# Development of an 8-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1.81 windmill using 8 neodymium magnets size ϕ 45 * 15 mm and a stator sheet made out of synthetic material. Calculation of the rotor geometry.

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## 1 Introduction

The VIRYA-1.81 is designed for manufacture in western as well as in developing countries. The VIRYA-1.81 can be used for 12 V or for 24 V battery charging depending on the connection of the stator coils. The head and tower pipe of the VIRYA-1.81 are identical to the head and tower pipe of the VIRYA-1.8. However, the VIRYA-1.8 head has a generator bracket for an asynchronous motor frame size 71. So a connecting bracket is needed with which the VIRYA-1.81 generator is connected to the VIRYA-1.8 generator bracket. For serial manufacture, one can modify the head such that the generator bracket for the VIRYA-1.81 generator is welded directly to the head pipe. The VIRYA-1.8 head has a 1 mm stainless steel vane blade and the rated wind speed for this vane blade is about 11 m/s.

The VIRYA-1.81 has an 8-pole axial flux PM-generator with a synthetic stator sheet and coils with a synthetic core. This idea of using a synthetic stator sheet is already described in report KD 608 (ref. 1) for the VIRYA-1 generator. The VIRYA-1.36 has an 8-pole axial flux PM-generator with a steel stator sheet. This generator is described in report KD 571 (ref. 2). The advantage of using a steel stator sheet is that the magnetic flux in the coils is higher than for a synthetic stator sheet and so the maximum torque level and the maximum power for a certain rotational speed are higher. The advantage of using a synthetic stator sheet is that no eddy currents are created in the sheet and this results in no heat generation in the sheet, a higher generator efficiency and a very low sticking torque at low rotational speeds. The lower magnetic flux for a synthetic stator sheet is compensated for the VIRYA-1.81 generator by using relatively large circular PM-magnets.

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

The armature consists of a square galvanised mild steel sheet with a width and height of 200 mm and a thickness of 4 mm. 50 sheets can be cut from a standard sheet size 1 * 2 m. 8 neodymium magnets size ϕ 45 * 15 mm are glued to the back side of the armature sheet at a pitch circle of 150 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. The magnet pattern is chosen such that there is just enough space for the three connecting bolts of the blades.

A rotor blade is cut out of stainless steel strip size 2 * 156 * 833 mm and 24 blades for 12 rotors can be made out of a standard sheet size 1.25 * 2.5 m with almost no waste material. A rotor blade is bolted to the front side of the armature sheet with three stainless steel hexagon bolts M8 * 30 which are shortened to 20 mm, three large washers for M8 and three self locking nuts M8. The overlap in between a blade and the armature sheet is 28 mm resulting in a rotor diameter of 2 * 833 + 200 – 2 * 28 = 1810 mm = 1.81 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 € 9.42 per magnet including VAT but excluding postage if at least 20 magnets are ordered, so the total magnet costs for one generator are about € 75 excluding postage. This seems acceptable.

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 two stator sheets can be made from one sheet. 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 VIRYA-1.81 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. 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. Rectification of a 3-phase current is explained in report KD 340 (ref. 3).

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. As 12 V is chosen at this moment, the 12-pole connector isn’t mentioned on the drawings. So both coil ends A of the same phase have to be connected to the same AC tag of the rectifier. All six coil ends B are soldered together at the back side of the stator and are forming the star point. The star point is covered with some isolation tape.

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 47 mm and a thickness of 13 mm. A coil is wound such that the maximum coil diameter is 73 mm. 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, a washer for M8 and a self locking stainless steel nut M8.

The average coil diameter is 60 mm. The distance in between the heart of two armature poles is 57.4 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 about 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.

The distance in between the steel armature sheet and the synthetic stator sheet is chosen 30 mm. The magnets have a thickness of 15 mm and the coils also have a thickness of 13 mm. So the distance in between the back side of a magnet and the front side of a coil is 2 mm.

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 Teflon disks with a diameter of 73 mm and a thickness of about 10 mm by a nut M8 and a large washer for M8. The right disk must have a 2 mm hole at a radius of 24.5 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.

Each layer of the winding is covered with some epoxy paint to prevent that the coil falls apart when it is removed from the winding thorn. The coil is only removed from the winding thorn when the epoxy is hardened. So if no long waiting time is acceptable, one needs several winding thorns to continue production.

The calculation of the flux density in the coils and the armature sheet is given in chapter 3. The determination of the wire thickness and the number of turns per coil is given in chapter 7.

The bearing housing 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 six hexagon screws M8 * 20 and six washer for M8 at a pitch circle of 61 mm. The stator sheet locks the front bearing. The bearing housing has four threaded holes M10 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.

To make it possible to use the head frame of the VIRYA-1.8, an auxiliary generator bracket must be made which can be bolted to the original generator bracket of the VIRYA-1.8 head frame and which has a sheet parallel to the rotor plane. This bracket is given as item 09 on drawing 1702-03. The bearing housing is connected to the front side of the generator bracket by four screws M10 * 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 mm 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 34 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 M16.

In figure 2 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 2 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 2 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. 3). 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.

A prototype has to be built and tested to prove that the generator is strong enough for the VIRYA-1.81. 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 with drawing numbers 1702-01, 1702-02 and 1702-03. These drawings are given at the end of a separate free manual of the rotor and the generator of the VIRYA-1.81. The drawings of the head and tower pipe and of the tower are not available for free as they belong to the VIRYA-1.8. In the folder of the free VIRYA designs, 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. 4). It is possible to test a prototype of the whole windmill on top of the 12 m high tower of the VIRYA-4.2 using the existing head and tower pipe of the VIRYA-1.8.

