Ideas about a 12-pole axial flux generator for the VIRYA-1.66 windmill using 12 neodymium magnets size 25.4 * 25.4 * 12.7 mm. Design report of the rotor (λ_d = 4.5, B = 3, stainless steel blades).

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October 2015
reviewed February 2016

KD 596

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1 Introduction

The 3-bladed VIRYA-1.8 and VIRYA-1.75 and the 2-bladed VIRYA-1.825 all make use of the same radial flux PM-generator made from an asynchronous motor. These three windmills make use of the same head and tower. The VIRYA-1.36 has a different 8-pole axial flux generator using eight magnets size 25.4 * 25.4 * 12.7 mm. This generator is described in free public report KD 571 (ref. 1).

The idea is to develop a 12-pole axial flux PM-generator using the same principles as used for the 8-pole generator of the VIRYA-1.36. The same magnets size 25.4 * 25.4 * 12.7 mm will be used. The coil cores will also be the same.

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 rotational speed. If the number of magnets is increased from eight to twelve, so by a factor 1.5, it means that the frequency is also increased by a factor 1.5 at the same rotational speed. However, the 12-pole generator will be used in combination with a larger rotor which has a lower design tip ratio than the VIRYA-1.36 rotor and so the maximum rotational speed will be a lot lower. The maximum frequency will therefore be about the same and it is expected that the increase of the stator sheet temperature will be acceptable.

It is expected that a 3-bladed rotor with 1.66 m diameter and a design tip speed ratio of 4.5 fits well to this generator. This windmill is therefore called the VIRYA-1.66. The head frame of the VIRYA-1.66 will be derived from the head frame of the VIRYA-1.8 but the vane blade will be a little smaller to compensate for the smaller rotor diameter and it will be made of 2 mm aluminium in stead of 1 mm stainless steel to realise a lower design wind speed of about 9 m/s in stead of 11 m/s for the VIRYA-1.8. The tower will be identical.

2 Description of the 12-pole axial flux generator (see figure 1)

The armature consists of a hexagonal galvanised steel sheet size with a width of 208 mm. 72 sheets can be laser cut from a standard sheet size 1.25 * 2.5 m if the sheets are positioned like honeycombs. 12 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 176 mm such that six north poles and six south poles are created. One may need a synthetic sheet with twelve square 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 * 125 * 750 mm and 48 blades for 16 rotors can be made out of a standard sheet size 1.5 * 3 m. A rotor blade is bolted to the front side of the armature sheet with three stainless steel inner hexagon bolts M6 * 35, twelve washers for M6 and three self locking nuts M6. The overlap in between a blade and the armature sheet is 24 mm resulting in a rotor diameter of 2 * 750 + 208 – 2 * 24 = 1660 mm = 1.66 m.

The magnets are supplied by the Internet company www.supermagnete.de. These magnets have quality N40 and a remanence B_r in between 1.26 T and 1.29 T. The current price is € 4.17 per magnet including VAT and excluding mailing costs for an order of 20 magnets, so the magnet costs for one generator are about € 50 which seems to be acceptable.

The stator consists of a 3 mm galvanised steel disk with a diameter of 236 mm. 9 coils are bolted to the stator sheet at a pitch circle of 176 mm. Three coils are of phase U, three coils are of phase V and three coils are of phase W. A coil is wound around a polyacetal (polyoxymethylene or POM, supplied as Delrin, Ertacetal and Hostaform) core. A coil core has a diameter of 36 mm and flanges at both sides with a diameter of 58 mm. The front flange has a thickness of 1.3 mm. The back flange is supported by the stator sheet and has a thickness of 0.7 mm. The distance in between the flanges is 10 mm so the total thickness of a coil core is 12 mm.

The distance in between the armature sheet and the stator sheet is chosen 26 mm so the air gap in between a magnet and the front flange is 26 – 12.7 – 12 = 1.3 mm. The stator sheet has three holes through which the three coil ends are guided to the backside. A 3-pole connector is connected to the back side of the stator sheet. An oil seal size 20 * 28 * 4 mm is pressed in the stator sheet and gives extra prevention against the penetration of water or dust in the bearings.

The average coil diameter is (58 + 36) / 2 = 47 mm. The pitch in between a north and a south pole is 45.6 mm, so only a little smaller. So if a north pole is passing the left side of a coil, a south pole is about passing the right side of a coil. This means that the voltage generated in the left side is in phase to the voltage generated in the right side and for this condition the maximum total voltage will be generated in a coil.

The nine coils all have the same dimensions and the same winding direction. The armature pole pitch is 30° for an armature with twelve poles. The stator coil pitch is 40° for a stator with nine coils. The positioning of the armature poles with respect to the coils is drawn in figure 1 such that north pole N1 is just opposite coil U1. In chapter 3 it will be proven that a 3-phase current is generated if the armature rotates. The calculation of the flux density in the coils and in the armature sheet is given in chapter 4. The procedure how the wire thickness and the number of turns per coil is determined, is given in chapter 9.

The construction of the bearing housing is about the same as for the VIRYA-1.36 which uses a M12 inner hexagon bolt as shaft and bearings size 12 * 32 * 10 mm. However, because of the larger rotor diameter, heavier bearings size 12 * 37 * 12 mm are used

The bearing housing is made out of stainless steel bar ϕ 55 mm. It has a length of 85 mm. The stator sheet is bolted to the front side of the bearings housing by four bolts M5 * 10 at a pitch circle of 46 mm. The stator sheet locks the front bearing. The bearing housing has four threaded holes M8 at the back side for connection to the head frame. The pitch circle of these holes is 42 mm.

The bearing housing has a 13 mm central hole at the back side and a 10 mm inner hexagon spanner can be put through this hole and in the bolt head to prevent that the shaft rotates when the nut M12 is tightened. The head frame of the VIRYA-1.66 has a generator bracket which is in parallel to the rotor plane. The bearing housing is connected to the front side of the generator bracket by four bolts M8 * 16.

