Ideas about a 4-pole, 3-phase permanent magnet generator using the housing of an asynchronous motor frame size 80 and four neodymium magnets size 80 * 20 * 10 mm with a magnet orientation such that the fluctuation of the sticking torque is minimal

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1 Introduction

One of the most critical parts of a small wind turbine is the generator. For my older 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 difficult to manufacture and rather expensive.

I did several attempts to design a PM-generator which is simpler or cheaper and wrote KD-reports about every new idea. I have described radial flux and axial flux generators and generators with and without iron in the coils. The main disadvantage of a generator without iron in the coils is that this results in a big air gap. A big air gap reduces the magnetic flux flowing through the coils and therefore many thick and expensive magnets have to be used. The main disadvantage of a generator with iron in the coils is that this iron results in eddy currents and that the generator may have a strong peak on the sticking torque if the armature isn't designed properly. A large peak on the sticking torque results in a high starting wind speed if a fast running windmill rotor with a low starting torque coefficient is used.

There are several ways to reduce the peak in the sticking torque. I way to realise this for an 8-pole generator made from an asynchronous motor is described in report KD 681 (ref. 2). In this report KD 683 it is researched if a similar way can be used for a 4-pole generator. An advantage of a 4-pole generator, is that the standard 3-phase motor winding can be used.

A starting point for this generator is that it can be made from the housing of a standard 4-pole asynchronous motor frame size 80. This has as advantage that the housing and the bearing covers are 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. A generator of frame size 80, has a shaft diameter at the front bearing of 20 mm and it can be used for a direct drive windmill rotor with a diameter in between about 2 m and 2.2 m. A PM-generator made from an asynchronous motor has a magnetic flux which is radial at the air gap in between the armature and the stator stamping, so this generator will be of the type "radial flux".

2 Description of the 4-pole PM-generator

2.1 General

It is chosen to take an asynchronous motor in which a stator stamping of the German manufacture Kienle & Spiess is used. Information about dimension of stator stampings of this manufacture are given on the website: www.kienle-spiess.de. The chosen stator stamping has the code: IEC 80/4.70. The outside diameter is 120 mm, the inside diameter is 70 mm. This stamping is used for a 0.75 kW, 4-pole motor and the length of the stator stamping is 80 mm for this motor. The stamping has 24 slots, so in between these slots there are 24 stator poles.

It is chosen to use this stamping for a 4-pole armature. A 4-pole armature has two north and two south poles. The angle in between the heart of a north pole and the heart of a south pole is normally 90° for a 4-pole generator. This means that the optimum angle in between two legs of a stator coil is 90° too.

However, it isn't possible to use this angle for all coils if the stator stamping has 24 slots. This problem is solved by using two coils which are lying within each other and for which the inner coil has an angle of 80° and for which the outer coil has an angle of 100°. A 2-layers winding can be laid in this stator for a 4-pole armature.

If the armature pole angle is chosen 90°, it means that the generator will get 24 preference positions per revolution. The armature will get a preference position when the magnetic flux in between armature and stator flows easiest. This is the case when there is a maximum overlap in between an armature pole and some of the stator poles.

If the armature poles are inclined with an angle such that there is just one stator pole pitch overlap in between the left and the right side of the armature pole, this problem is solved. However, inclined armature poles can only be gained if the magnets are placed in deep narrow grooves with the magnet area tangential and if there is magnetic isolation in between the north and the south poles. This procedure is used for the older VIRYA generators and the armature construction is explained in chapter 4 of KD 341.

2.2 Description of the armature

For this new generator, it is chosen that the magnets are positioned in wide shallow grooves with the magnet area radial and that the grooves are made in parallel to the armature axis. So a cutter with a large diameter can be used. Magnets are only used for the north poles. The magnets are glued in the grooves by anaerobic glue. The south poles are formed by the remaining steel of the armature. The outside of the north poles is flat but the outside of the south poles is curved. So the air gap at the north poles is larger than at the south poles. It is chosen to use neodymium magnets size 80 * 20 * 10 mm. The length of the armature becomes 80 mm for these magnets, so it is the same as the length of the stator.

