INTERNATIONAL JOURNAL FOR TRENDS IN ENGINEERING & TECHNOLOGY
VOLUME 32 ISSUE 1 – AUGUST 2018 - ISSN: 2349 – 9303

Axial Flux Genarator

Ganesh.A[1],AravindhSamy.T[2],Damodhran.S[3]
Ganesh moorthy.k[4]
Excel college of Engineering and Technology
ganeshcoolbaby1@gmail.com

Dr.V.S.Arul murugan[5] ME,PhD
Department of EEE
Excel college of Engineering and Technology

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

Index Terms –Axial Flux Generator**,** battery, Kragten Design ,windmill

Introduction

The first version of the VIRYA-1 windmill isdescribed in report KD 574 (ref. 1). The first version has a 6-pole axial flux generator with a 2-phase winding and a steel stator sheet. The eddy currents in the stator sheet create a sticking torque which increases about proportional to the rotational speed. At this moment it is thought that an 8-pole generator with a 3-phase winding and a synthetic stator sheet is a better choice and report KD 574 is therefore cancelled. The rotor calculations out of KD 574 are now given in this new report KD 608.The VIRYA-1 makes use of the head and tower of the VIRYA-1.04. The VIRYA-1.04 with a 3-bladed rotor is described in report KD 518 (ref. 2). The drawings of the VIRYA-
1.04 are given in a separate free manual (ref. 3). The VIRYA-1.04 makes use of a Nexus hub dynamo. The advantage is that therefore it isn't necessary to build a generator. However, a hub dynamo has some disadvantages of which the most important are that the maximum power is very low (about 6 W) and that there is a large peak on the sticking torque. This requires a rotor with a high starting torque coefficient other wise the starting wind speed will be much too high. The VIRYA-1.04 has a 1.5 mm aluminium vane blade which gives a rated wind speed of about 8 m/s. However, a 2 mm aluminium vane blade is used for the VIRYA-1 resulting in a rated wind speed of about 9 m/s.The idea is to develop an 8-pole, 3-phase axial flux generator with a synthetic stator sheet. So no eddy currents will be generated and therefore the sticking torque will be zero. However, using a synthetic stator sheet in stead of a steel stator sheet reduces the magnetic flux flowing through the coils as the magnetic air gap becomes much longer. The generated voltage per turn will therefore be lower and the maximum power will therefore be lower too. A way to compensate this is too use eight strong magnets and a 3-phase winding.

Description of the generator

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

For the bearing housing of the generator an old hub of the front wheel of a mountain bike is used. This hub has an aluminium casing with two flanges. Each flange has eighteen 3 mm holes for the spokes at a pitch angle of 20° and at a pitch circle of 45 mm. The hole pattern in the front flange is shifted 10° with respect to the hole pattern in the back flange. For both flanges, six holes at a pitch angle of 60° are enlarged up to a diameter of 4 mm. The hole pattern of the six 4 mm holes in the front flange is shifted 30° with respect to the hole pattern of the six 4 mm holes in the back flange. A drill press has to be used for accurate drilling. The shaft has to be removed and a large ring with parallel sides has to be mounted in between the bed of the drill press and the lower flange.The rotor blades are connected to the front flange by six stainless steel screws M4 * 10, six stainless steel washers for M4 and six self locking nuts M4. The armature sheet of the generator is connected to the back flange, by six stainless steel screws M4 * 10 and six self locking nuts M4. There are hubs with smaller flanges and smaller pitch circles of the spoke holes. These hubs can also be used if the hole pattern in the rotor and the armature sheet is adjusted.

