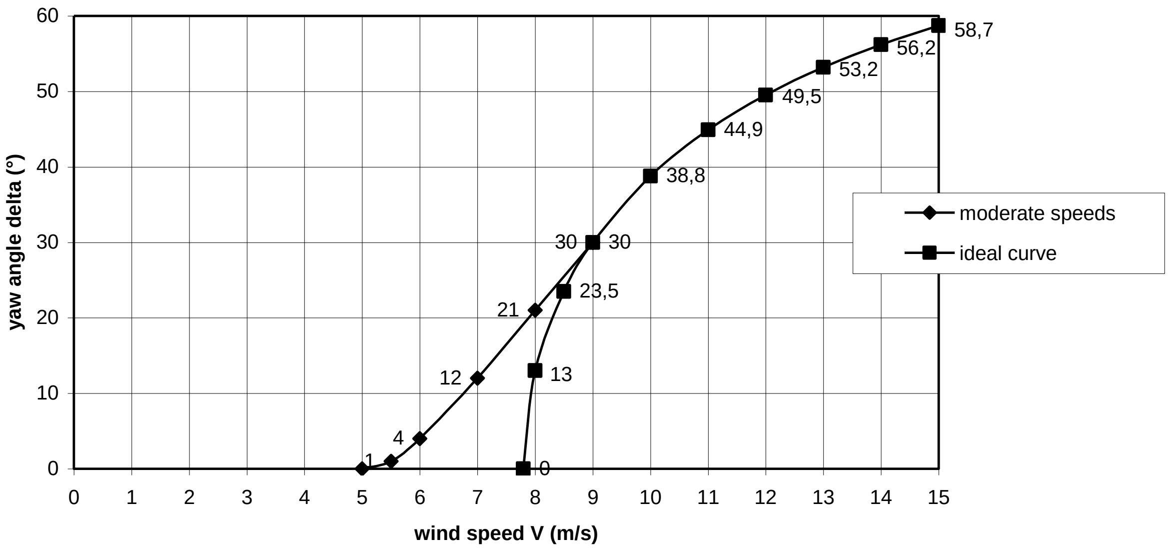

fig. 5 Estimated δ-V curve VIRYA-2.2 for a 2 mm aluminium vane blade

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-2.2 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 = 1.1 m in formula 7.1 of KD 35 gives:

$n_\delta = 8.6812 * \lambda * \cos\delta * V$ (rpm) (11)

Substitution of $\rho = 1.2$ kg / m^3 and R = 1.1 m in formula 7.10 of KD 35 gives:

$P_\delta = 2.2808 * C_p * \cos^3\delta * V^3$ (W) (12)

The P-n curves are determined for C_p values belonging to λ = 2.5, 3.5, 4.5, 5.5, 6.5 and 7.2. (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 5, is taken into account. The result of the calculations is given in table 2.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 4°		V = 7 m/s δ = 12°		V = 8 m/s δ = 21°		V = 9 m/s δ = 30°	
λ (-)	C_p (-)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2.5	0.15	65.1	9.2	86.8	21.9	108.5	42.8	129.9	73.4	148.6	109.8	162.1	142.5	169.2	162.0
3.5	0.32	91.2	19.7	121.5	46.7	151.9	91.2	181.9	156.5	208.0	234.3	226.9	304.1	236.8	345.6
4.5	0.37	117.2	22.8	156.3	54.0	195.3	105.5	233.8	181.0	267.5	270.9	291.8	351.6	304.5	399.6
5.5	0.32	143.2	19.7	191.0	46.7	238.7	91.2	285.8	156.5	326.9	234.3	356.6	304.1	372.1	345.6
6.5	0.165	169.3	10.2	225.7	24.1	282.1	47.0	337.7	80.7	386.4	120.8	421.4	156.8	439.8	178.2
7.2	0	187.5	0	250.0	0	312.5	0	374.1	0	428.0	0	466.8	0	487.2	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-2.2 rotor

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

The axial flux generator has not yet been built and measured so P_{mech}-n and P_{el}-n curves are not yet available. The P_{mech}-n curve is therefore estimated. The number of turns per coil is chosen such that the open battery voltage is reached for an unloaded rotor at 175 rpm, so the P_{mech}-n curve starts at 175 rpm. 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 0.756 for n = 200 rpm. The efficiency is estimated to be decreased up to 0.484 for n = 325 rpm because of the copper losses in the winding, the iron losses in the stator sheet and the voltage drop over the rectifier.

