Ideas about an 8-pole, 3-phase permanent magnet generator with a stator without iron in the coils, using eight neodymium magnets size 80 * 20 * 10 mm and a housing of an asynchronous motor with frame size 71

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KD 644

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1 Introduction

One of the most critical parts of a small wind turbine is the generator. For my current range of VIRYA windmills, I 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 (and several others types) are described in public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking torque isn't 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.

I did several attempts to design a PM-generator which is cheaper and wrote KD-reports about every new idea. One of the ideas is described in report KD 480 (ref. 2). This radial flux PM-generator makes use of the housing of a 4-pole asynchronous motor frame size 71 of Indian manufacture because the generator would be used for an Indian project. The original motor shaft is used but the original short-circuit armature is replaced by an 8-pole PM-armature. Magnets are used only for the north poles. The south poles are formed by the remaining material of the armature. The stator isn't provided with an iron stamping and the generator therefore will have almost no sticking torque. The stator is provided with 24 coils which are positioned radially. At this moment I expect that the armature of this generator isn't strong enough and that radial positioning of the coils is also not optimal. So in this new report KD 644, a new type PM-generator is described which also has no iron in the stator but which has a stronger armature and a different winding. KD 644 replaces KD 480 and KD 480 is no longer public available.

A PM-generator with an iron free stator is not new for windmill use. Generally this kind of generators are of the type ”axial flux”. Some small commercial windmills like the Marlec, make use of this generator type. This generator type 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 polyester or epoxy. The direction of the magnetic flux in the air gap is parallel to the generator axis and that's why this type is called ”axial flux”. This kind of generators is relatively short and has a large diameter.

I have designed axial flux generators with no iron in the stator for the VIRYA-1 and for the VIRYA-1.81. These generators have only one armature disk with magnets and are therefore rather easy to manufacture and to mount. However, they have as disadvantage that the stator winding has only one layer and that the amount of copper which can be put in one layer is limited. The generator described in this new report KD 644 has a 2-layers winding.

The direction of the magnetic flux in the air gap for the generator described in chapter 2, is perpendicular to the cylindrical armature and the generator is therefore of the type ”radial flux”. This kind of generator is relatively long and has a small diameter and that's why it is possible to use the housing of a standard asynchronous motor. This has as advantage that the housing, the bearing covers and the shaft will be rather cheap because they are already manufactured in large quantities. Another important advantage is that a housing of an asynchronous motor is water tight if the shaft is provided by an IP-55 seal.

The generator is meant for the 2-bladed VIRYA-1.5 rotor which has a design tip speed ratio of 4.5 and a rotor made out of one stainless steel strip (see report KD 465, ref. 3). Several attempts have been made to design a 4-pole PM-generator for this rotor from an Indian 4-pole asynchronous motor size 71 but these attempts failed, mainly because the Indian stator stamping has four outside grooves which cause a strong peak on the sticking torque.

2 Description of the generator

As the generator is no longer designed for an Indian project, now a housing of a European motor will be chosen. The housing and the armature are originally provided with a stamping of the German supplier Kienle & Spiess (see website www.kienle-spiess.de). No stamping is used for the armature nor for the stator but for the geometry of the housing and the shaft it is assumed that a frame size 71 housing meant for a 4-pole, 3-phase, 0.37 kW stamping of Kienle & Spiess is used.

2.1 Description of the armature

The original stator stamping has an outside diameter of 106.5 mm, an inside diameter of 62 mm and a length of 65 mm. The length of the wound stator is much longer because the coil heads of a 4-pole winding are rather large. This is because two coil heads of one phase are laid within each other and because there are crossing coil heads in between the first and the second layer of the winding. The winding of the new type 8-pole generator has smaller coil heads because the coil heads are not lying within each other. Therefore the stator can have a length of 80 mm without the risk that the coil heads are touching the bearing covers.

The original short-circuit armature has an outside diameter of 61.4 mm an inside diameter of 20 mm and an effective length of 65 mm but both sides are provided with aluminium disks with cooling fans and the total armature length is therefore much longer. The armature of the new 8-pole generator will have a length of 80 mm and there is certainly enough place for this armature length.