A 4-pole armature normally has two north and two south poles at an angle of 90°. However, for this generator two magnets size 80 * 20 * 10 mm are used for one magnetic north pole so totally four north poles are gained which are called N1, N2, N3 and N4. N1 and N2 are lying close to each other and both together are forming one magnetic north pole. N3 and N4 are also lying close to each other and both together and are forming the other magnetic north pole. N1 is positioned just opposite to N3 and N2 is positioned just opposite to N4. The angle in between N1 and N2 is chosen 45° + 7.5° = 52.5°. The armature construction is given in figure 1 in chapter 2.3.

The stator has 24 slots so it has 24 poles. The stator poles are numbered 1 – 24. In figure 1, the armature is drawn such that the heart of north pole N1 is just opposite stator pole no. 1 but stator poles no. 24 and no. 2 are also opposite north pole N1. North pole N2 is opposite to stator poles no. 4 and no. 5. So the largest stator pole area is opposed to north pole N1. The armature will therefore have a preference position for N1 for the drawn position but it will have a preference position for N2 if the armature has rotated 7.5°. This means that the positive torque fluctuation of N1 is compensated by the negative torque fluctuation of N2 if the torque fluctuation is sinusoidal. But it also means that the number of preference positions per revolution created by the north poles is 360° / 7.5° = 48° if the compensation isn't perfect.

The magnets are supplied by the Polish company Enes Magnets website: www.enesmagnets.pl. The magnets of this company are rather cheap if compared to magnets with the same volume of other magnet suppliers. The current price of one magnet is € 5.44 excluding VAT, excluding transport if a minimum quantity of 30 magnets is ordered. So the nett magnet costs for one generator are about € 22 which is rather cheap.

The south poles are created by the remaining material of the armature. Similar to the north poles, a magnetic south pole is also formed by two south poles. The north poles have a width of 20 mm which is the same as the magnet width. The south poles also get a width of 20 mm by making inclined grooves at the sides of the magnet grooves and by making a narrow groove in between two adjacent south poles.

If the two south poles S1 + S2 would be positioned symmetrically in between the north poles N2 and N3, the 48 preference positions of the south poles will coincide with the 48 preference positions of the north poles. The torque fluctuation of one north pole or one south pole is probably not sinusoidal which means that some final fluctuation remains. So it is chosen to rotate the pattern of the south poles by 3.75° with respect to the pattern of the north poles. This means that the preference positions of the south poles are now lying just in between the preference positions of the north poles and this results in 96 preference positions per revolution which must be high enough to flatten the final torque fluctuation almost completely.

However, there is one important condition and that is that it isn’t allowed to use a stator stamping with four outside grooves. Thin strips with bent ends, lying in these grooves, are used to connect all stampings together. These stampings are generally used in India. The chosen stamping of Kienle and Spiess doesn’t have four outside groves. Four outside groves in the stator stamping make that the armature will get four strong preference positions per revolution for the position of the armature for which the magnetic flux in the stator is least hindered by the four outside grooves.

The angle in between two adjacent north poles was chosen 7.5° larger than 45°, so 52.5° because other wise the magnets will touch each other. The angle in between two adjacent south poles is chosen 7.5° smaller that 45°, so 37.5°. The width of a south pole is chosen the same as that of a north pole, so 20 mm. So there are four south poles S1, S2, S3 and S4. S1 and S2 are lying close to each other and both together are forming one magnetic south pole. S3 and S4 are also lying close to each other and both together and are forming the other magnetic south pole. S1 is positioned opposite to S3 and S2 is positioned opposite to S4.

