Ideas about a 4-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1.5 windmill using square neodymium magnets size 30 * 30 * 15 mm and no iron in the stator

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1 Introduction

One of the most critical parts of a small wind turbine is the generator. As far as I know, simple and cheap direct drive 3-phase permanent magnet (PM) generators are not available on the market. For my current range of VIRYA windmills, I therefore have developed a range of PM-generators. These generators are derived from standard asynchronous 4-pole, 3-phase motors by replacing the original shaft and short-circuit armature by a stainless steel shaft and a mild steel armature which is provided by neodymium magnets. These generators are described in public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking torque is not fluctuating because the armature poles are making a certain angle with the axis. This facilitates starting of the rotor at low wind speeds.

The original shaft and armature is thrown away and a new stainless steel shaft and a new mild steel armature have to be made. Deep, inclined grooves have to be milled in the armature which needs special tools and is rather complicated and time consuming. 10 mm thick neodymium magnets have to be glued in the grooves. The whole generator is therefore rather expensive, especially if a housing of western manufacture is used.

The idea is to design a new type of a small PM-generator which does not use an asynchronous motor and which can be manufactured in developing countries. The generator will be of the type ”axial flux” which means that the air gap in between rotor and stator is perpendicular to the generator shaft. So the direction of the magnetic flux in the air gap is parallel to the generator shaft. The generator winding will be chosen such that the windmill can be used for 12 V or 24 V battery charging for star rectification of the winding.

The generator is meant for the 2-bladed rotor of the VIRYA-1.5 windmill. This rotor is described in report KD 452 (ref. 2). The rotor is made out of one stainless steel strip size 125 * 1500 * 2 mm which is cambered and twisted.

2 Description of the generator (see figure 1)

The use of an axial flux generator in a windmill is not new. Some small commercial windmills like the Ampair make use of this generator type. This type of generator is also used in the windmills designed by Hugh Piggott. The rotor of these generators consists of two steel disks with magnets glued to the inner side. The stator is positioned in between both rotor disks and is made of coils which are imbedded in epoxy or polyester. So there is no iron in the stator coils. This has as advantage that no magnetic losses will be generated in the stator and this means that no torque (except for the bearing friction) is required if the rotor rotates unloaded. This is favourable because it results in a very low starting wind speed of the rotor. However, this construction has the following disadvantages:

1. The gap in between the magnets is rather large and this results in a strong reduction of the magnetic flux which is flowing through the coils. If ceramic magnets are used, the final magnetic flux will be very much lower than the magnetic flux which is realised for my normal VIRYA generators. The only way to get an acceptable magnetic flux is to use rather thick neodymium magnets.
2. Mounting of the stator in between both rotor disks is difficult. A certain air gap must be realised at both sides of the stator. For the generators of Hugh Piggott, these air gaps are realised by adjusting threaded rods. I prefer a construction whereby the air gaps are realised automatically if the generator is mounted.
3. It is difficult to protect the generator against the penetration of water as there is a very long air gap in between the outside of rotor and stator.

I have tried to design an axial flux generator for which at least some of the disadvantages are prevented. One modification is that magnets will be glued only to the back side of the front rotor sheet. The sealed bearings are protected by an extra oil seal. The magnets and coils are covered by epoxy.

The most simple 3-phase generator has a rotor with only two poles and a stator with only three coils. However, the frequency will be rather low for this configuration if this generator is used as a direct drive windmill generator.

It is chosen to use four rotor poles, so the pole angle in between the rotor poles is 360 / 4 = 90°. The two north poles are called N1 and N2. The two south poles are called S1 and S2. It is chosen to use six stator poles, so the pole angle in between the stator poles is 360 / 6 = 60°.

The three phases are called U, V and W. The coils around the stator cores are called U1, U2, V1, V2, W1 and W2. The orientation of the rotor poles with respect to the stator poles is given in figure 1 for the position that rotor pole N1 is just opposite stator pole U1.

