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 440 (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 an 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 lying 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.

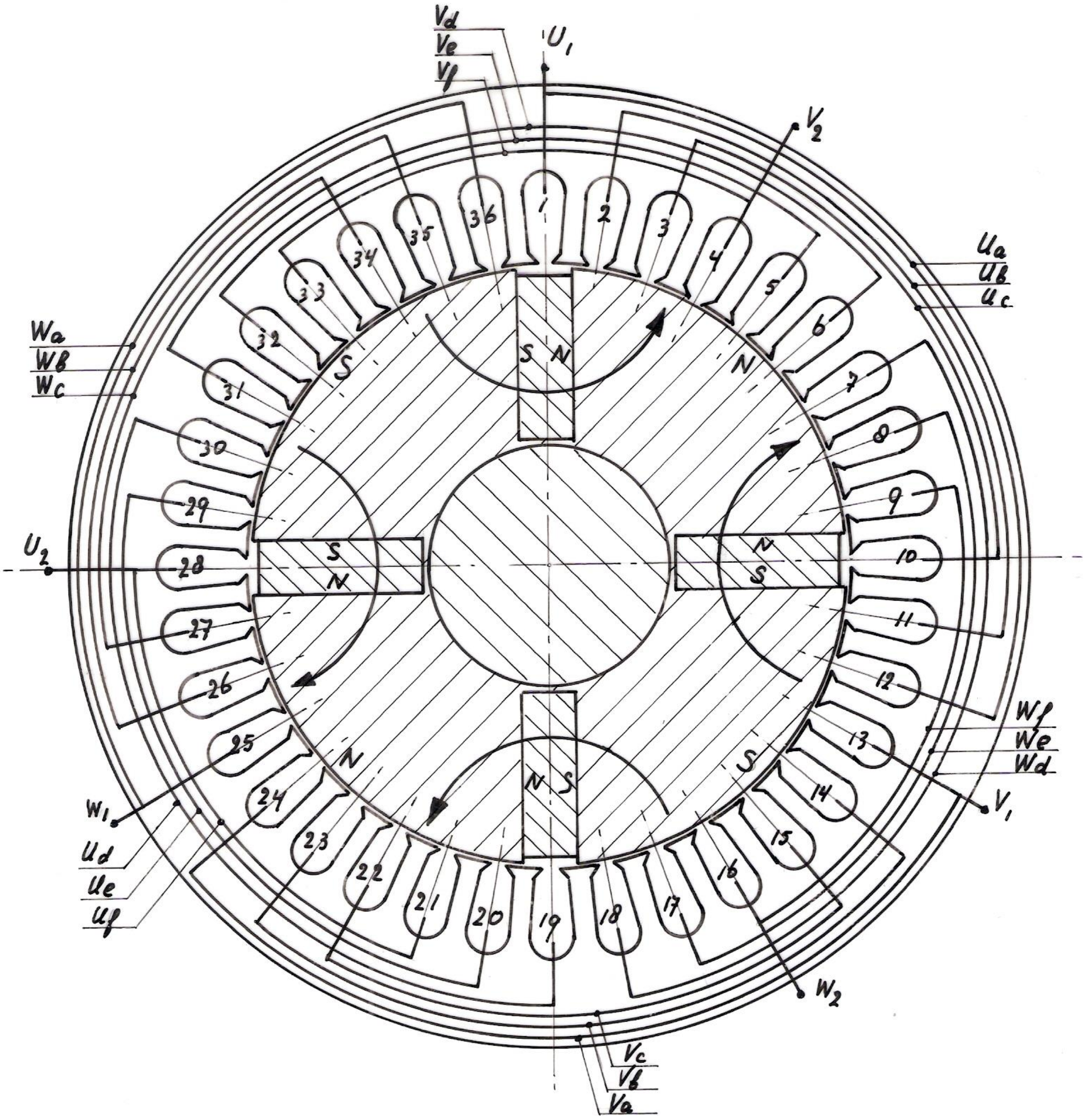

fig. 1 Cross section of a 4-pole armature at the hart of the armature. Side view of the stator.

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.