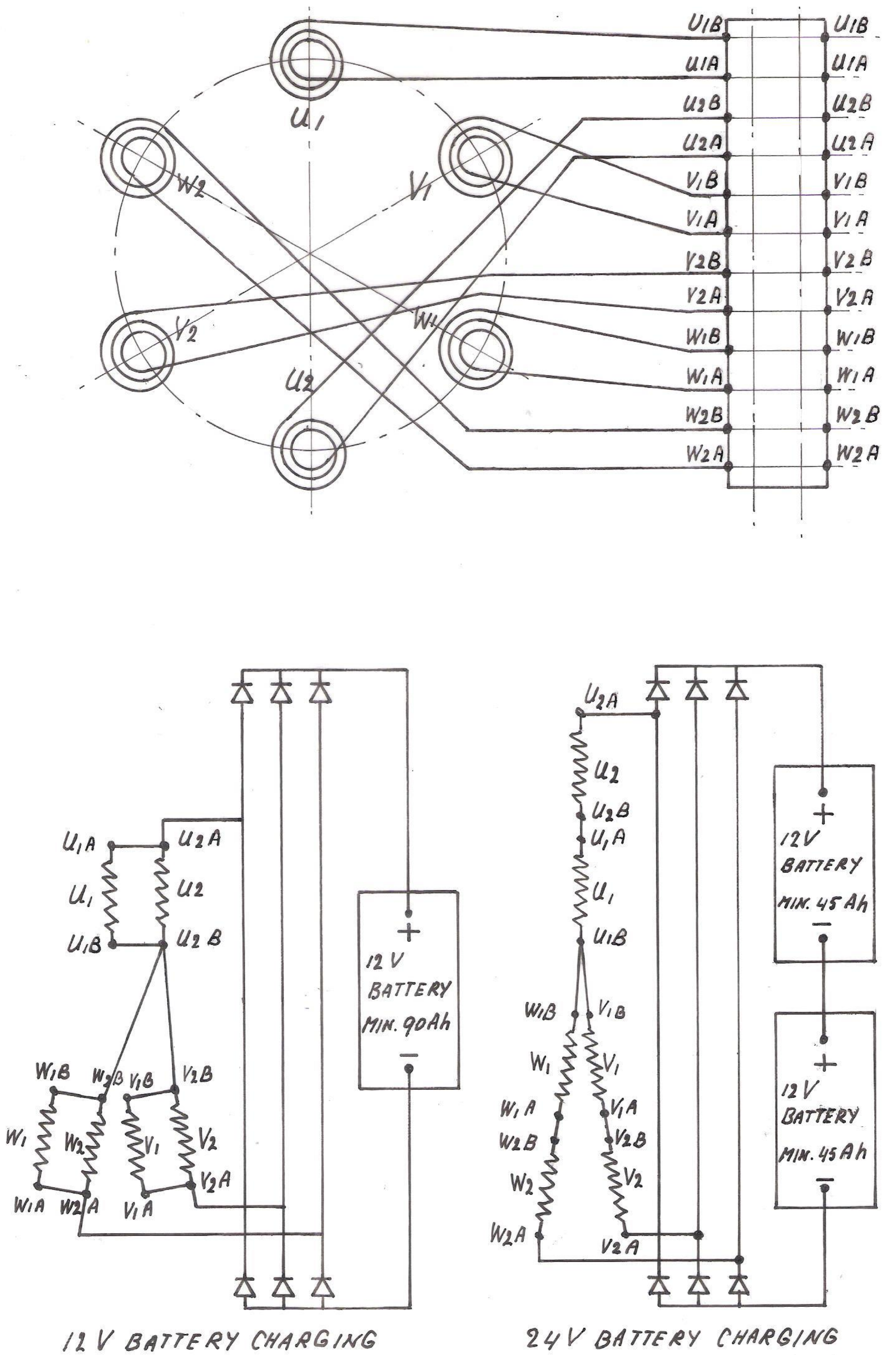


fig. 1 Sketch of the 3-phase winding. Rectification diagram for 12 V and 24 V battery charging