The armature is made of mild steel. The armature is pressed on the generator shaft which has a diameter of 24 mm at the armature. The generator shaft is made of stainless steel with a tapered shaft end because this prevents that the rotor hub can rust to the shaft and because it gives a better contact area for the seal at the shaft side. The bearing cover at the other side is closed so the cover has no seal at this side. The bearings have an internal seal at both sides. The space in between the front bearing and the shaft seal is filled with grease to create an extra barrier against the entrance of water and dust.

So stainless steel isn’t needed for its anti magnetic qualities as it is the case for the older VIRYA generators with inclined magnet grooves. If stainless steel isn’t available one can use a good quality shaft steel or even the original motor shaft. A cross section and a side view of the generator armature with the main measures are given in figure 1 at chapter 2.3.

2.3 Description of the stator

The stator stamping is pressed in the aluminium generator housing. The stator stamping has 24 slots in which the coils are laid. In between the 24 slots we have 24 stator poles which are numbered 1 – 24. Two slots are used for one coil, so twelve coils can be laid in 24 slots. Every phase has four coils for a 3-phase winding. The slots are provided with a thin slot isolation. After mounting of the coils, a slot cap is shifted in each slot to prevent that the coils can come out of the slots and touch the rotating armature. It may be needed so soak the whole assembly of coils in liquid lacquer to prevent vibration of the wires.

In chapter 2.2 it was already explained that two coils of one phase are positioned within each other. The two legs of the inner coil have a stator pitch of 80° and the two legs of the outer coil have a stator pitch of 100°. The winding is a so called 2-layers winding. This means that the three bundles of two coils U1 and U2, V1 and V2 and W1 and W2 are laid in the first layer. The coil heads of these six coils are bent to the outside to make place for the six coils of the second layer U3 and U4, V3 and V4 and W3 and W4. The two coils of a certain phase in one layer are connected in series. The two coils of the first layer can be connected in series with the two coils of the second layer or they can be connected in parallel. But all four coils of a standard 230 / 400 V winding are normally connected in series.

