Ideas about a 24-pole permanent magnet generator with a stator with no iron in the coils for the alternative VIRYA-4.2 rotor for battery charging or for combination to the 1.1 kW, 3-phase asynchronous motor of a centrifugal pump

ing. A. Kragten

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Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

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1 Introduction

The normal VIRYA-4.2 windmill has a rotor with a design tip speed ratio λ_d = 8 and two wooden blades with a chord of 200 mm and a Gö 623 airfoil. An alternative rotor with a design tip speed ratio λ_d = 7.5 and two wooden blades with a chord of 240 mm and a Gö 711-10% airfoil is described in report KD 382 (ref. 1). Advantages of this alternative rotor are that the starting torque coefficient is higher, that the blades are stronger and stiffer, that less wood is wasted if a rough plank size 255 * 27 mm is used and that the Gö 711-10% airfoil is easier to manufacture than the Gö 623 airfoil because the Gö 711-10% airfoil has a lower side which is flat over 97.5 % of the chord. The Gö 711-10% airfoil is described in report KD 333 (ref. 2). The alternative rotor with λ_d = 7.5 will be used in this report KD 668.

The normal and the alternative VIRYA-4.2 rotor can be used in combination with a 4-pole PM-generator made of an asynchronous motor frame size 112 (with lengthened stator stamping). Measurements for this generator are given in report KD 200 (ref. 3). Recently, the idea of a 12-pole PM-generator with no iron in the coils is described in report KD 667 (ref. 4) for the VIRYA-3B3 rotor. This generator makes use if the housing of an asynchronous motor frame size 100. It has an armature with 24 neodymium magnets size 80 * 20 * 10 mm and it has a special stator with a 1-layer winding. The armature has twelve grooves and two magnets are glued in each groove. The advantage of using a stator with no iron in the coils is that the peak efficiency is very high because there are no iron losses and that the generator has no clogging torque. The only sticking torque is caused by the bearing friction and by the friction of the seal on the rotor shaft. So the starting wind speed for this generator will be very low.

The idea is to develop a 24-pole PM-generator for the alternative VIRYA-4.2 rotor using the same magnets. However, the armature has 24 grooves and only one magnet is glued in each groove. The armature diameter is twice the armature diameter of the 12-pole generator but the armature length is half. This means that the armature volume is doubled and so the maximum torque level and the maximum power at a certain rotational speed are doubled. This allows the much larger diameter of the alternative VIRYA-4.2 rotor.

As the magnet costs and the copper costs are about the same as for the 12-pole generator, the 24-pole generator is more economic. Another advantage of using 24 poles is that it is possible to use the windmill in combination with the 1.1 kW asynchronous motor of a centrifugal pump if the generator has a high voltage 3-phase winding. If the generator is provided with a low voltage 3-phase winding and a 3-phase rectifier, it can be used for battery charging. Rectification of a 3-phase current is described in report KD 340 (ref. 5).

2 Description of the 24-pole PM-generator

2.1 General

The 12-pole generator of the VIRYA-3B3 makes use of the housing of an asynchronous motor frame size 100. Using the housing of an asynchronous motor for the 24-pole generator, means that at least a housing of frame size 160 would be needed. However, such housing is much too long for an armature length of 80 mm. Therefore it is decided to not use the housing of an asynchronous motor. So all components of the generator have to be manufactured. How this can be done efficient depends very much on the quantity. For large quantities, the bearing covers and may be the synthetic stator can be cast. For a single prototype, the components are manufactured from massive bar or from pipe. The generator construction will be described for the prototype.

The original 4-pole PM-generator of the VIRYA-4.2 has a 35 mm shaft at the bearings. The shaft end is tapered and has a half cone angle of 5°. The length of the tapered part of the shaft is 55 mm. The shaft end has no key groove and the rotor hub is clamped to the shaft by one central bolt M16. It is decided that the 24-pole generator gets the same shaft end and so the original hub of the VIRYA-4.2 rotor can be used on this shaft end.

2.2 Description of the armature

The armature has 24 poles, so twelve north and twelve south poles. The armature is made of an 80 mm long welded mild steel steam pipe with an outside diameter 193.7 mm and a wall thickness of 6.3 mm. So the inside diameter is 181.1 mm. Two 5 mm thick steel disks with an outside diameter of 183 mm and a 43 mm central hole are welded at both sides in the pipe. The inside distance in between the disks is 60 mm. The shaft is made from 45 mm shaft steel and this diameter is maintained within the two disks. The disks are welded to the shaft. So the armature is hollow which reduces the weight substantially. The shaft is provided with two heavy sealed bearings size 35 * 80 * 21 mm code 6307-2RS1 and an extra oil seal at the shaft side. The bearing cover at the other side is closed.