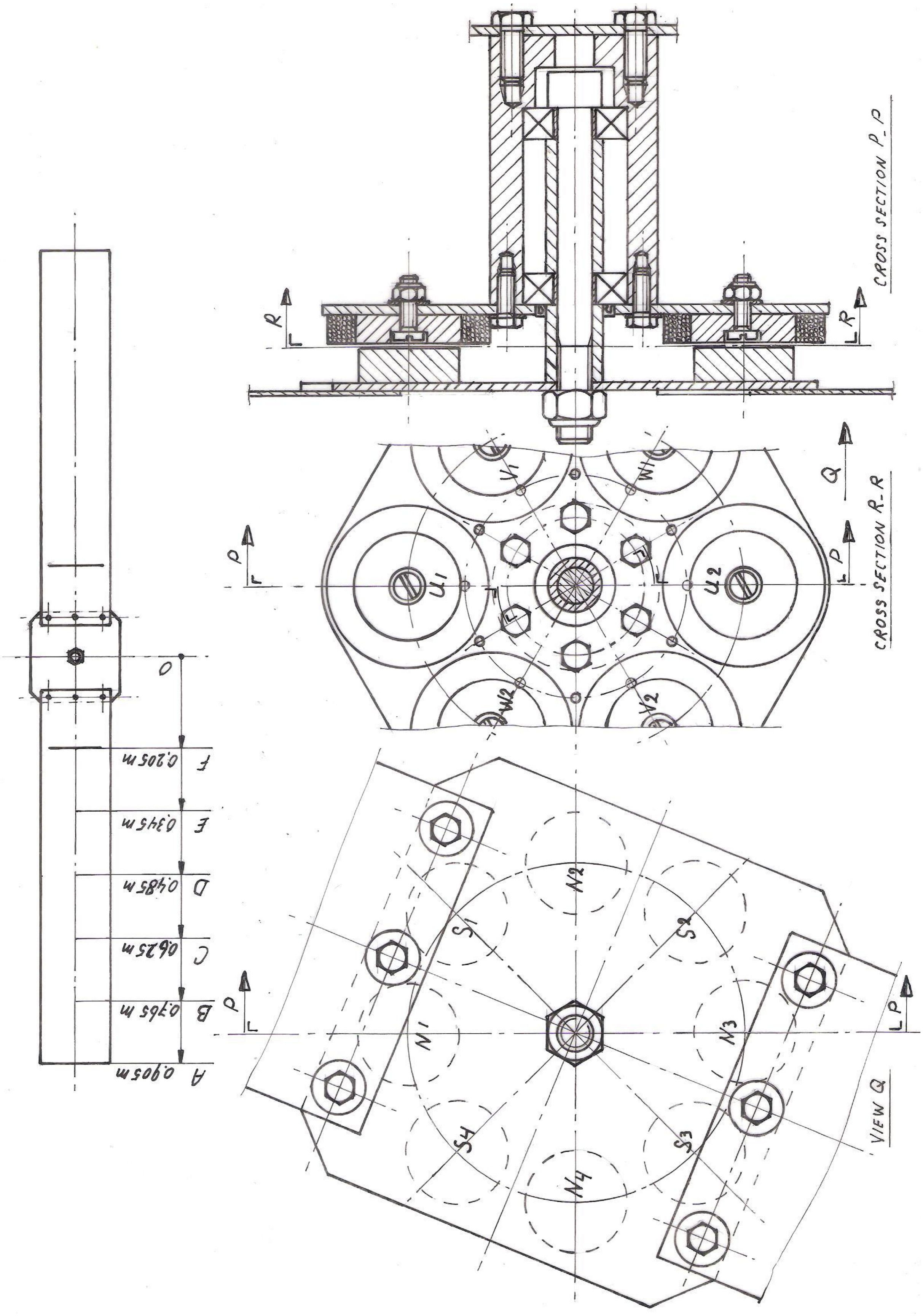


fig. 2  8-pole axial flux permanent magnet generator VIRYA-1.81

## 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 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 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 57.4 mm. Half a pole has a centre of gravity which lies at about a distance of 9 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 40 mm. The shape of a magnetic field 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 55 mm and that this length is representative for the average air gap. So $t_2 = 55$ 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:

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

Substitution of $B_r = 1.19$ T, $t_1 = 15$ mm and $t_2 = 55$ mm in formula 1 results in $B_{r\,eff} = 0.42$ T. This is much lower than the value $B_{r\,eff} = 0.623$ T which was calculated in report KD 571 for the VIRYA-1.36 generator with eight 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. To be sure if this 8-pole VIRYA-1.81 generator with a synthetic stator sheet has an acceptable maximum torque level, 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 4 mm. Let's look at magnet S1. As there is a rather large distance of about 8 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: $A_{sh} = \pi * 45 * 4 = 565\ mm^2$. $A_{mag}$ is called the magnet area and $i_1$ is called the concentration ratio in between $A_{mag}$ and $A_{sh}$.

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

Substitution of $A_{mag} = \pi/4 * 45^2 = 1590$ mm$^2$ and $A_{sh} = 565$ mm$^2$ in formula 2 gives $i_1 = 2.81$. 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 $B_{r\,eff} = 0.42$ T and $i_1 = 2.81$ in formula 3 gives $B_{r\,sh} = 1.18$ 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 16 mm hole. This bridge has a width of (200 – 16) / 2 = 92 mm. So the bridge area $A_{br} = 92 * 4 = 368$ mm$^2$. This is larger than halve $A_{sh}$ as halve $A_{sh} = 282.5$ mm$^2$. So there is also no saturation in other parts of the armature sheet.

## 4 Calculation of the geometry of the VIRYA-1.81 rotor

The 2-bladed rotor of the VIRYA-1.81 windmill has a diameter D = 1.81 m and a design tip speed ratio $\lambda_d = 5$. Advantages of a 2-bladed rotor are that no spoke assembly is required, that the rotor can be balanced easily and that it can be transported completely mounted.

The rotor has blades with a constant chord and is provided with a 7.14 % cambered airfoil. A rotor blade is made of one stainless strip with dimensions of 2 * 156 * 833 mm and 24 strips can be made out of a standard sheet of 1.25 * 2.5 m. Because the blade is cambered, the chord c is a little less than the blade width, resulting in c = 154 mm = 0.154 m. For cambering of the blades, it is possible to use a hydraulic blade press which is derived from the hydraulic blade press of the blades of the VIRYA-2.2S. However, the blade press should be made wider as the strip width of the VIRYA-1.81 blades is 156 mm and the strip width of the VIRYA-2.2S blades is 125 mm. It is also possible the make a simpler blade press according to the principle of the blade press which is given in the free manual of the VIRYA-1.04.

The camber is only made in the outer 700 mm of the blade. The inner 28 mm, where the blade is connected to the armature sheet of the generator, is flat. The 105 mm long transition part in between the flat inner part and the outer cambered part is twisted 8.5° to get the correct blade angle at the blade root.

