

**Ideas about a 16-pole, 3-phase permanent magnet generator using
the housing and winding of a 4-pole asynchronous motor frame size 112M**

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It is allowed to copy this report for private use and to use the principles of the described PM-generator. The generator has not yet been built and 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 my public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The cogging 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 cogging torque if the armature isn't designed properly. A large peak on the cogging 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 on the cogging torque. I way to realise this for a 4-pole generator made from an asynchronous motor frame size 80 with 24 stator slots and using four magnets size 80 * 20 * 10 mm, is described in report KD 683 (ref. 2). In this report KD 718 it is researched if another way can be used for a bigger generator with 36 stator slots using a housing of frame size 112 and smaller magnets. An advantage of a 4-pole generator is that the standard 230/400 V, 3-phase motor winding can be used for 24 V or 48 V battery charging if the winding is rectified.

A starting point for this generator is that it can be made from the housing of a standard 4-pole asynchronous motor frame size 112. 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 112 has a shaft diameter at the front bearing of 30 mm and a shaft end with a diameter of 28 mm, a length of 60 mm and an 8 mm wide key groove. It can be used for a direct drive windmill rotor with a diameter of about 3 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 16-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 112/4.103. The outside diameter is 170 mm, the inside diameter is 103 mm. This stamping is used for a 4 kW, 4-pole motor and the length of the stator stamping is 140 mm for this motor. The stamping has 36 slots, so in between these slots there are 36 stator poles.

The stamping has six 4.03 mm holes at a pitch circle of 164 mm. The manufacturer which uses this stamping of Kienle & Spiess for its 4 kW motor has not yet been selected.

It is chosen to use this stamping for an armature with four magnetic poles. A 4-pole armature has normally two north and two south poles. The angle in between the heart of a north pole and the heart of a south pole is 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 36 slots. This problem is solved by using three coils which are lying within each other and for which the inner coil has an angle of 70° , for which the middle coil has an angle of 90° and for which the outer coil has an angle of 110° .

If the armature pole angle is chosen 90° , it means that the generator will normally get 36 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 report KD 341 (ref. 1).

2.2 Description of the armature

This new generator has an armature which is made from a 103 mm diameter and 140 mm long steel bush which is pressed on the original motor shaft. The bush is turned to a diameter of 102.4 mm after pressing. It is chosen that the armature will get sixteen mechanical poles and so four mechanical poles for one magnetic pole. Magnets are only used for the north poles. The south poles are formed by the remaining material of the armature.

It is chosen to use neodymium magnets size $40 * 15 * 5$ mm. 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 magnets size $40 * 15 * 5$ mm have quality N38. The price for one magnet is € 3.16 including VAT (December 2022) excluding transport if at least 70 magnets are ordered.

Four 15 mm wide and 5.7 mm deep grooves are made for the magnets of one magnetic north pole. This can be done with a short and stiff 15 mm diameter cutter. The angle in between the heart of the grooves is 22.5° . The length of the armature is taken the same as the length of the stator, so 140 mm. As the length of a magnet is 40 mm, it means that $3 \frac{1}{2}$ magnets are glued in each groove. There are totally eight grooves, so four magnets have to be broken in two 20 mm long pieces. This can be done if a deep scratch is made in the middle of the magnet. The half magnets have to be mounted such that the broken side isn't facing to the outside of the armature. So this side is covered with glue and this prevents corrosion. So totally $8 * 3 \frac{1}{2} = 28$ magnets are needed for one armature resulting in total magnet costs of about € 89 which is very low for a PM-generator of this size.

The four south poles are separated by grooves such that the south poles also have a width of 15 mm. If the angle in between all sixteen poles would be 22.5° , it means that there is 2.5° difference in between the armature pole pitch and two times the stator pole pitch. This means that there is a preference position every 2.5° and so there are $360 / 2.5 = 144$ preference positions per revolution. I am not sure that this is large enough to flatten the peak on the cogging torque sufficiently. The number of preference positions can be doubled if the pattern of the group of four south poles is rotated 1.25° left or right hand with respect to the pattern of the group of four north poles. The peak on the cogging torque caused by the north poles will then not coincide with the peak on the cogging torque caused by the south poles.

So the armature has totally sixteen poles in the following sequence: N1, N2, N3, N4, S1, S2, S3, S4, N5, N6, N7, N8, S5, S6, S7 and S8. The north poles are formed by the magnets and therefore these are called the magnet poles. The south poles are formed by the steel armature bush and therefore these are called the iron poles.

In between two magnet grooves there is a 2 mm high rim. In between two south poles there is a 3 mm deep and 5 mm wide groove to make that the south poles also have a width of about 15 mm at the outside.

The stator has 36 slots so it has 36 poles and so the stator pole angle is 10° . The stator poles are numbered 1 – 36. In figure 1, the armature is drawn such that the heart of north pole N1 is just opposite stator pole no. 1. The armature will therefore have a preference position for the drawn position. 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. Four outside grooves 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 six 4.03 mm holes at a pitch circle of 164 mm in the stamping IEC 112/4.103 of Kienle and Spiess may cause six small extra preference positions per revolution. These preference positions can be prevented by placing of a mild steel rod with a diameter of 4 mm and a length of 140 mm in each hole.