For the magnets it is chosen to use square neodymium magnets size ϕ 30 * 30 * 15 mm which are supplied by the Internet company www.supermagnete.de. These magnets have quality N45 and a remanence B_r in between 1.32 T and 1.37 T. Four of these magnets are used in one armature. The price per volume of square magnets is substantial lower than the price per volume of round magnets and that's why square magnets were chosen. The current price is € 8.75 per magnet including VAT and excluding mailing costs for an order of 40 magnets, so the magnet costs for one generator are about € 35 which seems to be acceptable.

The magnets are glued to the backside of the front steel disk size 125 * 125 * 6 mm. The pitch circle of the magnets is chosen 102 mm. The windmill rotor is mounted to the front side of the front square sheet by six stainless steel bolts M6 * 20 mm and two stainless steel self locking nuts M6. The front square sheet is mounted to the generator shaft by a self locking nut M14. The windmill rotor has a 26 mm central hole so it can be mounted or removed without removing the M14 nut.

The back square sheet also has size 125 *125 * 6 mm but it has a central hole of 57 mm. The distance in between the front sheet and the back sheet is 30 mm. So the air gap for the magnetic flux is 15 mm. The front square sheet and the back square sheet are connected to each other by four stainless steel studs with a diameter of 10 mm and a length of 30 mm and eighth stainless steel bolts M6 * 20 mm.

The six coils all have the same dimensions and the same winding direction. A coil has an outside diameter of 45 mm, a core diameter of 30 mm and a thickness of 12 mm. The pitch circle of the coils is also 102 mm. The coils are pored into an epoxy (or polyester) disk with an outside diameter of 147 mm, an inside diameter of 55 mm and a thickness of 12 mm. So the real air gap at both sides of the stator is 1.5 mm. The procedure how to determine the wire thickness and the number of turns per coil is given in chapter 4.

A stainless steel ring is cast together with the epoxy disk. The ring has an outside diameter of 55 mm, an inside diameter of 30 mm and a width of 12 mm. It has a groove at the outside for better fixation to the epoxy disk. The ring is connected to the bearing housing by three inner hexagon bolts M6 * 20 mm at a pitch circle of 45 mm. A spring loaded oil seal size 20 * 30 * 7 mm is pressed in the centre of the stainless steel ring.

The stainless steel bearing housing is positioned at the back side of the stainless steel ring. The outside diameter is 55 mm and the length is 43 mm. The back side is closed. The back side is provided with three threaded holes M6 for connection of the generator to the head frame of the windmill.

The stainless steel shaft has a diameter of 15 mm. Two sealed bearings size 15 * 35 * 11 mm are used. A 15 mm long distance bush separates both bearings. So the distance in between the hart of both bearings is 26 mm. The shaft has a flange at the back side and M14 thread at the front side. The shaft has two flat sides at the front side to be able to tighten the central nut M14.