It is assumed that the outer 65 mm of this 105 mm long part is used for the transition of camber to flat. So the inner 40 mm is not cambered. This non cambered part makes the blade rather flexible which is necessary to prevent vibrations due to the gyroscopic moment.

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 6). This report (KD 631) has its own formula numbering. Substitution of $\lambda_d = 5$ and R = 0.905 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 5.5249 * r \qquad (-) \qquad (4)$$

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

$$\beta = \phi - \alpha \qquad (°) \qquad (5)$$

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

Substitution of B = 2 and c = 0.154 m in formula (5.4) of KD 35 gives:

$$C_l = 81.60\, r\, (1 - \cos\phi) \qquad (-) \qquad (7)$$

Substitution of V = 5.5 m/s and c = 0.154 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.565 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (8)

The blade is calculated for six stations A till F which have a distance of 0.14 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 1 mm aluminium vane blade is about 11 m/s. The aerodynamic characteristics of a 7.14 % cambered airfoil are given in report KD 398 (ref. 7). The Reynolds values for the stations are calculated for a wind speed of 5.5 m/s because this is a reasonable wind speed for a windmill which is designed for a rated wind speed of 11 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

| station | r (m) | $\lambda_{rd}$ (-) | 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 % | $\alpha_{th}$ (°) | $\alpha_{lin}$ (°) | $\beta_{th}$ (°) | $\beta_{lin}$ (°) | $C_d/C_{l\,lin}$ (-) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.905 | 5 | 7.5 | 0.154 | 0.64 | 0.54 | 2.85 | 2.5 | -0.5 | -1.0 | 8.0 | 8.5 | 0.064 |
| B | 0.765 | 4.227 | 8.9 | 0.154 | 0.75 | 0.78 | 2.42 | 2.5 | 0.2 | 0.4 | 8.7 | 8.5 | 0.039 |
| C | 0.625 | 3.453 | 10.8 | 0.154 | 0.90 | 0.88 | 1.99 | 1.7 | 2.5 | 2.3 | 8.3 | 8.5 | 0.040 |
| D | 0.485 | 2.680 | 13.6 | 0.154 | 1.12 | 1.15 | 1.56 | 1.7 | 4.7 | 5.1 | 8.9 | 8.5 | 0.048 |
| E | 0.345 | 1.906 | 18.5 | 0.154 | 1.45 | 1.42 | 1.14 | 1.2 | - | 10.0 | - | 8.5 | 0.10 |
| F | 0.205 | 1.133 | 27.6 | 0.154 | 1.91 | 1.27 | 0.74 | 1.2 | - | 19.1 | - | 8.5 | 0.31 |

table 1 Calculation of the blade geometry of the VIRYA-1.81 rotor

No value for $\alpha_{th}$ and therefore for $\beta_{th}$ is found for stations E and F because the required $C_l$ values can not be generated. The theoretical blade angle $\beta_{th}$ varies only in between 8.0° and 8.9°. If a constant blade angle of 8.5° is taken, the linearised blade angles are lying close to the theoretical values. So the cambered part of the blade isn't twisted. The transition part of the strip 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 0.045. Figure 4.6 of KD 35 (for B = 2) and $\lambda_{opt} = 5$ and $C_d/C_l = 0.045$ gives $C_{p\,th} = 0.4$. The blade is stalling in between station E and F so only the part of the blade till 0.05 m outside station F is taken for the calculation of $C_p$. This gives an effective blade length k' = 0.65 m.
Substitution of $C_{p\,th} = 0.4$, R = 0.905 m and blade length k = k' = 0.65 m in formula 6.3 of KD 35 gives $C_{p\,max} = 0.37$. $C_{q\,opt} = C_{p\,max} / \lambda_{opt} = 0.37 / 5 = 0.074$.
Substitution of $\lambda_{opt} = \lambda_d = 5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 8$.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

The average blade angle is 8.5° for the whole blade. For a non rotating rotor, the average 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. So now the real cambered blade length k = 0.7 m is taken.

Substitution of B = 2, R = 0.905 m, k = 0.7 m, $C_l$ = 0.29 and c = 0.154 m in formula 9 gives that $C_{q\ start}$ = 0.011. For the ratio in between the starting torque and the optimum torque we find that it is 0.011 / 0.074 = 0.15. This is acceptable for a rotor with a design tip speed ratio $\lambda_d$ = 5.

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

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

The sticking torque $Q_s$ of the VIRYA-1.81 generator will be very low because there is no iron in the coils and in the stator sheet. Only the bearings and the oil seal will give some little friction. It is estimated for $Q_s$ that $Q_s$ = 0.1 Nm. Substitution of $Q_s$ = 0.1 Nm, $C_{q\ start}$ = 0.011, ρ = 1.2 kg/m$^3$ and R = 0.905 m in formula 10 gives that $V_{start}$ = 2.6 m/s. This is acceptable for a 2-bladed rotor with a design tip speed ratio $\lambda_d$ = 5 and a rated wind speed $V_{rated}$ = 11 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. 8). 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-1.81 rotor are given in figure 3 and 4.