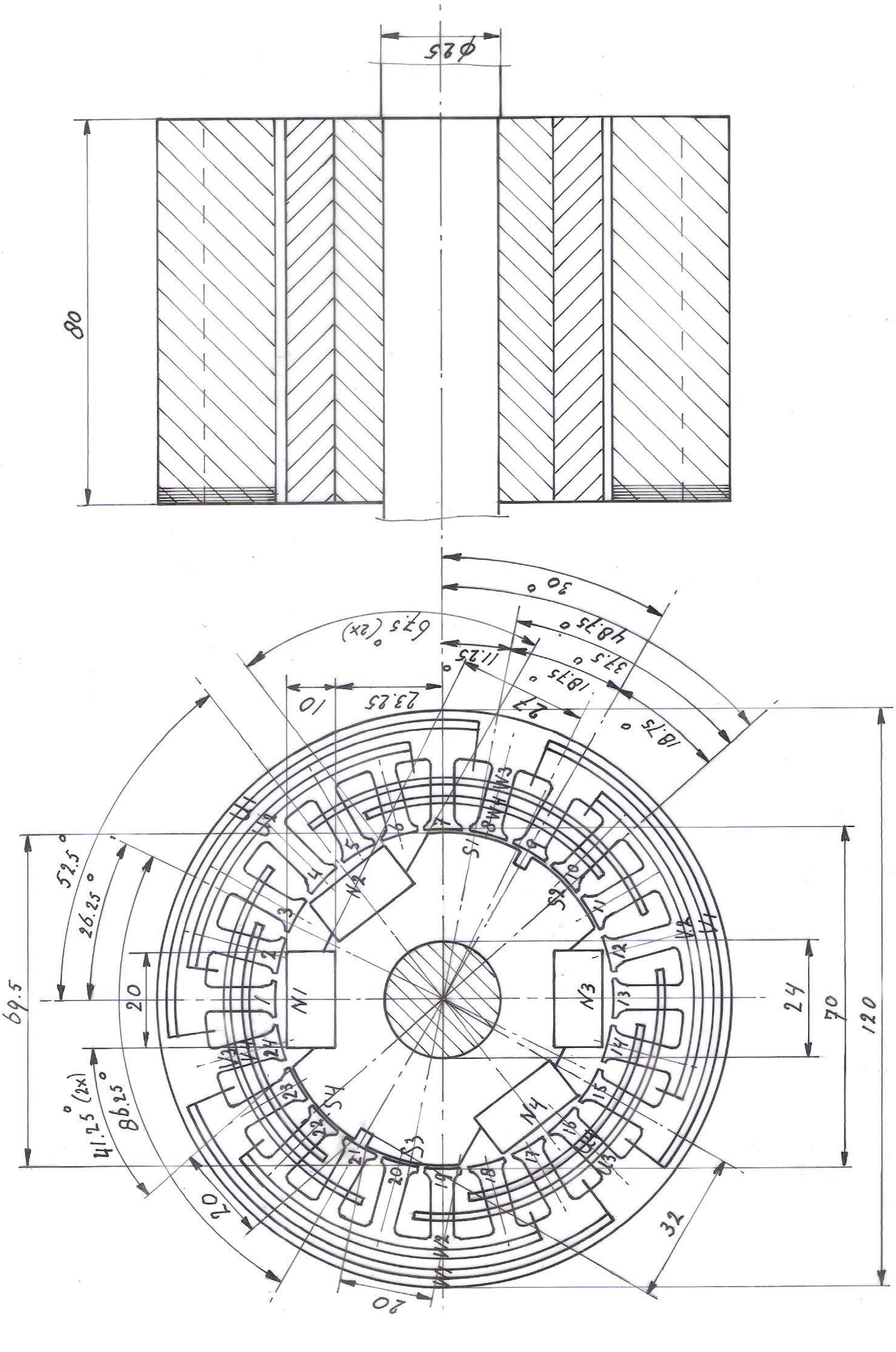

fig. 1 4-pole, 3-phase PM-generator with a 2-layers, 3-phase winding

The two coils of a coil bundle of one phase are made outside the generator. The connection point in between the coil bundles of the first and the second layer are normally soldered and isolated and are lying somewhere at the coil heads.

Every bundle of four coils has a beginning end labelled A and an ending end labelled B. The generator housing has a terminal box with six contacts. The both ends of each phase are connected to the terminal in a way as this is normally done for a 3-phase winding. The winding can be connected in star or in delta. For star connection, the three coil ends labelled A are connected to each other by brass strips and are forming the star point. The three coil ends labelled B are guided to the three contacts of a 3-phase rectifier. It is also possible to connect the winding in delta by using three brass strips in parallel and this reduces the voltage by a factor √3.

Which way of rectification has to be used depends on the choice of the windmill rotor and the battery voltage. A standard 230 / 400 V winding will give a rather high voltage already at low rotational speeds and so it won’t be possible to use the generator for 12 V battery charging. The winding might be useful for 24 V battery charging if the winding is rectified in delta and for 48 V battery charging if the winding is rectified in star. The standard 230 / 400 V winding can be modified into a 115 / 200 V winding if the coil bundles of the first layer are connected in parallel in stead of in series. This procedure is explained in report KD 341 (ref. 1).

3 Determination of the flux density in the air gap

A part of a magnetic loop is flowing inside the armature and a part is flowing inside the stator. Four magnetic loops are coming out of a 4-pole armature. Two loops are turning right hand and two loops are turning left hand. A magnetic loop flows through one magnet and through two air gaps. A magnet has a thickness t_1 = 10 mm. As the glue layer is very thin, it is assumed that there is no air gap in between the inside of the magnet and the groove.

