Ideas about a 10-pole, 3-phase permanent magnet generator with a stator without iron in the coils, using 20 neodymium magnets size 50 * 20 * 10 mm and a housing of an asynchronous motor with frame size 80

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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 simpler or cheaper and wrote KD-reports about every new idea. One of the ideas is described in report KD 632 (ref. 2). This radial flux PM-generator makes use of the housing of a 4-pole asynchronous motor frame size 80 and it has an iron stator with 24 slots. A 1-layer 3-phase winding with 12 coils is laid in the stator. The original motor shaft is used but the original short-circuit armature is replaced by a 26-pole PM-armature. Magnets are used only for the north poles. The south poles are formed by the remaining material of the armature. The total magnet volume is rather low. Because the number of armature poles is only two more than the number of stator slots, the fluctuation of the sticking torque, due to eddy currents in the stator, is very low.

Another idea is described in report KD 644 (ref. 3) This radial flux PM-generator makes use of the housing of a 4-pole asynchronous motor frame size 71 but it has a stator made out of the synthetic material Delrin. The stator has a 2-layers winding with 12 coils. The original motor shaft is used but the original armature is replaced by an 8-pole PM-armature. Magnets are used for both the north and the south poles to get a sufficient strong magnetic field in the coils. Because there is no iron in the coils the sticking torque due to eddy currents is zero. The only sticking torque is caused by the friction of the bearings and the seal on the rotor shaft.

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.

The idea came up to combine the principles as used in KD 632 and KD 644 so to design a radial flux generator with no iron in the coils but with a 1-layer, 3-phase winding with only six coils. For six coils, the stator must have twelve slots. The number of armature poles must be two more or two less than the number of slots in the stator for a 1-layer winding. It is chosen for a 10-pole armature and for a motor housing of frame size 80.

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 same rotor which is also used for the 26-pole generator. This 2-bladed steel rotor has a design tip speed ratio of 4.75 and a rotor diameter of 2.2 m.

2 Description of the 10-pole PM-generator

The 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 housing with frame size 80, meant for a 4-pole, 3-phase, 0.75 kW stamping of Kienle & Spiess, is used.

2.1 Description of the armature

The original stator stamping has an outside diameter of 120 mm, an inside diameter of 70 mm and a length of 80 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 this new type 10-pole generator has much smaller coil heads because the coil heads are not lying within each other and because there are no crossing coil heads. Therefore the stator can have a length of 100 mm without the risk that the coil heads are touching the bearing covers.

The original short-circuit armature has an outside diameter of 69.4 mm, an inside diameter of 25 mm and an effective length of 80 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 100 mm and there is certainly enough place for this armature length.

The armature has ten poles, so five north and five south poles. Ten magnetic loops are coming out of the armature. The direction of the magnetic field for five loops is turning left hand and for the other five loops it is turning right hand.

The armature is made of a 100 mm long mild steel bush with an outside diameter of 70 mm and an inside diameter of 25.1 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.

Ten 20 mm wide grooves are milled in the bush parallel to the shaft axis. The bottom of the groove is lying 32.5 mm from the shaft axis. Two magnet size 50 * 20 * 10 mm are glued in each groove. The ten magnets in five grooves are positioned with the north pole to the outside. The ten magnets in the other five grooves are positioned with the south pole to the outside. So for one armature, twenty magnets are needed.

The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl . The current price of one magnet is € 4.00 including VAT, excluding transport if a minimum quantity of 50 magnets is ordered. So the magnet costs for one generator are about € 80 which is rather high but it seems acceptable if the generator has a high efficiency and a low sticking torque.

The radius at the heart of the outer side of a magnet is 32.5 + 10 = 42.5 mm. It can be calculated that the radius at the corner of a magnet is 43.66 mm. If the air gap in between the corner of a magnet and the inside of the stator is chosen 0.84 mm, it means that the stator must have an inside diameter of 2 * (43.66 + 0.84) = 89 mm. A cross section and a side view of the generator are given in figure 1 in chapter 2.2.

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 aluminium housing is machined to an inside diameter of 120 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 120 mm, an inside diameter of 89 mm and a length at the coils of 100 mm. So the thickness of the bush is (120 – 89) / 2 = 15.5 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 10-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, 1-layer winding of a 10-pole generator, the armature needs 12 slots at an angle of 30°. The slots are numbered 1 – 12. For every phase, two coils are used, so the total number of coils for a 3-phase winding is six. The coils of phase U are called U1 and U2. Both coils of one phase are connected in series. The coils of phases V and W use the same numbering. If one of the two coils of one phase is opposite to a north pole, the other coil will be opposite to a south pole. So the voltage generated in one coil will only be enlarged by the voltage generated in the other coil if the other coil has an opposite winding direction!