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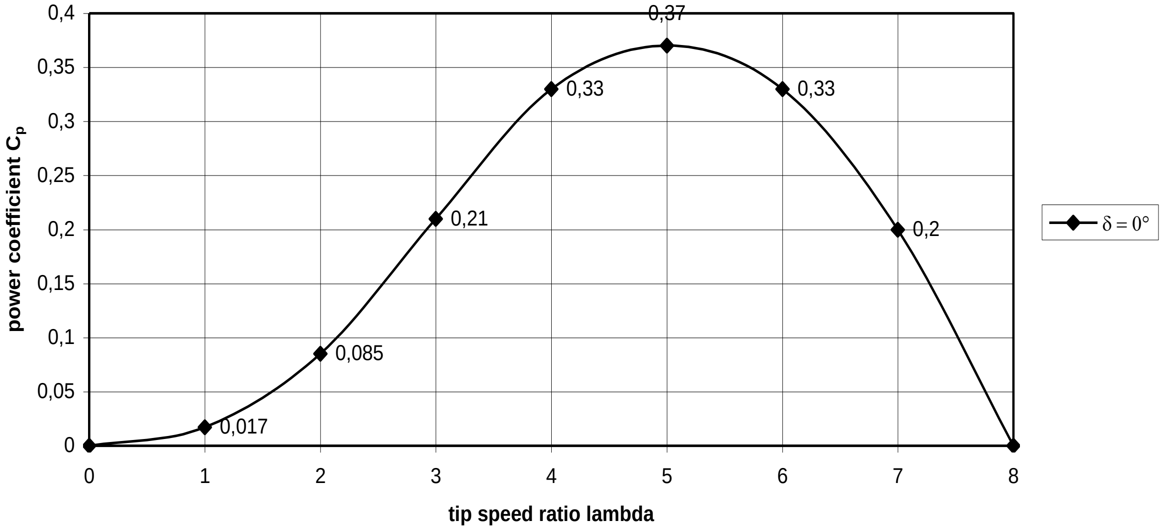


fig. 3 Estimated $C_p$-λ curve for the VIRYA-1.81 rotor for the wind direction perpendicular to the rotor (δ = 0°)

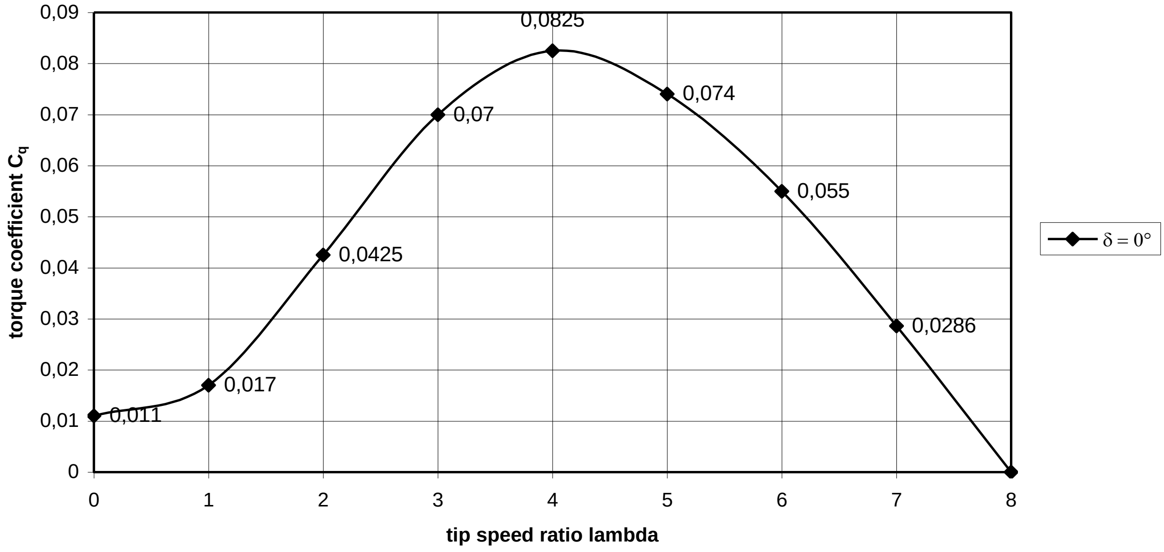


fig. 4 Estimated $C_q$-λ curve for the VIRYA-1.81 rotor for the wind direction perpendicular to the rotor (δ = 0°)

## 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 1 mm stainless steel. The rated wind speed for this vane blade is about 11 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 11 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 11 m/s will therefore also be valid for wind speeds higher than 11 m/s.

