Ideas about an 8-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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 The generator has not yet been tested.

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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 and in this report KD 681 it is researched if there is a way which results in a simple armature and a simple stator winding. 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 8-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 an 8-pole armature. An 8-pole armature has four north and four south poles. The angle in between the heart of a north pole and the heart of a south pole is normally 45° for an 8-pole generator. This means that the optimum angle in between two legs of a stator coil is 45° too. A simple 2-layers winding with twelve identical coils can be laid in this stator for an 8-pole armature.

If the armature pole angle is chosen 45°, 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.

The real width of a stator pole is less than the stator pitch because there is a gap in between the poles for mounting of the coils. The real width of an armature pole is less than the armature pitch because the technical construction results in a certain pole width depending on the magnet width. So there is a position for which there are a little less than three stator poles opposed to an armature pole and there is a position for which there are a little more than two stator poles opposed to an armature pole. The preference position will be the position for which there are a little less than three armature poles opposed to an armature pole.

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 four north poles. The magnets are glued in the grooves by anaerobic glue. The four south poles are formed by the remaining steel of the armature. The outside of the four north poles is flat but the outside of the four 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, so only four of these magnets are needed. The length of the armature becomes 80 mm for these magnets, so it is the same as the length of the stator.

These 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.

There are several ways to solve the problem of the peak on the sticking torque. One way is to split the armature in two 40 mm long parts and to rotate the right part by 7.5° with respect to the left part. However, this has as disadvantage that manufacture of the grooves is now difficult and that one has to use eight magnets size 40 * 20 * 10 mm. Magnets of these size are not supplied by Enes Magnets.

A second way is to make the angle in between the north poles 90° and to make the angles in between the south poles 90° but to rotate the south poles by 7.5° with respect to the north poles. However this makes that the distance in between adjacent north and south poles becomes very small. As the flat pole area of a north pole differs from the curved pole area of a south pole, it might also be that the positive fluctuation of the sticking torque of the north poles isn’t fully compensated by the negative fluctuation of the sticking torque of the south poles.

A third way, which is finally chosen, is to rotate the two north poles N2 and N4 by 7.5° left hand with respect to the two north poles N1 and N3. This means that there is an angle of 82.5° in between N1 and N2 and in between N3 and N4 and that there is an angle of 97.5° in between N2 and N3 and in between N4 and N1. So the positive peak on the sticking torque caused by the north poles N1 and N3 will be compensated by the negative peak on the sticking torque caused by the north poles N2 and N4.

The four south poles are created by the remaining material of the armature. 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. The south pole S1 is positioned symmetrically in between N1 and N2. The south pole S3 is positioned symmetrically in between N3 and N4.

The south poles S2 and S4 can’t be positioned symmetrically in between the adjacent north poles because this would result in an angle of 90° in between all four south poles. So the two south poles S2 and S4 are also rotated 7.5° left hand with respect to the two south poles S1 and S3. So now the positive peak on the sticking torque caused by the south poles S1 and S3 will be compensated by the negative peak on the sticking torque caused by the south poles S2 and S4.

If the torque fluctuation would be pure sinusoidal, it would mean that the positive torque fluctuation of the north poles N1 and N3 would be fully compensated by the negative torque fluctuation of the north poles N2 and N4. So no fluctuation will remain. However, I am afraid that the torque fluctuation isn’t pure sinusoidal and that some small fluctuation will remain. This means that the armature will have a preference position if two of the four north poles are just opposite three stator poles. This happens every 7.5°, so the armature will have 48 preference positions because of the north poles. The armature will also have 48 preference positions because of the south poles and these positions don’t coincide with the preference positions of the north poles as S1 was chosen just symmetrical in between N1 and N2. So the armature will get 96 very small preference positions per revolution which seems acceptable.

The fact that there is a shift of 7.5° in between two of the four north poles makes that the voltages generated in the coils opposite to these poles are somewhat out of phase. This effect is investigated in chapter 3.

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.

The winding is a so called 2-layers winding. This means that the six coils U1, V1, W1, U2, V2 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, V3, W3, U4, V4 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. The generated voltage for connection in series is double the voltage than for connection in parallel. The winding is rectified in star. It is assumed that the winding is used for 12 V battery charging if the layers are connected in series.