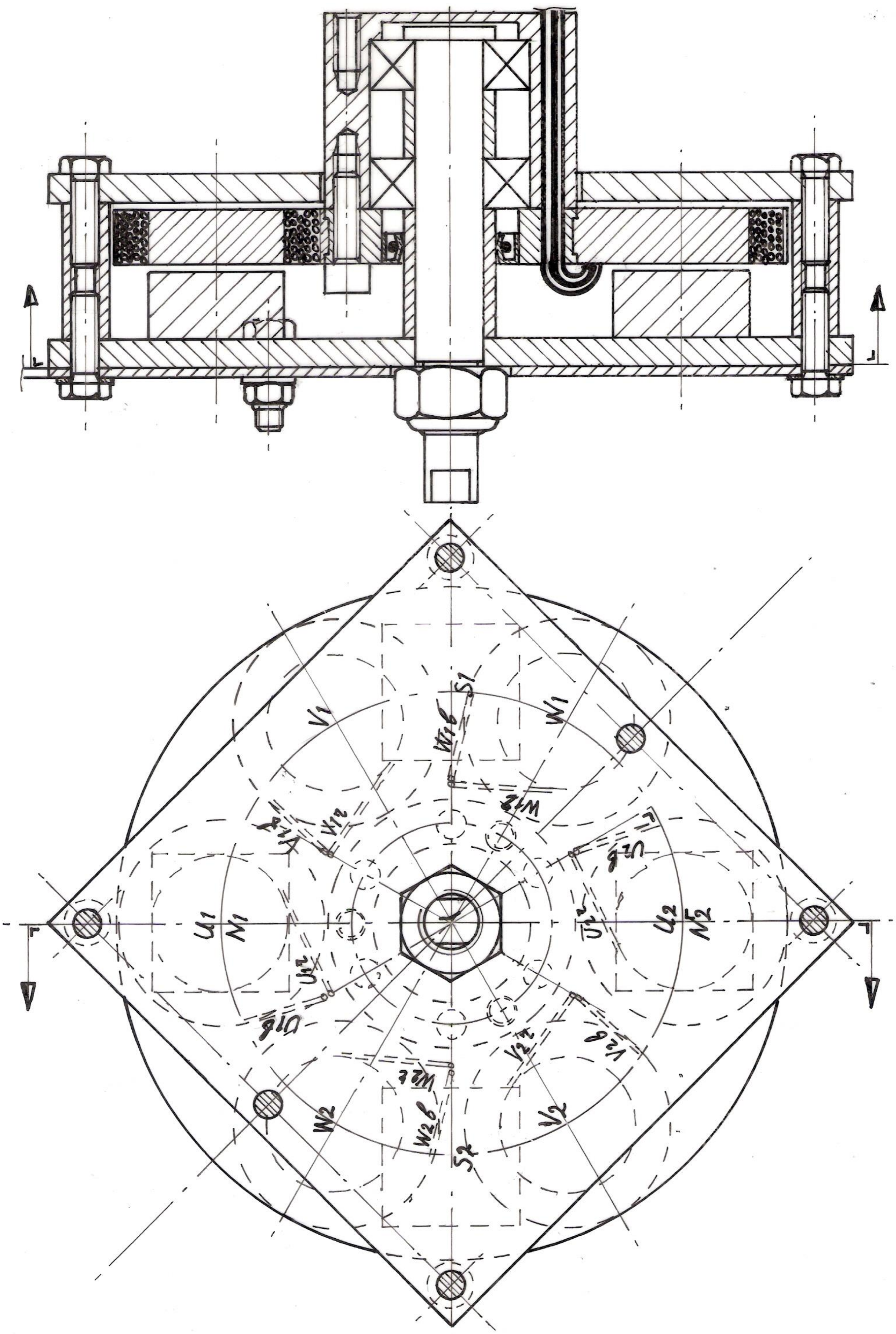

fig. 1 4-pole axial flux permanent magnet generator VIRYA-1.5

The bearing housing has a 4 mm deep chamber for the flange of the shaft. A 28.5 mm long stainless steel distance bush with an outside diameter of 20 mm is mounted in between the front bearing and the front square sheet.

A coil has an inside diameter of 30 mm, an outside diameter of 45 mm and a width of 12 mm. It is expected that this geometry is large enough to create a generator which is strong enough for the VIRYA-1.5 rotor. Every coil has two ends, one end connected to the centre of the coil and one end connected to the outside of the coil. The coil end connected to the centre of a coil is covered with a red isolation tube. The coil end connected to the outside of a coil is covered with a blue isolation tube. The coil ends are coming out of the front side of the epoxy disk. Six 6 mm holes are drilled in the stainless steel ring and in the bearing housing. The two isolated wires from one coil are guided trough one of these holes. All twelve coil ends are connected to a 12-pole connector which is connected to the backside of the generator bracket of the head frame. By choosing the correct connection wires, the two coils of one phase can be connected in series or in parallel (see chapter 5). A prototype of the generator has to be built and tested to prove if the generator is strong enough for the VIRYA-1.5.