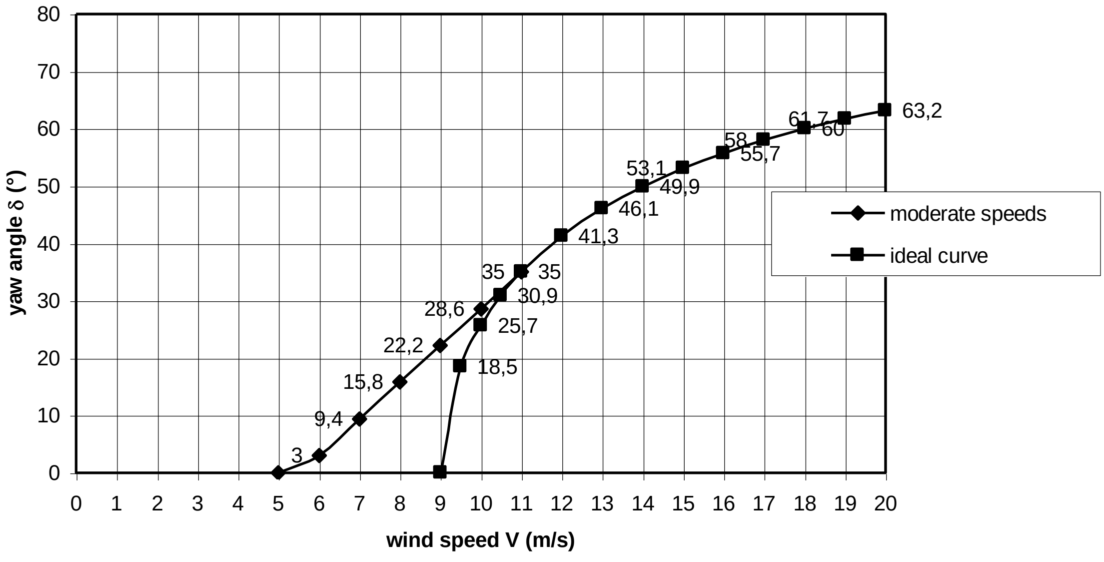


fig. 5 Estimated δ-V curve VIRYA-1.81 for a 1 mm stainless steel vane blade

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-1.81 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves for low values of λ appear to lie very close to each other, the P-n curves are not determined for low values of λ. The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10 and 11 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 = 0.905 m in formula 7.1 of KD 35 gives:

$n_\delta = 10.552 * \lambda * \cos\delta * V$ (rpm) (11)

Substitution of $\rho = 1.2$ kg / $m^3$ and R = 0.905 m in formula 7.10 of KD 35 gives:

$P_\delta = 1.5438 * C_p * \cos^3\delta * V^3$ (W) (12)

The P-n curves are determined for $C_p$ values belonging to λ = 2, 3, 4, 5, 6, 7 and 8. (see figure 3). For a certain wind speed, for instance V = 3 m/s, related values of $C_p$ and λ are substituted in formula 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 = 3° | | V = 7 m/s δ = 9.4° | | V = 8 m/s δ = 15.8° | | V = 9 m/s δ = 22.2° | | V = 10 m/s δ = 28.6° | | V = 11 m/s δ = 35° | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| λ (-) | $C_p$ (-) | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) |
| 2 | 0.085 | 63.3 | 3.5 | 84.4 | 8.4 | 105.5 | 16.4 | 126.5 | 28.2 | 145.7 | 43.2 | 162.5 | 59.9 | 175.9 | 75.9 | 185.3 | 88.8 | 190.2 | 96.0 |
| 3 | 0.21 | 95.0 | 8.8 | 126.6 | 20.7 | 158.3 | 40.5 | 189.7 | 69.7 | 218.6 | 106.8 | 243.7 | 147.9 | 263.8 | 187.6 | 277.9 | 219.4 | 285.2 | 237.2 |
| 4 | 0.33 | 126.6 | 13.8 | 168.8 | 32.6 | 211.0 | 63.7 | 252.9 | 109.6 | 291.5 | 167.8 | 324.9 | 232.4 | 351.7 | 294.8 | 370.6 | 344.8 | 380.3 | 372.7 |
| 5 | 0.37 | 158.3 | 15.4 | 211.0 | 36.6 | 263.8 | 71.4 | 316.1 | 122.9 | 364.4 | 188.1 | 406.1 | 260.5 | 439.6 | 330.5 | 463.2 | 386.6 | 475.4 | 417.9 |
| 6 | 0.33 | 189.9 | 13.8 | 253.2 | 32.6 | 316.6 | 63.7 | 379.4 | 109.6 | 437.2 | 167.8 | 487.4 | 232.4 | 527.6 | 294.8 | 555.9 | 344.8 | 570.5 | 372.7 |
| 7 | 0.2 | 221.6 | 8.3 | 295.5 | 19.8 | 369.3 | 38.6 | 442.6 | 66.4 | 510.1 | 101.7 | 568.6 | 140.8 | 615.5 | 178.6 | 648.5 | 209.0 | 665.6 | 225.9 |
| 8 | 0 | 253.2 | 0 | 337.7 | 0 | 422.1 | 0 | 505.8 | 0 | 583.0 | 0 | 649.8 | 0 | 703.4 | 0 | 741.2 | 0 | 760.6 | 0 |

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-1.81 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 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 0.85 for n = 300 rpm. The efficiency is estimated to be 0.5 for n = 600 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 star in figure 6 for a 12 V / 24 V winding with both coils of one phase connected in parallel. 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 7).

The matching of rotor and generator is good for wind speeds in between 4 and 11 m/s because the $P_{mech}$-n curve of the generator is lying close to the optimum cubic line.