The average charging voltage for a 12 V battery is about 13 V, so the P_{el}-n curve is given for 13 V. The estimated P_{mech}-n and P_{el}-n curves for 13 V are also given in figure 6. It is necessary to measure the curves if a prototype is available and to check if the estimated curves are about correct. The 13 V curve is gained if the two coils of one phase are connected in parallel. A 26 V curve is gained if the two coils of one phase are connected in series. The P_{el}-n curve for 26 V will lie a little higher because the rectifier losses will be less.

The point of intersection of the P_{mech}-n curve for 13 V of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The working point for V = 9 m/s is lying at about P = 400 W and n = 310 rpm. The electrical power P_{el} for the working point of a certain wind speed is found by going down vertically from that working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 7).

The matching of rotor and generator is good for wind speeds in between 4 and 9 m/s because the P_{mech}-n curve of the generator is lying close to the optimum cubic line. The supply of power starts at a wind speed of 3 m/s ($V_{cut\ in}$ = 3 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. In chapter 5 it was calculated that V_{start} = 2.6 m/s, so there is no hysteresis in the P_{el}-V curve.

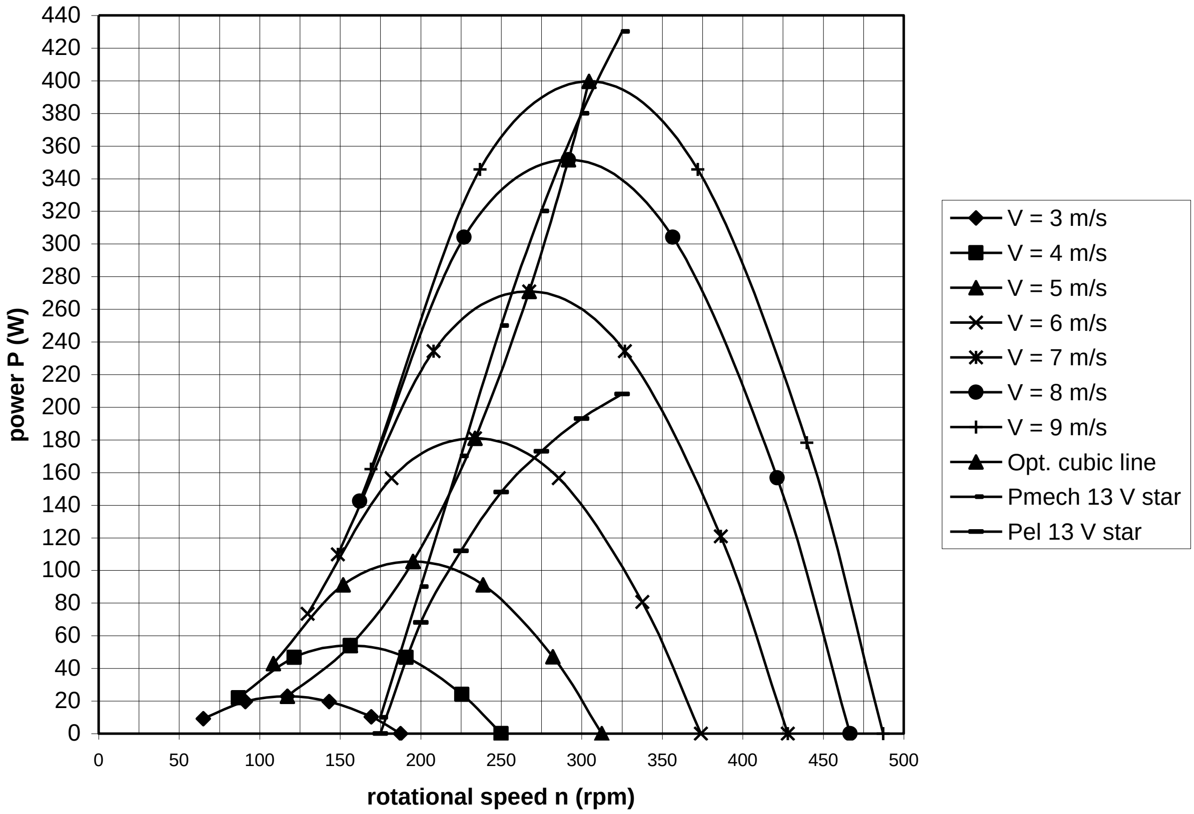

fig. 6 P-n curves of the VIRYA-2.2 rotor, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging for the chosen winding rectified in star