Twenty-four, 20 mm wide and 1.85 mm deep grooves are milled in the bush at an angle of 15° in parallel to the shaft axis. The bottom of the groove is lying 95 mm from the shaft axis. One magnet size 80 * 20 * 10 mm is glued in each groove. Twelve magnets are positioned with the north pole to the outside and twelve magnets are positioned with the south pole to the outside. So for one armature, 24 magnets are needed. The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl . The current price of one magnet is € 6.69 including VAT, excluding transport if a minimum quantity of 30 magnets is ordered. So the magnet costs for one generator are about € 161 which is rather high but it seems acceptable if the generator has a high efficiency and a low sticking torque.

Twenty-four magnetic loops are coming out of the armature. The direction of the magnetic field for twelve loops is turning left hand and for the other twelve loops it is turning right hand. A cross section and a side view of the armature are given in figure 1. Three field lines are drawn for each magnetic loop. The path of the middle field line is also drawn in the magnets and in the armature.

The radius at the heart of the outer side of a magnet is 95 + 10 = 105 mm. It can be calculated that the radius at the corner of a magnet is 105.48 mm. If the air gap in between the corner of a magnet and the inside of the stator is chosen 1.02 mm, it means that the stator must have an inside diameter of 2 * (105.48 + 1.02) = 213 mm.

The magnets are glued in the grooves by epoxy glue or by anaerobe glue Threebond 1132. A special tool has to be developed to mount the magnets during gluing. First twenty-four magnets have to be piled together (with some isolator in between the magnets) to find out the direction of the magnetic field. An arrow is placed at both small 10 * 20 mm sides. The magnets must be positioned such that the direction of the arrows alternate for adjacent magnets. It is assumed that the arrow points in the direction of the north pole.

So first twelve north poles are made and the arrows of these magnets are pointing to the outside. Mounting of these twelve magnets will be rather easy as the distance in between the magnets is large. It is advised to use a clamp in which a magnet can be clamped at the 80 * 10 mm sides and which has a long handle which can be hold by both hands. The clamp must be designed such that it can also be used for the magnets of the south poles. Don’t try to hold a magnet simply in the hand during mounting because the magnets are very strong and the fingers will certainly be clamped somewhere!

Mounting of the twelve magnets of the south poles in between the twelve magnets of the north poles will be more difficult as a south pole has a tendency to be pulled against a north pole. One should wait to mount the twelve magnets of the south poles until the glue of the magnets of the twelve north poles is fully hardened. A wooden strip of the correct thickness is placed against both adjacent north poles. These wooden strips guide the magnet of a south pole in the direction of the groove. With the correct clamp, it should be easy to mount the twelve magnets of the south poles. I expect that the magnets are pulled in the grooves by the magnetic force once they are in the right position and that no clamps are needed to push the magnets inwards during hardening of the glue but this should be tested in practice.