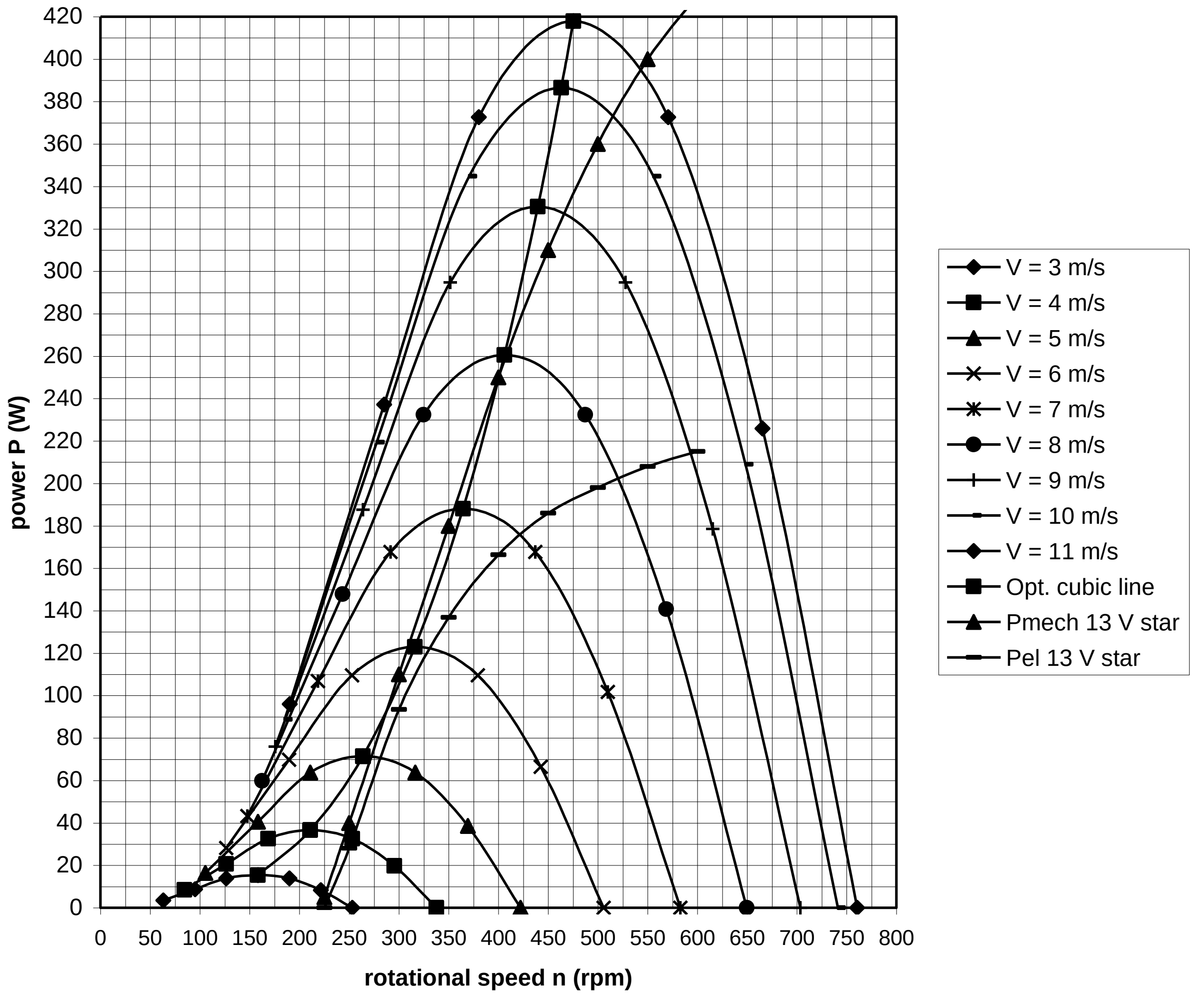


fig. 6 P-n curves of the VIRYA-1.81 rotor and a 1 mm stainless steel vane blade, optimum cubic line, estimated $P_{mech}$-n and $P_{el}$-n curves for 12 V battery charging for the chosen 12 V / 24 V winding for parallel connection of the two coils of one phase

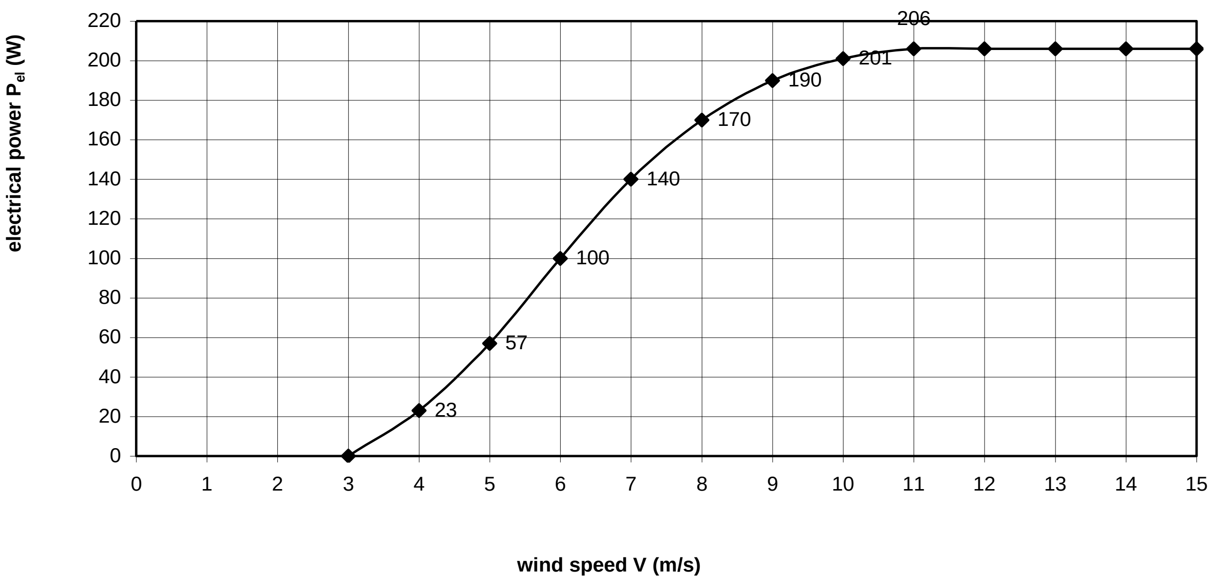


fig. 7 $P_{el}$-V curve of the VIRYA-1.81 windmill with $V_{rated}$ = 11 m/s for 12 V battery charging

The supply of power starts already 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.