For the rotor shaft, an inner hexagon bolt M12 * 110 mm is used. The cylindrical part of this bolt has a diameter of about 11.9 mm. Two rubber sealed bearings size 12 * 37 * 12 mm are used. The bearings are separated by a 40 mm long stainless steel distance bush with an outer diameter of 20 mm. A second 29 mm long distance bush separates the front bearing and the armature sheet. The rotor, the two distance bushes and the bearings are clamped together by a stainless steel self locking nut M12.

A prototype has to be built and tested to prove that the generator is strong enough for the VIRYA-1.66.

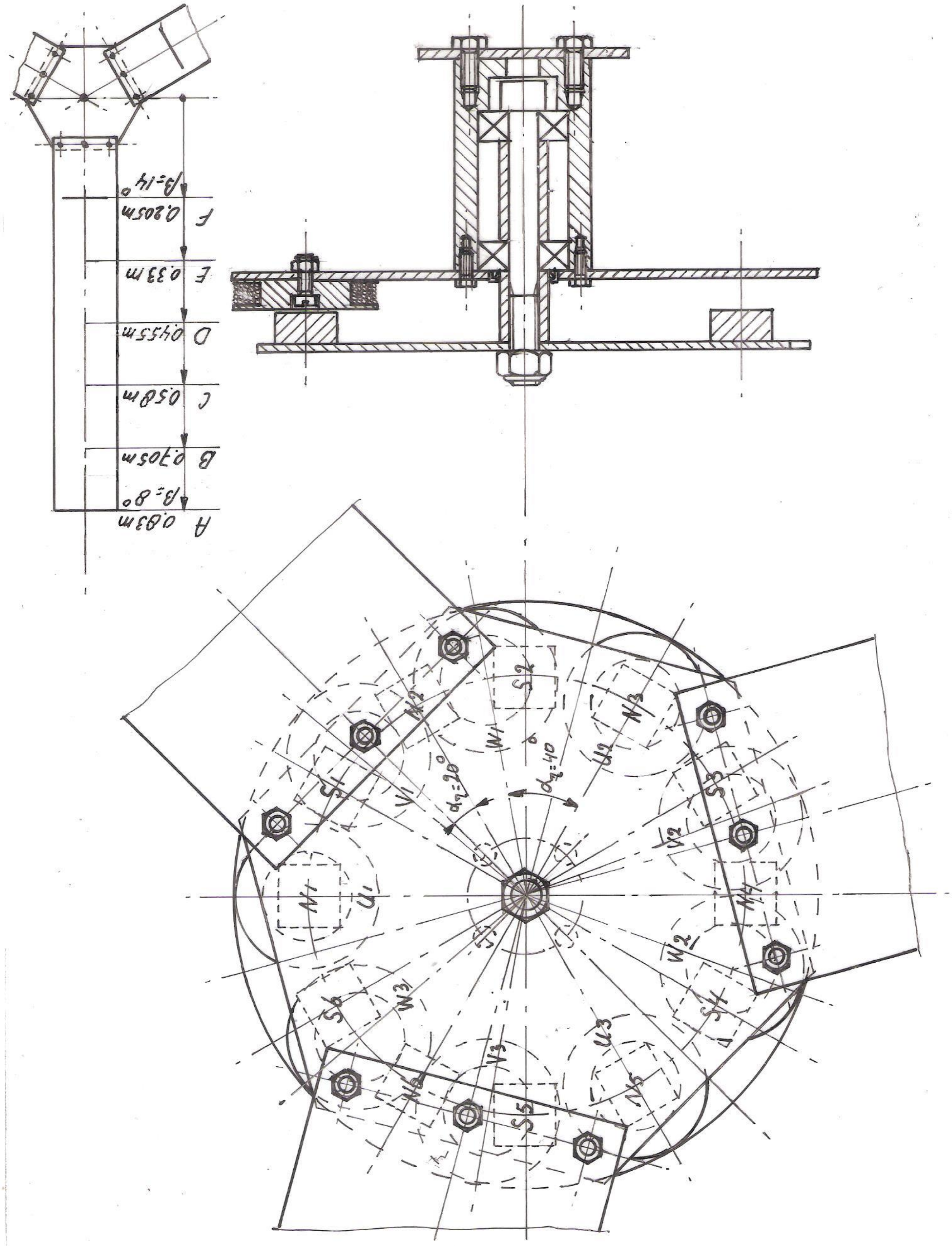

fig. 1 12-pole axial flux permanent magnet generator VIRYA-1.66

3 Checking if a 3-phase current is generated

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

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

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

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

The three curves are shown in figure 2.

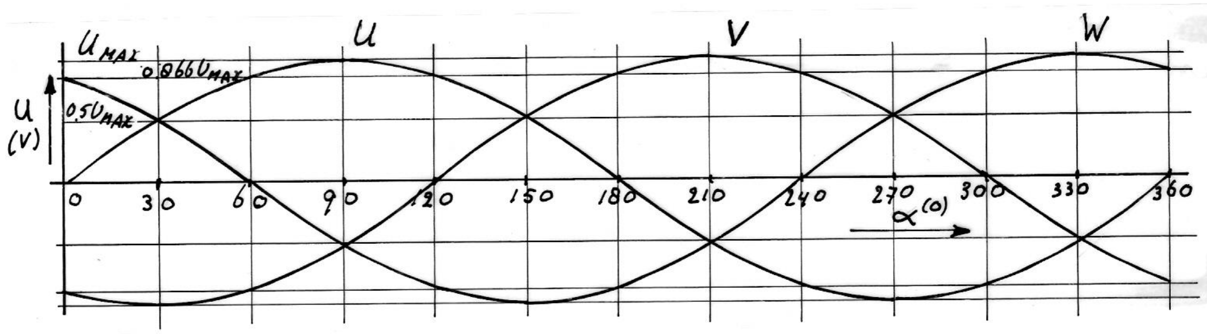

fig. 2 Three phases U, V and W

A pure sine wave is generated if a coil is rotating in a constant magnetic field because the magnetic field through the coil varies sinusoidal. If a permanent magnet is moving along a coil, the generated voltage may not be a pure sine wave, especially if the distance in between the magnets is large. But for the chosen generator configuration it is assumed that the generated voltage varies about sinusoidal. If the rotor has two poles, the position of the rotor with respect to the stator will be the same if the rotor has rotated 360°. So the phase angle α is the same as the rotational angle α_r of the rotor. If the rotor has 12 poles this will be the case for 360 * 2 / 12 = 60° rotation of the rotor. This results in the formula:

$\alpha = \alpha_r * p_r / 2$ (-) (4)

α is the phase angle, α_r is rotational angle of the rotor and p_r is the number of rotor poles.

