Development of the permanent magnet (PM) generators of the VIRYA windmills

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1 Introduction

Up to now Kragten Design has developed thirteen electricity generating windmills with rotor diameters in between 1.2 and 4.6 metre. Eight of these windmills are designed especially for manufacture in developing countries. All of these windmills are equipped with a 4-pole permanent magnet (PM) generator which is made of an asynchronous motor. The shaft and the short-circuit armature of the asynchronous motor are replaced by a stainless steel shaft and a mild steel armature which is equipped with neodymium magnets. Most generators make use of the standard 3-phase winding which is rectified for 24 V or 48 V battery charging. The rectification of 3-phase VIRYA windmill generators is described in report KD 340 (ref. 1).

The choice of the generator for a small windmill is not simple. I started my windmill activities in 1973 in the windmill group of De Kleine Aarde (The Small Earth) in Boxtel, The Netherlands. This group had the intention to design a small 2.4 m diameter windmill which could be built by someone privately. For this windmill, a generator had to be chosen and we investigated the options which were available at that time. Finally a 12 V, 3-phase car alternator was chosen but we faced a lot of problems with this type of generator. People very often come up with the idea to use a 12 V or 24 V car alternator and ask me for advice. In 1998 I have written a Dutch KD note about this subject and in 2005 this note was translated into English. The essence of this note is given in chapter 2. Most disadvantages of car alternators are valid for any generator for which the magnetic field is supplied by an electromagnet.

Mainly because of the negative experiences with car alternators, I decided to develop a permanent magnet generator. My first experiments with PM-generators are given in chapter 3. I give these experiments to prevent that someone else makes the same mistakes. However, certain ideas may not work in a certain time but can work later if new materials and new techniques are available. For the generator, which makes use of a modified asynchronous motor, several aspects are explained in detail in chapter 4. The generator calculations are given in chapter 5.

2 Disadvantages of car alternators

The main disadvantages of a car alternator for use as windmill generator are:

1. The generator housing is not closed because the windings are cooled internally. Therefore water and dust can go inside easily which is shortening the lifetime of the bearings. Thereby, a car alternator is designed for a lifetime of about 2000 hours and although the rotational speed as windmill generator is lower, it will be worn rather fast.
2. The magnetic field of the armature is supplied by an electromagnet. The required current for maximum strength of the magnetic field is about 2 A. If the charging voltage is 14 V, the needed electrical power is 28 W. As the maximum generator efficiency is about 0.5, it means that a mechanical power of at least 56 W has to be generated by the windmill before the output starts. This large field power itself has a bad effect on the efficiency at low powers and it increases the cut in wind speed of the windmill.
3. The field current is supported to the armature coil by brushes which wear and which cause a certain friction torque. This friction torque is about the same as the sticking torque of a well designed PM-generator of the same armature volume.
4. If the armature field is maximal, a car alternator is supplying an open voltage of 12 V at a rotational speed of about 900 rpm. This means that even for a small windmill, one will need an accelerating gearing if this rotational speed has to be reached at low wind speeds.
5. Car alternators have a three phase rectifier included in the generator. The voltage drop over the diodes of this rectifier is 2 * 0.7 = 1.4 V. Because of this voltage drop, the generator is only self starting at a rotational speed of about 2000 rpm. This is because after stopping of the generator, only a very small remanence remains.

If the generator is used in a car, a small lamp which gives an indication that the generator is working, is causing a small current through the armature and therefore in a car, the generator is already self starting at 900 rpm. But this lamp can not be used in a windmill because it will result in discharge of the battery if the windmill is not running.

6 Car alternators are available in many different makes depending on the type of car and the age of the car. The characteristics and dimensions will depend on the type. If a certain type is selected and if serial production of the windmill would be successful, this will result in becoming scarce of this type and therefore the second hand price will increase. If one wants to use different types one has to modify the windmill for every type.

7 If the battery is full, the charging voltage is limited by a voltage controller which is often included in the generator. If the voltage controller is included in the generator, it doesn’t take into account the voltage drop over the cable in between generator and battery. Therefore the real charging voltage at the battery will be too low for long cables and at high currents.

8 The voltage controller is limiting the voltage by reduction of the field current and so of the torque. Therefore, if the batteries are full, the windmill rotor will run at a much higher tip speed ratio than the design tip speed ratio and will produce more noise.

The advantage of an electromagnetic field is that the generator can start unloaded because no magnetic sticking torque is produced. However, this advantage is almost neutralised by the friction torque of the brushes. Because an accelerating gearing is required, the friction of this gearing and of the extra seals will also contribute to the starting torque of the generator.

A car alternator can be rewound to reduce the rotational speed at which an open voltage of 12 V is reached. However, if one wants to reduce this speed from 900 to e.g. 450 rpm, the number of turns per coil has to be doubled. But for the same amount of copper in a groove, the cross sectional area of a wire has to be halved. This will result in increase of the coil resistance by a factor 4 and this will result in a lower generator efficiency and in a much lower maximum electrical power. But the required field power stays the same.

3 First experiments with PM-generators

I started to design a PM-generator almost thirty years ago. The first idea was to transform a car alternator into a PM-generator. Car alternators normally have twelve armature poles and a 3-phase stator winding which is laid in a stator with 36 stator grooves and so it has 36 stator poles. The winding is rectified with a 3-phase rectifier with six diodes which are incorporated in the generator housing. The shaft is provided with an armature with two claws. Each claw has six claw ends. The claws are bent such that in between each claw end of the left claw is a claw end of the right claw. The coil of the electromagnet is mounted in between the claws. If a DC current is flowing in the coil, a magnetic field is created inside the coil. This magnetic field is guided to the claws and makes that one claw becomes the north pole and the other becomes the south pole. So at the outside of the armature, where the claws overlap, a north pole is followed by a south pole and so a 12 pole armature is created.

My first experiment was to remove the claws from the shaft and to replace the coil by a ceramic circular permanent loudspeakers magnet with a hole in the centre. The magnetic material was Ferroxdure, made by Phillips. The result was that an open voltage of 12 V was gained for a rotational speed of about 2000 rpm which was much higher than for the original electromagnet. So this idea didn’t work. May be it will work if a neodymium magnet is used because neodymium magnets are much stronger than ceramic magnets. However, circular neodymium magnets with a hole in the centre are not standard available for the correct size.

The second experiment was to replace the shaft and the claw armature by a stainless steel shaft and a mild steel armature which was provided with 12 ceramic magnets. The mild steel armature was a cylinder which was pressed on the stainless steel shaft and which was provided with 12 grooves parallel to the shaft. One ceramic magnet was glued in each groove in such a way that six north and six south poles were created on the outside of the armature. This armature appeared to be very strong and an open voltage of 12 V was created at a rotational speed of about 800 rpm. However, at low rotational speeds, there was a very large fluctuation of the sticking torque because the armature has a tendency to take that position were the overlap in between the 12 armature poles and the 36 stator poles is maximum. The large peak torque will result in a large starting wind speed of the windmill.

The third experiment was to make an armature for which the armature grooves were making an angle with the shaft axis. This angle was chosen such that one stator pole was just overlapped by the armature groove axis. In this case the overlap of the area in between an armature pole and a stator pole is constant for every position of the armature and the sticking torque is therefore almost not fluctuating. The armature appeared to be somewhat less strong than for parallel armature grooves and an open voltage of 12 V was created at a rotational speed of about 900 rpm. So this was the first PM-generator with an acceptable magnetic strength of the armature and with almost no fluctuation of the torque. But the required rotational speed was still much too high to mount the windmill rotor directly to the generator shaft. So an accelerating gearing would be required and I don’t like such gearing.

The fourth experiment was to make a 12-pole generator from an asynchronous motor size 112. These motors are not supplied with a 12-pole winding so it was ordered unwound and without armature and shaft. A 12-pole armature was made but as the stator iron and so the armature was rather long, four ceramic magnets were glued in each armature groove. The 3-phase stator winding was laid by hand in the stator grooves and rather thick copper wire was used. This generator was tested on a test rig at the University of Technology Eindhoven. The generator winding was rectified in star and coupled to a 24 V battery. The DC voltage and current were measured together with the torque and the rotational speed. The generator efficiency could therefore be determined for every rotational speed. The maximum efficiency was 76 % and it was realised at a very low rotational speed of 116 rpm. This generator was used in the VIRYA-3 windmill which was the first VIRYA windmill designed by Kragten Design. The VIRYA-3 was tested from about 1985 till about 1990 and worked well. However, manufacture of a 12-pole armature is rather time consuming and laying a 12-pole winding by hand needs special tools to curve the coil ends. It cost me more than a day to lay a complete winding. So it was investigated if it would be possible to make a PM-generator using a standard 3-phase winding and this research finally resulted in the 4-pole PM-generators of the current VIRYA windmills.

4 PM-generators of present VIRYA windmills

For the housing, the Dutch manufacture ROTOR is chosen because these houses are rather cheap and the manufacturer was willing to give me the required internal dimensions. But use of another manufacture might be possible if the stator iron has about the same internal dimensions. The housing of a standard 4-pole asynchronous motor is used but some modification is required. Asynchronous motors normally have a fan but this fan is not effective for a windmill generator because it runs at very low rotational speeds and because the housing is directly cooled by the wind. So the fan and the fan cover are removed and the back bearing cover is closed.

An asynchronous motor is the simplest motor imaginable. It contains a shaft with the short-circuit armature pressed on it and has a bearing at the front and at the back side. The stator iron is pressed in the central housing which is closed by the front and the back bearing cover. The 3-phase winding, laid in the stator iron, is connected to the terminal which is mounted in the terminal box situated at the top of the housing.