The armature is made of a 140 mm long mild steel bush with an outer diameter of 103 mm. The armature is pressed on the original motor shaft such that the sides of the armature coincide with the sides of the stator stamping. The bearings and the original short-circuit armature have to be removed first from the shaft if an original motor shaft is used. The original short-circuit armature has an inner diameter of 38 mm. The original motor shaft is provided with small grooves in the direction of the axis to guarantee a strong press fitting. As the original stator stamping is made of very soft steel, it might be required to give the new armature an inside diameter which is a little larger than 38 mm, so for instance 38.1 mm, otherwise the required pressing force may be too high. The armature is turned to a diameter of 102.4 mm after pressing it on the shaft. This must be done such that the outside is exactly concentric to the two bearing seats. So the air gap in between the poles which are formed by the armature bush and the stator becomes $(103 - 102.4) / 2 = 0.3$ mm.

The 15 mm wide grooves for the magnets are made that deep that the distance in between the bottom of the groove and the axis of the shaft is 45.5 mm. This means that the depth of the groove measured from the outside of the armature is $51.2 - 45.5 = 5.7$ mm. The magnets are not jutting out of the armature for this groove depth. The average air gap at the magnets of the north poles is somewhat larger than the air gap at the iron south poles formed by the armature bush but this is no problem.

The front bearing cover at the shaft side has an oil seal. No fan is needed and so the back bearing cover is closed and the back bearing cover therefore has no seal. The shaft has to be shortened if the back bearing cover is closed. The bearings have an internal rubber 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 the original motor shaft can be used and stainless steel isn't needed for its anti magnetic qualities as it is the case for the older VIRYA generators with inclined magnet grooves. A cross section and a side view of the generator armature are given in figure 1 at chapter 2.3.

A disadvantage of using four magnetic north poles and four iron south poles is that some magnets of the north poles may get scratches when the armature is mounted in the stator. The armature is only centred after tightening of the bearing covers. This problem can be solved by painting of the magnets with epoxy or by making an epoxy or plastic rim with $R = 51.2$ mm in between the magnets N2 and N3 and in between the magnets N6 and N7.

2.3 Description of the stator

The stator stamping is pressed in the aluminium generator housing. The stator stamping has 36 slots in which the coils are laid. In between the 36 slots we have 36 stator poles which are numbered 1 – 36.

Two slots are used for one coil, so 18 coils can be laid in 36 slots. Every phase has six 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 will be needed so soak the whole assembly of coils in liquid lacquer to prevent vibration of the wires if a new winding is laid. In chapter 2.1 it was already explained that three coils of one phase are positioned within each other.

The winding is a so called 2-layers winding. This means that the three bundles of three coils U1, U2 and U3, V1, V2 and V3 and W1, W2 and W3 are laid in the first layer. The coil heads of these nine coils are bent to the outside to make place for the nine coils of the second layer U4, U5 and U6, V4, V5 and V6 and W4, W5 and W6. The three coils of a certain phase in one layer are always connected in series because the voltage generated in each of the coils isn't the same. The three coils of the first layer can be connected in series with the three coils of the second layer or they can be connected in parallel. But all six coils of a standard 230 / 400 V winding are normally connected in series.

The three coils of a coil bundle of one phase are made outside the generator. The first layer with three coils has an end labelled A and an end labelled B. The second layer with three coils has an end labelled C and an end labelled D. So the ends B and C are normally soldered to each other. The soldering point is isolated and is lying somewhere on the coil heads. The both ends A and D of each phase are connected to a terminal with six tags 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 D 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 $\sqrt{3}$.

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 for the original winding. The original 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 and second layer of a certain phase are connected in parallel instead of in series. So coil end C is connected to coil end A and coil end D is connected to coil end B. This procedure is explained in detail in report KD 341 (ref. 1). A modified 115 / 200 V winding can be used for 24 V battery charging if the winding is rectified in star and for 12 V battery charging if the winding is rectified in delta. But a 12 V battery voltage will result in very large maximum currents and so in high cable losses in between the generator and the battery. So 12 V battery charging isn't advised for this rather large PM-generator.

A prototype of the generator has to be measured and a windmill rotor with the correct rotor diameter and design tip speed ratio has to be chosen for correct matching (see chapter 4).