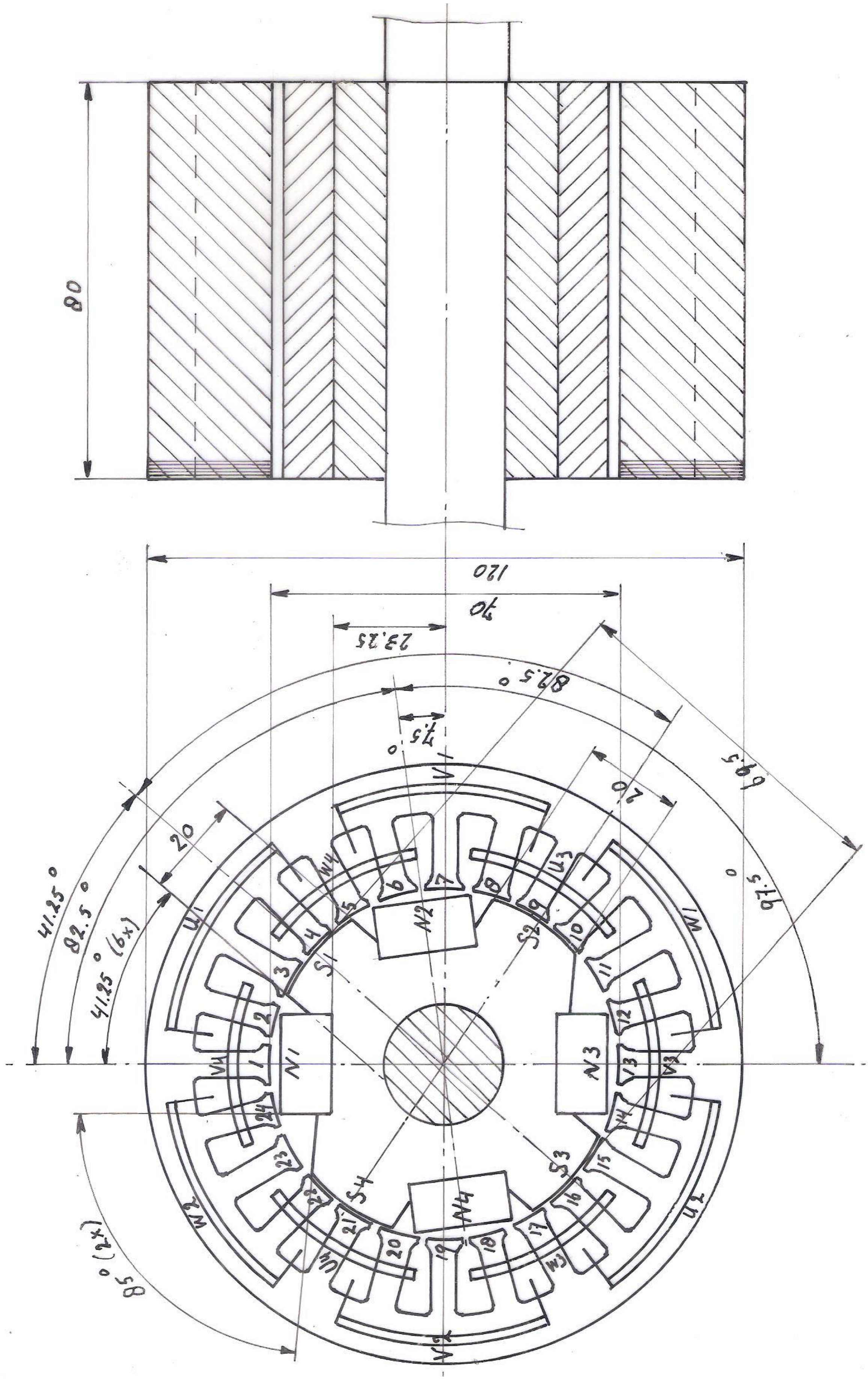

fig. 1 8-pole, 3-phase PM-generator with a 2-layers, 3-phase winding

This means that all four coils of one phase are connected in series. This must be done such that the voltage which is generated in the first layer is strengthening the voltage which is generated in the second layer. Two coils are made together on a winding thorn outside the generator. The isolated soldering points in between the layers are laid at the outside of the winding. So 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 is connected in star. 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 and this reduces the voltage by a factor √3 but delta connection isn't advised as this results in a higher sticking torque at increasing rotational speeds. But one may use this way of rectification if one wants to use the generator for 6 V battery charging.

3 Determination of the phase shift in between coils V4 and V1

The armature has been drawn in figure 1 such that the north pole N1 is just opposite the stator pole no 1. The same magnetic situation will be gained if the armature has rotated 90°. So a rotational angle of 90° corresponds to a phase angle α of 360° of the generated alternating current in one coil. So a rotational angle of 1° corresponds to a phase angle α of 4°.