The winding is a so called 1-layer winding. This means that all six coils are laid in one cylindrical layer. The coil sequence is U1, W2, V1, U2, W1 and V2. The used grooves are respectively (1 + 2), (3 + 4), (5 + 6), (7 + 8), (9 + 10) and (11 + 12). The two coils of one phase are connected in series for 24 V battery charging.

The two coils of one phase of one layer are wound outside the generator on a winding thorn so the winding direction is the same for both coils on the winding thorn. All three coils no. 1 are mounted in the stator such that the winding direction is right hand. However, all three coils no. 2 have to be mounted such in the stator that the winding direction is left hand! Only in this case the voltage generated in coil no. 1 of a certain phase is strengthened by the voltage generated in coil no. 2 of that phase.

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 12 outside slots in the Delrin stator bush all have a width of 12 mm and a depth of 14 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 100 + 2 * 15 = 130 mm. These rims also prevent that wires which connect different coils can be guided too much to the inside.

The six coils can be mounted in the bottom of the slots easily because all coils are lying in one cylindrical plane. However, it should be prevented that the coils bend to the outside and touch the aluminium housing. It might be necessary to use Delrin filling strips in the grooves on top of the coils. These filling strips have to be kept in position when the Delrin bush is pressed into the aluminium housing. It might also 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 armature and the stator is given in figure 1. Figure 1 is drawn for the armature position for which the north pole N1 is just opposite the coil U1.

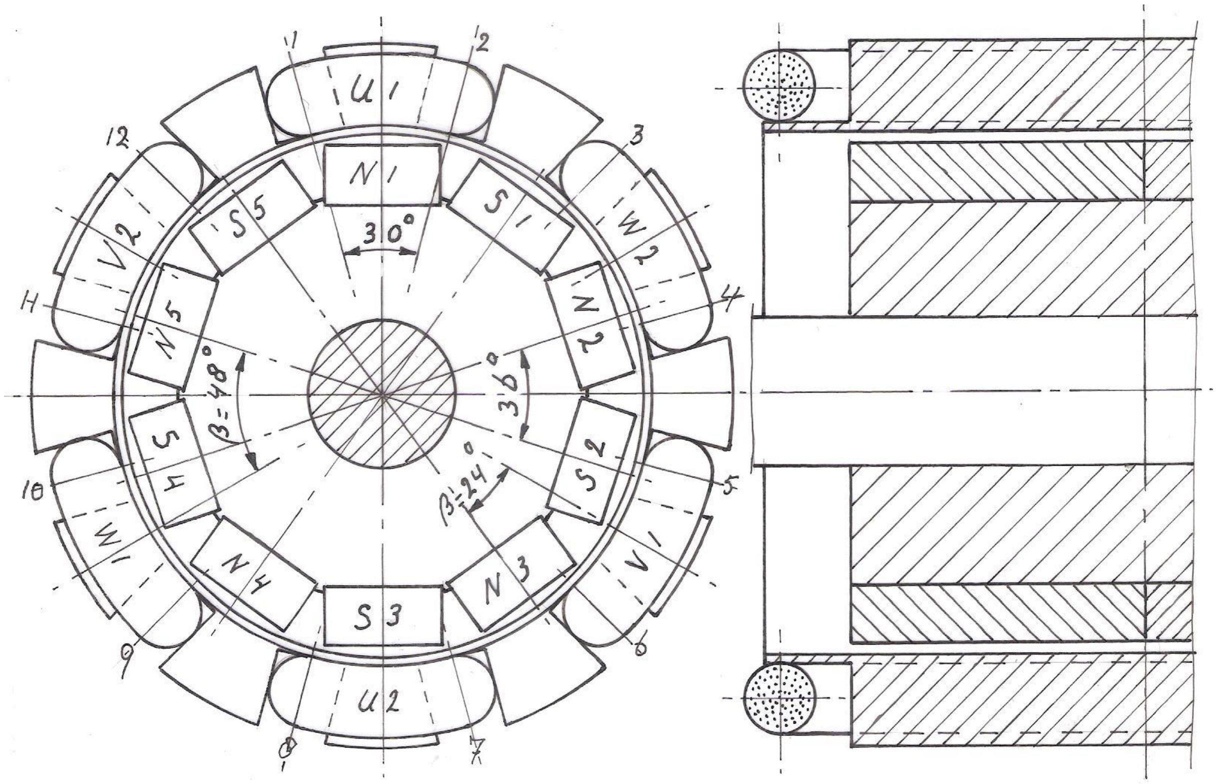

fig. 1 10-pole, 3-phase PM-generator with a 1-layers winding with two coils per phase

3 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.