The stator stamping has an inside diameter of 70 mm. It is assumed that the armature is turned at a diameter of 69.5 mm at the south poles. So the air gap at the south poles t_2 = 0.25 mm. The air gap at the north poles is maximal at the heart of the magnet and minimal at both sides. The groove depth is chosen 11.5 mm resulting in a distance of 23.25 mm from the bottom of the groove up to the shaft axis. This means that the air gap at the heart of the 10 mm thick magnet is 1.5 + 0.25 = 1.75 mm. The air gap at the sides of the magnet is about 0.28 mm so the magnets don’t jut out of the armature. The average air gap is more than half the mathematical average because the air gap is moon shaped. Assume that the average air gap at the north poles t_3 = 1.3 mm.

The flux density in the air gap is calculated by formula 5 from report KD 341 for a PM-generator with tangential orientation of the magnets. A simpler formula can be derived for this PM-generator with radial orientation of the magnets if the magnetic resistance of the iron is neglected and if it is assumed that the magnetic resistance of the magnets is the same as for air. Formula 1 of KD 341 changes into:

$$B_{r\,eff} = B_r * t_1 / (t_1 + t_2 + t_3) \quad \text{T} \qquad (1)$$

For radial positioning of the magnets, the pole area is the same as the magnet area. As the width of a south pole is chosen the same as the width of a north pole, both pole areas are the same. So it isn’t necessary to compare the magnet area with the pole area as it is required for tangential positioning of the magnets. So formula 1 can be used directly to calculate the flux density in the air gap. The used magnets with quality N35H have a remanence B_r of about 1.19 T. Substitution of B_r = 1.19 T, t_1 = 10 mm, t_2 = 0.25 mm and t_3 = 1.3 mm in formula 1 gives that $B_{r\,eff}$ = 1.03 T.

In KD 341 it is assumed that the stator stamping is saturated if the calculated flux density in the air gap is larger than 0.9 T. So it can be expected that the generator is saturated and so the maximum possible torque level is gained. The stator stamping can be saturated at the spokes in between the slots or at the bridge in between the bottom of the slots and the outside of the stamping. The stamping is designed for a 4-pole motor and it is used for a 4-pole generator. So if the stator stamping is saturated, it can be saturated at the spokes, at the bridge or at both.

4 Checking if the standard winding can be used

The standard winding of a 4-pole motor is meant for a 3-phase 230 / 400 V grid with a frequency of 50 Hz. It might be possible to use the PM-generator with this standard winding for 24 V or for 48 V battery charging. To verify this, one needs a test rig with which it is possible to measure the torque, the rotational speed, the voltage and the current. I have used a sophisticated test rig of the University of Technology Eindhoven for measuring my older VIRYA generators. I have also developed a simple private test rig but this one is too small for this 4-pole generator.

First the generator is connected in star and the P_{mech}-n and P_{el}-n curves are determined for a 48 V battery of sufficient capacity or for a battery charge controller which is adjusted at a constant voltage of 52 V. A voltage of 52 V is about the average charging voltage for a 48 V battery. Next the generator is connected in delta and the P_{mech}-n and P_{el}-n curves are determined for a 24 V battery of sufficient capacity or for a battery charge controller which is adjusted at a constant voltage of 26 V. A voltage of 26 V is about the average charging voltage for a 24 V battery. Rectification of a 3-phase winding is explained in KD 340 (ref. 3).

Next the P-n curves of the chosen windmill rotor are determined for different wind speeds and these curves are drawn in a P-n graph. 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. 4). The optimum cubic line is also drawn in the P-n graph with the generator measurements. If the correct parameters have been chosen for the windmill, the P_{mech}-n curve of the generator for 52 V star or for 26 V delta will have a good matching with the optimum cubic line of the chosen rotor. Good matching means that both curves have two points of intersection which are not lying far apart. If there is no good matching for none of the P_{mech}-n curves of the generator, one has to change the parameters of the windmill rotor (matching is explained in chapter 8 of report KD 35 ref. 4).