The armature has eight poles, so four north and four south poles. The armature is made of an 80 mm long mild steel bush with an outside diameter of 55 mm and an inside diameter of 20.1 mm which is pressed on the original motor shaft. The original motor shaft is provided with a fine teething for a tight press fit. As the armature is made of massive steel, no stamping is needed for the armature and as the stamping for the stator is cancelled, no stamping material is used for the whole generator. This has a favourable influence on the material costs if the housing can be bought without the stamping.

Eight 20 mm wide grooves are milled in the bush parallel to the shaft axis. The bottom of the groove is lying 25 mm from the shaft axis. One magnet size 80 * 20 * 10 mm is glued in each groove. Four magnets are positioned with the north pole to the outside. Four magnets are positioned with the south pole to the outside. So for one armature, eight magnets are needed. The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl . The current price of one magnet is € 6.69 including VAT, excluding transport if a minimum quantity of 30 magnets is ordered. So the magnet costs for one generator are about € 55 which is rather high but it seems acceptable if the generator has a high efficiency and a low sticking torque.

Eight magnetic loops are coming out of the armature. The direction of the magnetic field for four loops is turning left hand and for the other four loops it is turning right hand. A cross section and a side view of the armature are given in figure 1. Three field lines are drawn for each magnetic loop. The path of the middle field line is also drawn in the armature.

The radius at the heart of the outer side of a magnet is 25 + 10 = 35 mm. It can be calculated that the radius at the corner of a magnet is 36.4 mm. If the air gap in between the corner of a magnet and the inside of the stator is chosen 0.85 mm, it means that the stator must have an inside diameter of 2 * (36.4 + 0.85) = 74.5 mm.

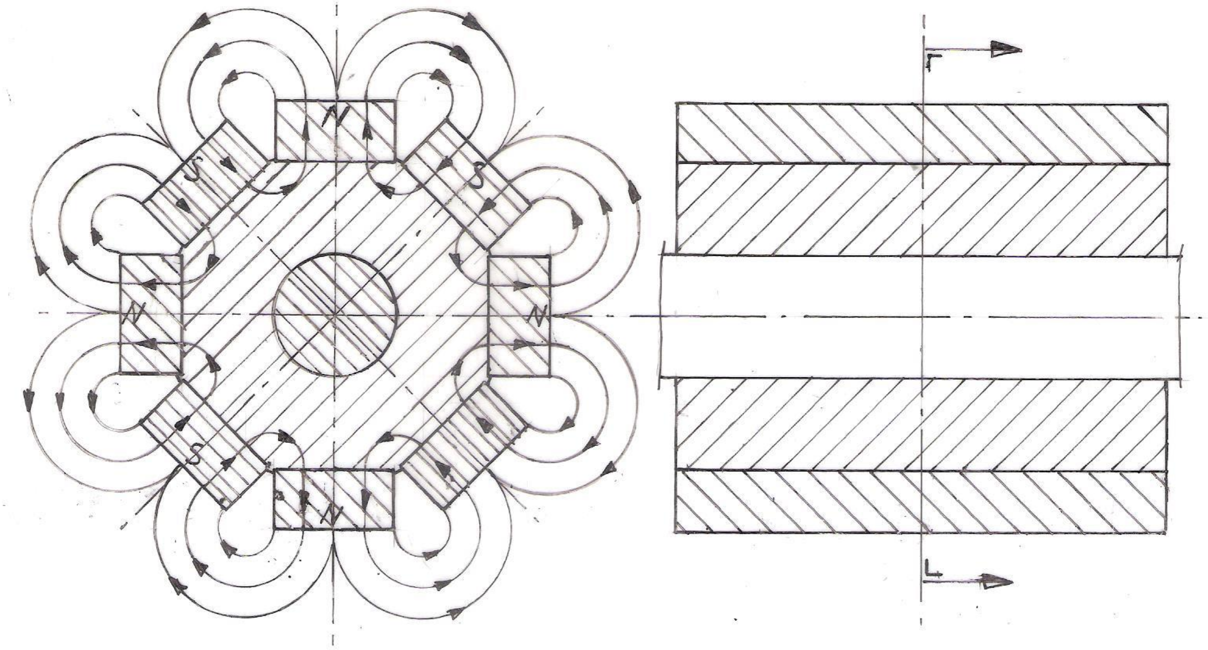

fig. 1 8-pole armature with eight neodymium magnets size 80 * 20 * 10 mm.