The maximum electrical power is 200 W which is rather good for a windmill with a 2.2 m diameter rotor and a rated wind speed of 9 m/s used for 12 V battery charging. This means that the maximum charging current is 14.3 A for a maximum charging voltage of 14 V. One needs a voltage controller plus dump load to limit the maximum charging voltage if the battery is full. The mechanical power at V = 9 m/s is 400 W. This means that the heat losses in the winding, the stator sheet and the rectifier are 400 - 200 = 200 W. It is expected that the heat loss in only the winding is about 150 W. It must be checked if the winding isn't becoming too hot for this power dissipation. But the maximum power is only generated at maximum wind speed where the cooling of the winding is optimal.

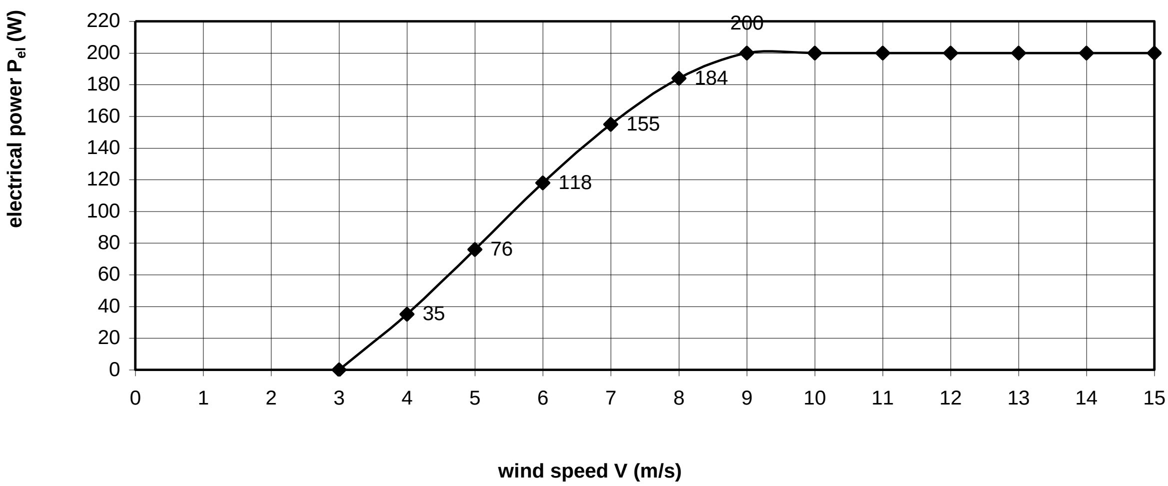

fig. 7 Estimated P_{el}-V curve of the VIRYA-2.2 windmill with V_{rated} = 9 m/s for 12 V battery charging

7 Tests to be performed to determine the winding

If it really comes to realisation of this generator, first a stator has to be made with a test winding with for instance 100 turns per coil. The wire thickness must be chosen such that the coils have the chosen geometry as given in figure 1. So a wire thickness has to be chosen such that the outer coil diameter is 88 mm for 100 turns per coil. This may need some try and error. Next the generator has to be measured for star connection and for parallel connection of the coils of one phase on an accurate test rig for a range of constant DC voltages of for instance 6, 8, 10, 12, 14, 16 and 18 V. The P_{mech}-n curves for different voltages have to be compared with the optimum cubic line of the rotor. The line which gives the best matching with this optimum cubic line is the optimum voltage for the test winding. Assume the best matching is realised for U = 10 V.

The generator will be used for 12 V battery charging for parallel connection of the two coils of one phase and for star connection of the coils. The average charging voltage for this nominal battery voltage is about 13 V. Next the winding must be modified such that the same P_{mech}-n curve is now generated for 13 V. This is realised if the number of turns per coil is increased by a factor 13/10 = 1.3. So the required number of turns per coil will be 130. The wire thickness has to be reduced such that a coil has still an outer diameter of 88 mm.

This procedure requires an accurate test rig which is available at the University of Technology Eindhoven and which can be hired at a certain fee. I have used this test rig for my current VIRYA generators but this test rig can’t be used for an axial flux generator. So another test rig is needed. Recently I have developed a test rig to measure a Chinese axial flux generator. It might be possible to use this test rig or to design a similar one. This test rig is described in report KD 595 (ref. 5). One needs an aluminium disk with a diameter of 80 mm and a thickness of 31 mm with a threaded central hole M16 and six threaded holes M8 at 60° and at a pitch circle of 65 mm to connect the generator to the flange of this test rig.