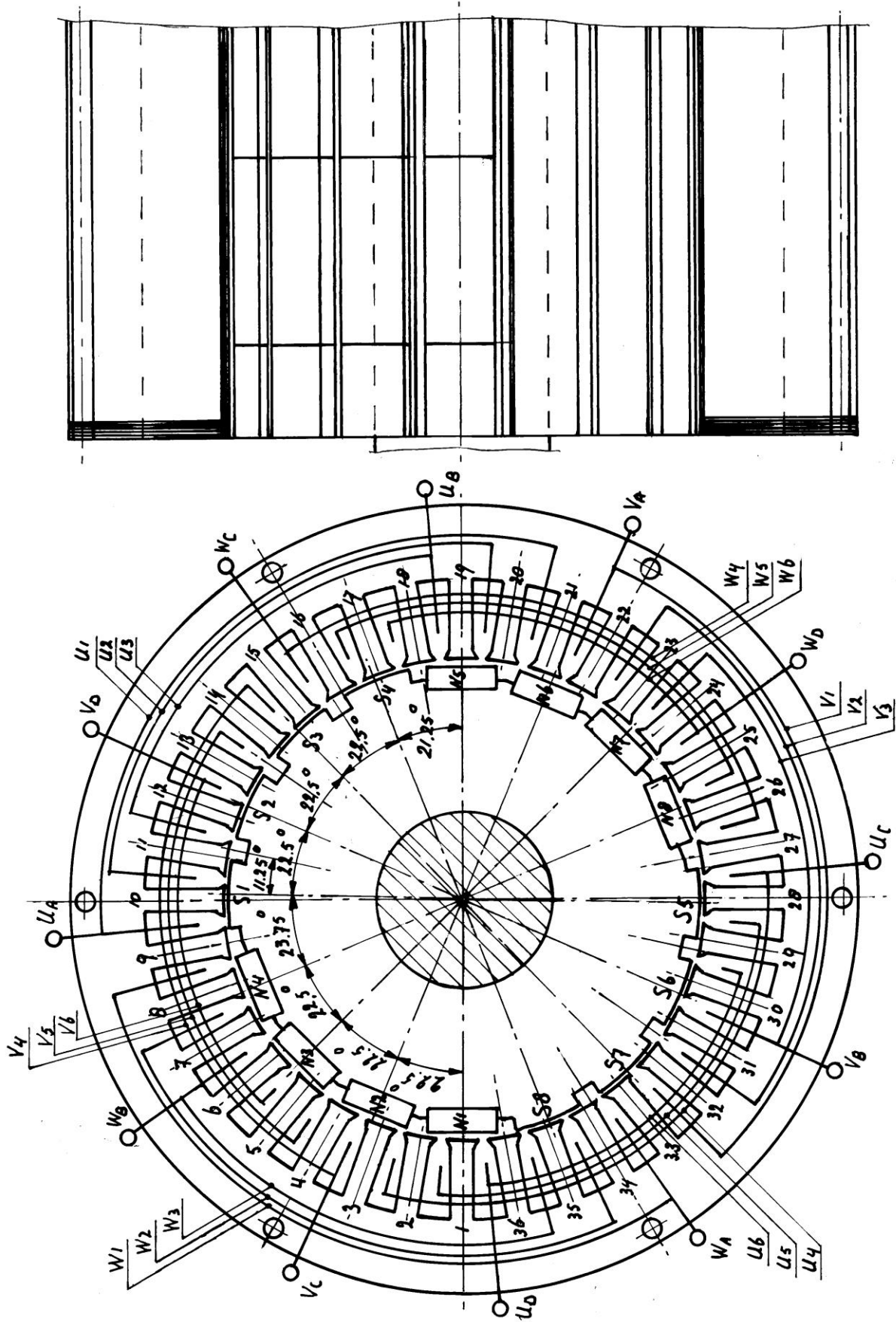


fig. 1 16-pole, 3-phase PM-generator with a 4-pole, 2-layers, 230/400 V, 3-phase winding

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 normal 4-pole armature. Two loops are turning left hand and two loops are turning right hand. However, eight magnetic loops are coming out of this special 16-pole armature. Four loops are turning left hand and four loops are turning right hand (see figure 2). Two left hand turning loops will be followed.

The magnetic flux coming out of the magnet of north pole N1 flows through the large air gap t_3 into the stator stamping. Next it makes a left hand bend. Next it flows through the small air gap t_2 and enters the south pole S8. Next it flows into the steel armature bush, making a left hand bend and enters the magnet of the north pole N1 again. So this magnetic loop flows through one magnet and the two air gaps t_2 and t_3 .

The magnetic flux coming out of the magnet of north pole N2 flows through the large air gap t_3 into the stator stamping. Next it makes a left hand bend. Next it flows through the small air gap t_2 and enters the south pole S7. Next it flows into the steel armature bush, making a left hand bend and enters the north pole N2 again. So also this magnetic loop flows through one magnet and the two air gaps t_2 and t_3 . The only difference is that this second loop is longer than the first one as it lies around the first one.

A magnet has a thickness $t_1 = 5$ 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 bottom of the groove.

The stator stamping has an inside diameter of 103 mm. It is assumed that the armature is turned at a diameter of 102.4 mm at the south poles. So the air gap at the south poles which are formed by the armature bush $t_2 = 0.3$ mm. The air gap opposed to the magnets is maximal at the heart of the magnet and minimal at both sides. The groove depth is chosen such that there is a distance of 45.5 mm from the bottom of the groove up to the shaft axis. This means that the air gap at the heart of the 5 mm thick magnet is $51.5 - (45.5 + 5) = 1$ mm. The air gap at the sides of the magnet is about 0.4 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 $t_3 = 0.8$ 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:

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

For radial positioning of the magnets, the pole area is the same as the magnet area. 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 if the iron in the stator isn't saturated. The used magnets with quality N38 have a remanence B_r of about 1.24 T. Substitution of $B_r = 1.24$ T, $t_1 = 5$ mm, $t_2 = 0.3$ mm and $t_3 = 0.8$ mm in formula 1 gives that $B_{r\text{eff}} = 1.02$ T.