2.2 Description of the stator

The complete iron stator stamping is cancelled, so a lot of space is available for the stator coils. It is assumed that the inside of the housing is machined to an inside diameter of 106.5 mm, so the same as for an iron stator stamping. The stator coils are positioned in a bush made out of a synthetic material like Delrin which is pressed or glued in the aluminium housing. The bush will have an outside diameter of 106.5 mm, an inside diameter of 74.5 mm and a length at the coils of 80 mm. So the thickness of the bush is (106.5 – 74.5) / 2 = 16 mm.

Normal iron stator stampings have slots at the inside because all stator spokes must be connected at the outside to guide the magnetic flux from a north pole to a south pole. The stator coils are mounted from the inside. This is a rather tricky procedure and slot strips are required to prevent that the coils come out of the grooves and touch the rotating armature. All coil heads are bound together with rope, also to prevent that they touch the armature when the armature is mounted in the housing.

The new synthetic stator of this 8-pole generator contains no iron and therefore it isn’t necessary that the spokes are connected to each other at the outside. So it is possible to make the slots from the outside and to mount the coils also from the outside which is much easier.

For a 3-phase winding of an 8-pole generator, the armature needs 24 slots at an angle of 15°. The slots are numbered 1 – 24. For every phase, four coils are used, so the total number of coils for a 3-phase winding is twelve. The coils of phase U are called: U1, U2, U3 and U4. All four coils of one phase are connected in series. The coils of phases V and W use the same numbering. If one of the four coils of one phase is opposite to a north pole, the other three coils will also be opposite to north poles. So the voltage generated in one coil will enlarge be the voltage generated in the other three coils if all coils have the same winding direction.

The winding is a so called two layers winding. This means that first layer is laid using the coils U1, U2, V1, V2, W1 and W2. For this first layer there are no crossing coil heads. The second layer contains the coils U3, U4, V3, V4, W3 and W4. The coil heads of the first layer are crossing with the coil heads of the second layer but this is no problem as there is enough space to do so. The two coils of one phase of one layer are wound outside the generator on a winding thorn. The end of the two coils of the first layer is soldered to the beginning of the two coils of the second layer of the same phase. The soldering points are isolated and are lying in between the coil heads.

The coils of the first layer use the following slots: U1 (1 + 4), V1 (5 + 8), W1 (9 + 12), U2 (13 + 16), V2 (17 + 20), W2 (21 + 24). The coils of the second layer use the following slots: U3 (7 + 10), V3 (11 + 14), W3 (15 + 18), U4 (19 + 22), V4 (23 + 2), W4 (3 + 6).

The winding is rectified in star but the star point is lying in the terminal box on top of the generator housing. So it is possible to short-circuit the star point too if the generator is used as a brake by making short-circuit. Making short-circuit in between all the coil ends of the three phases gives the maximum breaking torque.

The 24 outside slots in the Delrin stator bush all have a width of 8 mm and a depth of 14.5 mm. So there is a 1.5 mm wide bridge left in between the bottom of a slot and the inside of the stator bush. To prevent that the coil heads may touch the armature when the armature is mounted, a 1.5 mm thick and 15 mm wide rim is made at both sides of the stator bush. So the total width of the stator bush is 80 + 2 * 15 = 110 mm. These rims also prevent that wires which connect different coils can be guided too much to the inside.

The six coils of the first layer can be mounted in the bottom of the slots easily because all coils are lying in one cylindrical plane. The coil heads of the second layer are crossing the coil heads of the first layer. If the wires of the second layer are pressed in the grooves, the coil heads of the second layer will be bent outwards. This is no problem but it might be necessary to use Delrin filling strips in the grooves of the second layer (and may be also in the grooves of the first layer) to prevent that the wires go to the outside. These filling strips are kept in position when the Delrin bush is pressed into the aluminium housing. It may be required to bind all coil heads together with rope and to submerse the whole stator in isolating lacquer. The filling strips have to be pushed inwards during this procedure.