3 Mounting sequence of the generator and the rotor

1 The back bearing is pressed to the shaft.
2 The 15 mm long bush is shifted over the shaft.
3 The front bearing is pressed to the shaft.
4 The assembly of shaft and bearings is pushed in the bearing housing.
5 Six red isolation tubes are shifted over the inner coil ends and six blue isolation tubes are shifted over the outer coil ends
6 The oil seal is pressed in the stainless steel ring of the stator.
7 The six bundles of two coloured coil ends are pushed through the six holes in the stainless steel ring and in the bearing housing.
8 The stator is bolted to the bearing housing using three inner hexagon bolts M6 * 20 mm.
9 The 28.5 mm long distance bush is pushed over the shaft.
10 The magnets are glued to the front square sheet such that two north and two south poles are created.
11 The four 30 mm long stainless steel studs are bolted to the corners of the front sheet using four bolts M6 * 20 mm.
11 The assembly of the front sheet, the magnets and the studs is shifted over the shaft and locked with the M14 nut.
12 The back square sheet is shifted over the bearing housing till it is pulled against the four studs. It is connected to the studs by four bolts M6 * 20 mm.
13 The four bolts at the side of the font square sheet are removed. The position of the back sheet will not change because both sheets are pulled together very strongly by the four magnets.
14 The rotor is connected to the front square sheet using the four bolts and washers at the corners of the square sheet and two bolts, nuts and washers at the centre line of the rotor.
15 The generator bracket of the head frame has a thickness of 4 mm. It has the same hole pattern as the bearing housing, so three holes for the bolts M6 and six holes for the wires. The six bundles of wires are shifted through the six holes of the bracket.
16 The assembly of generator and rotor is bolted to the generator bracket of the head frame using three bolts M6 * 12 mm.
17 The 12-pole connector is mounted and the 12 coil ends are connected.
18 The connecting wires are laid according to figure 3 or 4 for the chosen battery voltage.
19 The 3-phase rectifier is mounted and the three wires to the rectifier are connected.

4 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.

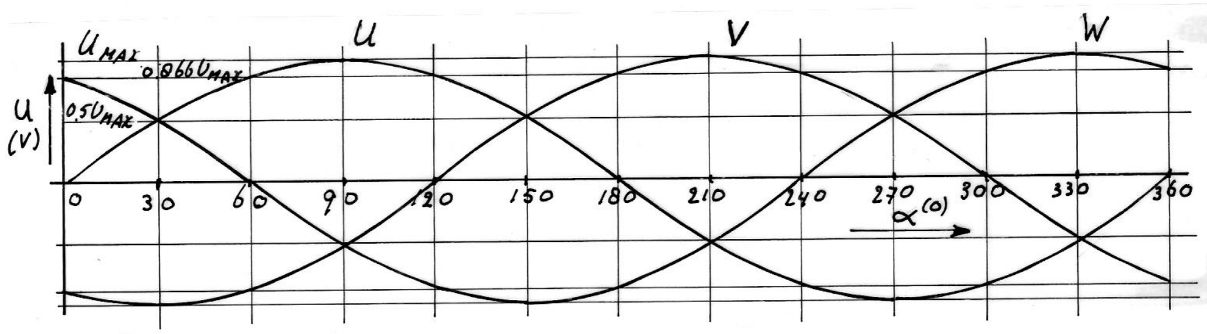

fig. 2 Three phases U, V and W

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 four poles this will be the case for 180° 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, that $\alpha_r = 60°$ in between N1 and V1 and that $\alpha_r = 120°$ in between N1 and W1. Substitution of $\alpha_r = 60°$ and $p_r = 4$ in formula 4 gives $\alpha = 120°$. Substitution of $\alpha_r = 120°$ and $p_r = 4$ in formula 4 gives $\alpha = 240°$. So a 3-phase voltage is created in between the coils U1, V1 and W1.