The standard shaft and armature are not used for the windmill generator. A stainless steel shaft is used and a mild steel armature is glued to the shaft by means of anaerobic glue. Four grooves are milled in the armature and the grooves are making an angle with the generator axis such that the groove axis is just overlapping one stator pole. The groove is so deep that the bottom is about 0.8 mm removed from the outside of the stainless steel shaft. A certain number of neodymium magnets are glued in each groove. The direction of the magnetic field in the magnets in adjacent grooves is chosen opposite. The remaining steel in between the armature grooves is forming the armature poles. So two north and two south poles are created at the armature outside. A picture of armature and stator is given in figure 1.

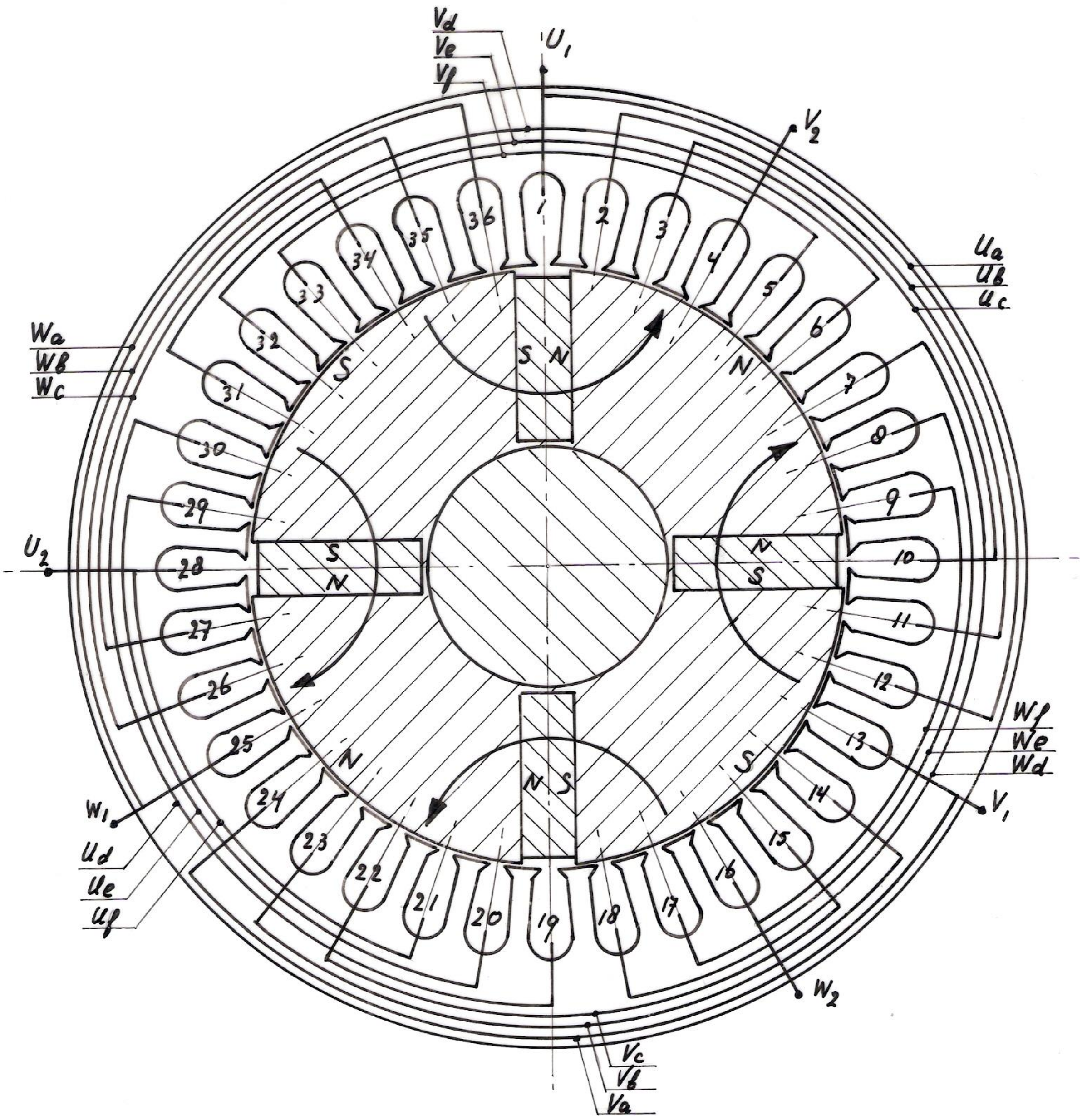


fig. 1 Cross section of a 4-pole armature at the hart of the armature. Side view of the stator.

The magnetic field coming out of a magnet in one armature groove is now followed. First it is flowing through the permanent magnet with thickness t_1. Next it is bridging the first glue gap t_2 in between the magnet and the side of the armature groove. Next it is flowing outside through a north pole. Next it is bridging the air gap t_3 in between armature and stator. Next it is flowing outside through certain stator poles. Next it is flowing tangential through the outside of the stator. Next it is flowing inside through other stator poles. Next it is bridging the air gap t_3 in between armature and stator again. Next it is flowing inside a south pole. Last it is bridging the second glue gap t_2 in between the magnet and the side of the armature groove. So for one complete magnetic circle, only one magnet but four air gaps are bridged. The air gap t_3 in between armature and stator is largest. Half of the magnetic field coming out of one armature pole is supplied by the row of magnets in one groove. The other half is supplied by the row of magnets in the adjacent groove (see figure 1).

The poles are connected to each other by the small, about 0.8 mm high bridge and that in combination with the glue is the reason why the poles stay at place during milling. The bridge height is taken as small as possible because one armature pole is magnetically short-circuited with its neighbour through this bridge. The magnetic field in this bridge is saturated. The main reason why stainless steel is used for the shaft is that this material is not conducting magnetism and will therefore not contribute to magnetic short-circuit of the armature poles.

The number of grooves in the stator depends on the number of armature poles, on the motor size and on the manufacture. The optimum number of stator grooves for a 4-pole, 3-phase motor is 12 or a multiple of 12. In practice, the manufacture ROTOR is using 24 grooves for motor size 71 and smaller, 36 grooves for motor size 80 up to 112 and 48 for motor size 132 and larger. In figure 1, a stator is drawn with 36 grooves. The material in between the grooves is called the stator spoke and the widened inner side of the spoke near the air gap is called the stator pole.

The armature pole angle of a 4-pole armature is 90°. The stator pole angle of a 36-pole stator is 10°. The maximum voltage in a stator coil is realised if the stator coil is laid in grooves which have an angle to each other which is the same as the armature pole angle, so which is 90° for a 4-pole armature. For each coil two stator grooves are needed so 18 coils can be laid in a stator with 36 grooves. The phase windings are called U, V and W. So each phase has six coils. It appears to be impossible to have an angle of 90° in between the grooves for each coil of a certain phase. This is only possible for a stator with 12 grooves. This problem is solved by giving: two coils the correct angle of 90°, two coils a smaller angle of 70° and two coils a larger angle of 110°.

The curved part of a coil which connects the straight parts in a groove is called the coil head. The coil heads of the 70° coils, the 90° coils and the 110° coils are lying within each other without crossing wires.

A three phase winding is normally laid as a so called two layers winding. The six coils of one phase can be distinguished from each other by the indices a, b, c, d, e and f. So all 18 coils are numbered U_a, U_b, U_c, U_d, U_e, U_f, V_a, V_b, V_c, V_d, V_e, V_f, W_a, W_b, W_c, W_d, W_e and W_f.

In the first layer coils U_a, U_b, U_c, V_a, V_b, V_c, W_a, W_b and W_c are laid. The coil heads of these nine coils are bent to the outside of the housing to open the groove ends of the remaining grooves. In the second layer coils U_d, U_e, U_f, V_d, V_e, V_f, W_d, W_e and W_f are laid. The stator grooves can be numbered 1 – 36. The relation in between the coil and the stator groove number is given in table 1. A coil is symbolised by a single line in figure 1. The coils are drawn for the same pattern as given in table 1.

coil	Ua	Ub	Uc	Ud	Ue	Uf	Va	Vb	Vc	Vd	Ve	Vf	Wa	Wb	Wc	Wd	We	Wf
groove	1+12	2+11	3+10	19+30	20+29	21+28	13+24	14+23	15+22	31+6	32+5	33+4	25+36	26+35	27+34	7+18	8+17	9+16

table 1 Relation in between the coil and the stator groove number

Only the six coils U_b, U_e, V_b, V_e, W_b and W_e have the correct groove angle of 90°. The voltage generated in the three coils of a phase lying in one layer, so for instance U_a, U_b and U_c, is not the same for each coil because the magnetic flux going through a coil is not the same for every coil. The middle coil U_b has the maximum voltage. The voltage for the outer coil U_a and the inner coil U_c is somewhat lower. The three coils of a certain phase of one layer are therefore always connected in series.

The three coils of a certain phase of the first layer are normally connected in series with the three coils of the same phase of the second layer. This connection is not guided to the terminal but it is soldered and isolated with a piece of isolation tube. So every phase has a soldering point and all three soldering points are normally at the same side of the winding. However, it is possible to disconnect the three coils of the first layer from the three coils of the second layer and to solder small isolated wires to each end of three coils. Now it is possible to connect the three coils of the first layer in parallel to the three coils of the second layer. This results in halving of the voltage and in doubling of the current (see figure 2 for wire diagrams). This procedure has to be followed for some of the VIRYA generators.

For a normal non modified winding, the ends of a string of six coils are given the indices 1 and 2. So the total coil U has a coil end U_1 and a coil end U_2. The total coil V has a coil end V_1 and a coil end V_2. The total coil W has a coil end W_1 and a coil end W_2. The coil ends are connected to the terminal. The terminal is situated in the terminal box which is positioned on top of the generator. The terminal has six connecting points in two rows of three points. The front points are called U_1, V_1 and W_1. The after most points are called W_2, U_2 and V_2. The name of the connecting point is the same as the name of the coil end which is connected to it. Point U_1 is opposite point W_2, point V_1 is opposite point U_2 and point W_1 is opposite point V_2. The three external cables to the rectifier are called L_1, L_2 and L_3. L_1 is connected to U_1, L_2 is connected to V_1 and L_3 is connected to W_1. These definitions are used by the Dutch manufacturer ROTOR which supplies the housings of the VIRYA generators.

