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 and a housing of an asynchronous motor with frame size 71

ing. A. Kragten

December 2011
reviewed January 2012

KD 480

Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

Contains page

1 Introduction

One of the most critical parts of a small wind turbine is the generator. As far as I know, simple, efficient 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 PM-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.

I did several attempts to design a PM-generator which is cheaper and wrote KD-reports about every new idea. One of the ideas was really built and tested and is described in report KD 451 (ref. 2). This PM-generator makes use of the housing of a 4-pole asynchronous motor frame size 71. An Indian manufacture is chosen which makes the housing much cheaper than similar housings of a Dutch supplier. The original motor shaft is used and the magnets are much thinner and therefore cheaper than the magnets as used for the normal VIRYA generators. However, a disadvantage of this PM-generator is that the sticking torque is fluctuating and has a rather large peak value. The generator can therefore only be used in combination with a rotor with a rather large starting torque coefficient, other wise the starting wind speed will be too high. The generator is used in combination with a rotor with a diameter of 1.5 m (or 1.46 m for India). The drawings of this VIRYA-1.5 windmill are ready and a prototype is built at this moment by the Indian company TinyTech from Rajkot.

Recently an idea came up for a new type of a small PM-generator which also makes use of an asynchronous motor but for which the stator stamping is removed. The stator coils are wound such that they contain no iron and the generator therefore will have no sticking torque. I was stimulated to get this idea by a Dutch guy named Brian with whom I had a discussion on the Dutch Windenergieforum: http://wind-energie.startpagina.nl/prikbord/ . He showed some small films in which he is testing a new type PM-generator which also has an iron free stator. The films can be seen on: http://www.energy-creator.com . Brian sells a DVD about the manufacture of his generators which I have seen recently. The internal construction of his PM-generator differs very much from my PM-generator which is described in chapter 2.

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 Ampair, 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.

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 generators 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 advantage is that a housing of an asynchronous motor is water tight if the shaft is provided by an IP-55 seal.

2 Description of the generator

2.1 Description of the armature

The new direct drive PM-generator type will be described for the same generator housing with frame size 71 as the one which was used for the VIRYA-1.5 generator and which is described in report KD 451 (ref. 2). The magnet thickness is chosen 10 mm in stead of 5 mm.

The original stator stamping has a length of 55 mm but the length of the wound stator is much longer as the coil heads are rather long. This is because coils of one phase are laid within each other and because a normal 3-phase winding has crossing coil heads in between the first and the second layer of the winding. The winding of the new type of generator has much shorter coil heads and therefore the effective length of the winding can be made much longer without the risk that the coil heads touch the bearing covers.

The original short-circuit armature has an outside diameter of 62.4 mm and an effective length of 55 mm but both sides are provided with aluminium disks and the total length is therefore about 80 mm. The armature of the new generator will also have a length of 80 mm and the effective length of the stator coils will be chosen 80 mm too.

The armature will have 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 62.4 mm which is pressed on the original motor shaft. 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.

Four 20 mm wide grooves are milled in the bush parallel to the shaft axis. Two magnets size 40 * 20 * 10 mm are glued in each groove with the north pole to the outside. The south poles are formed by the remaining material of the armature. So for one armature, eight magnets are needed. The magnets are supplied by the company Supermagnete, website: www.supermagnete.de . The current price of one magnet is € 4.15 including VAT, excluding transport if a minimum quantity of 30 magnets is ordered. So the magnet costs for one generator are about € 35 which seems acceptable.

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 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.