The bicycle hub has a threaded shaft with a diameter of about 9.4 mm. The 9 mm hole in the head frame of the VIRYA-1.04 has to be enlarged up to 9.5 mm. Standard, both shaftends which are jutting out of the hub are of equal length but the bearing cones are twisted such that one shaft end is about 22 mm longer than the other. The hub is mounted such that the longest shaft end is at the side of the head frame. The armature sheet is made from a square galvanised steel sheet size 125 * 125 * 3 mm with the corners bevelled such that the sheet becomes octagonal. 200 armature sheets can be made from a standard sheet size 1.25 * 2.5 m. The eight magnets are glued by epoxy to the back side of the armature sheet such that four north and four south poles are created. The pitch circle of the magnets is chosen 95 mm.

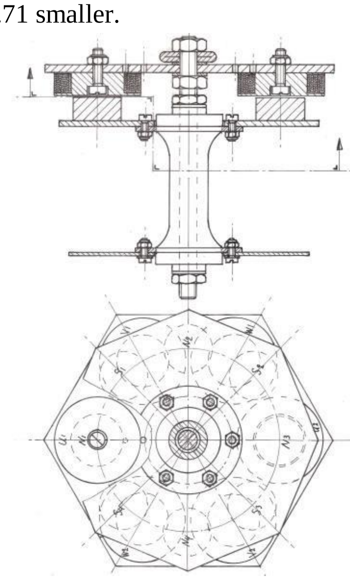
The hexagonal stator sheet is made from 4 mm brown Phenolic Fabric. This material is flat and very stiff and is not absorbing water. It is supplied by for instance the company RS, website: www.rsonline.nl. It is supplied by RS as a sheet with size 4 * 285 * 590 mm and eight stator sheets can be made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

The stator has a 3-phase winding with totally six coils, so two coils per phase. The coils are called U1, U2, V1, V2, W1 and W2. The coils are positioned every 60°. Opposite coils are of the same phase. The pitch circle of the cores is 95 mm too. A core is made of polyacetal (polyoxymethylene or POM, supplied as Delrin, Ertacetal and Hostaform). A core is connected to the stator sheet by a stainless steel screw M5 * 20 mm and a self locking nut M5.

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

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

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



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

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

The three coil ends U2B, V2B and W2B are connected to each other and are forming the star point. The three coil ends U1A, V1A and W1A are connected to the three AC point of a 3-phase rectifier which is mounted to the back side of the stator sheet. The coil ends are covered by an extra isolation tube. A 2-pole flexible cable with wires of 2 * 1.5 mm2 connects the rectifier to a 12 V battery of minimum 30 Ah. The calculation of the flux density in the coils and in the armature sheet is given in chapter 3. The procedure how the wire thickness and the number of turns per coil are determined, is given in chapter 8. The 3-phase winding and the armature poles are drawn in figure 1. Figure 1 is drawn such that pole N1 is opposite to coil U1. In figure 1 it can be seen that if coil U1 is opposite to a north pole, coil U2 is also opposite to a north pole. So the winding direction of coil U2 must be the same as the winding direction of coil U1 to realise that the voltage generated in U2 is strengthening the voltage generated in U1. In figure 1 it can be seen that a north pole is at the same position after 90° rotation of the armature. So a phase angle of 360° corresponds to a rotational angle of 90°. The frequency of the AC voltage will be four times higher than the rotational speed of the armature in revolutions per second. In figure 1 it can be seen that there is an angle of 30° in between north pole N2 and coil V1. So this angle corresponds with a phase angle of 120°. In figure 1 it can be seen that there is an angle of 60° in between north pole N3 and coil W1. So this angle corresponds with a phase angle of 240°. The winding therefore is a normal 3- phase winding. The fluctuation of the DC voltage and the DC current for a 3-phase winding is explained in chapter 3.2.1 of report KD 340 (ref. 4). The fluctuation is only little if the variation of the magnetic flux is sinusoidal. The variation of the magnetic flux is not sinusoidal for an axial flux generator, especially if rectangular magnets are used but for circular magnets it is assumed that the variation is about sinusoidal and that so the fluctuation of the DC voltage and current is only little. This has as advantage that the battery is not loaded and unloaded with a high frequency if the battery is charged by the windmill and simultaneously discharged by a load. Charging and discharging with a high frequency has an unfavourable influence on the lifetime of the battery. The three phases are connected in star. Assume the 12 V option is chosen for a 6 V / 12 V winding. So both coils of one phase have to be connected in series in the correct way. This means that coil end U1B has to be connected to coil end U2A, that coil end V1B has to be connected to coil end V2A and that coil end W1B has to be connected to coil end W2A .