If a test rig isn’t available, one can use the following procedure for which one needs only one coil for each phase, so totally three coils. The estimated P_{el}-n curve given in figure 6 starts at a rotational speed of 175 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 number of turns per coil must be chosen such that the open DC voltage is 12.5 V for n = 175 rpm. In this case the starting point of the real P_{el}-n curve will be the same as for the estimated P_{el}-n curve. However, the remaining part of the real P_{el}-n curve can only be found by building and measuring of a generator prototype.

The generated effective AC voltage U_{eff} of one phase for a certain stator and armature geometry is proportional to the rotational speed n and proportional to the number of turns per coil. Rectification of a 3-phase current is explained in report KD 340 (ref. 3). The winding is rectified in star (see fig. 1). The voltage drop over the rectifier U_{rect} depends on the current. It can be neglected for the very small current flowing through a digital volt meter if the open DC voltage is measured. But for medium up to large currents, the voltage drop U_{rect} is about 1.4 V for a 3-phase rectifier with silicon diodes and the value of U_{DCeff} has to be reduced by 1.4 V to find the loaded voltage. The voltage drop over the rectifier can be reduced up to about 0.4 V if a rectifier is used which is provided with so called Schottky diodes. However, I could not find a 3-phase bridge rectifier provided with these diodes of enough power and therefore a rectifier with normal diodes is used. But one can make a rectifier with six separate Schottky diodes and this will reduce power loss in the rectifier.

If the test winding with three coils generates an open DC voltage of 12.5 V at 175 rpm, one can make a final winding with six coils connected as given in figure 1 for 12 V battery charging. The generator with this final winding is then measured for a real 12 V battery load or for a 12 V battery simulator which keeps the voltage at the average loaded voltage of 13 V. At least one should measure the P_{el}-n curve and compare this curve with the estimated curve as given in figure 6. But the matching can only be checked if the P_{mech}-n curve is measured.

8 Alternatives

In chapters 2 and 3 it is explained that a disadvantage of using a steel stator disk, is that eddy currents are causing increase of the sheet temperature. At this moment it is uncertain if the rise of the stator temperature is acceptable for the chosen magnets and the chosen stator geometry. A way to solve the problem is to use a synthetic stator sheet. This idea is described in report KD 608 (ref. 10) for an alternative 8-pole, 3-phase generator of the VIRYA-1 windmill.

A disadvantage of using a synthetic stator sheet is that the air gap becomes longer and this reduces the strength of the magnetic flux which is flowing through the coils. The generated voltage at a certain rotational speed will therefore be lower. For a prototype of the VIRYA-1.36 generator, it has been measured that replacement of the steel stator sheet by a synthetic stator sheet results in decrease of the generated voltage by about a factor 0.7. So this means that for getting a certain DC voltage at a certain rotational speed, a winding with more turns per coil and a thinner wire must be used. It can be doubted if the maximum torque level of the generator with this winding is large enough to load the windmill rotor enough at high wind speeds. However, one can only be sure if this is the case, if a prototype is built and measured.

A way to increase the effectiveness of the winding is to use coil cores without flanges. This requires a manufacturing technique for which every layer of the winding is covered by epoxy and for which a coil is only removed from the winding thorn if the epoxy is hardened. In stead of aluminium disks for the winding thorn, one should use disks made out of Teflon to prevent that a coil is glued to the disks. The present width of a coil core is 15 mm. The width of the front flange is 2 mm and of the back flange is 1 mm, so the width of the coil is 15 - 2 -1 = 12 mm. If the flanges are cancelled, it means that the coil can get a width of 15 mm and that the amount of copper is increased by a factor 15 / 12 = 1.25. This partly compensates the lower strength of the magnetic flux flowing through the coils.

An attendant advantage of using a synthetic stator sheet is that this sheet can’t make short-circuit in between the coils or the wires of the coil ends. The sheet can be made from 6 mm HPL sheet which is supplied as for instance Trespa. The original steel stator sheet has a thickness of 5 mm, so the length of the front distance bush has to be increased by 1 mm if the distance in between a magnet and a coil is kept the same. So the length of the front distance bush becomes 38 mm in stead of 37 mm.

Another advantage of using a synthetic stator sheet is that there is no longer a pulling force in between the armature sheet and the stator sheet and therefore no pulling force has to be taken by the bearings.

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