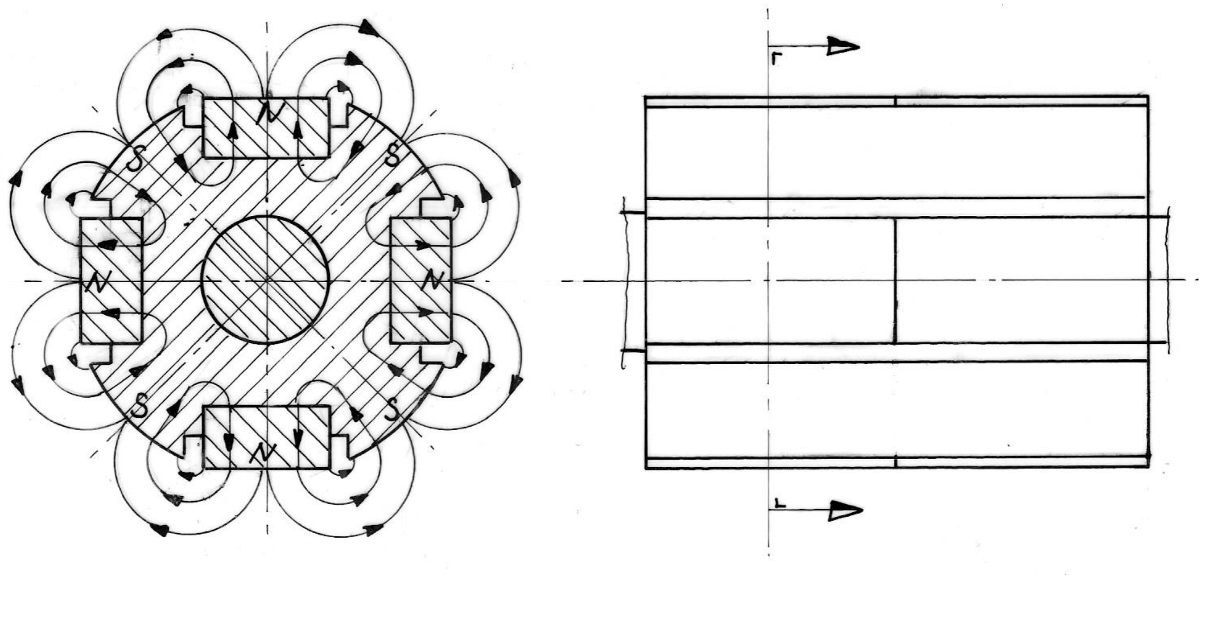

fig. 1 8-pole armature with eight neodymium magnets size 40 * 20 * 10 mm.

2.2 Description of the stator

The complete stator stamping is cancelled, so a lot of space is available for the stator coils. This large space and the much longer armature, substantially compensates the lower power caused by the lower magnetic flux (see chapter 3). The coils of a normal stator of an asynchronous motor are laid tangential because the coils are wound around the spokes of the stator stamping. However, the coils of this new PM-generator are laid radial and this makes the stamping much simpler because there are no crossing coil heads, even not if a 3-phase winding is laid.

For every phase, eight coils are used, so the total number of coils for a 3-phase winding is 24. This means that a 15° wide segment is available for every coil. The coils of phase U are called: U1, U2, U3, U4, U5, U6, U7 and U8. All eight coils of one phase are connected in series. For the phases V and W the same numbering is used. In figure 1 it can be seen that half of the magnetic loops is turning left hand and the other half is turning right hand. This means that if the even coils are wound right hand, the odd coils must be wound left hand other wise the voltage generated in the even coils is neutralised by the voltage generated in the odd coils.

All eight coils of one phase are wound outside the generator in the same winding direction because this is easiest. A bundle of eight coils is placed in the motor housing. However, to create alternation of left hand and right hand wound coils, the odd coils are rotated 180°. Two wires are coming from a coil, one wire from the outside and one from the inside of the coil. If the odd coils are rotated 180°, it means that two adjacent coils of one phase have the wires coming from the outside of the coils, connected to each other and the two next adjacent coils have the wires coming from the inside of the coils, connected to each other. Knowing this, it is very easy to check if the coils of one phase are placed correctly. The wires for phase U are drawn in figure 2. A coil head is symbolised by three radial lines.

The three phases are created by sequential positioning of the coils, so the sequence is U1, V1, W1, U2, V2, W2, U3, V3, W3 and so on. A cross section and side view of the stator is given in figure 2.