In figure 1 it can be seen that one armature pole is about opposite to two stator poles. A stator pole is formed by the spokes left in between the stator slots. These stator slots have a tapered shape and the spokes therefore have a constant width of about 5 mm except for the most inner part for which the width is about 7 mm. The armature poles have a width of 15 mm. So the magnetic flow is concentrated in the spokes by a factor $15 / (2 * 5) = 1.5$. This means that the flux density in the spokes is $1.5 * 1.02 = 1.53$ T. The stator iron is saturated at about 1.6 T. So the stator is just not saturated at the spokes but close to saturation and formula 1 is therefore valid. This calculation shows that the chosen magnet configuration is rather optimal and that it is useless to use thicker magnets.

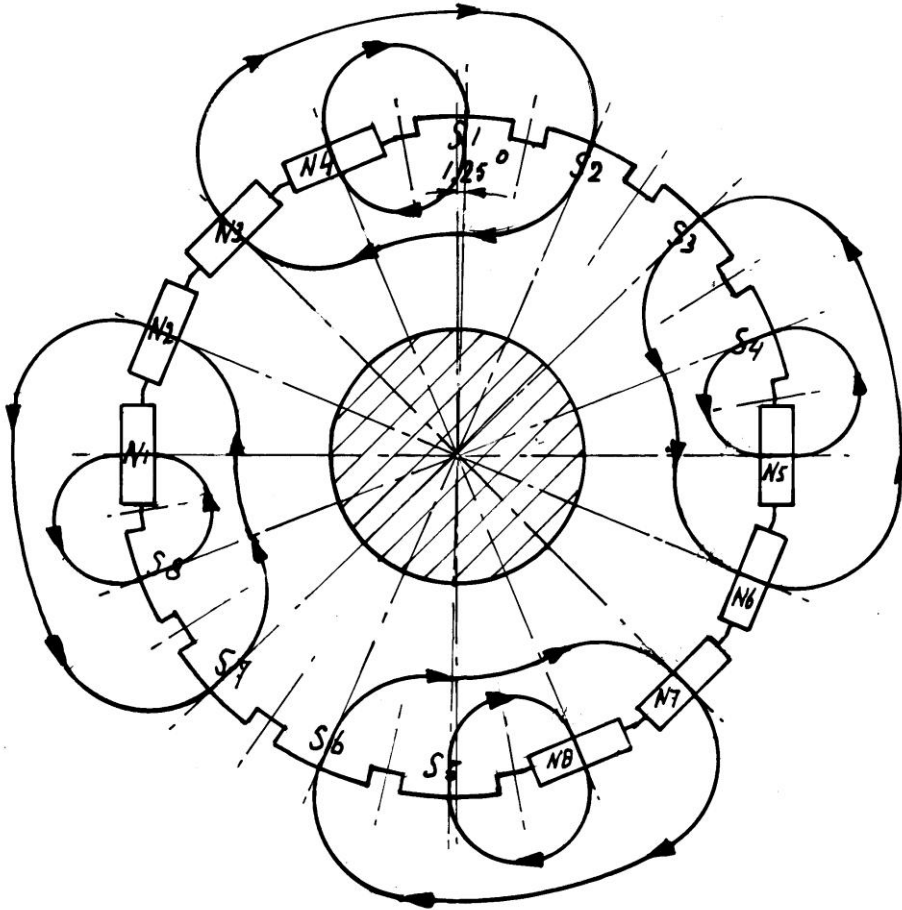


fig. 2 16-pole armature with four left hand and four right hand magnetic loops

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 but this was done long ago. I have also developed a simple private test rig for very small axial flux generators but this test rig is much too small for this 4-pole generator. I will not perform measurements for this new generator.

First the generator is connected in star and the $P_{\text{mech-n}}$ and $P_{\text{el-n}}$ 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 $P_{\text{mech-n}}$ and $P_{\text{el-n}}$ 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 rotor, the $P_{\text{mech-n}}$ curve of the generator for 52 V star and 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 $P_{\text{mech}}-n$ 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).

It is expected that the matching is good for the VIRYA-3B3 rotor using the generator with the original 230/400 V winding for 48 V battery charging rectified in star and for 24 V battery charging rectified in delta. The $P-n$ curves of this rotor are given in figure 4 of report KD 484 (ref. 5). This figure is copied as figure 3 but the $P_{\text{mech}}-n$ curve, the $P_{\text{el}}-n$ curve and the $P-n$ curve for short-circuit in star and delta of the original VIRYA-3B3 generator are removed.