In figure 1 it can be seen that $\alpha_r = 0°$ in between N1 and U1 and that all coils U are opposite north poles. So the voltages generated in coils of the same phase are all in phase. In figure 1 it can be seen that the angel $\alpha_r = 20°$ in between N2 and V1. Substitution of $\alpha_r = 20°$ and $p_r = 12$ in formula 4 gives $\alpha = 120°$.

In figure 1 it can be seen that the angel $\alpha_r = 40°$ in between N3 and W1. Substitution of $\alpha_r = 40°$ and $p_r = 12$ in formula 4 gives $\alpha = 240°$. So a 3-phase voltage is created in between the coils U1, V1 and W1.

The three coils of one phase are wound together on a three steps winding thorn. The winding direction of all three coils is the same and the coils are positioned in the stator such that the winding direction is the same for all coils. First three coils of phase U are positioned, next three coils of phase V and next three coils of phase W. A bundle of three coils U has two wire ends which are labelled U_A and U_B. The three coils V have wire ends V_A and V_B. The three coils W have wire ends W_A and W_B.

The wire ends U_B, V_B and W_B are connected to each other and are forming the star point. The wire ends U_A, V_A and W_A are connected to the 3-pole connector.

4 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. 2). However, the magnet configuration of this new type PM-generator is completely different and so the formulas out of KD 341 can't be used.

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

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

Let's follow the magnetic flux coming out of north pole N1. This flux passes the 13.3 mm wide magnetic air gap in between the magnet and the steel stator sheet. Halve of this flux bends to the right and flows through the steel stator sheet. Then it bends to the right again and passes the second air gap. Then it passes through halve of magnet S1. Then it bends to the right again and flows through the steel armature sheet. Then it bends to the right again and flows through halve of magnet N1. So this flux is turning right hand. The other half flux bends to the left and flows through the stator sheet, halve the south pole S6, the armature sheet and half the north pole N1. This flux is turning left hand. So twelve magnetic loops are coming out of the twelve 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:

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

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

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

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

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

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

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

5 Mounting sequence of the generator and the rotor

1 Clean the shaft and the inside of the bearings with acetone or alcohol.
2 The back bearing is shifted over the shaft. Use some anaerobe or epoxy glue.
3 The 40 mm long distance bush is shifted over the shaft.
4 The front bearing is shifted over the shaft. Use some glue. The bearings have to be pressed together during hardening of the glue. This can be done by the second distance bush and the nut M12. The second bush shouldn’t be glued to the shaft.
5 The nut and the second bush are removed after hardening of the glue.
6 The assembly of shaft and bearings is pushed in the bearing housing.
7 The oil seal is pressed in the stator sheet.
8 The nine coils are mounted against the stator sheet. The three cable ends U_B, V_B an W_B are soldered to each other thus forming the star point. The star point is isolated with a piece of isolation tube. The three cable ends U_A, U_B and U_C are isolated by an isolation tube and pushed through the three holes in the stator sheet. It is advised to paint the winding with epoxy lacquer for better protection against corrosion.
9 A 3-pole connector is mounted to the back side of the stator sheet and the three isolated cables are connected to the connector.
10 The stator is bolted to the bearing housing using four bolts M5 * 10.
11 The second 29 mm long distance bush is pushed over the shaft.
12 The 12 magnets are glued to the back side of the rectangular armature sheet such that six north and six south poles are created. To prevent corrosion, the assembly of sheet and magnets has to be painted by epoxy lacquer.
13 The assembly of the armature sheet and the magnets and is shifted over the shaft and locked with the central M12 nut.
14 The three blades are bolted to the front side of the armature sheet using nine stainless steel hexagon screws M6 * 16, nine stainless steel self locking nuts M6 and nine large stainless steel washers.
15 The rotor is balanced on a frictionless shaft at a windless place.
16 The assembly of generator and rotor is bolted to the generator bracket of the head frame using four bolts M8 * 16 mm.

6 Calculation of the geometry of the VIRYA-1.66 rotor

The 3-bladed rotor of the VIRYA-1.66 windmill has a diameter D = 1.66 m and a design tip speed ratio λ_d = 4.5. Advantages of a 3-bladed rotor are that the gyroscopic moment in the rotor shaft isn't fluctuating and that a 3-bladed rotor looks better than a 2-bladed rotor.

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 * 125 * 750 mm and 48 strips can be made out of a standard sheet of 1.5 * 3 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 designed for the VIRYA-2.2S blades but the camber should be made only in the outer 625 mm of the blade. For twisting one can also use the VIRYA-2.2S tools but one has to use an 14° jig to measure the correct blade angle at the blade root and a 6° jig to measure the correct blade twist.

The camber is only made in the outer 625 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 101 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 61 mm of this 101 mm long part is used for the transition of camber to flat. So the inner 40 mm is not cambered. This non cambered part makes the blade rather flexible which prevents vibrations due to wind gusts.