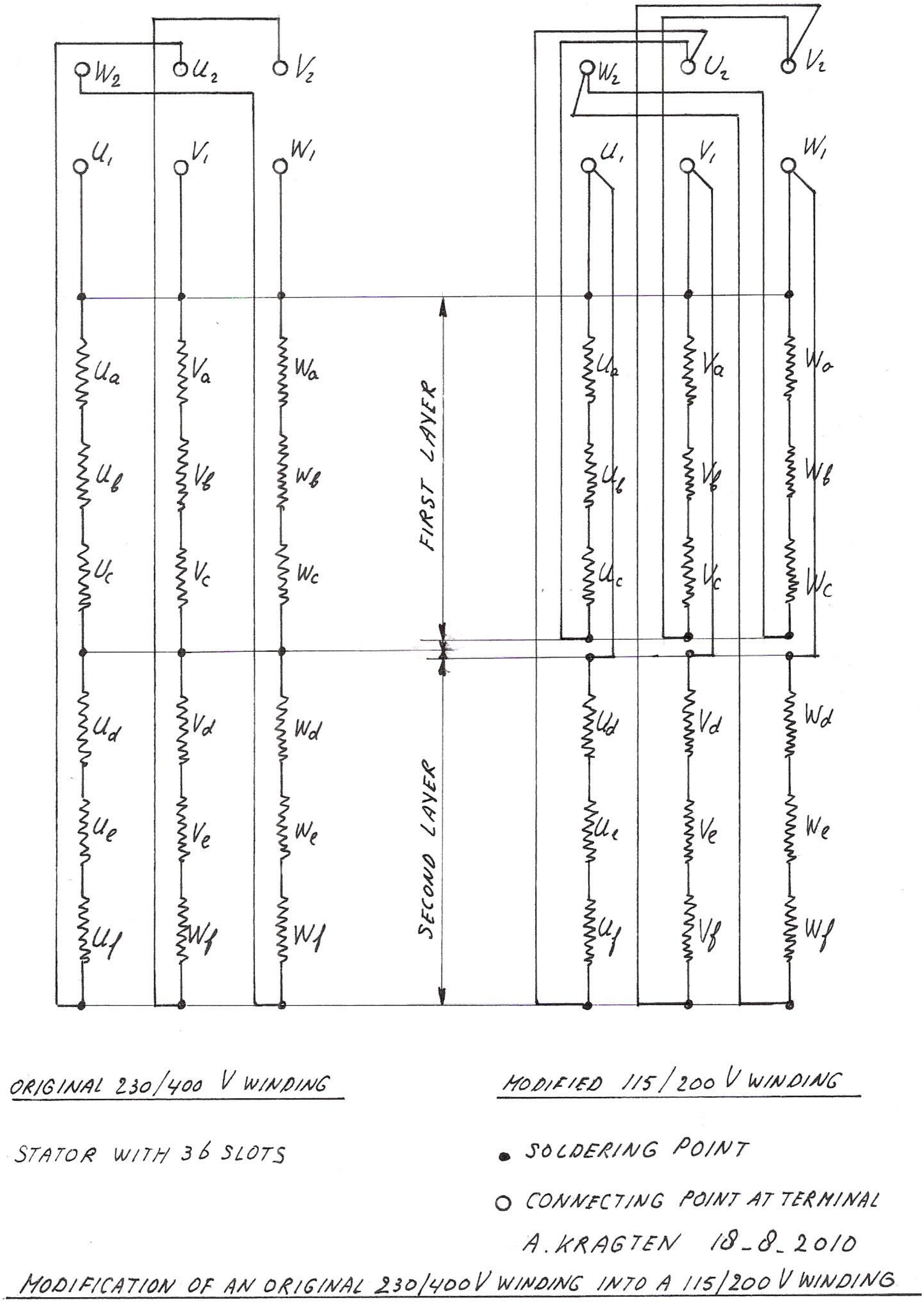

fig. 2 Wire diagrams for a 230/400 V winding and for a modified 115/200 V winding

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:

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

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 given in free public report KD 503 (ref. 5).
Warning: A PM-generator should never be connected to the grid because it will not rotate!

6 Recent developments

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. 6). Figure 1 out of this report is copied as figure 3. A prototype of this generator is being built at this moment by an Indian company.

The number of armature poles must be two less or two more than the number of stator poles. So for a stator with 24 poles it is possible to use the same principle for an armature with 22 or with 26 poles. A 22-pole generator is described in report KD 553 (ref. 7). This generator has been built and tested by me and it worked well. For a stator with 54 poles it is possible to use the same principle for an armature with 52 or with 56 poles.

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 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 5 mm thick magnets are used. These magnets are rather cheap.
7) The magnets 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.

Some KD-reports have been written with ideas about axial flux generators. The most recent reports are KD 571 (ref. 8) and KD 574 (ref. 9). Both generators have been tested for one coil and the test results are promising. The generator described in report KD 571 is meant for the VIRYA-1.36 windmill. This licence of this windmill is given free and the manual of the windmill including all drawings can be copied directly from my website. The generator described in report KD 574 is an alternative for the Nexus hub dynamo of the VIRYA-1.04 windmill for which the manual can also be copied for free from my website.