Rectification in star will give the lowest sticking torque because higher harmonic currents can't circulate in the winding. Therefore star rectification is preferred. Rectification of a 3-phase current is explained in report KD 340 (ref. 3). The 3-phase rectifier is also mounted to the back side of the generator bracket of the windmill head. A two-core cable goes from the rectifier to the batteries. This cable must have a four times larger cross sectional copper area for 12 V battery charging than for 24 V battery charging if the same cable losses are wanted.

5 Series or parallel connection of the coils for 24 V or 12 V battery charging

The generator can be used for 24 V battery charging if the two coils of one phase are connected in series and for 12 V battery charging if the two coils of one phase are connected in parallel. All twelve coil ends of the six coils are guided to a 12-pole connector. The coil ends coming from the centre of the coils have a red isolation tube and are indicated by r. The coil ends coming from the outside of a coil have a blue isolation tube and are indicated by b. All six coils have the same winding direction. The twelve coil ends have indications: U1r, U1b, U2r, U2b, V1r, V1b, V2r, V2b, W1r, W1b, W2r and W2b.

The coils have to be connected such that the voltages of two coils of the same phase are always strengthening each other and therefore a colour indication of the inside and the outside of the coil is necessary.

A 12-pole connector has 24 connecting points. The twelve coil ends are connected to the 12 lower connecting points. These connections are not changed for 12 V or 24 V battery charging. The 12 upper connecting points are used to choose serial or parallel connection. The rectifier is always connected to points U1r, V1r and W1r. The wires which connect U2b, V2b and W2b are also permanent. Series-star connection for 24 battery charging is given in figure 3. Parallel-star connection for 12 V battery charging is given in figure 4.

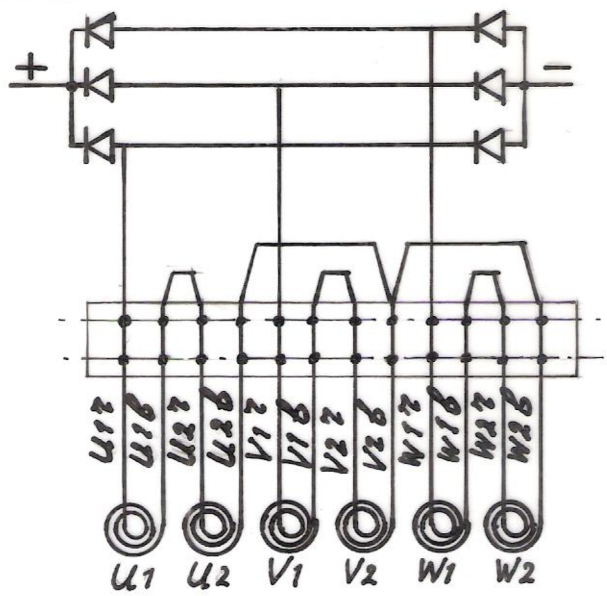

fig. 3 Series-star connection
for 24 V battery charging

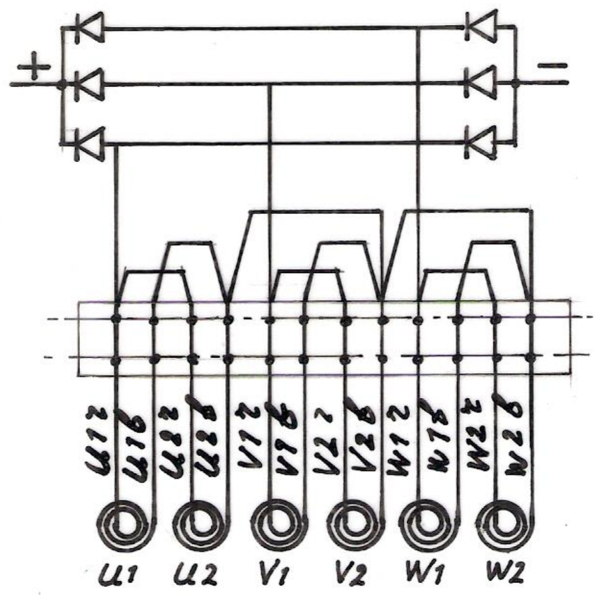

fig. 4 Parallel-star connection
for 12 V battery charging

6 Calculation of the flux density in the steel of the core 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. 1). 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 rotor sheets are saturated because saturated rotor sheets will reduce the magnetic flux in the air gap. Saturation has to be checked for the front and for the back square sheet. The iron of a mild steel sheet is saturated at a flux density of about 1.6 Tesla (T).