Assume that finally one has chosen a windmill rotor which matches optimal with the P_{mech}-n curve of the generator for 52 V star but one wants to use this windmill for 24 V battery charging. This means that the 230 / 400 V winding has to be modified into a 115 / 200 V winding.

Assume that finally one has chosen a windmill rotor which matches optimal with the P_{mech}-n curve of the generator for 26 V delta but one wants to use this windmill for 12 V battery charging. This means that the 230 / 400 V winding has to be modified into a 115 / 200 V winding.

The disadvantage of delta rectification is that the sticking torque of the generator is rising faster at increasing rotational speed than for star rectification. This is because higher harmonic currents can circulate in the winding for delta rectification. Delta rectification can only be used if the starting torque coefficient of the chosen rotor is high enough.

It seems possible to use a similar armature construction for a bigger 6-pole PM-generator which makes use of an asynchronous 6-pole motor with a stator stamping with 36 slots. However, the voltage of a 6-pole generator will be about a factor 1.5 higher than for a 4-pole generator if both have a standard winding. A 6-pole motor may have a 3-layers winding with all six coils of one phase lying in one layer and then it isn’t possible to halve the voltage by modification of a standard 230 / 400 V winding into a 115 / 200 V winding.

5 Alternative armatures

5.1 Using south poles with a width 5 times the stator pitch

The reason why a preference position exists, is that the overlapping area in between an armature pole and several stator poles has a certain maximum. In figure 1 it can be seen that the overlapping area for north pole N1 is somewhat larger than for north pole N2. This is caused by the fact that there is a groove in between the stator poles with a width of 2.5 mm. The stator pitch is π * 70 / 24 = 9.16 mm and so the curved width of a stator pole is 9.16 - 2.5 = 6.66 mm. Magnets with a width of 20 mm cover two stator poles for north pole N2 but about 2 1/3 stator poles for north pole N1. So the magnetic flux flows easier from north pole N1 to the armature than for north pole N2 and therefore the position of north pole N1 is a preference position. But the positive peak on the sticking torque of magnet N1 is almost compensated because magnet N2 is at the position where there is a negative peak on the sticking torque. The same principle is used for the south poles but this requires making of a groove in between south poles S1 and S2 and in between south poles S3 and S4. The south poles are positioned not symmetrical in between the north poles to get an armature with 96 preference positions in stead of with 48 preference positions per revolution.

It might be possible that preference positions are prevented if the width of an armature is exactly a whole times the stator pitch. This can’t be realised for the north poles, as 20 mm wide magnets are used for the north poles but it can be realised for the south poles. Assume that a south pole is made that wide that is covers exactly five stator pitches. Five stator pitches have a pitch angle of 5 * 15° = 75°. So a south pole has to be that wide, that there is an angle of 75° in between the corners of a south pole. If a south pole has this width, there will always be the same overlapping area in between a south pole and five stator poles and so the magnetic flux will feel the same resistance for every position of the armature. If such a south pole has no preference positions, it can be positioned symmetrically in between the north poles and no groove is required to create two south poles. A 45° inclined groove has to be made at the outer side of a magnet groove. Such an armature is given in figure 2.