The terminal is supplied with three brass strips which are used to connect certain connecting points to each other. For delta connection three strips are required. For star connection only two strips are enough but mostly one strip is doubled to prevent strip lost.

For star connection points W_2, U_2 and V_2 are connected to each other. For delta connection point U_1 is connected to point W_2, point V_1 is connected to point U_2 and point W_1 is connected to point V_2 and all three strips are mechanically placed in parallel.

4-pole asynchronous motors of manufacture ROTOR with powers in of 0.09 kW up to 1.5 kW are standard supplied with a 230/400 V winding. This means that the winding is meant for 400 V in star and for 230 V in delta. Motors with a power of 2.5 kW up to 5.5 kW (size 112) can be supplied with a 230/400 V winding or with a 400/690 V winding. Motors with powers of 5.5 kW (size 132) and larger are always supplied with a 400/690 V winding. These larger motors are started in star to reduce the starting current and are switched to delta after starting. So the voltage level of a 400/690 V winding is a factor $\sqrt{3}$ higher than for a 230/400 V winding. The voltage for rectification in star is also a factor $\sqrt{3}$ higher than for rectification in delta.

If a generator is made from an asynchronous motor and if a standard 230/400 V winding is used, it will generate a rectified open voltage which is proportional to the rotational speed and which is a factor $\sqrt{3}$ higher for star rectification than for delta rectification. If a 400/690 V winding is used, the rectified open voltage will be again a factor $\sqrt{3}$ higher. So the open voltage at a certain rotational speed for star rectification of a 230/400 V winding will be the same as the open voltage for delta rectification of a 400/690 V winding. So these two different windings result in three options for the open voltage at a certain rotational speed. If a standard winding is modified by connecting the first and the second layer in parallel in stead of in series, the voltage halves. So this results in totally six options for the open voltage for two standard and two modified windings. All VIRYA windmills except the VIRYA-4.6, make use of a standard or a modified winding, so it is not necessary to rewind the generator.

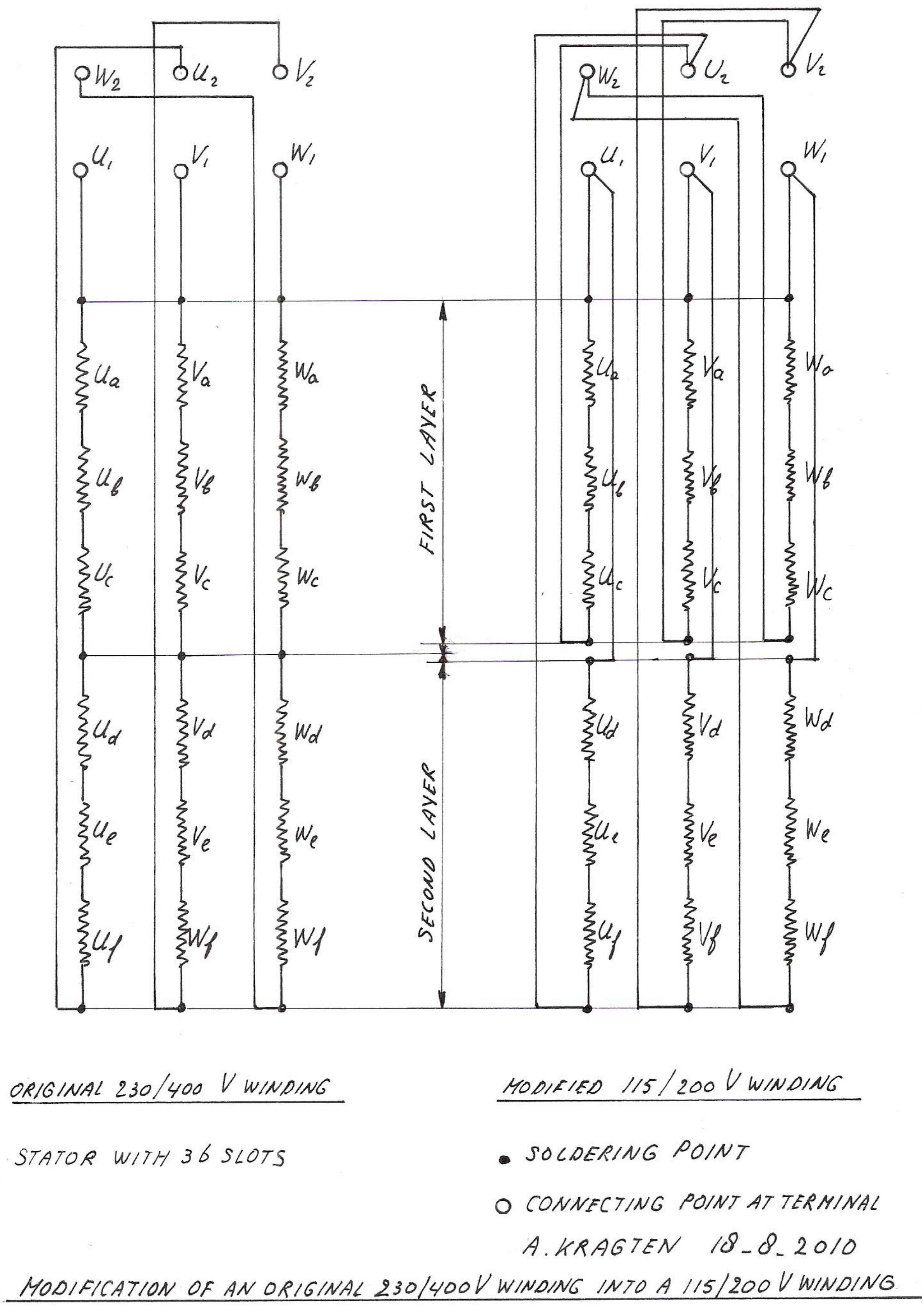


fig. 2 Wire diagrams for a 230/400 V winding and for a modified 115/200 V winding

The wires from the soldering points to the connecting points at the terminal have different colours for each phase. Red, orange and black are used for motors of manufacture ROTOR.

5 Calculation of PM-generators

A PM-generator of a VIRYA windmill is designed such that the magnetic field in the stator is saturated or almost saturated. For this condition, the generator has its maximum torque level and this means that it can supply the maximum electrical power for a certain rotational speed. The stator is saturated at the narrowest cross section of the spokes in between the stator grooves. The magnetic field coming out of one armature pole is guided through nine stator poles if the armature pole angle is 90° and if the stator pole angle is 10°. However, the real armature pole angle is less than 90° because of the groove needed for the permanent magnets.

For some VIRYA generators the length of the armature is taken somewhat larger than the length of the stator iron. But for comparing the armature pole area and the total area of the stator spokes which are conducting the magnetic field coming out of one armature pole, only the part of the armature pole which is laying within the stator length has to be taken into account. The area of one armature pole is much larger than the total area of the stator spokes which are conducting the magnetic flux coming out of one armature pole. The stator iron is saturated at a flux density of about 1.6 Tesla (T). The flux density in the air gap in between armature and stator will therefore be much lower than 1.6 T. It is assumed that the stator is saturated for a calculated flux density in the air gap of 0.9 T or more. The method for calculation of the flux density in the air gap is given in the Dutch report KD 118 (ref. 2). The main part of this report is translated into English and is forming this chapter 5.

Not all the magnetic flux coming out of the magnets in one armature groove is conducted to the outside of an armature pole. As adjacent armature poles are connected to each other by a small, 0.8 mm high bridge, a small part of the flux is going into this bridge. The magnetic field in the bridge is saturated. It is assumed that this bridge results in loss of 1 mm of the magnet height H.

There are two more reasons why some magnetic flux is lost. There is a magnetic flux flowing along both armature sides. However, the average air gap which has to be bridged by this flux is very large and this flux can therefore be neglected. The armature groves are making a certain angle with the armature axis to prevent fluctuation of the sticking torque. A small triangular area of an armature north pole and a small triangular area of an armature south pole are therefore facing the same stator pole. The magnetic flux through these triangular areas is therefore short-circuited by this stator pole and is not flowing into the stator. For a 4-pole armature, the total armature pole area is very large with respect to the triangular areas which are causing this loss and this loss can therefore also be neglected.

The remanence B_r (magnetic flux) in a neodymium magnet supplied by Bakker Magnetics with quality BM 35 is about 1.22 T if the magnet is short-circuited with a mild steel arc which is not saturated. In chapter 4 it was shown that the magnetic flux coming out of one magnet, has to bridge two times the glue gap t_2 and two times the air gap t_3. The resistance to a magnetic flux for the magnet itself is about the same as for air. The magnet thickness is t_1. The magnetic resistance of the iron of the armature can be neglected as it is far from saturation. The magnetic resistance of the iron in the stator can't properly be neglected if the stator is close to saturation. However, this is complicating the calculation a lot and so the magnetic resistance of the iron in the stator is also neglected. So the total magnetic resistance is only caused by the magnet itself and by the four air gaps. So the four air gaps result in an increase of the magnetic resistance by a factor $(t_1 + 2\ t_2 + 2\ t_3) / t_1$. This results in decrease of the remanence B_r to the effective remanence $B_{r\ eff}$. $B_{r\ eff}$ is given by:

$$B_{r\ eff} = B_r * t_1 / (t_1 + 2\ t_2 + 2\ t_3) \qquad \text{(T)} \qquad (1)$$

All neodymium magnets used in the VIRYA generators have a thickness t_1 = 10 mm. The groove wide is taken 0.2 mm larger than the magnet thickness and it is assumed that the glue gap is the same for both sides of the magnet. This gives t_2 = 0.1 mm.