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Calculation of the flux density in the air gap and the armature sheet

A calculation of the flux density in the air gap for the current VIRYA generators is given in chapter 5 of KD 341 (ref. 5). However, the magnet configuration of this new type PM- generator is completely different and so the formulas out of KD 341 can't be used. A radial flux PM-generator with a laminated stator is normally designed such that the magnetic field in the stator is just saturated. For this condition, the generator has its maximum torque level and this means that it can supply the maximum electrical power for a certain rotational speed. However, for this new axial flux generator it is not allowed that the armature sheet is saturated because a saturated sheet will reduce the magnetic flux in the air gap. The iron of a steel sheet is saturated at a flux density of about 1.6 Tesla (T). The remanence Br (magnetic flux) in a neodymium magnet with quality N38 is about 1.24 T if the magnet is short-circuited with a mild steel arc which is not saturated. However, an air gap in the arc reduces themagnetic 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 t1. 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 t1. The length of the magnetic air gap is called t2. The length of t2 is difficult to determine because for a 180° bend, it differs for all field lines. The distance in between the heart of a north pole and the heart of a south pole is 36.4 mm. Half a pole has a centre of gravity which lies at about a distance of 5 mm from the magnet heart. So the distance in between the centres of gravity of half a north pole and halve a south pole is about 26 mm. The shape of a magnetic filed line in the air gap is about halve an ellipse. It is assumed that the length of the ellipse which connects the centres of gravity is about 36 mm and that this length is representative for the average air gap. So t2 = 36 mm.

The air gap results in an increase of the magnetic resistance by a factor (2 t1 + t2) / 2 t1. This results in decrease of the remanence Br to the effective remanence Br eff. Br eff is given by:

$Br\ eff = Br * 2\ t1 / (2\ t1 + t2)$ (T) (1)

Substitution of Br = 1.24 T, t1 = 12 mm and t2 = 36 mm in formula 1 results in Br eff =
0.496 T.

This is lower than the value Br eff = 0.623 T which was calculated in report KD 574 for the VIRYA-1 generator with six magnets size
25.4 * 25.4 * 12.7 and a 3 mm steel stator sheet but this is the consequence of using a synthetic stator sheet. So Br eff is a factor
0.496 / 0.623 = 0.796 lower. However, it is expected that the 3-phase winding of the 8- pole generator is more effective than the 2- phase winding of the 6-pole generator and that this compensates the lower flux density in the air gap. To be sure if this alternative 8- pole generator has an acceptable maximum power and an acceptable efficiency, it is necessary to build and measure a prototype. Next it is checked if the iron of the armature sheet isn't saturated. The sheet has a thickness of 3 mm. Let's look at magnet S1. As there is a rather large distance of about 6 mm in between a magnet and the outside of the armature sheet, the magnetic flux coming out of magnet S1 can flow in all directions of the

armature sheet. So in the steel sheet, the magnet flux has to pass a circular area with the circumference of a magnet and a height identical to the thickness of the sheet. This area has a sheet area Ash which is given by: Ash 2. Amag is called the magnet area and i1 is called the concentration ratio in between Amag and Ash.i1 = Amag / Ash (-) (2)Substitution of Amag 2 = 491 mm2 and Ash = 236 mm2 in formula 2 gives i1 = 2.08. The fact that Amag is larger than Ash results in concentration of the magnetic flux in the sheet Br sh with a factor i1. So Br sh is given by:

Br sh = Br eff * i1 (T) (3)

Substitution of Br eff = 0.496 T and i1 = 2.08 in formula 3 gives Br sh = 1.03 T. This is much smaller than 1.6 T, so the armature sheet isn't saturated.