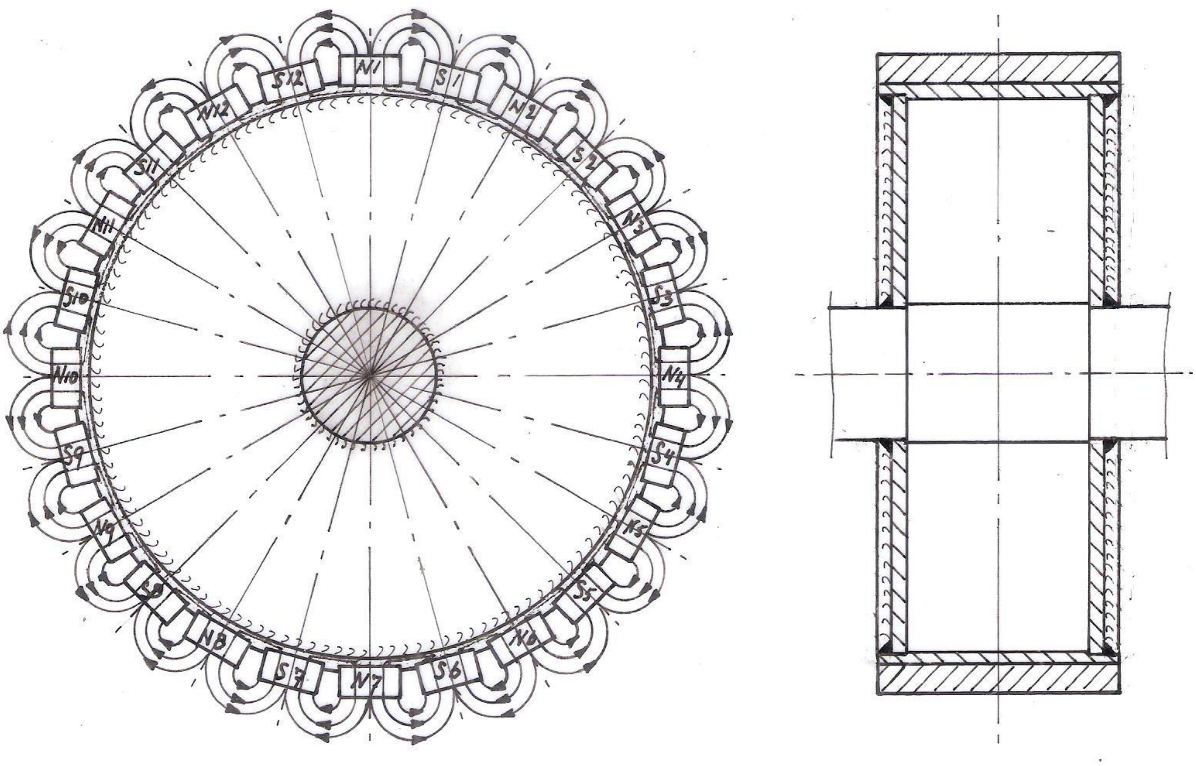

fig. 1 24-pole armature with twenty-four neodymium magnets size 80 * 20 * 10 mm.

2.3 Description of the stator and the housing

As no housing of an asynchronous motor is used for this 24-pole generator, the housing must be designed and built. The construction will be about the same as for the housing of an asynchronous motor so it will have two bearing covers separated by the stator. The bearing covers are made from 275 mm aluminium bar. The front bearing cover has a central hole through which the shaft points outwards. This cover is provided with an extra oil seal to prevent the entrance of water in the front bearing. The back bearing cover is closed. Both bearing covers are provided with six threaded holes M12. The back bearing cover of the generator is mounted against the head frame of the wind turbine by six bolts M12 and some locking liquid. So the generator has no foot like the asynchronous motor housing of the original generator and therefore the head frame has to be modified.

The two bearing covers are separated by a 126 mm long stainless steel bush made of standard pipe ϕ 254 * 2 mm, so the inside pipe diameter is 250 mm. If this pipe isn't available, it might be possible to make the bush from 2 mm stainless steel sheet which is rolled and welded. The bearing covers have a 3 mm deep groove at the inner side in which the bush just fit. Some silicone sealant is used to make the connection water tight. The two bearing covers are pulled against each other by six long stainless steel bolts M6 and six stainless steel self-locking nuts M6. The pitch circle of these bolts is 262 mm. This means that the distance in between a bolt and the stainless steel bush is 1 mm and that the bolt heads and the M6 nuts don't jut out of the bearing covers.

The stator coils are positioned in a bush made out of a synthetic material like Delrin which is glued or bolted in the stainless steel bush. The Delrin bush will have an outside diameter of 250 mm, an inside diameter of 213 mm and a length at the coils of 80 mm. So the thickness of the bush is (250 – 213) / 2 = 18.5 mm which is enough for large coils. For the prototype, this bush is made from massive rod but for serial manufacture it might be possible to order Delrin pipe with an outside diameter of 250 mm and an inside diameter of 213 mm. It may also be possible to make the bush with a 3D-printer.

Normal iron stator stampings have slots at the inside because all stator spokes must be connected at the outside to guide the magnetic flux from a north pole to a south pole. The stator coils are mounted from the inside. This is a rather tricky procedure and slot strips are required to prevent that the coils come out of the grooves and touch the rotating armature. All coil heads are bound together with rope, also to prevent that they touch the armature when the armature is mounted in the housing.

The new synthetic stator of this 24-pole generator contains no iron and therefore it isn't necessary that the spokes are connected to each other at the outside. So it is possible to make the slots from the outside and to mount the coils also from the outside which is much easier. A 1-layer winding is chosen for this 24-pole PM-generator.

For a 3-phase winding of a 24-pole generator, 18 coils are needed, so six coils for each phase. Every coil needs two grooves, so 36 grooves are needed. The pitch angle in between the poles of a 24-pole generator is 15°. The optimum pitch angle in between the heart of two legs of a stator pole is also 15° because, if a north pole is passing the left arm of a coil, a south pole is just passing the right arm. So the voltages generated in both arms of a coil are just in phase to each other and this gives the maximum total voltage.

The three phases are called U, V and W. The sequence of the coils for a 3-phase winding is: U1, V1, W1, U2, V2, W2, U3, V3, W3, U4, V4, W4, U5, V5, W5, U6, V6 and W6. The pitch angle in between the grooves of adjacent phases is 5° which is rather small. For a certain groove width, both grooves will touch each other. Therefore it is decided to use one 20 mm wide and 17 mm deep groove for two adjacent coils and to make eighteen grooves every 20°. So the left leg of one coil and the right leg of its neighbour are laid in the same groove.

Assume that the generator is coupled to the asynchronous motor of a centrifugal pump. So a high voltage winding is needed. All six coils of one phase have the same winding direction and are connected in series. Six coils are made together on a winding thorn, so there are no soldering points in between the coils of one phase. Each bundle of six coils has a beginning end called A and an ending end called B. The totally six coil ends of the three phases are guided to an outside terminal block. The coil ends U_A, V_A and W_A are connected to each other and are forming the star point. The coil ends U_B, V_B and W_B have each their own terminal.