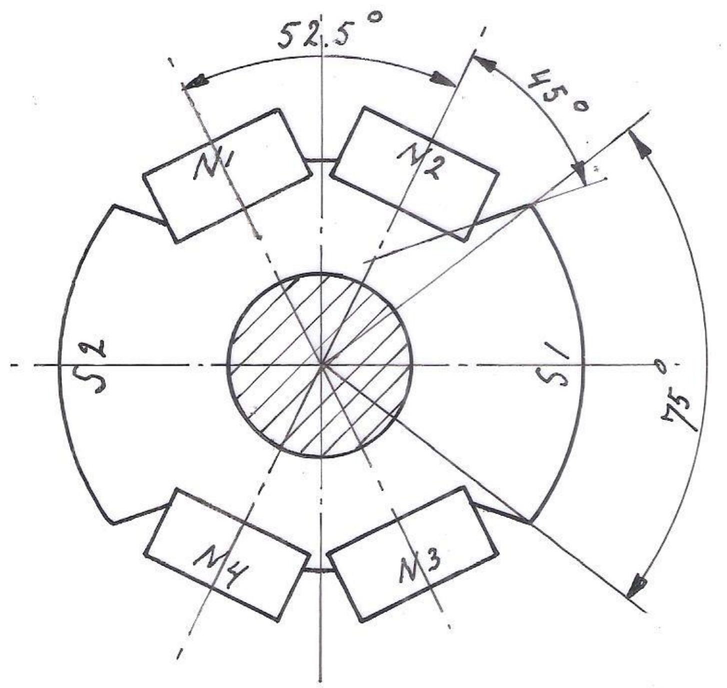

fig. 2 Armature with four north poles and two south poles

5.2 Using the original short-circuit armature

Up to now it is assumed that the original short-circuit armature is removed from the shaft and replaced by a massive mild steel bush. There are two options to use the original short-circuit armature.

The simplest option is to make the groove pattern according to figure 1 or figure 2 directly in the original short-circuit armature. However, the original short-circuit armature has 22 aluminium bars in it to guide the short-circuit current. These bars have a large magnetic resistance and the magnetic flux which flows from a south to a north pole inside the armature will therefore be hindered. So the final magnetic flux which flows through the stator from a north to a south pole will be smaller than when a massive iron bar is used for the armature. Therefore the generated voltage in the stator winding will be lower. But the generated voltage may still be high enough if the generator is used in combination with a certain rotor. So this is a cheap option if a lower voltage and a lower maximum torque level is accepted. A disadvantage of making grooves in the original short-circuit armature may be that the grooves won't have a nice flat surface as some small aluminium parts or some small parts of the steel stamping may come loose.

The second option is to turn the armature to a diameter of 42 mm and to use a 80 mm long part of a steel pipe with an outside diameter of 70 mm and an inside diameter of 42 mm. This pipe is available in The Netherlands at MCB but probably not in developing countries. The pipe is turned to an inside diameter of 42.2 mm and glued to the armature using epoxy or anaerobe glue. The aluminium bars have a depth of 13.75 mm and are completely removed if the armature is turned to a diameter of 42 mm. It is also possible to use 70 mm pipe with an inside diameter of 38 mm or 35 mm which are also supplied by MCB. If the bush has to be manufactured from massive bar, it is better to remove the original short-circuit armature and to press the bush directly onto the shaft.

5.3 Using radial magnets in four inclined grooves

The magnet construction as given in figure 1 was chosen because it was expected that milling is faster than for the magnet construction of my older generators with inclined magnet grooves. But it can be questioned if this is really true. Milling of the four 20 mm wide and 11.5 mm deep magnet grooves is rather fast as a thick 20 mm cutter can be used. However, material has to be removed in between adjacent north poles. This requires two extra armature positions. To create the four south poles, inclined groves with two different angles have to be made at the sides of the magnet grooves. This requires four extra armature positions. Narrow grooves have to be made to separate the adjacent south poles. This requires two extra armature positions and one needs a thin saw cutter. So these extra machining operations and tool changes also have to be taken into account.

For the armature construction with four radial positioned magnets glued in inclined grooves, only four identical 10.2 mm wide grooves have to be made. These grooves have a depth of 21.75 mm and this isn't very deep for a 10 mm finger cutter. This option was described in the first version of this report KD 683 but it is also described in the recent report KD 690 (ref. 5) and therefore it is cancelled in this latest version of KD 683. KD 690 also describes the VIRYA-2S rotor and it might be possible to use this rotor also in combination with the generator with tangentially positioned magnets.

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