The air gap in between armature and stator depends on the motor size. The average value is about 0.3 mm for the sizes used for VIRYA generators. Substitution of these values and $B_r = 1.22$ T in formula 1 gives that $B_{r\ eff} = 1.13$. This is a factor 0.926 of B_r which is an indication that it is not allowed to neglect the air gaps, even for a rather thick magnet.

For the calculation of the magnetic flux in the air gap in between armature and stator, the armature pole area lying within the stator iron is compared to the effective magnet area which is supplying this flux. The magnetic flux going through one armature pole is supplied by all magnets laying in two adjacent armature grooves (see figure 1). The number of magnets in one groove is called n. The magnet length is called L_m (mm). The magnet height is called H (mm). The effective magnet height is (H – 1) because of the flux loss through the bridge. So the total effective magnet area in two armature grooves $A_{m\ tot}$, is given by:

$$A_{m\ tot} = 2\ n * L_m * (H - 1) \qquad (mm^2) \qquad (2)$$

A_a is the area of an armature pole which is lying within the stator iron with length L_b. The pole chord is reduced by the magnet thickness t_1 (mm). The armature pole number is called p. Sometimes p is used for the number of armature pole pairs which is half the number armature poles but I use p for the number of armature pole. So p = 4 for a 4-pole armature. The armature diameter is called D (mm). The armature pole area A_a is given by:

$$A_a = (\pi * D/p - t_1) * L_b \qquad (mm^2) \qquad (3)$$

The flux density in the air gap is increased (or decreased) by the factor $A_{m\ tot} / A_a$. The flux density in the air gap B_l (l comes from the Dutch word lucht for air) is therefore given by:

$$B_l = B_{r\ eff} * A_{m\ tot} / A_a \qquad (T) \qquad (4)$$

(1) + (2) + (3) + (4) gives:

$$B_l = \frac{2\ B_r * t_1 * n * L_m * (H - 1)}{L_b * (t_1 + 2\ t_2 + 2\ t_3) * (\pi * D/p - t_1)} \qquad (T) \qquad (5)$$

As an example, B_l is now calculated for the generator of the VIRYA-4.2 windmill. This generator is also used for the VIRYA-3.8. The remanence of the used neodymium magnets $B_r = 1.22$ T. The magnet thickness $t_1 = 10$ mm. The number of magnets in one armature groove n = 4. The magnet length $L_m = 40$ mm. The magnet height H = 30 mm. The length of the stator iron $L_b = 150$ mm. The glue gap $t_2 = 0.1$ mm. The air gap $t_3 = 0.3$ mm. The armature diameter D = 107.94 mm. The number of armature poles p = 4. Substitution of these values in formula 5 gives $B_l = 0.935$ T. This is larger than 0.9 T which means that the stator iron is saturated. So the maximum torque level will be realised.

The VIRYA-4.2 generator is made of a 5.5 kW asynchronous motor size 112 (with lengthened stator iron). The maximum torque level for short-circuit in delta is 78 Nm. The sticking torque for very low rotational speeds is 0.9 Nm. This is a factor 0.0115 of the maximum torque which is very low for a PM-generator. The low sticking torque results in a low starting wind speed of the rotor. The measurements for this generator are given in report KD 200 (ref. 3). All generators used in the VIRYA windmills have been measured on a very accurate test rig of the University of Technology Eindhoven and all measuring reports are public and can be ordered at Kragten Design. The measuring report in which the most different types of measurements are given, is report KD 78 (ref. 4). An alternative 4-pole generator for the VIRYA-3 windmill using a motor housing size 100 and eight neodymium magnets size 50 * 25 * 10 mm is described in public report KD 503 (ref. 5). A 4-pole generator for the VIRYA-2S windmill is described in public report KD 690 (ref. 25).

6 Recent developments

A 22-pole generator using a housing of frame size 90 is described in report KD 708 (ref. 6). I have built and tested a 22-pole generator using an Indian housing frame size 71 but the report in which this generator is described isn't public because it was written for an Indian company which finally decided not to start production.

The number of armature poles must be two less or two more than the number of stator grooves or stator poles. So for a stator with 24 poles it is possible to use this principle for an armature with 22 or with 26 poles. For a stator with 36 poles it is possible to use this principle for an armature with 34 or with 38 poles. For a stator with 48 poles it is possible to use this principle for an armature with 46 or with 50 poles.

A 26-pole generator is described in report KD 632 (ref. 7). This generator is meant for the VIRYA-2.2 rotor with a diameter of 2.2 m. A 34-pole PM-generator has been designed for the VIRYA-3.3S windmill to be coupled directly to the 3-phase motor of a centrifugal pump. This generator is described in free public report KD 560 (ref. 8). Figure 1 out of this report is copied as figure 3.

A small 34-pole generator is described in report KD 580 (ref. 9). This generator makes use of a stator stamping of a 6-pole motor frame size 80 and is meant to be driven by a rotor with a diameter of about 1.5 m or by human power. A big 34-pole generator is described in report KD 614 (ref. 10) for the VIRYA-5. A very big 46-pole generator is described in report KD 624 (ref. 11) for the VIRYA-6.5. A 38-pole generator using frame size 100 is described in report KD 648 for the VIRYA-3B3 (ref. 21).

The main advantages of this type of generator are:

1) The generator has a high frequency, so it can be used for coupling to an asynchronous motor of a pump or the motor of another tool which accepts a certain variation of the rotational speed like a grinding mill or a compressor.
2) The number of preference positions per revolution is equal to the product of the number of armature poles times the number of stator poles divided by two. So the VIRYA-3.3S generator with 36 stator poles and 34 armature poles has 612 preference positions. The peak on the sticking torque for these many preference positions is almost flattened and this results in a low starting wind speed of the rotor.
3) The generator can also be used for battery charging if it is provided with a low voltage winding.
4) The grooves in the armature are milled parallel to the armature axis which is simpler than the inclined grooves of the normal VIRYA-generators.
5) The grooves are very shallow and a short cutter can therefore be used which bends less than the long cutter which is required for the deep grooves of the normal VIRYA-generators.
6) Rather thin 3 mm, 5 mm or 8 mm thick magnets are used. These magnets are rather cheap.
7) The magnets can be handled easily and have almost no tendency to jump out of the grooves during gluing.
8) The original steel motor shaft can be used. The normal VIRYA-generators require a stainless steel shaft to prevent short-circuit in between the armature poles.
9) The winding is a single layer winding with no crossing coil heads. The coil heads are very short, so less copper is needed and the copper losses in the winding are also less.

In figure 3 it can be seen that magnets are only used for the north poles and that the south poles are formed by the remaining material of the armature. Every phase has three coils which are about opposite to north poles and three coils which are about opposite to south poles for the drawn armature position as given in figure 3.

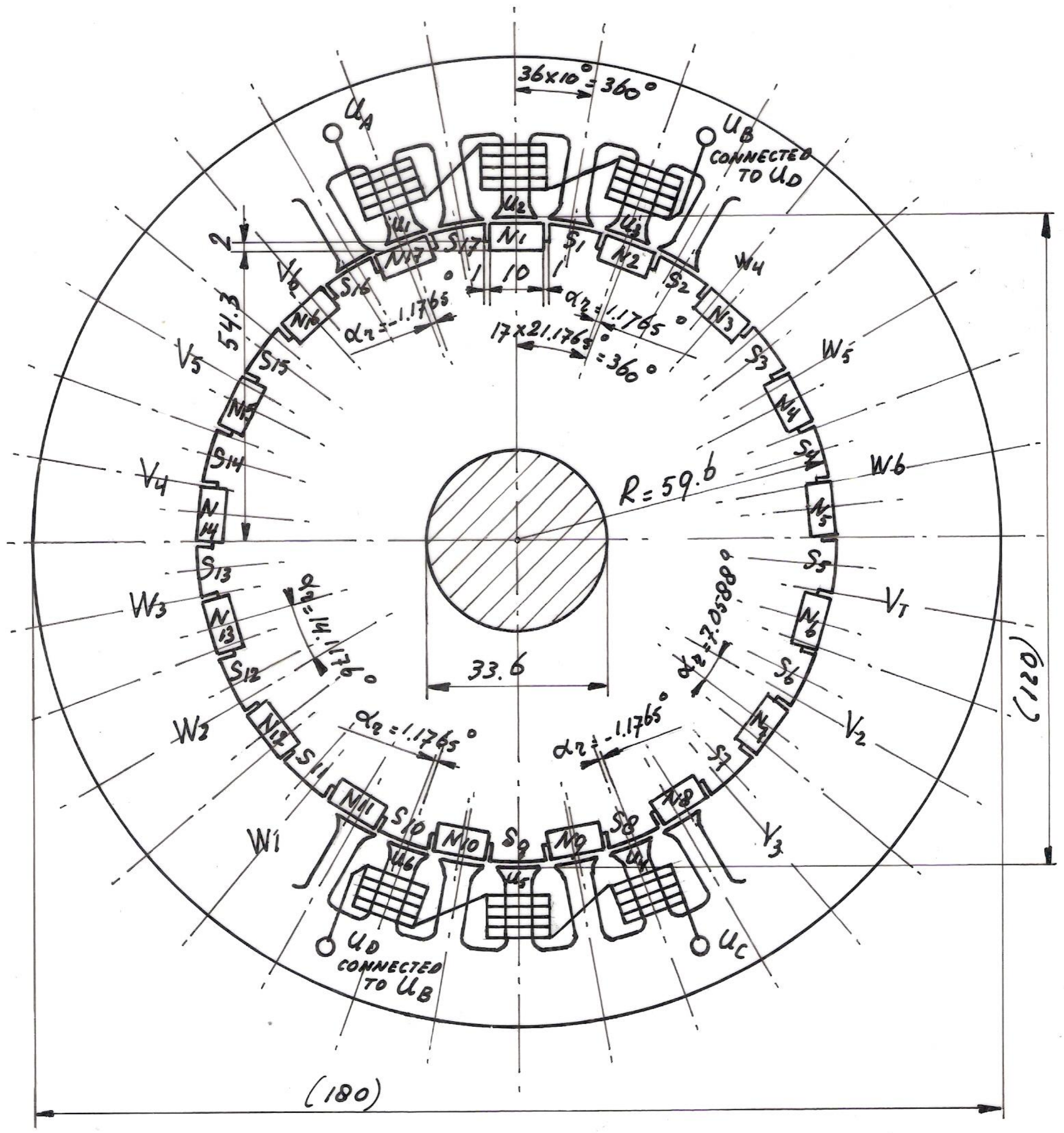


figure 3 34-pole armature and 36-pole stator for housing size 112F-6P, 180 * 120 * 33.5 mm

A 10-pole generator in a housing with 36 slots is described in the note: 10-pole PM-generator (ref. 12).