Half of the magnetic flux coming out of a magnet is a part of a magnetic loop in the stator sheet which has to pass the bridge in between the outside of the armature sheet and the central 36 mm hole. This bridge has a width of (125 – 36) / 2 = 44.5 mm. So the bridge area Abr = 44.5 * 3 = 133.5 mm2. This is larger than halve Ash as halve Ash = 118 mm2. So there is also no saturation in other parts of the armature sheet.

Mounting sequence of the generator and the rotor

1 The hub of the bicycle wheel is modified according to the description in chapter 2.

2 The eight magnets are glued to the armature sheet with epoxy glue such that four north and four south poles are created. It is advised to make a square Teflon sheet with eight 25 mm circular holes in it to get the magnets on the right position. The Teflon sheet should have at least three 4 mm holes at a pitch circle of 45 mm to connect the Teflon sheet to the armature sheet. To prevent corrosion of the magnets, it is advised to paint the whole armature with epoxy lacquer.

3 The coil ends are pushed through the corresponding 3 mm holes in the stator sheet and the six coils are mounted against the stator sheet. The coil ends are isolated by an isolation tube. The 3-phase rectifier is connected to the back side of the stator sheet. It is assumed that the winding is a 6 V / 12 V winding which is used for 12 V battery charging. So both coils of the same phase are connected in series. The coil ends U1A, V1A and W1A are connected to the AC terminals of the rectifier. All coil ends U2B, V2B and W2B are connected to each other and are forming the star point. It is advised to wrap a piece of isolation tape around each coil to prevent unwinding and to protect the wires against corrosion.

4 The armature sheet is mounted against the back flange of the hub using six stainless steelscrews M4 * 10 and six stainless steel nuts M4.

5 A shaft nut and a shaft washer are placed at the long end of the generator shaft. Next the stator sheet is placed. Next one washer is placed and the second shaft nut is tightened. The nuts are adjusted such that the distance in between a magnet and the front core flange is just 1 mm. The generator is ready now.

6 The head is mounted and connected to the tower pipe.

7 The back shaft nut is removed when the generator is connected to the head frame and tightened again if the generator is mounted.

8 The windmill rotor is mounted to the front flange of the hub using six stainless steel screws M4 * 10, six washers for M4 and six stainless steel nuts M4.

To prevent entrance of water and dust at the front bearing, it might be possible to cover the front side of the generator by a metal or synthetic cap (not specified). Sealing of the back bearing isn't possible so it is required to renew the grease in the bearings regularly if a long lifetime is wanted. Mounting of the remaining parts of the VIRYA-1 windmill is described in the manual of the VIRYA-1.04.

Calculation of the geometry of the VIRYA-1 rotor

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

The rotor has blades with a constant chord and is provided with a 7.14 % cambered airfoil. The rotor is made of one aluminium strip with dimensions of 125 * 1000 * 1.5 mm and 16 strips can be made out of a standard sheet of 1 * 2 m. Because the blade is cambered, the chord c is a little less than the blade width, resulting in c = 123.3 mm =0.1233 m. For cambering the blades, it is possible to use the same blade press which is also used for the blades of the VIRYA-1.04.For twisting one can also use the VIRYA-1.04 tools but one has to use a 8° jig to measure the correct twisting angle of the cambered part and a 16° jig to measure the correct blade angle at the blade root.The camber is only made in the outer 400 mm of the blade. This part of the blade is twisted linear. The central 60 mm, where the blade is connected to the front flange of the hub 1 is flat. The 70 mm long transition part in between the flat central part and the outer cambered part is twisted 16° to get the correct blade angle at the blade root.