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 3). This report (KD 596) has its own formula numbering. Substitution of λ_d = 4.5 and R = 0.83 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 5.4217 * r \qquad (-) \qquad (8)$$

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

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

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

Substitution of B = 3 and c = 0.1233 m in formula (5.4) of KD 35 gives:

$$C_l = 67.945\, r\, (1 - \cos\phi) \qquad (-) \qquad (11)$$

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

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

The blade is calculated for six stations A till F which have a distance of 0.125 m of one to another (see figure 1). The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root. First the theoretical values are determined for C_l, α and β and next β is linearised such that the twist is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of a 7.14 % cambered airfoil are given in report KD 398 (ref. 4). 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	0.83	4.5	8.4	0.1233	0.60	0.77	2.06	2.5	-0.7	0.4	9.1	8.0	0.035
B	0.705	3.822	9.8	0.1233	0.70	0.70	1.75	1.7	0.6	0.6	9.2	9.2	0.051
C	0.58	3.145	11.8	0.1233	0.83	0.76	1.45	1.2	1.8	1.4	10.0	10.4	0.038
D	0.455	2.467	14.7	0.1233	1.01	0.99	1.16	1.2	3.3	3.1	11.4	11.6	0.030
E	0.33	1.789	19.5	0.1233	1.28	1.29	0.86	1.2	6.5	6.7	13.0	12.8	0.052
F	0.205	1.111	28.0	0.1233	1.63	1.32	0.59	1.2	-	14.0	-	14.0	0.215

table 1 Calculation of the blade geometry of the VIRYA-1.66 rotor

The theoretical blade angle β_{th} varies in between 9.1° and 13.0°. If a blade angle of 8° is taken at the blade tip and of 14° at the blade root, the linearised blade angles are lying close to the theoretical values. The transition part of the blade is twisted 14° to get the correct blade angle at the blade root.

7 Determination of the C_p-λ and the C_q-λ curves

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the most important outer part of the blade is about 0.04. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 4.5$ and $C_d/C_l = 0.04$ gives $C_{p\ th} = 0.43$. The blade is stalling at station F only so only the part of the blade till 0.045 m outside station F is taken for the calculation of C_p. This gives an effective blade length k' = 0.58 m.
Substitution of $C_{p\ th} = 0.43$, R = 0.83 m and blade length k = k' = 0.58 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.39$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.39 / 4.5 = 0.0867$.
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:

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

The average blade angle is 11°. For a non rotating rotor, the average angle of attack α is therefore 90° - 11° = 79°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 79° it can be read that $C_l = 0.37$. During starting, the whole blade is stalling. About 45 mm of the transition part also contributes to the starting torque. So now a blade length k = 0.67 m is taken.
Substitution of B = 3, R = 0.83 m, k = 0.67 m, $C_l = 0.37$ and c = 0.1233 m in formula 13 gives that $C_{q\ start} = 0.019$. The real start torque coefficient is somewhat lower than the calculated value because we have used the average blade angle. Assume $C_{q\ start} = 0.018$. For the ratio in between the starting torque and the optimum torque we find that it is 0.018 / 0.0867 = 0.21. 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:

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

The sticking torque Q_s of the VIRYA-1.66 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 = 0.1 Nm. Substitution of Q_s = 0.1 Nm, $C_{q\ start}$ = 0.018, ρ = 1.2 kg/m^3 and R = 0.83 m in formula 15 gives that V_{start} = 2.3 m/s. This is acceptable low for a 3-bladed rotor with a design tip speed ratio λ_d = 4.5 and a rated wind speed V_{rated} = 9 m/s.

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

Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 5). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a 7.14 % cambered 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-1.66 rotor are given in figure 3 and 4.

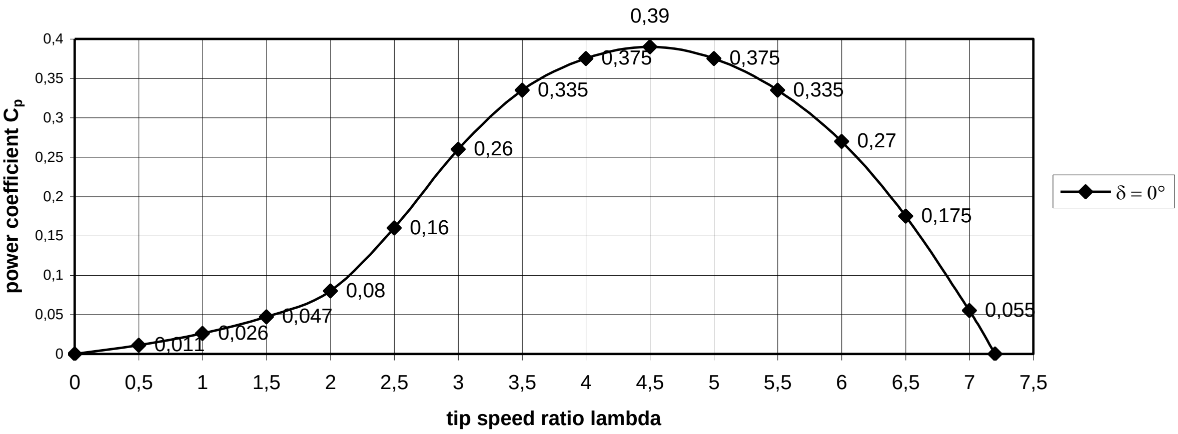

fig. 3 Estimated C_p-λ curve for the VIRYA-1.66 rotor for the wind direction perpendicular to the rotor (δ = 0°)

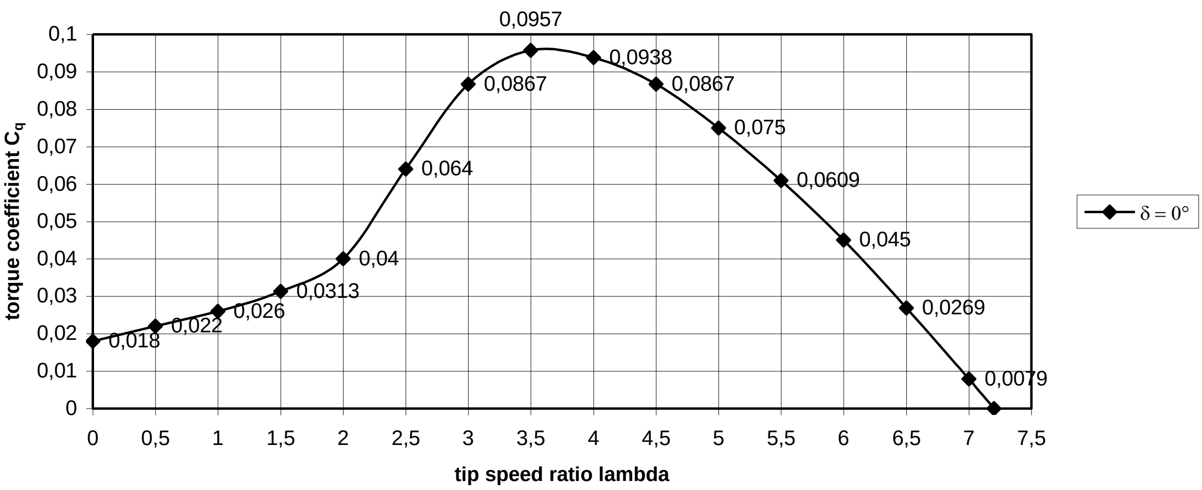

fig. 4 Estimated C_q-λ curve for the VIRYA-1.66 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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