The remanence B_r (magnetic flux) in a neodymium magnet supplied by Supermagnete with quality N 45 is about 1.34 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 rotor sheets can be neglected if there is no saturation. So the total magnetic resistance is only caused by the magnet itself and by the air gap. For each magnet there is one air gap. The thickness of the air gap is called t_2. The air gap results in an increase of the magnetic resistance by a factor $(t_1 + t_2) / t_1$. This results in decrease of the remanence B_r to the effective remanence $B_{r\,eff}$. $B_{r\,eff}$ is given by:

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

Substitution of $B_r = 1.34$ T, $t_1 = 15$ mm and $t_2 = 15$ mm in formula 5 results in $B_{r\,eff} = 0.67$ T.

Next it is checked if the iron of the front square sheet is not saturated. Both sheets have the same thickness of 6 mm but the back square sheet has a 57 mm central hole. Let's look at magnet N1.

Half of the magnetic flux coming out of magnet N1 will bend to the left and will flow to magnet S2. The other half will bend to the right and will flow to magnet S1. It is assumed that almost no magnet flux is flowing in the direction of the upper corner of the square sheet. So the magnetic flux is flowing in the direction of the left, the bottom and the right side of magnet N1. So the sheet area A_{sh} through which the total magnetic flux has to pass is given by: $A_{sh} = 3 * 30 * 6 = 540$ mm^2. A_{mag} is called the magnet area and i_1 is called the concentration ratio in between A_{mag} and A_{sh}.

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

Substitution of $A_{mag} = 30 * 30 = 900$ mm^2 and $A_{sh} = 540$ mm^2 in formula 7 gives $i_1 = 1.667$. 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:

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

Substitution of $B_{r\,eff} = 0.67$ T and $i_1 = 1.667$ in formula 7 gives $B_{r\,sh} = 1.12$ T. This is smaller than 1.6 T, so the rotor sheet is not saturated. The same counts for the back square sheet opposite the position of the magnets. However, halve of the magnetic flux from N1 has to flow to S1 and has to pass the narrow bridge in between the 57 mm central hole and the side of the square sheet. This bridge has a width of 34 mm and a thickness of 6 mm. So the bridge area $A_{br} = 204$ mm. Halve the magnet area is 450 mm. So $i_2 = 2.12$ and this gives for the magnetic flux in the bridge that $B_{r\,br} = 1.48$ T. This is rather high. However, the real flux through the bridge will be smaller than the calculated value because a part of the flux will flow directly from magnet to magnet and will not pass the back sheet. So the bridge in the back sheet is also not saturated.

At this moment I don't know if I will make a prototype of this new axial flux PM-generator. As there is no iron in the coils, the generator will have no clogging torque. The only torque will be caused by the bearing friction and by the friction of the oil seal but this torque will be very low.

If it comes to realisation, first a stator will be made with a test winding with for instance 50 turns per coil. The wire thickness will be chosen such that the coil has the chosen volume belonging to an inside diameter of 30 mm, an outside diameter of 45 mm and a thickness of 12 mm. Next the generator has to be measured for series-star connection on an accurate test rig for a range of constant voltages, for instance 12, 16, 20, 24, 28, 32 and 36 V.

The P_{mech}-n curves for different voltages have to be compared with the optimum cubic line of the rotor. The line which gives the best matching with this optimum cubic line is the optimum voltage for the test winding. Assume the best matching is realised for U = 20 V.