Assume that the generator is used for 24 V or 48 V battery charging. So now a low voltage winding is needed. This requires a winding with much less turns per coil and a much thicker wire. The 3-phase rectifier and the short-circuit switch are positioned at the foot of the tower. A flexible cable with four wires connects the terminal block to the rectifier and the short-circuit switch. The advantage of an external star point is that this star point can also be short-circuited and this gives a larger breaking torque than for only short-circuit of points U_B, V_B and W_B.

It might be possible to use the high voltage winding for 24 V or 48 V battery charging if a DC-DC converter is mounted in between the rectifier and the batteries. However, in this case the short-circuit switch has to be mounted at the tower foot and the rectifier has to be mounted near the batteries. The advantage of using a high voltage is that the cable losses are low even if the wind turbine is positioned at a large distance from the batteries.

It is chosen that a coil bundle has a square cross section with 9.5 mm sides so there is a lot of copper in each coil. There is a gap of 1 mm in between the legs of adjacent coils. This gap is filled with a 1 mm thick, 9.5 mm wide and 120 mm long synthetic strip to prevent short-circuit in between the phases.

It must be prevented that the coils can come out of the grooves and touch the stainless steel bush. Therefore a 2 mm wide and 2 mm deep slot is made at each side of the 20 mm wide groove and a synthetic strip size 24 * 2 * 120 mm is shifted in each slot. As this strip has a length of 120 mm, it also prevents that the coil heads may touch the stainless steel bush. It must also be prevented that the coil heads may touch the armature when it is mounted and a 2 mm thick and 20 mm wide rim is therefore made at both sides of the Delrin stator. This rim also prevents that the wires, which connect the six coils of one phase, may contact the armature.

The main magnetic flux outside the armature will flow in the space in between the armature and the stainless steel bush because the distance in between the armature and the stainless steel bush is rather large (about 20 mm). However, a little part of the magnetic flux will flow through the stainless steel bush and this flux will cause small eddy currents in the stainless steel. It is expected that the torque and the temperature rise because of these eddy currents can be neglected. A front view and a cross section of the housing and the stator with the 1-layer winding is given in figure 2.

It might be difficult to find a heat resistant glue with which the Delrin bush can be glued in the stainless steel bush. Pressing of the Delrin bush in the housing, as it is done for a normal iron stator, isn’t possible because this will cause too much pressure in the 1.5 mm thick bridges at the bottom of the grooves. It seems possible to connect the bush with twelve stainless steel screws M8 * 20. This option requires drilling of twelve holes at 60° in the stainless steel bush. The stainless steel bush must be positioned such that there is an angle of 30° in between the twelve bolts M8 and the six bolts M6 which pull the bearing covers to each other.