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

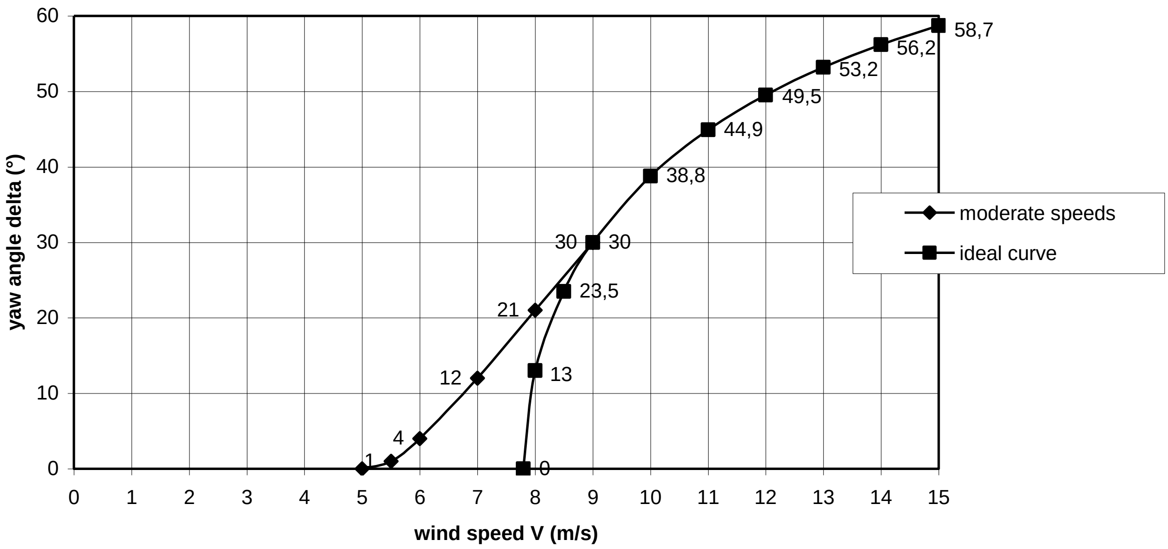

fig. 5 Estimated δ-V curve VIRYA-1.66 for a 2 mm aluminium vane blade

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator for a certain gear ratio i (the VIRYA-1.36 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves for low values of λ appear to lie very close to each other, the P-n curves are not determined for low values of λ. The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8 and 9 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 0.83 m in formula 7.1 of KD 35 gives:

$n_\delta = 11.5052 * \lambda * \cos\delta * V$ (rpm) (15)

Substitution of $\rho = 1.2 \text{ kg / m}^3$ en R = 0.83 m in formula 7.10 of KD 35 gives:

$P_\delta = 1.2985 * C_p * \cos^3\delta * V^3$ (W) (16)

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 15 and 16 and this gives the P-n curve for that wind speed.

For the higher wind speeds the yaw angle as given by figure 5, is taken into account. The result of the calculations is given in table 2.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 4°		V = 7 m/s δ = 12°		V = 8 m/s δ = 21°		V = 9 m/s δ = 30°	
λ (-)	C_p (-)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2.5	0.16	86.3	5.6	115.1	13.3	143.8	26.0	172.2	44.5	196.9	66.7	214.8	86.6	224.2	98.4
3.5	0.335	120.8	11.7	161.1	27.8	201.3	54.4	241.0	93.3	275.7	139.6	300.7	181.2	313.9	206.0
4.5	0.39	155.3	13.7	207.1	32.4	258.9	63.3	309.9	108.6	354.5	162.6	386.7	211.0	403.5	239.8
5.5	0.335	189.8	11.7	253.1	27.8	316.4	54.4	378.7	93.3	433.3	139.6	472.6	181.2	493.2	206.0
6.5	0.175	224.4	6.1	299.1	14.5	373.9	28.4	447.6	48.7	512.0	72.9	558.5	94.7	582.9	107.6
7.2	0	248.5	0	331.3	0	414.2	0	495.8	0	567.2	0	618.7	0	645.7	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-1.66 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 240 rpm, so the P_{mech}-n curve starts at 240 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 0.75 for n = 280 rpm. The efficiency is estimated to be decreased up to 0.4 for n = 520 rpm because of the copper losses in the winding, the voltage drop over the rectifier and the iron losses in the stator sheet. 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 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 = 240 W and n = 404 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 7 it was calculated that V_{start} = 2.3 m/s, so there is no hysteresis in the P_{el}-V curve.