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. The windmill will still have a low starting wind speed for such rotor.

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.

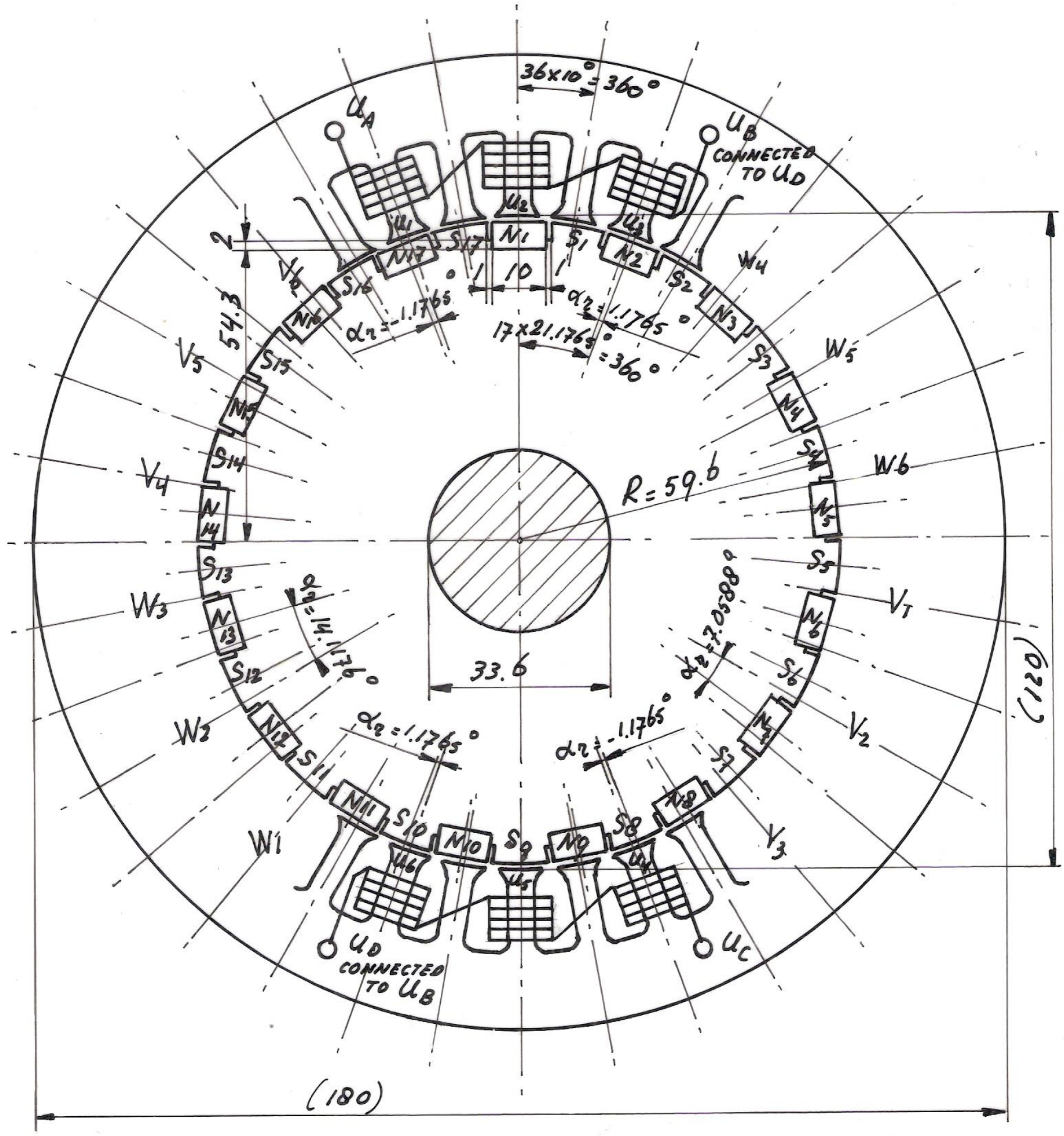

figure 3 34-pole armature and 36-pole stator for housing size 112F-6P, 180 * 120 * 33.5 mm

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.

The same principle of a 34-pole generator is described in report KD 580 (ref. 10) for a much smaller stator stamping of a 6-pole motor frame size 80 meant to be driven by a rotor with a diameter of about 1.5 m or by human power.

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