Some recent KD-reports have been written about ideas for axial flux generators which are used in a range of VIRYA-windmills for which no licence is required. An 8-pole generator is described in report KD 571 (ref. 13) for the VIRYA-1.36 windmill. This generator has been tested for one coil to determine the number of turns per coil. A 12-pole generator is described in report KD 596 (ref. 14) for the VIRYA-1.66 windmill. The 8-pole generator of the VIRYA-1 and the VIRYA-1.02 with a steel stator sheet as described in report KD 679 (ref. 15) is an alternative for the Nexus hub dynamo of the VIRYA-1.04. An earlier cancelled version for the VIRYA-1.25AF is described in report KD 626 (ref. 16). The VIRYA-1 and the VIRYA-1.02 both make use of the front wheel hub of a mountain bike as generator housing. The generator has been tested and measurements are given in KD 679 (ref. 15). An 8-pole generator with a synthetic stator sheet for the VIRYA-1.81 is described in report KD 631 (ref. 17).

8-pole, 10-pole and 12-pole radial flux PM-generators using the housing of an asynchronous motor with no iron in the stator are described in respectively report KD 644 (ref. 18), KD 645 (ref. 19) and KD 667 (ref. 20). 24-pole and 16-pole PM-generators with no iron in the coils are described in KD 668 (ref. 22) and KD 748 (ref. 35). An 8-pole generator with minimal fluctuation of the sticking torque is described in report KD 681 (ref. 23).

A 4-pole generator is described in KD 683 (ref. 24). 16-pole, 32-pole, 28-pole and 40-pole generators are described in KD 718 (ref. 30). An 18-pole generator is described in KD 723 (ref. 31). A 28-pole generator is described in KD 730 (ref. 32). A 30-pole generator is described in KD 747 (ref. 33). A Sparta hub motor is described in report KD 746 (ref. 34).

7 Comparing of a 26-pole radial flux generator with an 8-pole axial flux generator

The main advantage of an axial flux generator is that the coils contain no iron and that the generator therefore has almost no sticking torque. This allows the use of a rotor with a high tip speed ratio and a low starting torque coefficient. The windmill will have a high peak efficiency and a low starting wind speed. The main disadvantage of an axial flux generator is that it has a large air gap and this air gap reduces the magnetic flux through the coils. For a certain torque level, a much larger magnet volume is therefore needed than for the radial flux generators with a laminated stator and a small air gap. This results in much higher magnet costs. As the flux density in the coils is much lower, much more copper will be needed than for a generator with iron lamination in the coils. So it also results in higher copper costs for an axial flux generator. The effects of the magnet costs are illustrated by comparing the 26-pole radial flux generator as described in report KD 632 (ref. 7) with the 8-pole axial flux generator of the VIRYA-1.81 as described in report KD 631 (ref. 17). For the 26-pole generator the housing and the shaft of a 4-pole, 3-phase, 0.75 kW asynchronous motor are used. These components are manufactured in large quantities and are therefore rather cheap if they are ordered at the original manufacturer. Other advantages are that the winding and the magnets are lying inside the generator housing and that they are therefore well protected against the elements. The small magnets of the 26-pole generator are also easier to handle than the big magnets of the 8-pole generator.

Now it will be explained why the magnet costs of the 8-pole axial flux generator are much higher than those of the 26-pole radial flux generator. The 26-pole generator uses 26 rectangular magnets size 40 * 7 * 3 mm. So the volume of one magnet is 0.84 cm^3 and the total magnet volume is 21.84 cm^3. The 8-pole generator uses 8 circular magnets with a diameter of 45 mm and a thickness of 15 mm. So the volume of one magnet is 23.86 cm^3 and the total magnet volume is 190.88 cm^3. So the total magnet volume of the 8-pole generator is a factor 8.74 larger than that of the 26-pole generator.

The magnet costs depend on the magnet size, the quantity, the costs of transport, the quality of the magnetic material, if VAT is included or not and on the chosen supplier. Both magnets can be ordered at the same rather cheap Polish supplier Enes Magnets, so a different supplier is not the cause of the price difference. The costs of transport are relatively high if only a small number of magnets is ordered. Therefore I always order at least the quantity needed for manufacture of two generators. An extra advantage of buying a rather large quantity is that the price per magnet goes down at increasing quantity. For comparing both options, the costs of transport are neglected. The quality of the small rectangular magnets is N38SH and of the big round magnets is N35. So the remanence B_r will be a little less for the round magnets but this difference is neglected too.

For two generators, 52 magnets size 40 * 7 * 3 mm or 16 magnets size ϕ 45 * 15 mm are needed. The magnet supplier gives on his website a list with prices (including VAT but excluding costs of transport) depending on the quantity.

For a quantity of at least 40 pieces, the price per piece is € 0.70 for magnet size 40 * 7 * 3 mm. So the total magnet costs are 26 * 0.70 = € 18.20. The price is € 0.83 / cm^3.

For a quantity of at least 7 pieces, the price per piece is € 9.88 for the magnet size ϕ 45 * 15 mm. So the total magnet costs are 8 * € 9.88 = € 79.04. The price is € 0.41 / cm^3.

So the price per cm^3 is about double for the small magnets. However, the required total magnet volume of the 8-pole generator is a factor 8.74 higher than that of the 26-pole generator and this finally results in the fact that the total magnet costs of the 8-pole generator are a factor 79.04 / 18.20 = 4.34 higher than those of the 26-pole generator.

It is expected that the maximum torque level of both generators is about the same. In the first instance it may look strange that the 8-pole axial flux generator with a total magnet volume which is a factor 8.74 higher than that of the 26-pole radial flux generator would have about the same maximum torque level. But basically the torque is determined by the magnet area and not by the magnet volume. The magnet thickness is only important for the determination of the effect of the air gap on the strength of the magnetic flux B_r in the air gap.

The 26-pole generator has one 3 mm thick magnet in one magnetic loop. The total length of the two air gaps is 0.75 mm. So the ratio in between the total length of the air gap and the thickness of the magnet is 0.75 / 3 = 0.25. In chapter 4 of KD 632 it has been calculated that this results in a flux density in the air gap of B_r = 0.992 T. This is very high.

The 8-pole generator has two 15 mm thick magnets in one magnetic loop. The average length of the air gap is about 55 mm. So the ratio in between the average length of the air gap and the total thickness of two magnets is 55 / 30 = 1.83. In chapter 3 of KD 631 it has been calculated that this results in a flux density in the air gap of B_r = 0.42 T. This is rather low.

How a torque is produced can best be understood for a radial flux generator. The magnetic flux which is flowing in the air gap from armature to stator results in a kind of shearing stress τ which can have a certain maximum value for a high load. The maximum shearing stress is proportional to the flux density B_r. This shearing stress gives a tangential force F which is proportional to the total area $A_{p\ tot}$ of all armature poles together. The tangential force F multiplied by the radius r on which F is acting, gives the torque Q. The real maximum torque Q_{max} in Nm can only be found if the generator is measured on a test rig. But for comparing of two different generators the real torque isn't important. Only the ratio in between the torques is important. So the maximum torque is given by:

$$Q_{max} = C_1 * B_r * A_{p\ tot} * r \quad (\text{Nm}) \qquad (6)$$

The constant C_1 isn't known but it is assumed that it is the same for the 26-pole and the 8-pole generator. The 26-pole generator has 26 magnets which are only used for the north poles. The south poles are formed by the remaining material of the armature but also have a width of 7 mm. So the total area of the south poles is the same as the total area of the north poles. So for the 26-pole generator it is found that $A_{p\ tot}$ = 2 * 26 * 40 * 7 = 14560 mm^2. The diameter of the armature is 69.4 mm. So for the radius r of the armature it is valid that r = 34.7 mm. Substitution of B_r = 0.992 T, $A_{p\ tot}$ = 14560 mm^2 and r = 34.7 mm in formula 6 gives that $Q_{max} = C_1$ * 501190 T mm^3 for the 26-pole generator.

The 8-pole generator has four magnets used for north poles and four magnets used for south poles. So for the 8-pole generator it is found that $A_{p\ tot} = 8 * \pi/4 * 45^2$ = 12723 mm^2. The pitch circle of the magnets is 150 mm so r = 75 mm. Substitution of B_r = 0.42 T, $A_{p\ tot}$ = 12723 mm^2 and r = 75 mm in formula 6 gives that $Q_{max} = C_1$ * 400775 T mm^3 for the 26-pole generator.

So according to this provisional calculations, the torque level of the 26-pole generator is even a factor 501190 / 400775 = 1.25 higher than that of the 8-pole generator. It might be that the constant C_1 isn't the same for both generator types but the calculation shows that there isn't a very big difference in between both generators. To be sure which generator has really the highest maximum torque level, it is necessary to build both generators and test them on a test rig. But this is a lot of work and I won't do that.