The generator will be used for 24 V battery charging for series-star connection of the coils. The average charging voltage for this nominal battery voltage is about 26 V. Next the winding must be modified such that the same P_{mech}-n curve is now generated for 26 V. This is realised if the number of turns per coil is increased by a factor 26/20 = 1.3. So the required number of turns per coil will be 65. The wire thickness has to be reduced such that the coil has just the same volume as the test coil.

This procedure requires an accurate test rig which is available at the University of Technology Eindhoven and which can be hired at a certain fee. I have used this test rig for my current VIRYA generators. From these measurements with the final winding, the efficiency curve can be determined too. The P_{el}-V curve can be determined from the measured generator curves and estimated P-n curves of the rotor. This procedure is described in chapter 8 of report KD 35 (ref. 4).

7 Checking the bearings

In figure 1 it can be seen that two ball bearings size 15 * 35 * 11 mm are chosen which are mounted at a distance of 15 mm from each other. So the distance e in between the hart of the bearings is 26 mm. The static load factor of this type of bearing C_{stat} = 3550 N. The dynamic load factor C = 7800 N. The static radial load is caused by the sum of the weight of the rotor and the two square sheets which is only about 42 N. The distance in between the centre of gravity and the hart of the front bearing is about 34 mm. The distance in between the centre of gravity and the hart of the back bearing is about 60 mm. This results in an upwards reaction load on the front bearing of 42 * 60 / 26 = 97 N and a downwards reaction load on the back bearing of 97 - 42 = 55 N. These loads are very low so the static load can be neglected. The dynamic load has to be checked.

The axial load is caused by the rotor thrust. The maximum rotor thrust on one blade has been calculated in report KD 452 (ref. 2) to be 36 N, so the thrust on the two blades of the whole rotor is 72 N. This load is taken by the back bearing. A load of 72 N is a very low value. The allowable axial load is even larger than the allowable radial load because all balls take an axial load but only one ball takes a radial load. So the axial load can be neglected.

The rotor thrust will cause no bending moment in the shaft if there is no aerodynamic imbalance. It is assumed that the rotor mass is balanced perfectly so also no bending moment is caused by mass imbalance. The only bending moment is caused by the gyroscopic moment M_{gyr}. The maximum gyroscopic moment for one blade $M_{gyr\ bl\ max}$ has been calculated in report KD 452 and it was found that $M_{gyr\ bl\ max}$ = 5780 Nmm for a rotation speed n = 610 rpm. The maximum gyroscopic moment of the whole rotor is double this value, so $M_{gyr\ max}$ = 11560 Nmm. The maximum radial bearing load F_{max} is given by:

$$F_{max} = M_{gyr\ max} / e \qquad \text{(N)} \qquad (8)$$

Substitution of $M_{gyr\ max}$ = 11560 Nmm and e = 26 mm in formula 8 gives F_{max} = 445 N.

This force is much lower than the static load factor C_{stat} = 3550 N so the bearing can certainly have this load for a short moment. For the lifetime of the bearing the dynamic load factor C has to be used.

The lifetime for ball bearings L, is given by the formula (from the SKF catalogue):

$$L = 10^6 * (C / P)^3 / (60 * n) \qquad \text{(hour)} \qquad (9)$$

Substitution of C = 7800 N, P = F_{max} = 445 N and n = 610 rpm in formula 9 gives L = 147137 hour or about 16.8 year. This is certainly long enough. The maximum gyroscopic moment and the corresponding rotational speed occur only during very short times at very high wind speeds so it is not realistic to calculate the lifetime of the bearings for the peak load.

The average gyroscopic moment and the average rotational speed are much lower. Assume that the average values are half the peak values which is certainly a pessimistic assumption. So assume F_{av} = 223 N and n_{av} = 305 rpm. Substitution of these values in formula 9 gives L = 2338396 hour or about 267 year. So it can be concluded that the bearings are strong enough. Generator bearings normally don't fail because of the load but because of wear of the seals and penetration of water. Wear of the oil seal and the internal seals of the front bearing can be minimised if the space in between the seal and the front bearing is filled with grease.

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