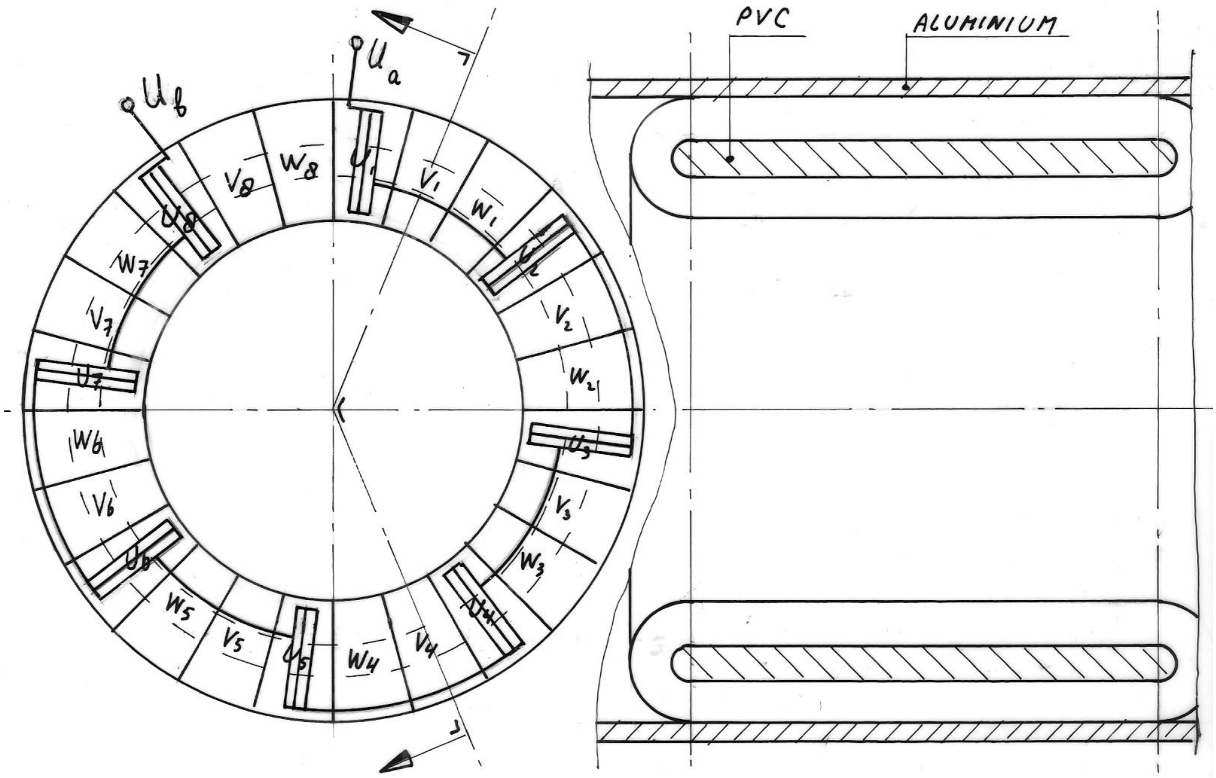

fig. 2 8-pole, 3-phase stator with 24 coils

In the side view of figure 2 it can be seen that the coils are positioned radial. The coil heads are rather small which allows an effective coil length of 80 mm without the risk that the coil heads touch the bearing covers.

A problem is the connection of the coils in the aluminium generator housing. The following procedure might be possible. Each coil has a centre with no wire. Assume a PVC bush is placed in the centre of all 24 coils. If the bush is made out of two 180° halves which are clicked together, halve of the coils can be shifted over the left halve and the other halve can be shifted over the right halve. Clicking both bush halves together creates one stator with 24 coils. A piece of glass fibre cloth is wrapped around the stator to prevent direct contact of the coils to the aluminium housing. The inside of the aluminium housing is turned over the whole length to a diameter which is the same as the outside diameter of a normal stator stamping (105 mm). This stator is glued in the aluminium housing by epoxy.

A synthetic bar with an outer diameter of 63 mm is placed in the centre of the stator. The synthetic bar has a collar at the bottom with a diameter identical to the facing diameter of the back bearing cover (about 107 mm) and a second collar with a diameter identical to the inside diameter of the housing (105 mm). This second collar is that long that the stator is positioned symmetrical to the sides of the housing. The complete stator winding and the synthetic bar are placed from the back side in the aluminium housing. The stator is placed such that all six coil ends are facing upwards and so they can be connected to the terminal. The hole in the housing through which the six wires pass, has to be closed.

Next thin slow drying epoxy is cast over the stator till the whole stator is submersed in epoxy. After hardening of the epoxy, the synthetic bar is removed. One has to use a type of synthetic to which epoxy is not attaching. The outer surface of the bar must be very smooth other wise the bar can’t be pushed out of the hardened stator.

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. 3).