The 26-pole generator will have a certain sticking torque which will increase about proportional to the rotational speed. This sticking torque will have an unfavourable influence on the efficiency but, as it is almost not fluctuating, it won't give starting problems. So I doubt if the somewhat higher output of the 8-pole generator will compensate the larger investment costs of this generator. Other aspects which influence what is the optimum choice for a certain generator type are the availability of machines, materials and craftsmanship.

8 Experiments with Chinese axial flux generators of Hefei Top Grand

Manufacture of a PM-generator is the most difficult part of the manufacture of an electricity generating windmill. So it would be nice if the generator could be bought somewhere. PM-generators are supplied by different Chinese companies like Hefei Top Grand, Xinda green Energy, Hiestmotor and Qiangsheng Magnets. Some of these companies supply the same generator type and it has not become clear to me which company is the real manufacturer. I have asked questions in English to different companies and a got the clearest answers from Hefei Top Grand. Another advantage of Hefei Top Grand is that they supply a very large range of axial flux PM-generators and therefore this company was chosen.

Information about each axial flux generator is given on the website of Hefei Top Grand: www.china-topgrand.com at the menu “product”. At this page of the website, there are two options, PM-generators inner rotor and PM-generators outer rotor. I have chosen the type with an outer rotor because connection of the windmill rotor to the generator is easy for this type. Outer rotor means that the whole generator housing is rotating around the generator shaft.

For all generators, a data sheet is given if you go to a specific type. This data sheet gives: Shape Drawing at point 4, Performance Parameter at point 5 and Curve Graph at point 6. At point 6, one gives a graph with the measured loaded voltage U and the electrical power P_{el} as a function of the rotational speed n. As the P_{el}-n curves are parabolas, the load must have been a fixed resistor. All types have a 3-phase winding connected in star. The star point is internal, so only the three phase wires are guided outwards through the hollow shaft. For the smaller types, the DC voltage after rectification is given but for the bigger types, the AC voltage in between two of the three phases is given. These generators have no iron in the coils so the sticking torque is only caused by the friction of the bearings. No oil seal is mounted on the rotor shaft but the bearing cover is provided with a chamber in which an oil seal can be mounted. The sticking torque with an oil seal is much higher than without one.

The generator will mostly be used to charge a battery. The charging voltage for a 12 V lead acid battery varies in between about 12 V and 14 V and the average charging voltage is about 13 V. The generator characteristics for a constant voltage are completely different from the characteristics for a resistance load (see KD 78, ref. 4). So the generators should have been measured for different constant DC voltages like 13 V, 26 V and 52 V to check the matching in between rotor and generator for a battery load but no Chinese manufacturer supplies this kind of measurements. So I have bought one the smallest and cheapest type TGET165-0.15kW-500R and measured it on my test rig for a constant voltage of 13 VDC. These measurements are given in report KD 595 (ref. 26). The maximum power and the maximum efficiency are a lot lower than as specified but technically the generator is well designed and it has been tested now for more than three years on a small VIRYA windmill without any problems.

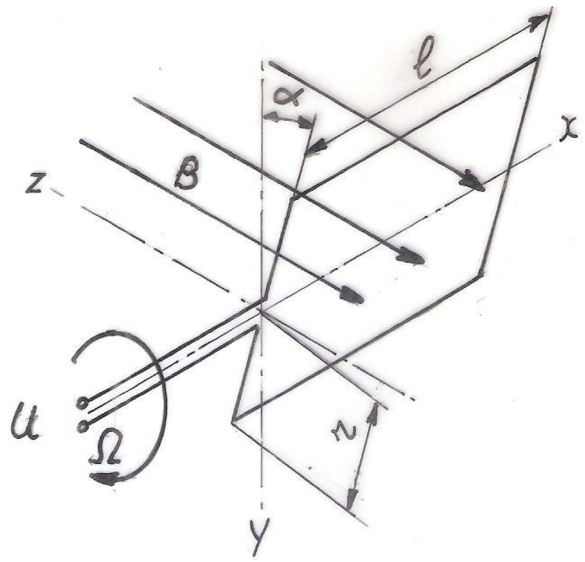
Use of the type TGET260-0.5KW-350R is described in report KD 676 (ref. 27) for use in combination with the VIRYA-2.22 rotor and for 24 V battery charging. Use of the type TGET320-1KW-350R is described in report KD 705 (ref. 28) for use in combination with the VIRYA-3B3 rotor and for 48 V battery charging. This generator is the largest one for which the nominal voltage is given for direct current (DC).

For bigger types the nominal loaded AC voltage is given for a certain nominal rotational speed but this voltage can be transferred to the loaded DC voltage. For some bigger types, the loaded AC voltage is very high, so this types can’t be used for low voltage battery charging. Generators with housing TGET380 are supplied for five different AC voltages. The one with the lowest voltage at a certain rotational speed is the TGET380-10kW-1200R. The nominal AC voltage of this type is 220 V at 1200 rpm but at low rotational speeds this type can be used for 48 V battery charging. The use of this type in combination with the VIRYA-4.2 rotor is explained in report KD 707 (ref. 29). Transformation of the given characteristics for a resistance load at n = 1200 rpm to the characteristics for a 48 V battery load is rather complex but the method how to do this is given in KD 707.

9 Voltage generation in a coil

The information given in this chapter is also given in a discussion with the same name which I started on December 11, 2020 at the section wind of the Otherpower discussion board, website: www.fieldlines.com .

There are two ways to explain how a voltage is generated in a coil. Assume we have a constant magnetic field B in which a rectangular coil is rotating. The coil has two in parallel long sides with a length l and two in parallel short sides with a halve length r. The axis of rotation is lying half way the short sides and is in parallel to the long sides. The axis of rotation is perpendicular to the direction of the magnetic field. Assume that the position of the coil for which the coil is perpendicular to the magnetic field is called the zero position. The angle of rotation from this zero position is called α. The coil is given in figure 4.



$$\Omega = 2\pi f \ (rad/s)$$

$$U = C \times B \times r \times l \times \Omega \times \sin\alpha \ (V)$$

figure 4 Rectangular coil rotating in a constant magnetic field

The Ω in the first formula is the angular velocity in rad/s. To prevent confusion with the dimension Ω for a resistance, one can also use the small ω. But in my report KD 35, I have used the capital Ω for angular velocity and therefore I do it here too. The f in the first formula is the frequency in Hz. A radian is the arc for which the arc length is equal to r. As 360° = 2 * π rad, 1 rad = 360° / (2 * π) = 57,296°. The angular velocity Ω in rad/s can be transformed into the rotational speed n in rev/min by: n = 30 * Ω / π rev/min. The C in the second formula is a certain constant added to make the equation right. I don't know the value. The given coil has only one turn. If the coil has more than one turn, C decreases proportional to the number of turns per coil. The product r * Ω is the speed of the long sides of the coil. The product r * Ω * sinα is the component of the speed perpendicular to the magnetic field B.

First way of explanation

The maximum number of field lines are flowing through the coil for the zero position. If the coil has rotated 90°, the coil is in parallel to the magnetic field and no magnetic field lines are flowing through the coil. The generated voltage is proportional to the speed for which the magnetic flux is changing. The change is zero for the zero position and maximal if the coil has rotated 90°. This is because the direction of the magnetic field with respect to the coil, changes at this point. It can easily be proven that the change of the number of magnetic field lines flowing through the coil is sinusoidal and that it has a maximum for a rotational angle of 90° and 270°. So the generated AC voltage is maximal for α = 90° and for α = 270°.

Second way of explanation

A voltage is generated in a straight wire which is moving perpendicular to a magnetic field. The voltage is proportional to the strength of the magnetic field, to the length of the wire and to the component of the speed perpendicular to the magnetic field. A short side of the rectangular coil can be divided into a part left from the turning point and a part right from the turning point. The voltages generated in these parts are just opposite each other and so the total voltage is zero. The voltage generated in a long part of the rectangular coil is proportional to the component of the speed perpendicular to the magnetic field. This component is zero for the zero position and at a rotational angle $\alpha = 180°$. This component is maximal at a rotational angle $\alpha = 90°$ and $\alpha = 270°$. The generated voltages in both long parts of the coil are strengthening each other. The component of the speed perpendicular to the magnetic field also changes sinusoidal so the generated voltage varies sinusoidal.

So both ways of explanation give the same result. If a PM-generator has coils with an iron core, like for most radial flux generators, the magnetic flux is concentrated in the iron and almost no field lines are flowing through the air in the grooves which are used for the coils. For this kind of generator, it is therefore easiest to use the first way of explanation for the generation of the voltage.

For an axial flux generator with two steel sheets with magnets at the inside and a disk with coils without iron in between, the second way of explanation can better be used. As there is no iron which concentrates the magnetic field, there is about a constant magnetic field in between two opposite magnets. A coil has two legs and an inner and an outer coil head. The voltage is only generated in the legs as only the legs are moving through the magnetic field. The coil heads are required to connect the legs but the length of the coil heads should be made a small as possible to reduce the Ohmic resistance of a coil.

The average pitch in between the left and the right leg should be the same as the pitch in between two adjacent magnets because then the generated voltages in both legs are in phase. If the generator has eight poles, the pitch angle in between two adjacent magnets is 45°. This means that the average pitch angle in between two legs of a coil should also be 45°. But as a coil has a certain thickness, the pitch angle of the inner turns will be somewhat smaller than 45° and of the outer turns will be somewhat larger than 45°.

For a 1-layer, 3-phase winding, the number of armature poles must be dividable by four. The number of stator coils is 3/4 of the number of armature poles. So for an 8-pole armature we get six coils. The coils are laid in the sequence U1, V1, W1, U2, V2 and W2. The optimum positions of the heart of the coil legs are then respectively 0° and 45°, 60° and 105°, 120° and 165°, 180° and 225°, 240° and 285°, 300° and 345°.