The main magnetic flux outside the armature will flow in the space in between the armature and the aluminium of the housing because the distance in between the armature and the aluminium housing is rather large. However, a little part of the magnetic flux will flow through the aluminium of the housing and this flux will cause small eddy currents in the aluminium. It is expected that the torque and the temperature rise because of these eddy currents can be neglected. A cross section and side view of the stator is given in figure 2.

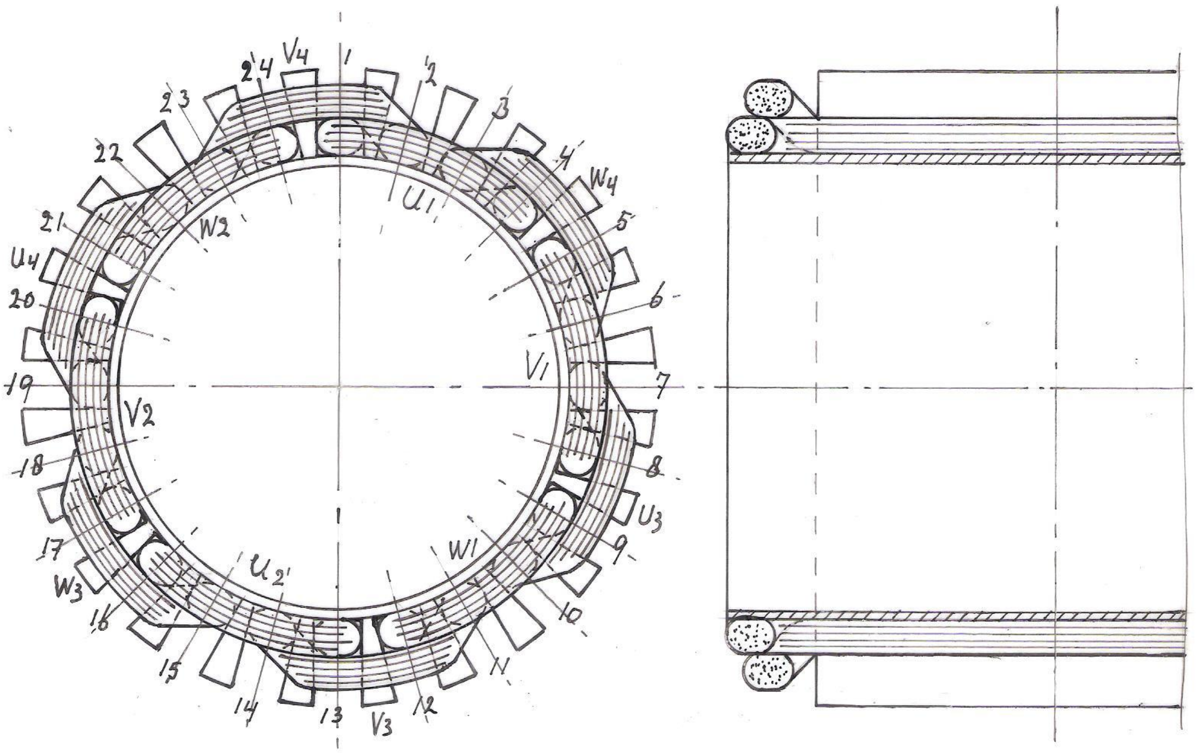

fig. 2 8-pole, 3-phase stator with a 2-layers winding with four coils per phase

2.3 Determination of the number of turns per coils

The required number of turns per coil and the maximum allowable wire thickness can be determined by try and error. First one makes a certain choice, assume 100 turns per coil and one makes a prototype of the stator with the largest wire thickness possible. The winding is rectified in star by a 3-phase rectifier. Rectification of a 3-phase current is described in report KD 340 (ref. 4).

Next the generator is placed on a test rig with which it is possible to measure the torque, the rotational speed, the voltage and the current. I have used a test rig of the University of Technology Eindhoven for measuring my normal VIRYA generators. Next a series of measurements is executed for a range of voltages for instance 8, 12, 16, 20, 24, 28 and 32 V. For every voltage, the P_{mech}-n and P_{el}-n curves are determined.