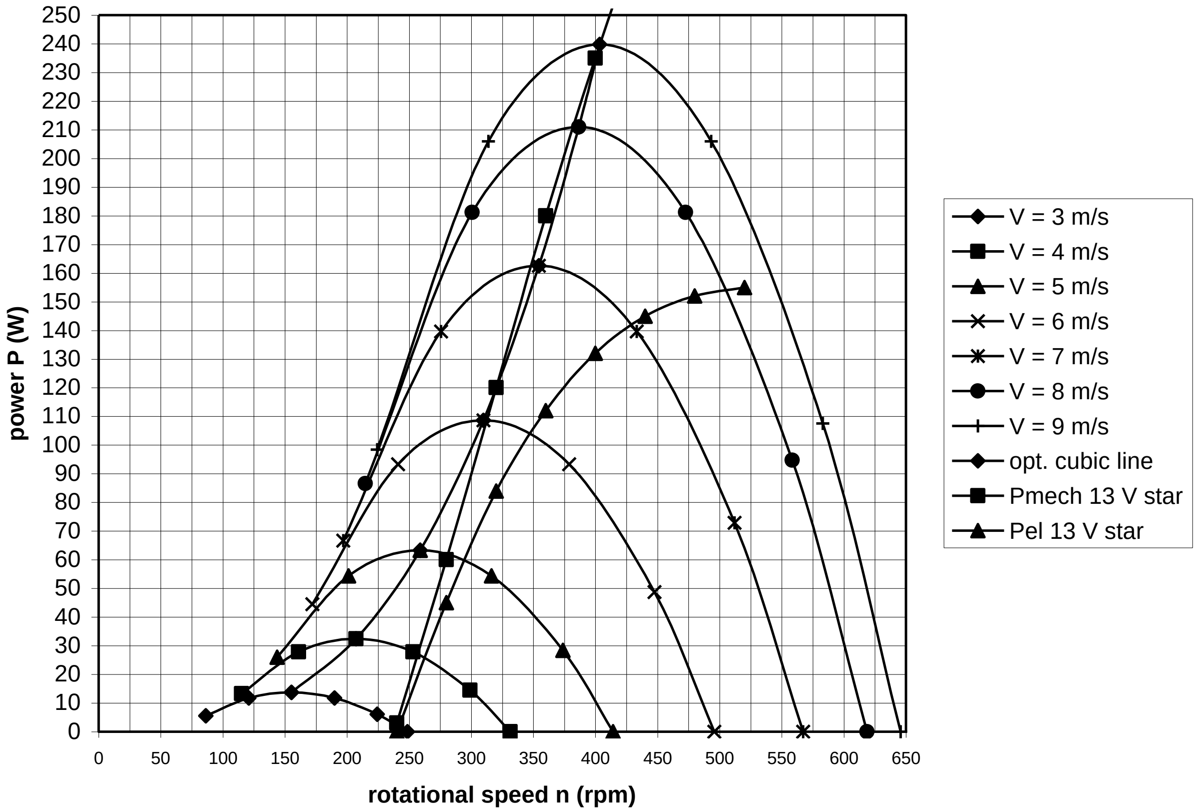

fig. 6 P-n curves of the VIRYA-1.66 rotor, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves for 12 V battery charging for the chosen winding rectified in star

The maximum electrical power is 130 W which is rather good for a windmill with a 1.66 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 9.3 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 240 W. This means that the heat losses in the winding, the rectifier and the stator sheet are 240 - 130 = 110 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.

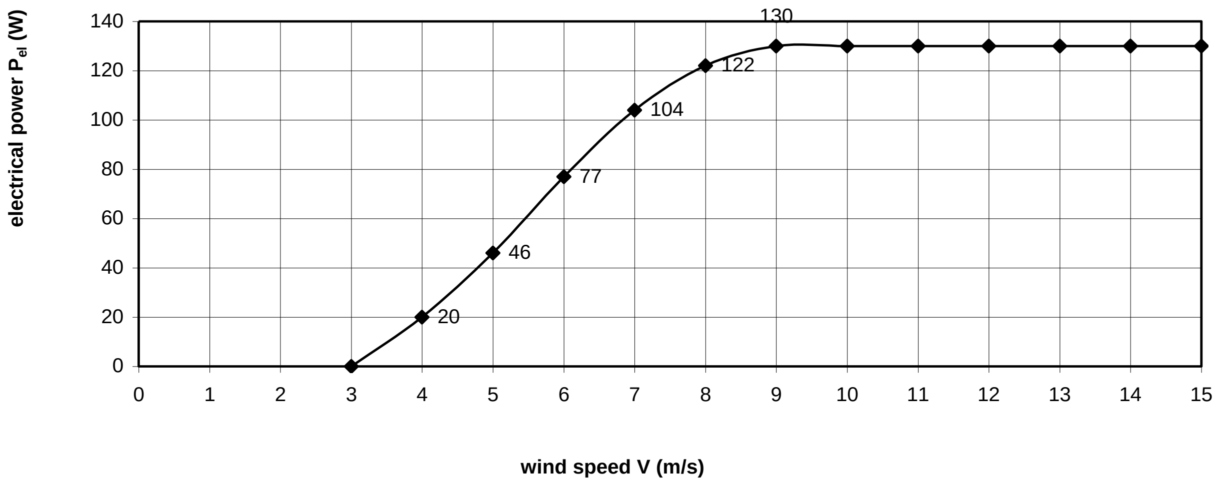

fig. 7 Estimated P_{el}-V curve of the VIRYA-1.66 windmill with V_{rated} = 9 m/s for 12 V battery charging

9 Tests to be performed to determine the winding

The estimated P_{el}-n curve given in figure 6 starts at a rotational speed of 240 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 = 240 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. 6). The winding is rectified in star. The relation in between the effective DC voltage U_{DCeff} and the effective AC voltage U_{eff} is given by formula 13 of KD 340 if the voltage drop over the rectifier U_{rect} is neglected. Formula 13 of KD 340 is copied as formula 17.

$$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff} \quad \text{(V)} \quad \text{(star rectification)} \qquad (17)$$

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 will be 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 three coils. The effective voltage of three coils is a factor 3 larger than the effective voltage of one coil $U_{eff\,1}$. This gives:

$$U_{eff} = 3 * U_{eff\,1} \quad \text{(V)} \qquad (18)$$

(17) + (18) gives:

$$U_{DCeff} = 2.865 * \sqrt{2} * \sqrt{3} * U_{eff\,1} \quad \text{(V)} \quad \text{(star rectification)} \qquad (19)$$

The following tests have to be performed to determine the optimum number of turns per coil.

A hexagon steel armature sheet and a round steel stator disk have to be made. Twelve magnets are glued to the armature sheet. The armature sheet is mounted to the flange of a permanent magnet DC motor which can be driven at variable speed. The motor current and voltage can be measured, so the absorbed electrical motor power can be calculated. The rotational speed is measured by a laser rpm meter pointing to a white dot on the motor flange.