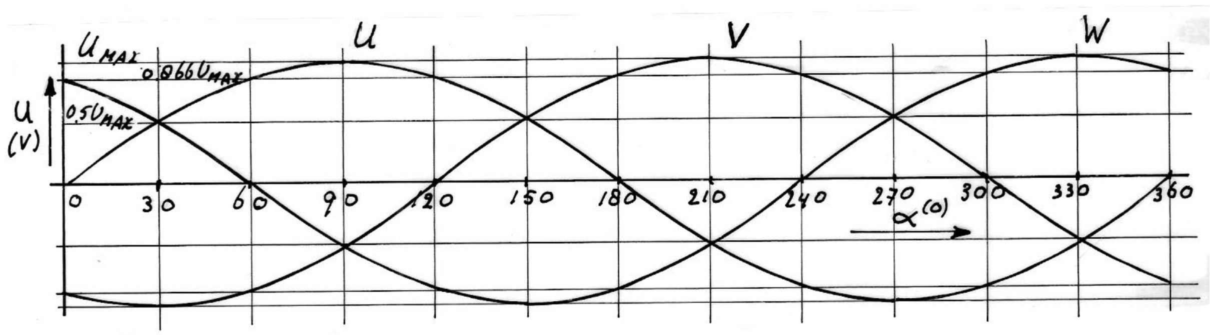

fig. 2 Three phases U, V and W

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 armature has two poles, the magnetic position of the armature with respect to the stator will be the same if the armature has rotated 360°. So the phase angle α is the same as the rotational angle β of the rotor. If the armature has 10 poles this will be the case for 360 * 2 / 10 = 72° rotation of the armature. This results in the formula:

$\alpha = \beta * p / 2$ (-) (4)

α is the phase angle, β is rotational angle of the armature and p is the number of armature poles.

In figure 1 it can be seen U1 is opposite to north pole N1 so $\beta = 0°$. It is assumed that $\alpha = 0°$ for this position of the armature. In figure 1 it can be seen that $\beta = 24°$ in between N3 and V1. Substitution of $\beta = 24°$ and p = 10 in formula 4 gives $\alpha = 120°$. In figure 1 it can be seen that $\beta = 48°$ in between N5 and W1. Substitution of $\beta = 48°$ and p = 10 in formula 4 gives $\alpha = 240°$. So a 3-phase current is generated in between the coils U1, V1 and W1.

A coil has two arms which are lying in the stator slots and a coil head at the left and the right side which connect both arms. In figure 1 it can be seen that the angle in between the heart of the two arms of one coil is 30°. In figure 1 it can be seen that the angle in between the heart of two adjacent magnets is 36°. So if the heart of a north pole is just opposed to the heart of the left arm of a coil, the heart of a south pole is already 6° farther than the heart of the right arm of a coil. This means that the voltage generated in the left arm of a coil is not in phase to the voltage generated in the right arm of a coil. Substitution of $\beta = 6°$ in formula 4 gives that $\alpha = 30°$. So there is a shift in phase angle of 30° in between the voltages generated in the left and the right arm of a coil. The voltages of the sine waves in the left arm and in the right arm of a coil have the following equations:

$U_l = U_{max} * \sin\alpha$ (V) (5)

$U_r = U_{max} * \sin(\alpha - 30°)$ (V) (6)

The summarised voltage of the sine wave in the left and the right arm is given by:

$U_{l+r} = U_{max} * \{\sin\alpha + \sin(\alpha - 30°)\}$ (V) (7)

It can be proven that this function has a maximum for $\alpha = 105°$. Substitution of $\alpha = 105°$ in formula 7 gives that $U_{l+r} = 1.932 * U_{max}$. If the voltages in both arms would be exactly in phase to each other, the total voltage U_{l+r} would have been $2 * U_{max}$. So the fact that there is a phase shift of 30° in between the voltages in between both arms of a coil results in a reduction of the voltage of only a factor 1.932 / 2 = 0.966. So it is certainly acceptable that the voltages in the left and the right arm of a coil aren't exactly in phase to each other.

There is enough space to increase the angle in between the slots of a coil from 30° up to 36° and to reduce the angle in between adjacent slots from 30° up to 24°. This results in a little increase of the width of the coil heads but now there is no phase shift in between the voltages generated in the left and the right arm of a coil. Manufacture of the slots in the Delrin stator might be a bit more difficult for two different angles.

The generator winding is very simple if compared to the winding of a normal 4-pole asynchronous motor. This is because all coils have the same shape and because there are no crossing coil heads. The strength of the magnetic field flowing through a coil will be the same for each coil and the generated voltage in each coil will therefore be the same too. This is not the case for a normal 4-pole winding as some coils have a different pitch. The coil heads are very small if compared to the length of the part of the coil lying in the slots. A minimum amount of copper will therefore be used and the winding will have a relatively low resistance resulting in a high generator efficiency.