Next the P-n curves of the rotor are determined for different wind speeds. This is done in figure 4 of KD 465 (ref. 3). A windmill rotor has a certain optimum cubic line which can be drawn through the tops of the P-n curves of the rotor for different wind speeds. The formula for the optimum cubic line is given in chapter 8 of report KD 35 (ref. 5). The optimum cubic line is also drawn in figure 4 of KD 465. All measured P_{mech}-n curves are drawn in the same graph. One curve will have the best matching. This means that it has two points of intersection with the optimum cubic line, which are lying not very far apart.

Assume that the best matching is realised for the P_{mech}-n curve which belongs to V = 20 V. Assume that the generator is used for 24 V battery charging. This means that the average charging voltage is about 26 V. So the voltage of the test winding is a factor 20 / 26 = 0.769 too low. So the number of turns per coil has to be increased by a factor 26 / 20 = 1.3 and so it must be 1.3 * 100 = 130. The wire thickness must be reduced by a factor $\sqrt{}$ (1 / 1.3) = 0.877 to get the same amount of copper. The modified winding will have the same P_{mech}-n and P_{el}-n curves for 26 V, as the curves of the test winding for 20 V.

3 Determination of the flux density in the air gap

In figure 1, field lines are drawn for each magnetic loop. A part of a magnetic loop is flowing outside the armature and a part is flowing inside the armature. It can be seen that the length of the outer loop through air is much longer than the length of the inner loop through iron. The length of the middle loop is about average. The length of the part of the middle loop outside the armature of the middle loop is called t_2. It is assumed that the length of the middle loop is representative for the magnetic resistance of all field lines of the outside part of the whole loop. It is assumed that this part of the loop is about a part of a circle. It is calculated that t_2 is about 37 mm for the given armature geometry.

There is a strong analogy in between the magnetic resistance of a magnetic flux and the ohmic resistance of a DC current. The total magnetic resistance of a complete magnetic loop depends on the magnetic resistance of the part of the loop where it flows in the air gap, of the part of the loop where it flows in the magnet and of the part of the loop where it flows in the iron of the armature. The magnetic resistance of iron is very low and as the iron of the armature is not saturated, the magnetic resistance of the iron part of the loop can be neglected.

The chosen magnets have quality N35H. The remanence B_r in a neodymium magnet with quality N35H is about 1.19 T if the magnet is short-circuited with a mild steel arc which isn’t 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 and it was chosen that t_1 = 10 mm.

As the magnetic resistance of the iron can be neglected, the total magnetic resistance is only caused by the two magnets and by the 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 $2 * t_1 + t_2 / 2 * t_1$.

This results in decrease of the remanence B_r to, what I call, the effective remanence $B_{r\ eff}$ or the flux density in the air gap. $B_{r\ eff}$ in Tesla (T) is given by:

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

Substitution of B_r = 1.19 T, t_1 = 10 mm and t_2 = 37 mm in formula 1 results in $B_{r\ eff}$ = 0.42 T which is rather low.

For the normal VIRYA generators, the iron of the stator is saturated and this means that the flux density in the air gap is about 0.9 T. So the flux density which can be realised in the coils of an iron free stator is about a factor 0.42 / 0.9 = 0.467 of the flux density of a PM-generator which has a mild steel stator stamping. However, the length of the Delrin stator is 80 mm instead of 65 mm for the original iron stator stamping. The coils can be made rather big because the slots can be made rather wide and deep. So the stator winding will have less heat losses for a certain current. The generator will also have no iron losses and so the generator will have a higher maximum efficiency. The final result may be that about the same electrical power can be realised at a certain rotational speed then when the same motor housing would be used for a 4-pole PM-generator with an iron stator stamping. This has to be verified by building and testing of a prototype but I have no intention to do so.

4 References

1 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, reviewed November 2017, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Ideas about an 8-pole, 3-phase permanent magnet generator with a stator without iron in the coils, using neodymium magnets size 40 * 20 * 10 mm, December 2011, reviewed January 2012, report KD 480, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Calculations executed for the 2-bladed rotor of the VIRYA-1.5 windmill (λ_d = 4.5, steel blades) with generator frame size 71 and original motor shaft, August 2011, report KD 465, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed October 2014, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, reviewed February 2017, free public report KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.