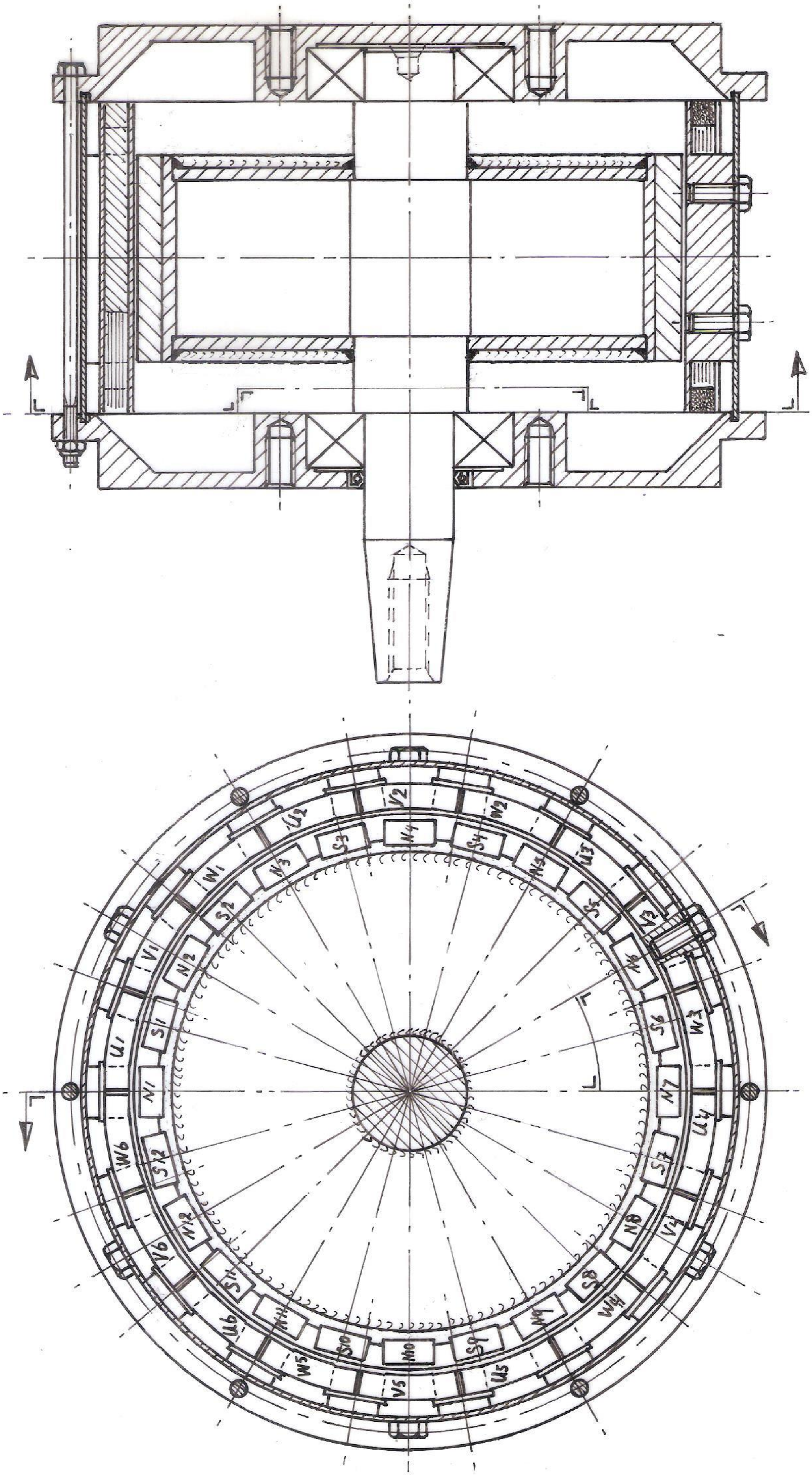

fig. 2 24-pole, 3-phase stator with a 1-layer winding with six coils per phase

3 Determination of the flux density in the air gap

In figure 1, three field lines are drawn for each magnetic loop outside the armature. A part of a magnetic loop is flowing outside the armature and a part is flowing inside the armature. The middle field line is also drawn in the magnets and in the armature. It can be seen that the length of the middle outer loop through air is much longer than the length of the inner loop through iron. The length of the middle loop is about average. The length of the part of the middle loop outside the armature is called t_2. It is assumed that the length of the middle loop is representative for the magnetic resistance of all field lines of the outside part of the whole loop. It is assumed that this part of the loop is about a part of a circle. It is calculated that t_2 is about 30 mm for the given armature geometry.

There is a strong analogy in between the magnetic resistance of a magnetic flux and the Ohmic resistance of a DC current. The total magnetic resistance of a complete magnetic loop depends on the magnetic resistance of the part of the loop where it flows in the air gap, of the part of the loop where it flows in the magnet and of the part of the loop where it flows in the iron of the armature. The magnetic resistance of iron is very low and as the iron of the armature is not saturated, the magnetic resistance of the iron part of the loop can be neglected.

The chosen magnets have quality N35H. The remanence B_r in a neodymium magnet with quality N35H is about 1.19 T if the magnet is short-circuited with a mild steel arc which isn't saturated. However, an air gap in the arc reduces the magnetic flux because it has a certain magnetic resistance. The resistance to a magnetic flux for the magnet itself is about the same as for air. The magnet thickness is called t_1 and it was chosen that t_1 = 10 mm.

As the magnetic resistance of the iron can be neglected, the total magnetic resistance is only caused by the two magnets and by the air gap. The thickness of the air gap is called t_2. The air gap results in an increase of the magnetic resistance by a factor $2 * t_1 + t_2 / 2 * t_1$.
This results in decrease of the remanence B_r to, what I call, the effective remanence $B_{r\ eff}$ or the flux density in the air gap. $B_{r\ eff}$ in Tesla (T) is given by:

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

Substitution of B_r = 1.19 T, t_1 = 10 mm and t_2 = 30 mm in formula 1 results in $B_{r\ eff}$ = 0.48 T which is rather low. It has to be checked if the armature isn't saturated. Half the magnetic flux coming out of the bottom on a magnet flows through the armature to half of the neighbouring magnet. The thickness of the armature is about 5 mm at the edge of the magnet which means that the magnetic flux is concentrated by a factor 10 / 5 = 2. So the flux density in the armature becomes 2 * 0.48 = 0.96 T. Normal iron is saturated at about 1.6 T so the stator is far from saturation.

For the normal VIRYA generators, the iron of the stator is saturated and this means that the flux density in the air gap is about 0.9 T. So the flux density which can be realised in the coils of an iron free stator is about a factor 0.48 / 0.9 = 0.53 of the flux density of a PM-generator which has a mild steel stator stamping. However, armature volume of this 24-pole generator is a factor 2.06 larger than that of the original 4-pole generator and the stator has no iron losses and has coils which contain a lot of copper and only small coil heads. The final result may be that about the same maximum torque level and so the same maximum power can be realised at a certain rotational speed. As the efficiency is higher, the maximum electrical power may be higher than for the original 4-pole generator. This has to be verified by building and testing of a prototype but I have no intention to do so.