A coil is mounted on the stator sheet and the stator sheet is mounted at the right distance of 26 mm from the armature sheet. The coil is provided with a thin wire of about 0.5 mm and with a certain number of turns per coil for instance 50. The open AC voltage is measured for a rotational speed of 240 rpm. Assume that the measured open voltage is 1.5 V. Substitution of this value in formula 19 gives U_{DCeff} = 10.5 V. The open DC voltage should be 12.5 V so the number of turns per coil has to be increased by a factor 12.5 / 10.5 = 1.19 and becomes 1.19 * 50 = 60.

Next nine coils are made with 60 turns per coil and the wire thickness is chosen such that the last turn has just an outside diameter of 58 mm. One may try wires with different thickness to find the largest possible wire thickness. Next it is checked if this winding generates an open DC voltage of 12.5 V at 240 rpm. If not, the winding has to be modified.

Next a complete generator hast to be built and measured for a real 12 V battery load or for a 12 V battery simulator which keeps the voltage at the average load voltage of 13 V. It might be possible to use the test rig which is designed for measuring of the axial flux generator of the VIRYA-1.65 windmill equipped with a Chinese axial flux generator. This test rig is described in chapter 2 of report KD 595 (ref. 7).

The drawings of the rotor and the generator have been made on A3 format and reduced to A4 format. Only these drawings are incorporated in a provisional free manual of the VIRYA-1.66 (see for remaining drawings chapter 1 of the manual ref. 8).

10 Ideas about a winding with a higher filling rate

For the original winding, the three coils of one phase are wound together on a winding thorn. This has as advantage that a bundle of three coils has only two wire ends which are labelled A and B. The wire ends labelled A are guided to the 3-phase rectifier. The wire ends labelled B are connected to each other and are forming the star point. However, making three coils together has a certain disadvantage.

Making the winding of one coil starts with the beginning wire end which is guided along the inner side of the back core flange. For the first layer all turns can be laid close to each other but the beginning wire end is disturbing the next layers and the winding becomes more chaotic if more layers are laid. Therefore it isn’t possible to fill the available space with the maximum filling rate of copper wire.

This problem can be solved if the beginning wire isn’t guided along the back core flange but if it enters the core from behind. Therefore, a small hole has to be made in the back core flange at the position of the core diameter. But in this case only a single coil can be made on the winding thorn. It also requires that two holes are made in the stator sheet for every coil and that both coil ends are guided to the back side of the stator sheet. Serial connection of the three coils of the same phase is now made at the back side of the stator sheet. This is a little more work but the filling rate will be higher and therefore thicker wire can be used for a certain number of turns per coil.

All nine coils are made identical, so they have the same winding direction. Now the wire ends of every single coil are labelled A and B and coil end A is the beginning wire end. Every wire end is covered with a short isolation tube.

U1B is connected to U2A. U2B is connected to U3A.
V1B is connected to V2A. V2B is connected to V3A.
W1B is connected to W2A. W2B is connected to W3A.
U3B, V3B and W3B are connected to each other and are forming the star point.
U1A, V1A and W1A are connected to the 3-phase rectifier which is mounted at the back side of the stator sheet.

In figure 1 it can be seen that if coil U1 is opposite a north pole, coils U2 and U3 are also opposite a north pole. So the three coils of one phase must be connected such that if the current in coil 1 is turning right hand, the current in coil 2 and 3 is also turning right hand to make that the generated voltages are strengthening each other. This is realised if all coils have the same winding direction and if the coils of the same phase are connected to each other as mentioned earlier.

It is also possible to connect all three coils of one phase in parallel but in this case the generated voltage for a certain number of turns per coil will be a factor three lower. Parallel connection might have the advantage that a thinner wire with more turns per coil can be used for 12 V battery charging and that the filling rate for a thinner wire may be higher. For parallel connection, coil ends with the same letter have to be connected to each other.

11 Ideas about an alternative 2-layers, 3-phase winding

It might be possible to get more power out of the VIRYA-1.66 generator if a different winding is used. The original winding consist of nine circular coils, so three coils for each phase. It might be possible to use a so called 2-layers, 3-phase winding which has the double number of coils and for which more copper can be put into the winding. However, for a 2-layers winding, the coils can no longer be circular and another way has to be found to make the winding.

The armature isn’t changed, so it is made out of a 3 mm hexagonal steel sheet with 12 magnets size 25.4 * 25.4 * 12.7 mm glued to it. The steel stator sheet is also kept the same, so it is made out of a 3 mm round sheet. De distance in between the sheets is also kept the same, so 26 mm. But the winding is completely different.

The stator sheet is provided with a special 2-layers, 3-phase winding. One layer has nine coils, so three coils for each phase. The original VIRYA-1.66 generator has circular coils. Circular coils are easy to manufacture but don’t have the optimal geometry and it isn’t possible to use circular coils for a 2-layers, 3-phase winding.

The armature pole angle is 30° for an armature with 12 magnets. An optimal coil has a left and a light side which are positioned radial. The optimal angle in between the hart of the left and the hart of the right side is the same as the armature pole angle, so 30° for a 12 pole armature. Suppose that the direction of the current is pointing to the outside if a north pole is passing the left side of a coil. At the same time a south pole is passing the right side of a coil and this means that there the direction of the current is pointing to the inside. For this configuration, the voltage and current generated in the left side of the coil are maximally supported by the voltage and current generated in the right side of the coil.

So the left and the right side of the coil are a part of a trapezium with an angle of 30° in between the legs. Both legs are connected to each other by an outer and an inner curved coil head. The optimal shape of these coil heads is probably a part of an ellipse. A coil is wound circular on a winding thorn but is bent in the wanted shape when the coil is mounted in the stator. However, it might also be possible to wind a coil directly in the wanted shape but this requires a special winding thorn and then winding must probably take place at a lower speed.

A synthetic stator sheet is glued and bolted with 18 screws M4 * 16 mm to the front side of the steel stator sheet. This synthetic sheet is provided with 36 radial 10 mm wide grooves numbered 1 - 36. The angle in between adjacent grooves is 10°. One coil makes use of 2 grooves so totally 18 coils can be laid in 36 grooves. The three phases are called U, V and W. The nine coils of the first layer are labelled: U1, V1, W1, U2, V2, W2, U3, V3 and W3. The nine coils of the second layer are labelled: U4, V4, W4, U5, V5, W5, U6, V6 and W6. The three coils of one phase in one layer are connected in series. The three coils of one phase are manufactured together so only one wire is used for these coils and a bundle of three coils has only two coil ends. These coil ends are labelled A for the coil with the lowest number and B for the coil with the highest number.