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 a certain windmill rotor is selected. This 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. 4). The optimum cubic line is drawn in a graph. 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 the best matching is realised for the P_{mech}-n curve which belongs to V = 20 V. Assume 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 three field lines are drawn for each magnetic loop. A part of a magnetic loop is flowing outside the armature. It can be seen that the length of this part of the outer loop is much longer than the length of the inner loop. The length of the middle loop is about average. The length of the part of the 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 filed 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 24 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 remanence B_r in a neodymium magnet supplied by Supermagnete with quality N 45 is about 1.35 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 and it is 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 magnet itself 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 $(t_1 + t_2) / t_1$. 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:

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

Substitution of $B_r = 1.35$ T, $t_1 = 10$ mm and $t_2 = 24$ mm in formula 1 results in $B_{r\ eff} = 0.4$ T.

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 0.4 / 0.9 = 0.44 of the flux density of a PM-generator which has a mild steel stator stamping. However, the length of the armature is a factor 80 / 55 = 1.45 longer and much more copper can be used for the stator winding. 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 if the same motor housing is used. This has to be verified by building and testing a prototype but I have no intention to do this.

4 Alternatives

In figure 2, a PVC bush is drawn in the core of all 24 coils. If this PVC bush is replaced by a mild steel bush with a thickness of 6 mm, the length of the average air gap will become shorter. The distance in between a south pole and the bush will be about 7.5 mm and in between a north pole and the bush will be a bout 8.5 mm. So the total length of the air gap will be about 16 mm. Substitution of $B_r = 1.35$ T, $t_1 = 10$ mm and $t_2 = 16$ mm in formula 1 results in $B_{r\ eff} = 0.52$ T. This is a factor 1.3 larger than for a PVC ring, so the voltage at a certain rotational speed and a certain number of turns per coil will be a factor 1.3 higher. This means that the maximum electrical power which can be generated at a certain rotational speed will also be a factor 1.3 larger. However, this is only true if the steel ring is not saturated.

This can be checked as follows. The magnetic flux coming out of a half row of the magnets of a north pole is flowing through one magnetic loop. Half a north pole has an area of 10 * 80 = 800 mm^2. The cross sectional area of the mild steel ring is 6 * 80 = 480 mm^2. Next it is assumed that the whole magnetic flux is flowing through the mild steel ring. So the flux density in the steel ring is multiplied by a concentration factor 800 / 480 = 1.67 and becomes 1.67 * 0.52 = 0.87 T. In reality not all the magnetic flux will flow through the mild steel ring, so the real flux density in the ring will even be lower than 0.87 T. Mild steel is saturated at about 1.6 T, so the steel ring is far from saturation and the magnetic resistance of it can therefore be neglected.

The stator stamping of a normal asynchronous motor is laminated. This is done to prevent eddy currents because of the varying magnetic flux in the iron. Eddy currents will also be prevented if the mild steel ring is laminated. However, this makes manufacture of the ring more complicated. I expect that the rather low flux density in the mild steel ring and the rather low frequency of the fluctuation for direct drive use of the generator, allows to use a non laminated mild steel ring without getting too large eddy currents and so too large heat dissipation in the ring. But it has to be tested if this is true. The eddy currents in the steel ring will cause a certain sticking torque. However, this torque will not fluctuate because the magnetic resistance of a loop is the same for any position of the armature.

For every stator coil a circle segment of 15° is available if the stator has 24 coils. If all stator coils are made the same way, it can be expected that they all have the same thickness and that every coil will use about 15°, if the coils are piled together on the PVC ring. But there might be some difference. One can use two synthetic separator rings with 24 short inside spokes. A separator ring is shifted over each end of the stator. The spokes separate the coils from each other at the outside and keep each coil at the correct place during poring of the epoxy.

There is a different way to make the stator than poring it in epoxy. Assume a synthetic bush is made which is pressed into the aluminium housing. Assume 24 rectangular or trapezoid shaped holes are made in this bush and that every coil is pushed in a hole from one side of the bush. In this case, a PVC or steel ring can’t be used but ever coil must have its own core which can already be placed when the coil is wound.

5 References

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

2 Kragten A. Development of a simple permanent magnet generator for a small windmill using a 4-pole, 3-phase, 0.37 kW asynchronous motor frame size 71 and twelve neodymium magnets size 20 * 20 * 5 mm, May 2011, reviewed October 2011, report KD 451, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

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

4 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, latest review November 2015, free public report KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.