The north poles N2 and N4 are shifted 7.5° with respect to the north poles N1 and N3. This means that the voltage generated in coils V1 and V2 is shifted 4 * 7.5° = 30° with respect to the voltage generated in coils V3 and V4. The sum of two sinusoidal voltages which have the same frequency and the same value U_{max} but which have a phase shift of 30° is also a sinusoidal voltage with the same frequency. Assume:

$$U_{V4} = U_{max} * \sin\alpha \quad \text{(V)} \tag{1}$$

$$U_{V1} = U_{max} * \sin(\alpha - 30°) \quad \text{(V)} \tag{2}$$

$$U_{V4 + V1} = U_{max} * \{\sin\alpha + \sin(\alpha - 30°)\} \quad \text{(V)} \tag{3}$$

It can be proven that formula 3 has a maximum for α = 105°. Substitution of α = 105° in formula 3 gives:

$$U_{max\ V4 + V1} = 1.932 * U_{max} \tag{4}$$

If the voltages generated in coils V4 and V1 would have been in phase, the resulting voltage would have been 2 * U_{max}. So the fact that there is a phase shift of 30° in between both voltages results in a decrease of the voltage and so also in the power by a factor 1.932 / 2 = 0.966. This reduction is certainly acceptable.

4 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. Eight magnetic loops are coming out of an 8-pole armature. Four loops are turning right hand and four 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 fact that the magnets don't jut out of the armature has as advantage that the magnets can't touch the stator if the armature is mounted in the stator.

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:

$$B_{r\ eff} = B_r * t_1 / (t_1 + t_2 + t_3) \qquad T \qquad (5)$$

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 5 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 5 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 but it is used for an 8-pole generator. The magnetic flux flowing through the bridge is much lower for an 8-pole armature than for a 4-pole armature. So if the stator stamping is saturated, it will be saturated at the spokes.

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. 2).

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 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 8-pole generator. Next a series of measurements is executed for star rectification and for a voltage range of for instance 8, 10, 12, 14, 16, 18 and 20 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 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. 3). The optimum cubic line is also drawn in the P-n graph with the generator measurements.

One P_{mech}-n curve of the generator 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 = 16 V. Assume that the generator is used for 12 V battery charging. This means that the average charging voltage is about 13 V. So the voltage of the test winding is a factor 16 / 13 = 1.231 too high. So the number of turns per coil has to be reduced by a factor 13 / 16 = 0.813 and so it must be 0.813 * 100 = 81. The wire thickness must be increased by a factor √ (16 /13) = 1.109 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 13 V, as the curves of the test winding for 16 V. But to be sure, the generator has to be measured again for the modified winding and for a constant voltage of 13 V star or for a real 12 V battery of enough capacity which is only half full.

6 Design of a 12-pole or a 16-pole PM-generator

The pitch angles in between the poles can be derived from figure 1.
The pitch angle in between N1 and S1 is 360° * 11/96 = 41.25°.
The pitch angle in between S1 and N2 is 360° * 11/96 = 41.25°.
The pitch angle in between N2 and S3 is 360° * 11/96 = 41.25°.
The pitch angle in between S3 and S1 is 360° * 15/96 = 56.25°.
So the ratio in between the pole pitch angles is 11 : 11 : 11 : 15. The same ratio is found for the poles N3-S3, S3-N4, N4-S4 and S4-N1. It is possible to design a 12-pole or a 16-pole PM-generator according to the same principle as used for the 8-pole PM-generator if the same pitch angle ratio is maintained. But a 12-pole generator needs a stator stamping with 36 slots so with 36 poles. A 16-pole generator needs a stator stamping with 48 slots so with 48 poles.

For a 12-pole generator one can use a stator stamping frame size 100 of Kienle & Spiess of a 1.5 kW, 6-pole motor. This stamping has an outside diameter of 150 mm, an inside diameter of 103 mm and a length of 120 mm. If the armature has a length of 130 mm, one can use one magnet size 80 * 20 * 10 mm and one magnet size 50 * 20 * 10 mm in one armature groove. The shaft diameter at the front bearing is 30 mm, so this generator can be used for a rotor diameter of about 3 – 3.3 m. This generator has 144 preference positions per revolution.

For a 16-pole generator one can use a stator stamping frame size 132 of Kienle & Spiess of a 3.3 kW, 8-pole motor. This stamping has an outside diameter of 200 mm, an inside diameter of 140 mm and a length of 150 mm. If the armature has a length of 160 mm, one can use two magnets size 80 * 20 * 10 mm in one armature groove. The shaft diameter at the front bearing is 40 mm, so this generator can be used for a rotor diameter of about 4 – 4.4 m. This generator has 192 preference positions per revolution.

7 References

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