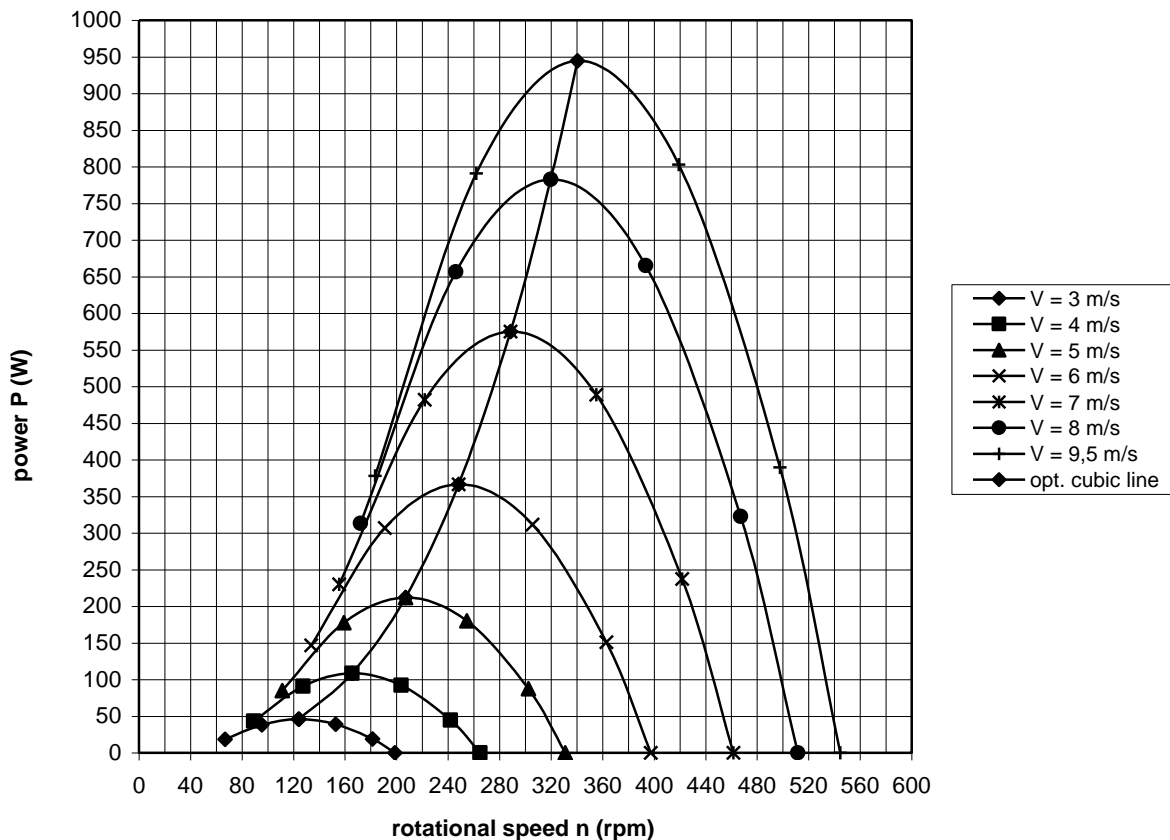


fig. 3 $P-n$ curves of the VIRYA-3B3 rotor for $V_{\text{rated}} = 9.5$ m/s and optimum cubic line

The original VIRYA-3B3 generator has a frame size 90 and a 25 mm tapered shaft. So the rotor hub has to be modified for a 28 mm cylindrical shaft and the generator bracket of the head has to be modified for a generator of frame size 112.

The disadvantage of delta rectification is that the cogging 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. The advantage of delta rectification is that the maximum breaking torque is larger. So stopping the rotor by making short-circuit in the winding, can better be done for connection in delta. Short-circuit in star is the same as short-circuit in delta if the star point is short-circuited too.

The short-circuit switch has to be mounted as close as possible to the generator. So mounting on a box in the tower foot is the best place. The 3-phase rectifier has to be mounted in the box. A 4-wires elastic cable connects the generator to the box. A massive 2-wires cable can be used to connect the rectifier to the batteries and the battery charge controller.

5 Checking of the strength of the glue in between magnets and armature

The neodymium magnets are glued in the magnet grooves. As a prototype has not yet been built and tested, it is not proven that the glue is strong enough. However, I have built several other PM-generators with glued magnets and never one of the magnets came loose. But the quality of the glue connection depends on the type of glue which is used and on the cleaning of the grooves before gluing. The history of the development of the VIRYA generators is given in report KD 341 (ref. 1). For the oldest 12-pole generators using ferroxdure magnets, I have used industrial epoxy glue. For the later 4-pole generators using neodymium magnets, I have used a special anaerobe glue type ThreeBond 1132.

Anaerobe glue has some advantages above epoxy glue which are:

- 1 The glue hardens only in the air gap. So superfluous glue can be removed easily if the glue in the air gap has hardened.
- 2 The glue starts hardening in about a quarter of an hour in the air gap. So if clamps are used to press the magnets in the grooves, these clamps can be removed soon. The final strength is gained only after some hours.
- 3 Anaerobe glue can have a much higher temperature than epoxy glue. No heat is generated in the armature but some of the heat generated in the stator is radiated to the armature. Most epoxy glues have lost all strength at about 100 °C. So the armature temperature may become too high for epoxy glue if the generator is used long at its maximum power.
- 4 Anaerobe glue is thinner than normal epoxy glue. So if the magnet is pushed in the groove, the glue layer at the bottom of the groove will become thinner and so the magnet position is defined more precisely.

The disadvantage of most anaerobe glues is that it hardens only in very small gaps. But the chosen type ThreeBond 1132 hardens in an air gap of maximum 0.5 mm and this is certainly acceptable. The grooves must be cleaned very well and one must use the correct solvent which is acetone or alcohol. One should not use refined petrol or thinner as these solvents have a negative influence on the hardening time and the final strength of the glue!

ThreeBond 1132 is supplied by the Dutch company Viba website: www.viba.nl. I have bought a 250 gram tube which costs about € 54 excluding VAT and costs of transport in 2021. This glue can be used in between temperatures of – 60 °C and 200 °C. The maximum shearing stress lies in between 14 and 17 N/mm².