A disadvantage of a 1-layer winding is that only half of the possible leg positions is used. Within each coil, there are two positions which aren't used. The remaining twelve positions can be used for a second winding with six more coils so with coils U3, V3, W3, U4, V4 and W4. However, this results in crossing coil heads and crossing coil heads make the winding much thicker. Therefore a 2-layers winding is normally not used for axial flux PM-generators.

Another disadvantage of the described 1-layer winding is that the legs of adjacent coils make an angle of 15° with each other. This means that the thickness of a bundle of wires must be rather small to prevent that two adjacent coils touch each other at a small radius. The thickness of a bundle of wires can be increased if the two adjacent legs of two different coils are taken in parallel to each other. This means that the angle in between the legs of one coil is now increased from 45° up to 60°. The average pitch of a coil in mm may now differ from the pitch in mm of the magnets at the pitch circle. So now the voltage generated in the left leg of a coil may be not exactly in phase to the voltage generated in the right leg of a coil. This results in some reduction of the total voltage generated in both legs but this is acceptable as now there is place for much more copper.

A drawing for an 8-pole PM-generator with a 1-layer, 3-phase winding is given in figure 5. I have used magnets size 30 * 20 * 10 mm at a pitch circle of 90 mm. You need 16 magnets for an 8-pole generator. You look at the coils so you only see the magnets glued on the back steel sheet. The magnets can be bought at Enes Magnets in Polen. The gross price is about € 2.50 per magnet so the total magnet costs are about € 40 (excluding transport).

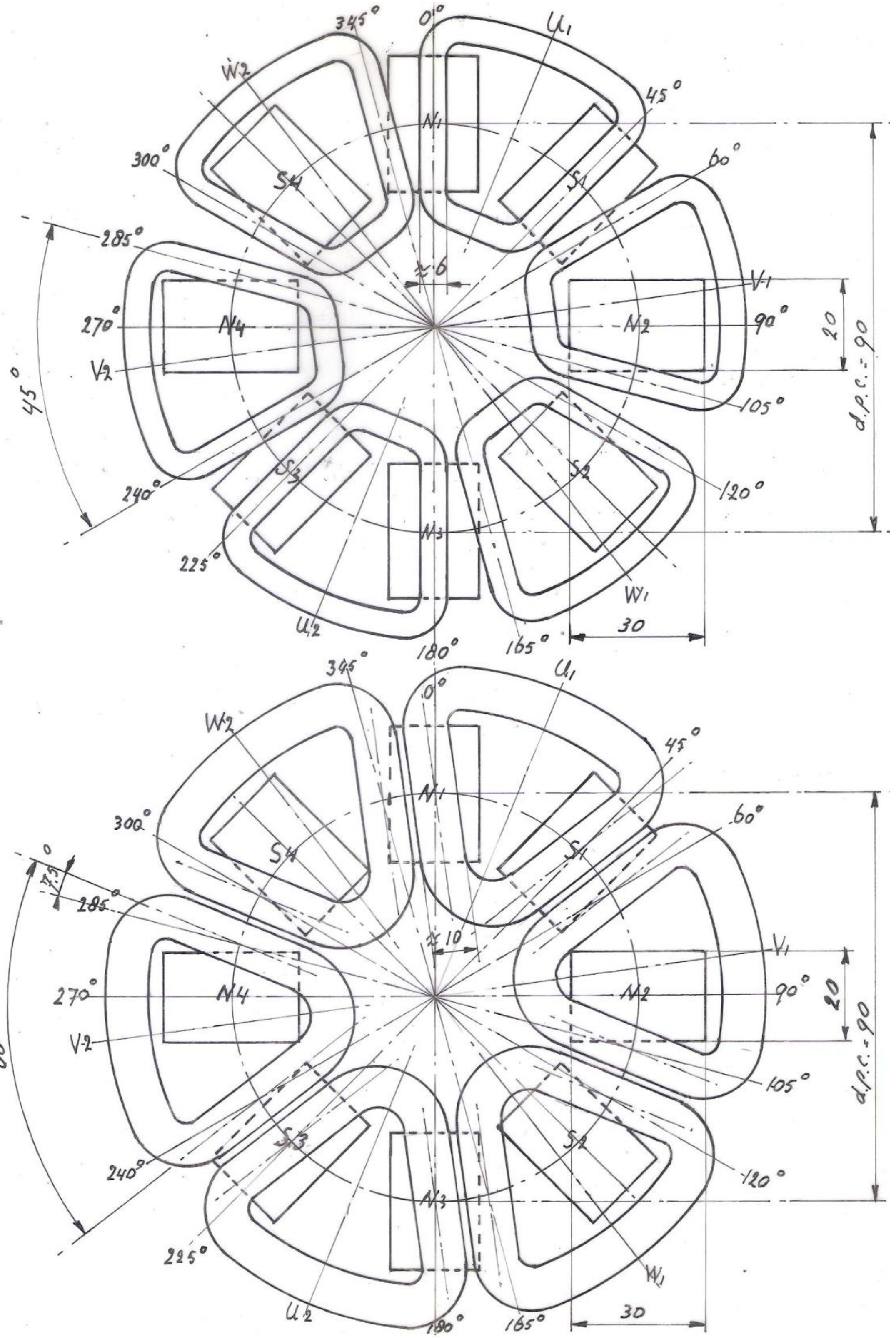


figure 5 8-pole PM-generator with 3-phase 1-layer winding with coil angle of 45° and 60°

The upper picture gives the coil configuration if the angle in between the legs is chosen 45°. The thickness of a wire bundle can be about 6 mm for this winding. The lower picture gives the coil configuration if the angle in between the legs is chosen 60°. The position of the wires has been chosen such that the coil pitch at the pitch circle of the magnets is exactly correct. The pitch at a smaller radius is somewhat too small and at a larger radius is somewhat too large but these effects can be neglected and the voltage generated in the left leg of a coil will be almost in phase to the voltage generated in the right leg of a coil. It can be seen that for this option, a thickness of a coil bundle of about 10 mm can be used and still have enough room in between two adjacent legs.

It might even be possible to give the coils the shape of the rotor of a Wankel motor. So in this case both legs are curved with the same radius as used for the outer coil head. Manufacture of such coils might be easier than manufacture of coils with straight legs.

For the second way of explanation a straight wire is moving through a constant magnetic field. For a generator, the coil is static and the magnetic field is moving but the effect is the same. I assume that the magnetic field is almost constant in between two opposite magnets. As long as a straight leg of a coil is moving in between two magnets, a constant voltage will be generated. For the given position of the upper picture, the heart of the left legs of the coils U1 and U2 coincide with the heart of the north poles N1 and N3. The heart of the right legs of the coils U1 and U2 coincide with the heart of the south poles S1 and S3. So if the left leg of a coil is just opposite to a north pole, the right leg is just opposite to a south pole. This means that the direction of the voltage generated in both legs will be opposite but as both legs are connected in a loop, the voltages will strengthen each other.

After a certain angle of rotation, the legs come out of the magnetic field in between two opposite magnets and the generated voltage will be zero. After a certain larger angle of rotation, the left and the right legs of a coil come in the region of other magnets for which the direction of the magnetic field is opposite to the starting position. So now a voltage is generated which has the opposite direction as for the starting condition. So rectangular magnets and straight coil legs result in a block voltage which deviates strongly from a sinus. In reality the change of the magnetic field in the air gap is not as suddenly as described and for the lowest picture there is a small region for which only a part of the wire is in between two opposite magnets. The corners of the block shaped voltage will therefore be rounded and so the real voltage will look more like a sinus.

For an 8-pole generator, the situation is the same as for the drawn zero position after 90° rotation of the armature. So a rotational angle of 90° corresponds to a phase angle of 360°. So a rotational angle of 1° corresponds to a phase angle of 4°. In figure 5 it can be seen that there is an angle of 0° in between the north pole N1 and the left leg of the coil U1. The generated voltage is maximal for this position. So this position corresponds to a phase angle $\alpha = 90°$. In figure 5 it can be seen that there is an angle of 30° in between north pole N2 and the left leg of coil V1. So this corresponds to a phase angle $\alpha = 90° + 4 * 30° = 210°$. In figure 5 it can be seen that there is an angle of 60° in between the north pole N3 and the left leg of the coil W1. So this corresponds to a phase angle $\alpha = 90° + 4 * 60° = 330°$. So the difference in between the phase angles is 120° and therefore a 3-phase current will be generated in between the phases U, V and W.

Earlier it has been said that it might be possible to give the coils the shape of the rotor of a Wankel motor. It has been investigated if this is really possible. A starting point is that the coil becomes a triangle with identically curved sides. A picture of a PM-generator with such coils is given in figure 6. The optimum geometry was found by try and error. For the drawn position, there is an angle of 22.5° in between the heart of coil U1 and the heart of the north pole N1. The diameter pitch circle of the outer coil head is 136 mm at the centre of a coil bundle. So the radius at the centre of a coil bundle is 68 mm. Finally it was found that one has to take an equilateral triangle with sides of 49 mm for which two corners coincide with the 136 mm pitch circle. The centre points for the curved left and right coil legs are lying on the perpendicular lines of this triangle.

The distance in between the heart of the generator and the outer side of the triangle is 63.4 mm. This distance has also been taken for the centre points of both curved coil legs because for this position it is valid that the radius at the heart of a coil bundle is also 68 mm.

A coil bundle has an inner radius of 68 – 5 = 63 mm and an outer radius of 68 + 5 = 73 mm. To prevent too strong bending of the inside wires of a coil, the inside corners are rounded with a radius of 3 mm. The minimum distance in between two adjacent legs is about 2.5 mm for a triangle with sides of 49 mm. The coil pitch at the pitch circle of the magnets is about the same as the magnet pitch so the generated voltage in the left leg will be about in phase to the voltage generated in the right leg. The coil pitch at smaller radius is somewhat smaller but this is no problem and it will make that the real voltage fluctuation is more sinusoidal than for straight legs.