Determination of the Cp- and the Cq- curves

The determination of the Cp- q-curves is given in chapter 6 of KD 35. The average Cd/Cl ratio for the most important outer part of the blade is about 0.04. Figure opt = 4.25 andCd/Cl = 0.04 gives Cp th = 0.415. The blade is stalling in between station D and E so only the part of the blade till 0.05 m outside station E is taken for the calculation of Cp. This gives an effective blade length k' = 0.35 m. Substitution of Cp th = 0.415, R = 0.5 m and blade length k = k' = 0.35 m in formula 6.3 of KD 35 gives Cp max = 0.38. Cq opt = Cp max opt = 0.38 / 4.25 = 0.0894.opt d = 4.25 in formula unl = 6.8.The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

Cq start = 0.75 * B * (R – ½k) * Cl * c * k /3 (-) (9)

The average blade angle is 12° for the whole blade. For a non rotating rotor, the average- 12° = 78°. The estimated Cl-it can be read that Cl = 0.4. During starting, the whole blade is stalling. So now the real blade length k = 0.4 m is taken.Substitution of B = 2, R = 0.5 m, k = 0.4 m, Cl = 0.4 en c = 0.1233 m in formula 9 gives that Cq start = 0.0226. The real coefficient will be somewhat lower because we have used the average blade angle. Assume Cq start = 0.021. For the ratio in between the starting torque and the optimum torque we find that it is 0.021 / 0.0894 = 0.235. This is acceptable for a rotor with a design tip speed

d = 4.25.

Determination of the P-n curves, the optimum cubic line and the Pel-V curve The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a Cp-V curve of the safety system together with the formulas for the power P and the rotational speed n. The Cp- -V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 2 mm aluminum. The rated wind speed for this V curve is given in figure 4.

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

The axial flux generator is not yet built and measured so Pmech-n and Pel-n curves are not yet available. The Pmech-n curve is -n curve, the Pel-n curve is derived from the Pmech- is estimated to be 0.8 for n = 350 rpm. The efficiency is estimated to be 0.4 for n = 700 rpm. The average charging voltage for a 12 V battery is about 13 V. So the estimated Pmech-n and Pel-n curves are given for 13 V in figure 5. It is necessary to measure the curves for 13 V if a prototype is available and to check if the estimated curves are about correct.

The point of intersection of the Pmech-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 Pel for that wind speed is found by going down vertically from the working point up to the point of intersection with the Pel-n curve. The values of Pel found this way for all wind speeds, are plotted in the Pel-V curve (see figure 6).The matching of rotor and generator is good for wind speeds in between 3 and 9 m/s because the Pmech-n curve of the generator is lying close to the optimum cubic line.

Determination of the winding

The estimated Pel-n curve given in figure 5 starts at a rotational speed of 300 rpm. This means that the generated unloaded DC voltage must be equal to the open battery voltage at this rotational speed. It is assumed that the open battery voltage is 12.5 V. So the winding must be such that the open DC voltage is 12.5 V for n = 300 rpm. In this case the starting point of the real Pel-n curve will be the same as for the estimated Pel-n curve. However, the remaining part of the real Pel-n curve can only be found by building and measuring of a generator prototype.

The generated effective AC voltage Ueff of one phase for a certain stator and armature geometry is proportional to the rotational speed n and proportional to the number of turns per coil. Star rectification of a 3-phase current is explained in chapter 3.2.1 of report KD 340 (ref. 4). The relation in between the effective DC voltage UDCeff and the effective AC voltage Ueff is given by formula 13 of KD 340 if the voltage drop over the rectifier Urect is neglected. Formula 13 of KD 340 is copied as formula 13.

Conclusion

This paper represents about the design of generator, 6-pole axial flux generator with a 2-phase winding and a steel stator sheet. The hexagonal stator sheet is made from 4 mm brown Phenolic Fabric.

This material is flat and very stiff and is not absorbing water.

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