A magnet is pulled in a groove by the magnetic holding force and pushed out of the groove by the centrifugal force and may be also by the magnetic force caused by currents in the stator. It is assumed that no magnetic force is active and so only the centrifugal force is acting on a magnet.

The centrifugal force depends on the rotational speed. The highest rotational speed is gained if the windmill rotor is turning unloaded. Normally this doesn't happen but the worst case scenario is taken. In figure 3 it can be seen that the maximum unloaded rotational speed for the VIRYA-3B3 rotor is about 550 rpm but lets take $n_{\max} = 600$ rpm. The centrifugal force F_c is given by:

$$F_c = m * r * \omega^2 \quad (\text{N}) \quad (2)$$

m is the mass of one magnet in kg. r is the radius of the centre of gravity of a magnet in m. ω is the angular velocity in rad/s. The relation in between the angular velocity and the rotational speed n in rpm is given by:

$$\omega = \pi * n / 30 \quad (\text{rad/s}) \quad (3)$$

(2) + (3) gives:

$$F_c = m * r * \pi^2 * n^2 / 900 \quad (\text{N}) \quad (4)$$

One magnet has as dimensions 40 * 15 * 5 mm. So the volume of one magnet is 3000 mm³ = 3 cm³. Neodymium magnets have a density of about 7.5 gram/cm³. So the mass of one magnet is 3 * 7.5 = 22.5 gram = 0.0225 kg.

The centre of gravity of a magnet lies in the centre of the magnet so at a distance of 2.5 mm from the bottom of a groove. The bottom of a groove lies at a distance of 45.5 mm from the armature axis. So the centre of gravity of a magnet lies at 45.5 + 2.5 = 48 mm from the axis of the armature. This gives that $r = 0.048$ m. Substitution of $m = 0.0225$ kg, $r = 0.048$ m and $n = 600$ rpm in formula 4 gives that $F_c = 4.3$ N which is very low.

The magnet makes contact with the bottom of the groove but also with the 2 mm high sides of the groove. Let's forget the sides. The contact area A at the bottom of the groove is 40 * 15 = 600 mm². So the pulling stress in the glue is 4.3 / 600 = 0.0072 N/mm² which is very low. The allowable pulling stress isn't given and it may be somewhat smaller than the maximum shearing stress which is at least 14 N/mm². Assume that the allowable pulling stress is 10 N/mm². The calculated stress is a factor 1389 lower!

So this calculation shows that the glue in between magnets and armature is absolutely strong enough and that a much higher rotational speed than 600 rpm is allowed.

6 Use of a 4-pole motor frame size 132M and 28 magnets size 50 * 20 * 5 mm

It seems possible to use the same principle of a 16-pole armature also for a bigger motor frame size 132 if bigger magnets size 50 * 20 * 5 mm are used. The stator stamping of a 7.5 kW, 4-pole motor of Kienle & Spiess has an outside diameter of 200 mm, an inside diameter of 125 mm and a length of 170 mm. It is assumed that the armature gets an outside diameter of 124.4 mm and a length of 175 mm. So the armature juts out 2.5 mm at each side of the stator stamping. The air gap at the south poles is 0.3 mm.

It is assumed that the original motor has a 230/400 V, 4-pole, 3-phase winding and that this original winding can be used for 24 battery charging if the winding is rectified in delta and for 48 V battery charging if the winding is rectified in star. But to be sure that there is an acceptable matching for the chosen windmill rotor, a prototype of the generator has to be measured on an accurate test rig.

The four grooves for the north poles have a width of 20 mm and a depth of 0.9 mm. This depth makes that the magnets don't jut outside the armature. The south poles are separated by 4.5 mm wide and 3 mm deep grooves to make that the south poles also have a width of about 20 mm. The pattern of four south poles is also rotated 1.25° with respect to the pattern of four north poles to increase the number of preference positions from 144 to 288.

Magnets size 50 * 20 * 5 are also supplied by Enes Magnets. The price including VAT but excluding costs of transport is € 5.23 if 80 magnets are ordered. 3 ½ magnets are used in one groove, so a 50 mm long magnet has to be broken in two 25 mm long parts. The total number of magnets needed is 8 * 3 ½ = 28 and so the total magnet costs for one armature are about € 150 which seems acceptable for such a big PM-generator.

The front end of the original motor shaft has a diameter of 38 mm, a length of 80 mm and a 10 mm wide key groove. It is expected that this shaft is strong enough for a 3-bladed windmill rotor with a diameter of maximal 4.5 m if the windmill is provided with a proper safety system.

7 Use of a 4-pole motor frame size 100L and a 32-pole armature

A way to increase the number of preference positions per revolution is to increase the number of mechanical armature poles from 16 to 32. However, this requires smaller magnets. It is chosen to use magnets size $40 * 7 * 3$ mm which are also supplied by Enes magnets. These magnets have quality N38SH. The current price (May 2023) is € 0.96 per piece including VAT but excluding costs of transport if 200 pieces are ordered.

It is chosen to use a 4-pole, 3 kW asynchronous motor frame size 100L with a stator stamping if Kienle & Spiess code IEC 100/4.944. This stator stamping has an outside diameter of 150 mm, an inside diameter of 90 mm and a length of 120 mm. The outside diameter of the armature is 89.5 mm and so the air gap at the south poles is 0.25 mm. Magnets are only used for the north poles. Every magnetic pole has eight mechanical poles.