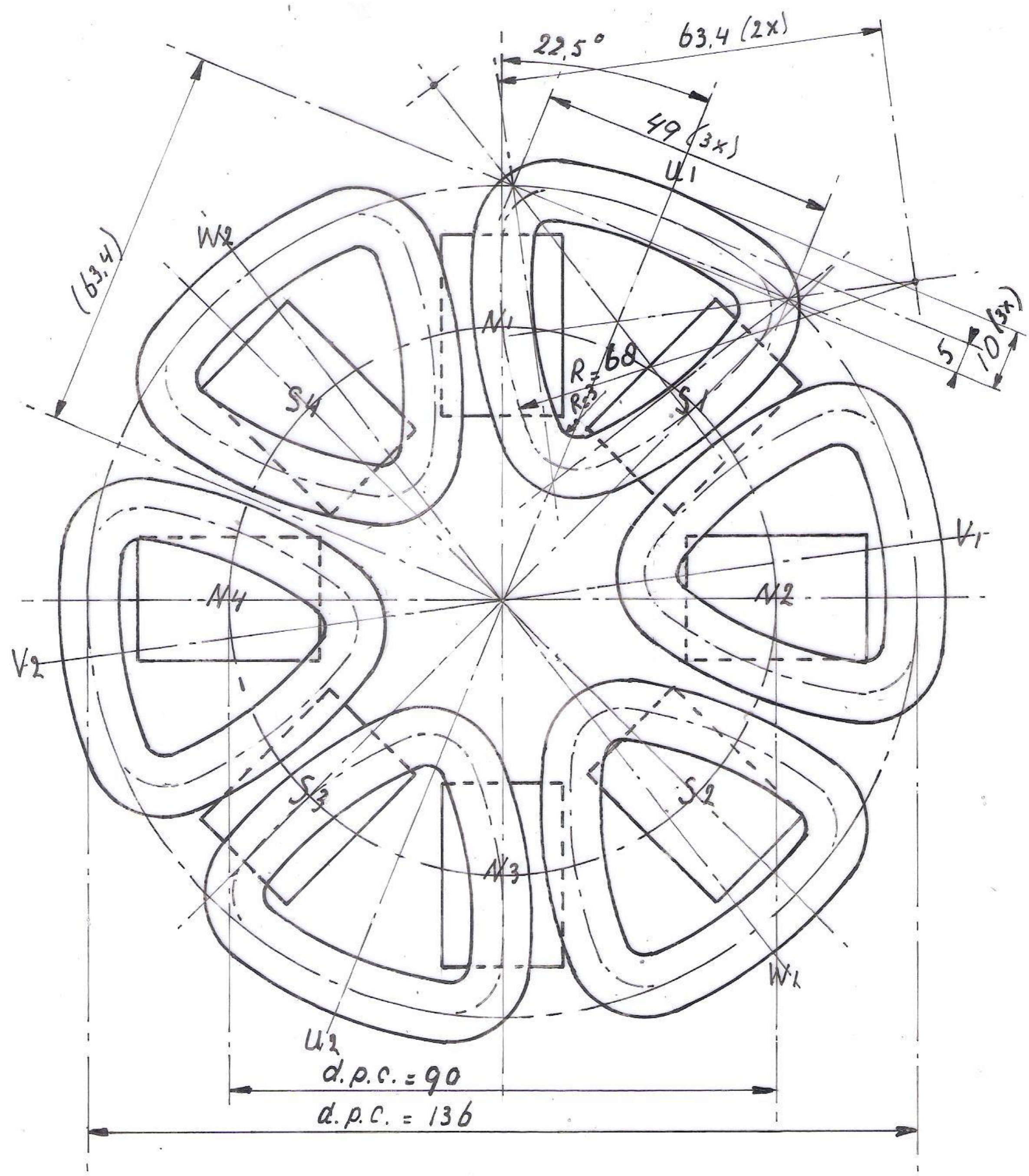


figure 6 8-pole PM-generator with coils shaped like the rotor of a Wankel motor

10 Back to the modified 4-pole asynchronous motor with a standard 230/400 V winding

The 4-pole generator as described in chapter 4 is rather expensive because 10 mm thick neodymium magnets are used. Manufacture of the armature is rather difficult as deep inclined grooves have to be made in the armature. To prevent magnetic short-circuit in between the north and the south poles, it is required to use a stainless steel shaft. So it is tried to develop a PM-generator with a simpler armature but still using the original housing and winding of a 4-pole asynchronous motor. This procedure is described in report KD 718 (ref. 30).

In report KD 718, several options are described. I think that the most promising option is described in chapter 7. This chapter is called: “Use of a 4-pole motor frame size 100L and a 32-pole armature”. Magnets size 40 * 7 * 3 mm are used for this armature. A magnetic north pole consist of eight mechanical poles formed by the magnets. Three magnets are glued in one magnet groove and so 2 * 8 * 3 = 48 magnets are needed for one armature. A magnetic south pole consist of eight iron poles separated by small grooves. The stator has 36 poles. So there are eight armature poles opposed to nine stator poles. This results in 8 * 9 * 4 = 288 preference positions per revolution and the peak on the cogging torque will therefore be very low. As the used magnets have only a thickness of 3 mm, the total magnet volume is much smaller and the magnet costs are therefore much lower than that of the generator as described in chapter 4. It is also possible to use the original motor shaft and this makes the generator much cheaper. A picture of the armature is given in figure 7.

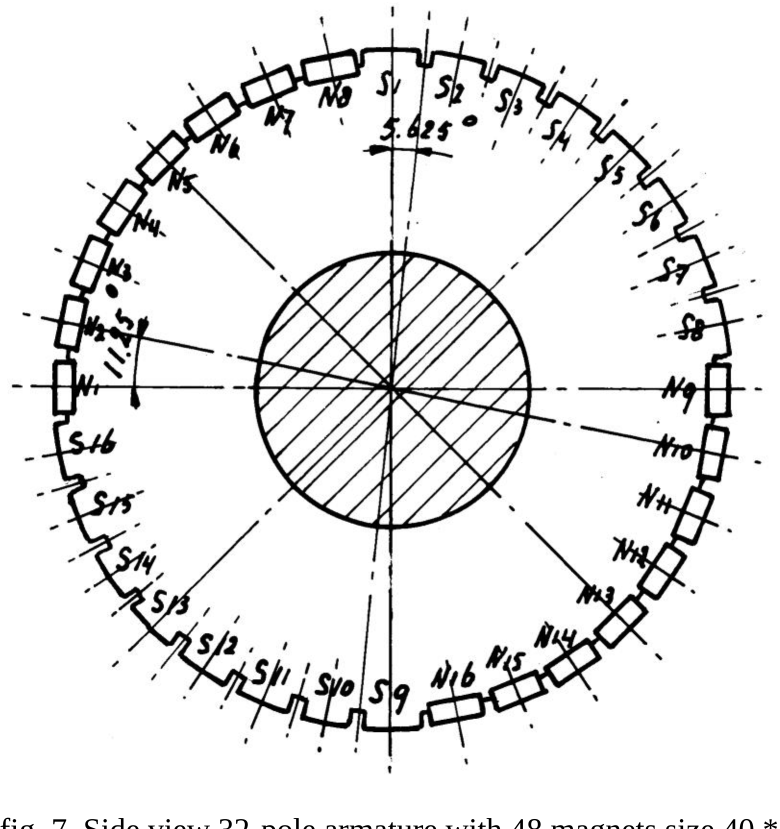


fig. 7 Side view 32-pole armature with 48 magnets size 40 * 7 * 3 mm

This generator has not yet been built and tested and I won’t do that. But it seems worthwhile to make one and test it with the original 230/400 V winding rectified in star for a 24 V or 48 V battery load and rectified in delta for a 12 V or 24 V battery load. If the voltage appears to be too high, it is possible to modify the original 230/400 V winding into a 115/200 V winding by connecting the first and the second layer in parallel instead of in series. This procedure is described in chapter 4. It is expected that this generator can be used in combination with the VIRYA-3B3 rotor.

The disadvantage of most multi pole armatures for generators as described in KD 718, is that the standard short-circuit armature can’t be used because it has aluminium short-circuit bars at the wrong positions. A 28-pole armature is described in chapter 10 of KD 718 for which the original short-circuit armature of a 4-pole motor with frame size 112 is used. The magnet grooves are made just in between the 28 aluminium short-circuit bars. Magnets are used for the north and for the south poles. The magnet size is 40 * 7 * 3 mm and totally 84 magnets are used. The total magnet costs are only about € 52.

11 Ideas about a big direct drive PM-generator for the VIRYA-6.5 and the VIRYA-12

The new report KD 777 (ref. 36) has as title: “Ideas about a big direct drive PM-generator for the VIRYA-6.5 windmill using the housing, winding and armature of a 6-pole asynchronous motor frame size 200 L”. So this generator makes use of the original short-circuit armature. The armature is turned to a diameter of 153 mm and a mild steel bush is glued to this armature. A magnetic north pole is formed by eight rows of magnets size 40 * 10 * 10 mm. There are seven magnets in each row. The total number of magnets is 8 * 7 * 3 = 168. A magnetic south pole is formed by eight rows of 10 mm wide rims. There are eight mechanical armature opposed to nine mechanical stator poles. This means that the generator has 8 * 9 * 6 = 432 preference positions per revolution. The peak of the cogging torque will be rather low for this many preference positions. The total magnet costs are about € 300 which is rather low for a PM-generator of this size.

A very big PM-generator using the housing, winding, shaft and armature of an 8-pole motor frame size 355, is described in chapter 8 and 9 of report KD 727 (ref. 37) for the VIRYA-12. This generator uses 572 magnets size 40 * 10 * 10 mm in between 84 aluminium short-circuit bars. So the magnet grooves of this generator are inclined and manufacture of these grooves are more difficult than for the generator as described in KD 777.

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