4 Determination of the number of turns per coils for 48 V battery charging

The required number of turns per coil and the maximum allowable wire thickness can be determined by try and error. First one makes a certain choice, assume 100 turns per coil and one makes a prototype of the stator with the largest wire thickness possible in the available space of the Delrin bush. The winding is rectified in star by a 3-phase rectifier. Rectification of a 3-phase current is described in report KD 340 (ref. 5).

Next the generator is placed on a test rig with which it is possible to measure the torque, the rotational speed, the voltage and the current. I have used a test rig of the University of Technology Eindhoven for measuring my normal VIRYA generators. Next a series of measurements is executed for a range of voltages for instance 16, 24, 32, 40, 48, 56 and 64 V. For every voltage, the P_{mech}-n and P_{el}-n curves are determined.

Next the P-n curves of the rotor are determined for different wind speeds. The P-n curves for the alternative VIRYA-4.2 rotor are given in figure 3 (see chapter 5). The optimum cubic line is also drawn in figure 3. All measured P_{mech}-n curves are also drawn in this graph. One curve will have the best matching. This means that it has two points of intersection with the optimum cubic line, which are lying not very far apart.

Assume that the best matching is realised for the P_{mech}-n curve which belongs to V = 40 V. Assume that the generator is used for 48 V battery charging. This means that the average charging voltage is about 52 V. So the voltage of the test winding is a factor 40 / 52 = 0.769 too low. So the number of turns per coil has to be increased by a factor 26 / 20 = 1.3 and so it must be 1.3 * 100 = 130. The wire thickness must be reduced by a factor √ (1 / 1.3) = 0.877 to get the same amount of copper. The modified winding will have the same P_{mech}-n and P_{el}-n curves for 52 V, as the curves of the test winding for 40 V. This is the best method but one has to make a test winding and a final winding which is a lot of work.

5 Determination of the number of turns per coil for water pumping

For water pumping, it is assumed that the three phases of the generator are coupled to the three phases of the 1.1 kW asynchronous motor of a centrifugal pump. The pump motor of such a pump is designed to function at a grid frequency of 50 Hz and at an AC phase voltage of 230 V. Frequency and voltage of a normal grid are hold very stable but will vary very much for the 24-pole generator driven by a wind turbine. But at least one has to make that the loaded AC voltage at a frequency of 50 Hz is about 230 V.

A 24-pole PM-generator gives a frequency of 50 Hz at a rotational speed of 250 rpm. The voltage decreases as the load increases so the open AC phase voltage at n = 250 rpm must be a lot higher than 230 V. I assume that an open AC phase voltage of 280 V is a good first choice. The AC phase voltage is the AC voltage measured in between the star point of the winding and one of the phases. The AC voltage in between two different phases is a factor √3 higher.

To find the correct number of turns per coil it isn't necessary to make a full test winding. It is enough to make only one coil of one phase. Assume one makes a test coil with 100 turns per coil and one choses a wire thickness for which the available space in the Delrin bush is just completely filled with copper. Next one measures the open AC voltage of this coil at n = 250 rpm. Assume one measures an open AC voltage of 30 V. So the open AC voltage of six of these coils connected is series would be 6 * 30 = 180 V. So this is a factor 180 / 280 = 0.643 too low. This means that the number of turns per coil has to be increased by a factor 280 / 180 = 1.556 and so it must be 1.556 * 100 = 156. The wire thickness has to be reduced by a factor √ 0.643 = 0.802 to get the same amount of copper in a groove. Next a complete 3-phase winding has to be made with 156 turns per coil and the maximum possible wire thickness. Next the generator has to be connected to a 1.1 kW, 3-phase motor. It is assumed that the pump motor is not loaded to its nominal power of 1100 W but to about 80 % of its nominal power. So the motor should supply a mechanical power of about 880 W.

Next it is measured if the loaded phase voltage is about 230 V. If this is the case, the winding is correct. If one measures an AC voltage of for instance 249 V, it means that the number of turns per coil has to be reduced by a factor 230 / 249 = 0.924 and so it must be 0.924 * 156 = 144. The wire thickness has to be increased by a factor √ (249 / 230) = 1.04 to get the same amount of copper in a groove. So finding of the optimum winding is a rather complex procedure.

6 Description of the functioning of the VIRYA-4.2 for water pumping

The P-n curves and the optimum cubic line of the alternative VIRYA-4.2 rotor for different wind speeds are determined in chapter 5 of KD 382 (ref. 1) and are given in figure 4 of KD 382. This figure is copied as figure 3 but the P_{mech}-n and P_{el}-n curves of the original 4-pole generator for 52 V star are removed. It is assumed that the P-n curve for short-circuit in delta is about the same as for the original 4-pole generator so this curve is maintained.