The grooves for the north poles have a width of 7 mm and a depth of 3.2 mm. An advantage of 7 mm wide magnets is that the air gap at the north poles is much smaller than for 15 mm wide magnets. There is a 1 mm high rim which separates the grooves of the north poles. To make that the south poles also have a width of about 7 mm, a 1.8 mm wide and 2.2 mm deep groove is made to separate the south poles. To make the 1 mm high rim which separates the north poles, it is easy to make first 32, 1.8 mm wide and 2.2 mm grooves every 11.25° and to make the 7 mm wide magnet grooves afterwards. Three magnets are glued in each groove and so totally $3 * 8 * 2 = 48$ magnets are needed for one armature. The total magnet costs are about € 47 which is rather low for a PM-generator of this size. A side view this armature is given in figure 4.

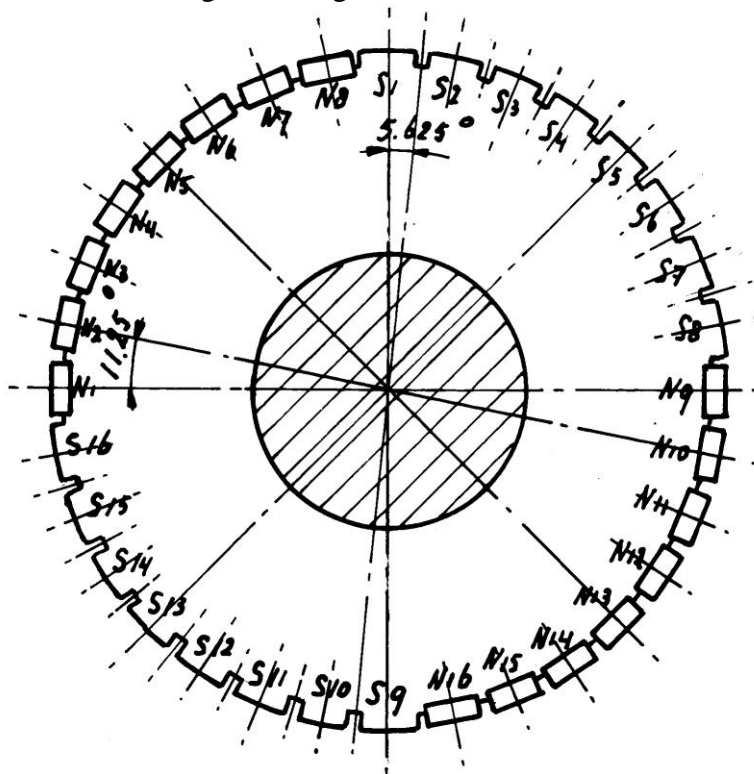


fig. 4 Side view 32-pole armature with 48 magnets size $40 * 7 * 3$ mm

The armature pole angle is $360 / 32 = 11.25^\circ$. The stator pole angle is $360 / 36 = 10^\circ$. So the difference is 1.25° . Assume that there is a preference position if an armature pole is just opposite a stator pole. This is the case for 4 of the 32 armature poles. This changes every 1.25° and so the armature will have $360 / 1.25 = 288$ preference positions per revolution. The peak on the cogging torque will be very low for that many preference positions and the starting wind speed will therefore be rather low. It is expected that this generator can be used in combination with the VIRYA-3B3 rotor (see chapter 4).

The shaft end dimensions of a motor frame size 100L are the same as that of a motor frame size 112M. The shaft diameter at the bearings is 30 mm. But the shaft diameter at the armature stamping is 36 mm instead of 38 mm. The shaft end has a diameter of 28 mm, a length of 60 mm and an 8 mm wide key groove. So the rotor hub has to be modified for a 28 mm cylindrical shaft and the generator bracket has to be modified for a generator frame size 100 instead of 90. The original VIRYA-3B3 generator has a generator made from a motor frame size 90 with lengthened stator stamping and a shaft diameter of 25 mm with a tapered shaft end with a half taper angle of 5° . So a 28 mm shaft end will be strong enough.

The armature of the original generator has a diameter of 82.02 mm. The armature has a length of 135 mm but the length of the armature within the stator stamping is 125 mm. So the armature volume within the stator stamping is 660449 mm^3 . The armature makes use of eight neodymium magnets size $67 * 20 * 10 \text{ mm}$. So the total magnet volume is 107200 mm^3 .

The armature of a generator made from a motor frame size 100L has a diameter of 89.5 mm and a length of 120 mm. So the armature volume is 754948 mm^3 . This is a factor 1.143 larger. The armature makes use of 48 neodymium magnets size $40 * 7 * 3 \text{ mm}$. So the total magnet volume is 40320 mm^3 . This is only a factor 0.376 of the magnet volume of the original generator and the magnet costs are therefore much lower. It is calculated that even with 3 mm thick magnets, the stator spokes are saturated. So even with much thinner magnets, the torque level will be high enough for the VIRYA-3B3 rotor. But it is good to build a prototype and to measure it on a test rig to verify if the characteristics are acceptable and if they are about the same as for the original generator as given in report KD 78 (ref. 6).