The three coils of a certain phase in the first layer can be connected in parallel to the three coils of the same phase in the second layer for 12 V battery charging but they can be connected in series for 24 V battery charging.

The nine coils of the first layer make use of the following grooves:
U1: 1 + 4
V1: 5 + 8
W1: 9 + 12
U2: 13 + 16
V2: 17 + 20
W2: 21 + 24
U3: 25 + 28
V3: 29 + 32
W3: 33 + 36
So the nine coils of the first layer can be laid without crossing coil heads. Every stator groove is provided with small ears at the top of each side of the groove in the same way as it is also done for the stator grooves of an asynchronous motor. A synthetic strip is shifted under the ears to close the groove when the coil is mounted. This prevents the coils coming out of the grooves and touching the magnets. The strips are 28 mm long which is that long that the whole winding is as thin as possible where it is opposed to the magnets of the armature.

The nine coils of the second layer make use of the following grooves:
U4: 19 + 22
V4: 23 + 26
W4: 27 + 30
U5: 31 + 34
V5: 35 + 2
W5: 3 + 6
U6: 7 + 10
V6: 11 + 14
W6: 15 + 18
All outer coil heads of the first layer are crossing the outer coil heads of the second layer. All inner coil heads of the first layer are crossing the inner coil heads of the second layer. The coil heads of the second layer are bent to the front side. So for this construction, the total winding is thin where it is opposed to the magnets of the armature sheet. Because of the crossing coil heads, it is much thicker at the coil heads but at that positions there are no magnets and the distance in between the coil heads and the steel armature sheet is large enough. Mounting seems no problem as the disk with magnets is approaching the stator sheet with coils from the left side during mounting of the armature sheet to the generator shaft.

A view in the direction of the coils and a cross section over the coils and the magnets is given in figure 8.

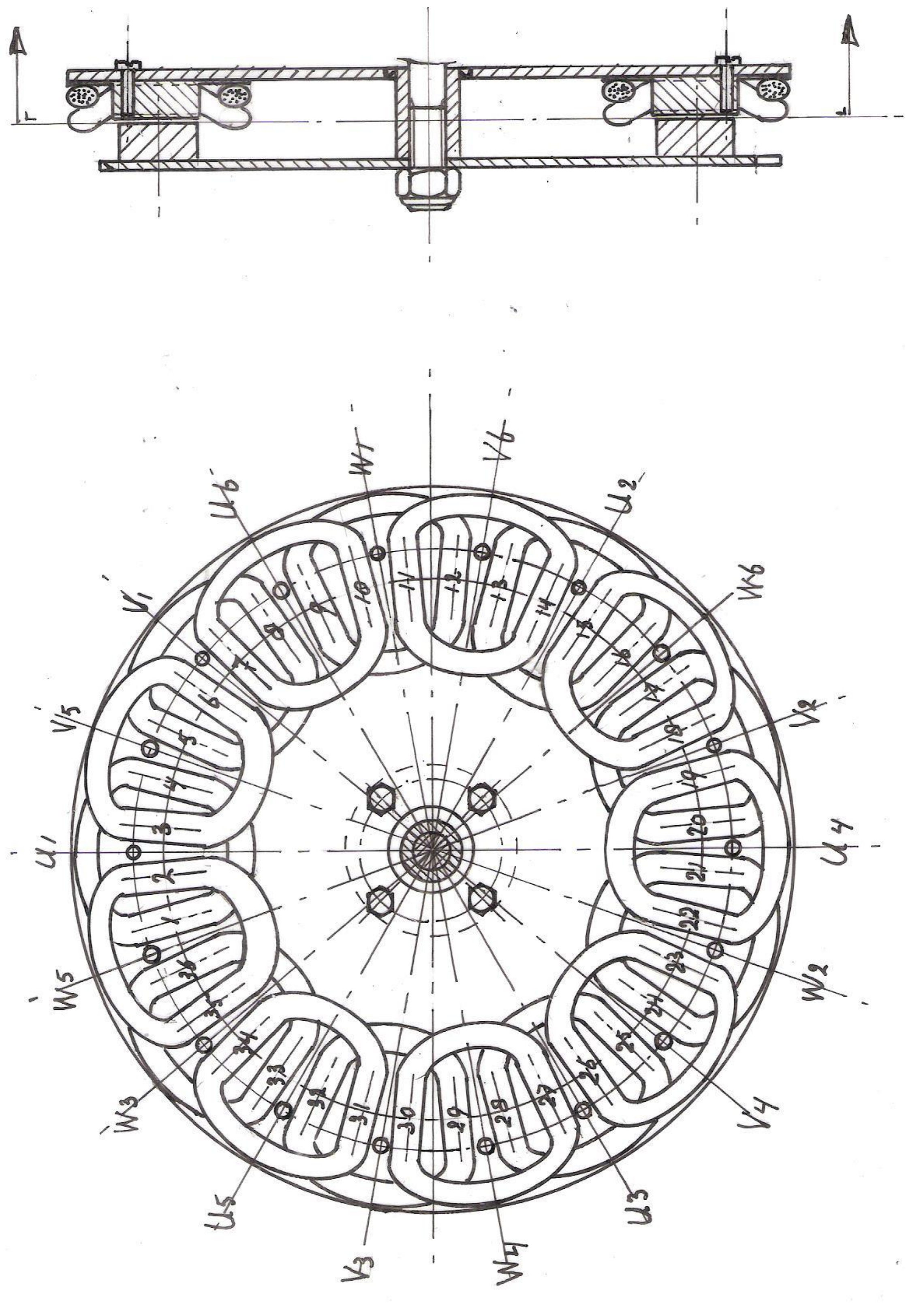

fig. 8 Alternative 2-layers, 3-phase winding for VIRYA-1.66 generator

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