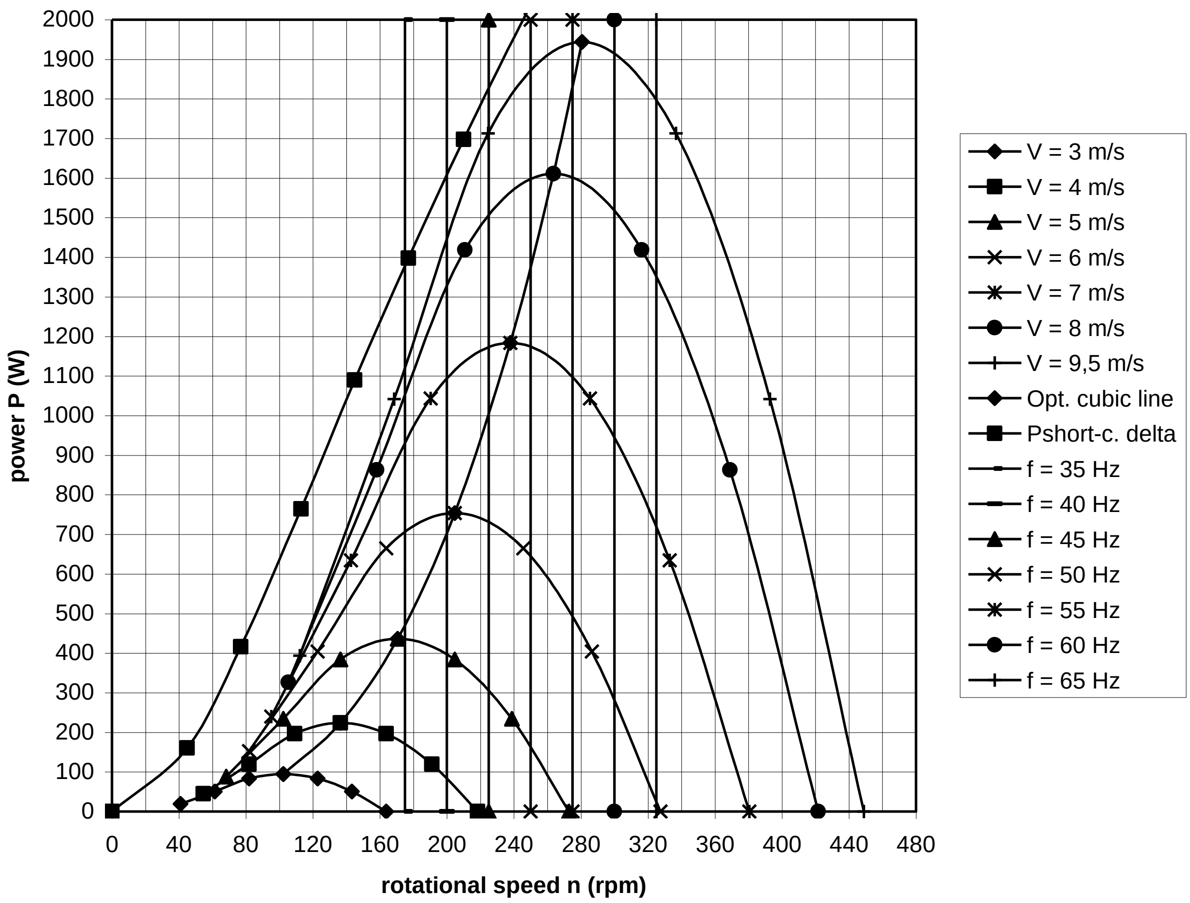

fig. 3 P-n curves alternative VIRYA-4.2 rotor, optimum cubic line, lines for constant frequencies of 35, 40, 45, 50, 55, 60 and 65 Hz.

The 24-pole generator has not yet been built and measured, so measured characteristics are not available. However, it is possible to derive the lines for which the frequency has a certain value. A 2-pole PM-generator has a frequency of 50 Hz for a rotational speed of 3000 rpm. So a 24-pole generator has a frequency of 50 Hz for a rotational speed of 3000 * 2 / 24 = 250 rpm. As the frequency is proportional to the rotational speed, the rotational speeds for other frequencies can be determined easily. It is found that:

n = 175 rpm for f = 35 Hz.
n = 200 rpm for f = 40 Hz.
n = 225 rpm for f = 45 Hz.
n = 250 rpm for f = 50 Hz.
n = 275 rpm for f = 55 Hz.
n = 300 rpm for f = 60 Hz.
n = 325 rpm for f = 65 Hz.

The lines for constant frequencies of 35, 40, 45, 50, 55, 60 and 65 Hz are also given in figure 3. In figure 3 it can be seen that the line for f = 50 Hz is intersecting with the optimum cubic line at a power of about 1380 W. The available electrical power will be lower because of the generator efficiency. Assume the generator efficiency is 0.85, so the electrical power is about 1173 W. This power is generated at a wind speed of about 7.5 m/s. The wind speed for which the line for 50 Hz is intersecting with the optimum cubic line is called the design wind speed V_d. So V_d = 7.5 m/s.