8 Use of a 4-pole motor frame size 80 and a 28-pole armature

It seems possible to use the same principle as described in chapter 7, for a smaller 4-pole motor frame size 80. However, such a motor has a stator stamping with 24 poles instead of 36 poles. So there are six instead of nine stator poles opposed to one magnetic armature pole. Now it is chosen to take seven mechanical north poles for one magnetic north pole. The same magnets size $40 * 7 * 3 \text{ mm}$ are used for the north poles as used for the 32-pole generator.

The stator pole angle is $360 / 24 = 15^\circ$. The armature pole angle is $360 / 28 = 12.857^\circ$. So the difference is $15^\circ - 12.857^\circ = 2.143^\circ$. This means that the armature will have $360 / 2.143 = 168$ preference positions per revolution. This is less than the 288 preference positions of the 32-pole generator but I expect that the peak on the cogging torque will be low enough to get a sufficiently low starting wind speed if a windmill rotor with a rather high starting torque coefficient is chosen.

It is chosen to use a 4-pole, 0.75 kW asynchronous motor frame size 80 with a stator stamping of Kienle & Spiess code IEC 80/4.70. This stator stamping has an outside diameter of 120 mm, an inside diameter of 70 mm and a length of 120 mm. The outside diameter of the armature is 69.5 mm and so the air gap at the south poles is 0.25 mm. The armature stamping has an inside diameter of 25 mm. The original short-circuit armature is removed and replaced by a mild steel bush with a diameter of 70 mm and a length of 80 mm. This bush is turned to a diameter of 69.5 mm after pressing it onto the original motor shaft.

It might also be possible to use an 80 mm long seamless steel pipe size $70 * 6 \text{ mm}$. This pipe has an inside diameter of 58 mm. The original short-circuit armature is turned to a diameter of 57.8 mm and the bush is glued to the original armature using epoxy glue or anaerobe glue.

Magnets are only used for the north poles. Every magnetic pole has seven mechanical poles. The grooves for the north poles have a width of 7 mm and a depth of 3.3 mm. For this groove depth, it appears that the magnets don't jut out of the armature. The armature pole pitch is $\pi * 69.5 / 28 = 7.8 \text{ mm}$ which is rather small for 7 mm wide magnets. It is calculated that the distance in between the magnets at the bottom of the magnet grooves is only about 0.1 mm. So there is no space for a rim in between the magnets. It seems easiest to glue first the three left magnets, then the three right magnets and to finish with the central magnet.

The south poles are formed by the remaining material of the armature. To make that the south poles have a width of about 6.8 mm, a 1 mm wide and 2 mm deep groove is made to separate the south poles. To prevent that there is a 0.1 mm wide rim in between the grooves of the north poles, it is easy to make first six, 1 mm wide and 3.1 mm deep grooves in between seven north poles. The seven 7 mm wide and 3.3 mm deep magnet grooves are made afterwards.

Two magnets are glued in each groove and so totally $2 * 7 * 2 = 28$ magnets are needed for one armature. The total magnet costs are about € 27 which is rather low for a PM-generator of this size. A side view this armature is given in figure 5.

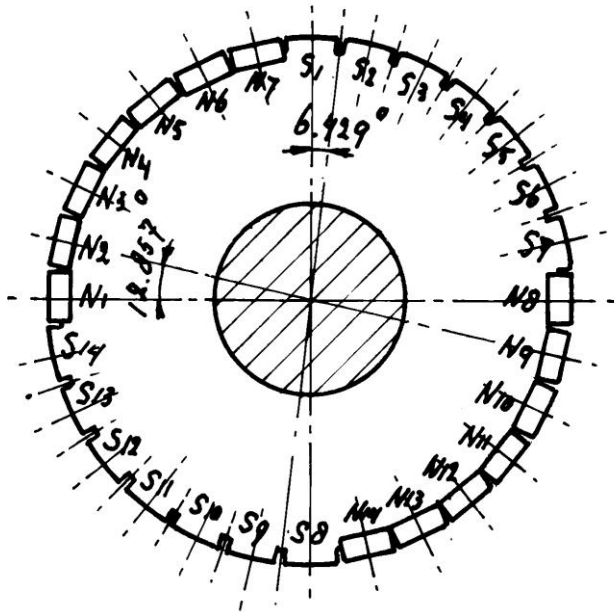


fig. 5 Side view 28-pole armature with 28 magnets size $40 * 7 * 3$ mm

A motor frame size 80 has a shaft with a diameter of 20 mm at the bearings. The cylindrical shaft end has a diameter of 19 mm, a length of 40 mm and a 6 mm wide key groove. No fan is used and the bearing cover at the original fan side is closed. It is expected that this generator can be used in combination with a windmill rotor with a diameter of maximal 2 m.

It is good to build a prototype and to measure the characteristics for the original 230/400 V winding but I won't do that. One should measure the $P_{\text{mech-n}}$ and $P_{\text{el-n}}$ curves for a 24 V and a 48 V battery if the winding is rectified in star and for a 12 V and a 24 V battery if the winding is rectified in delta. The peak on the cogging torque at stand still position has to be measured too. The diameter and design tip speed ratio of the windmill rotor should be chosen such that there is good matching in between rotor and generator with one of the measured $P_{\text{mech-n}}$ curves. Matching is explained in chapter 8 of report KD 35 (ref. 4).

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