The maximum power is about 206 W which is acceptable for a rotor with 1.81 m diameter and for a rated wind speed of 11 m/s. It seems possible to use the 200 W battery charge controller which is described in a free manual (ref. 9). However, this controller is meant for a 24 V battery. If it is chosen to use the VIRYA-1.81 for 12 V battery charging, the resistance of the two resistors on the dump load has to be changed.

In figure 6 it can be seen that the mechanical power is 394 W for V = 11 m/s. The electrical power is 206 W so the heat dissipation in the copper of the winding and in the rectifier is 394 – 206 = 188 W. At maximum power, the real charging voltage will be about 14 V for a 12 V battery. The current for an electrical power of 206 W and a voltage of 14 V is 14.7 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 21 W. So the heat loss in the copper winding is 188 – 21 = 167 W. This seems acceptable as the generator is cooled well by the wind when the maximum power is generated. But it must be checked for a prototype if this heat dissipation isn't causing a too high temperature of the winding.

If the generator is used for 12 V battery charging, the maximum DC current is about 14.7 A which is rather high. So the cross sectional copper area of the cable to the battery must be rather large to prevent large cable losses. The rectifier is mounted at the generator, so the cable to the battery must have two wires or four wires with two times two wires connected in parallel. The VIRYA-1.8 head has a head pin with a 10.5 mm central hole through which the cable is guided. This hole isn't large enough for a 4-phase wire size 4 * 2.5 $mm^2$ with rubber casing. However, it is possible to use four separate flexible automotive wires 2.5 $mm^2$ and connect two wires in parallel such creating two wires of 5 $mm^2$. A water tight connector at the tower foot connects this wire to a 4 phase ground cable with massive copper wires size 4 * 2.5 $mm^2$. The voltage drop over this cable seems acceptable if the cable isn't very long. The connector can also be used to neutralise too much cable twist. For 24 V battery charging, the current is half the current as for 12 V battery charging and the cables can be a factor four smaller for the same losses.

**7 Determination of the winding**

The estimated $P_{el}$-n curve given in figure 6 starts at a rotational speed of 225 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 = 225 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. 3). Assume it is chosen to use a 12 V / 24 V winding for 12 V battery charging. So both coils of one phase are connected in parallel. 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.

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

$U_{eff}$ is the effective AC voltage of one complete phase. One complete phase has two coils in parallel for the chosen winding and for 12 V battery charging. So the effective AC voltage of one coil is the same as for two coils in parallel. So formula 13 is also valid for one coil.

Formula 13 can be written as:

$U_{eff} = 0.427 * U_{DCeff}$ (V) (star rectification) (14)

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. 4). 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-1.81 generator also has a rather high maximum torque level and therefore the reducing chain transmission must also be used to test a prototype of the VIRYA-1.81 generator.

The armature sheet has to be mounted to the slow shaft of the test rig. 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. The DC voltage and current are measured with digital universal meters. 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 a first indication of the required number of turns per coil and the required wire thickness can be found if the following procedure is followed.

Substitution of $U_{DCeff}$ = 12.5 V in formula 14 gives that $U_{eff}$ = 5.34 V. So the effective AC voltage of one coil must be 5.34 V at n = 225 rpm.

Assume that all generator components are made and that the generator is mounted with eight magnets glued to the armature sheet. However, only one coil core is connected to the stator sheet. Assume that enamelled copper wire with a thickness of 1 mm is available. One coil core with flanges is made. Assume that it is possible to lie 200 turns on the coil core for an outside coil diameter of 73 mm. The steel armature sheet is connected to the slow shaft of the test. It must be prevented that the stator sheet rotates with the armature.

Next the effective open AC voltage is measured for a rotational speed of 225 rpm. Assume that it is measured that $U_{eff}$ = 3.5 V. So this means that the number of turns per coil has to be increased by a factor 5.34 / 3.5 = 1.526 and becomes 1.526 * 200 = 305.

The wire must be thinner for 305 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 $\sqrt{(1 / 1.526)}$ = 0.81. So it should become 0.81 * 1 = 0.81 mm. The available closest standard wire diameter is 0.8 mm so this wire diameter is chosen. The final number of turns per coil is chosen a little higher because of the voltage drop over the rectifier. Assume that the final number of turns per coil is 310.

Next at least three coils have to be made with this wire thickness and this number of turns per coil and the open DC voltage has to be measured for 225 rpm. If it is about 12.5 V for star rectification, three more coils are made and then the $P_{mech}$-n and $P_{el}$-n curves can be measured for a real 12 V battery as load or for a battery charge controller adjusted at 13 V. If the curves are almost the same as the estimated curves, the generator is ready.

If the matching of the $P_{mech}$-n curve with the optimum cubic line of the rotor isn't well, one has to measure the generator again for a higher or for a lower voltage. Assume that now the matching is optimal for a voltage of 11 V. This means that the number of turns per coil has to be increased by a factor 13 / 11 = 1.182 and becomes 1.182 * 310 = 366.

However, the maximum coil diameter might become too large for this number of turns per coil if a wire diameter of 0.8 mm is maintained. So one has to take one size lower and chose a wire diameter of 0.71 mm. With this new wire diameter and this new number of turns per coil, six new coils are made and the $P_{mech}$-n and $P_{el}$-n curves for 13 V are measured again. It can be expected that now the matching will be good for 13 V star. So finding of the optimum number of turns per coil and the optimum wire diameter is a lot of work.

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