The winding can be rectified in star or in delta. However, rectification in delta has as disadvantage that the unloaded sticking torque may rise rather fast at low rotational speeds because higher harmonic currents can circulate in the winding. This will result in a higher starting wind speed. Circulation of higher harmonic currents isn't possible for star rectification and the sticking torque is therefore not rising. So star rectification is preferred. If the generator is used as a brake, the star point should be short-circuited too because this gives a higher maximum braking torque.

4 Determination of the flux density in the air gap

A part of a magnetic loop is flowing outside the armature and a part is flowing inside the armature. Ten magnetic loops are coming out of the armature. Five loops are turning right hand and five loops are turning left hand. Let's look at the right hand loop coming out of the north pole N1. This loop uses the right half of the magnet N1, then it makes a right hand turn through the air over 216°, then it uses the left half of the magnet S1 and then it makes a right hand turn through the iron of the armature over 144°. The length of the outer loop through air is much longer than the length of the inner loop through iron.

The length of the outer loop through air depends on which field line is followed. The length of the field line through the heart of the magnet is the longest and through the side of a magnet is the shortest. It is assumed that the average length l_2 is gained for the field line which is flowing through the point which lies at ¼ of the magnet width from the side. It is also assumed that the shape of this line is a circle segment with an arc of 216°. The radius of this circle segment is about 8.5 mm resulting in $l_2 = 32$ mm.

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 $t_2 = 32$ mm in formula 1 results in $B_{r\ eff} = 0.46$ 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 0.46 / 0.9 = 0.51 of the flux density of a PM-generator which has a mild steel stator stamping. However, the length of the Delrin stator is 100 mm instead of 80 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.

5 Determination of the winding

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 star rectification and 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 chosen windmill rotor are determined for different wind speeds. This is done in figure 7 of KD 632 (ref. 2) for the 2.2 m rotor. 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 7 of KD 632. 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 in a slot. It can be expected that 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. But to be sure, the generator has to be measured again for the modified winding and for a voltage of 26 V star.

6 Alternative

There might be a way to increase the flux density in the coils by using a part of the original iron stator stamping. If the spokes are removed, so if only the outer ring of the stator stamping is maintained, the magnetic field will flow from a north pole to this outer ring and then from the outer ring to a south pole and then through the armature. So two air gaps have to be passed for one magnetic loop but the total length of these two air gaps is much shorter than the value l_2 = 32 mm as calculated in chapter 4.

The original stator stamping of a 4-pole motor frame size 80 has a length of 80 mm so now the armature must also get a length of 80 mm. Now it is possible to use one magnet size 80 * 20 * 10 mm in one groove. Magnets of this size are also supplied by ENES Magnesy. The quality of this magnet is N35H and the price is € 6,69 including VAT excluding costs of transport if at least 30 magnets are ordered. So now the total magnet costs for the ten magnets of one generator are about € 68. The original stator stamping has an outside diameter of 120 mm and an inside diameter of 70 mm. The 24 slots have a depth of 15 mm so the nominal thickness of the outer ring is 10 mm. Assume that the stator stamping is turned to an inside diameter of 106 mm, so the thickness of the stator ring is reduced to 7 mm.

The armature diameter at the heart of the magnets is 2 * 42.5 = 85 mm. The armature diameter at the corners of the magnets is 2 * 43.66 = 87.32 mm. So the average armature diameter is about 86 mm. So the average air gap in between the armature and the iron stator ring is (106 - 86) / 2 = 10 mm. So the total thickness of the two air gaps t_2 = 20 mm. This is much less than the value as calculated in chapter 4 for a stator with no iron. So the magnetic flux in the air gap will become much stronger. Substitution of B_r = 1.19 T, t_1 = 10 mm and t_2 = 20 mm in formula 1 results in $B_{r\ eff}$ = 0.595 T which seems acceptable.

The thickness of the stator ring is 7 mm and half the width of a magnet is 10 mm. So the flux density in the stator ring is concentrated by a factor 10 / 7 = 1.43. So the flux density in the stator ring becomes 1.43 * 0.595 = 0.84 T. This is far from the value 1.6 T for which the stator is saturated.

The fact that the magnetic flux is now flowing through the iron ring of the stator will cause a sticking torque due to eddy currents but this sticking torque will have no fluctuation as the stator has no poles. As the iron stator ring is made out of thin isolated laminations, the eddy currents will be rather small. So I expect that this sticking torque will give no starting problems for the windmill rotor.

The available space for the stator winding is now much less because the 7 mm wide iron stator ring takes a lot place. The Delrin bush must now have an outer diameter of 106 mm. To get enough copper in the coils, it seems better to increase the groove width from 12 mm up to 14 mm. The groove depth now becomes only 7 mm but still a lot of copper can be laid in this groove if the winding is pressed inwards firmly. It will steel be needed to use a thin isolation cap in the top of the groove to prevent that the winding touches the iron stator ring. The distance in between the coil heads and the aluminium housing now becomes 7 mm, so no isolation is required at the coil heads.

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