A centrifugal pump with a 1.1 kW pump motor used at a factor 0.8 of its nominal power and with a motor efficiency of 0.75 will absorb an electrical power of about 1170 W, so a 1.1 kW pump motor seems an acceptable choice. The working point will lie about on the optimum cubic line for a pump with a 1.1 kW motor used at a factor 0.8 of its nominal power.

In figure 4 it can be seen that the maximum power at a wind speed of 9.5 m/s is 1940 W if the optimum cubic line is followed. The frequency is about 56 Hz. The load characteristic of a centrifugal pump is about a cubic line which means that the optimum cubic line of the windmill will be followed upwards from the design point if the design point is lying on the optimum cubic line. I expect that a maximum frequency of 56 Hz is allowed for the pump and for the pump motor but this must be verified in practice.

Below a frequency of about 35 Hz, belonging to a rotational speed of 175 rpm, the pump is no longer able to produce the static water height, so no water will be pumped. Probably it is necessary to disconnect the generator and the pump motor by a 3-phase switch below a frequency of about 35 Hz. This makes that the rotor will always start unloaded at low wind speeds. If the connection is broken at f = 35 Hz for a running rotor, this results in acceleration of the rotor. The connection can be made at a frequency of 55 Hz belonging to a rotational speed of 275 rpm. This frequency will be reached for an unloaded rotor for a wind speed of about 5.1 m/s. So the pump will start pumping at this wind speed but it will stop only if the frequency becomes lower than 35 Hz. This means that even at low wind speeds there will be some intermittent output.

If the pump is a centrifugal pump, the system will probably also work if there is no 3-phase switch which disconnects the generator and the pump motor but in this case water is not pumped intermittently if the wind speed is just above 5.1 m/s. A switch will certainly be needed for a positive displacement pump as such pump demands a torque directly from stand still position.

The generator winding must be chosen such that the loaded voltage is 230 V at a frequency of 50 Hz. This means that the unloaded voltage at 50 Hz must be a lot higher (see chapter 5). I expect about 280 V but this must be tested for a prototype of the generator.

7 Use of the generator as synchronous motor

There is a strong trend to generate electricity by renewable energy and to electrify transport. So electric cars, scooters and boats are developed. These means of transport all store energy in batteries and have an electric motor. Sometimes permanent magnet DC-motors are used but these motors mostly have brushes which wear and give a certain friction torque. It is possible to use a 3-phase PM-motor if there is a 3-phase inverter with variable frequency in between the battery and the motor. These kind of inverters have already been developed and have a very high efficiency.

It might be possible to use the described 24-pole PM-generator as synchronous 24-pole PM-motor in combination with an electric car or an electric boat. As the generator has no iron in the coils it has no clogging torque and the efficiency will be very high, even at low power.

The motor has a high maximum torque level and therefore it might be possible to use it direct drive on both back wheels of a small car. The efficiency loss in a gear box is prevented this way. The motor has a very strong 35 mm tapered shaft and it might even be possible to connect a wheel directly to the generator shaft in the same way as the wind turbine rotor is mounted. As six threaded holes M12 are made in both bearing covers, it is possible to mount an U-shaped bracket very sturdy to the generator using twelve bolts M12. The bracket then can be mounted very sturdy to the car frame.

The motor has a hollow armature and aluminium bearing covers and is therefore rather light for its armature volume. So the moving mass of the wheel and the motor is limited. If the inverter can also work as 3-phase rectifier, it is possible to use the motor as generator and so to use it as a brake and send the brake energy back to the batteries.

8 Alternative stator with 18 separate coils

The construction of the stator as given in figure 2 requires a piece of large diameter stainless steel pipe and a piece of a large diameter Delrin bar. It might be that only a standard length can be bought and manufacture of a prototype will then be very expensive. To prove that the principle works it seems possible to make an alternative stator with 18 separate coils. The two bearing covers are the provided with a regular 18-angle with a width of the sides of 212 mm. A threaded hole M10 is made in the heart of each plane. A coil is bolted to each bearing cover by two stainless steel bolts M10 * 30 and two stainless steel washers to reduce the pressure in between the bolt head and the Delrin.

The coil heads have to be made as small as possible and the bearing covers therefore have to be mounted as close as possible to each other. But to prevent eddy currents in the aluminium because of the magnetic flux coming out of the 10 * 20 mm sides of the magnets, it is chosen that there is a gap of 5 mm in between the armature and a bearing cover. So the inside distance in between the bearing covers is 90 mm at the outside and at the bearings.

The core is made from 12 mm Delrin sheet. A coil core has an oval shape. It has a thickness of 12 mm, a width of 36 mm and a length of 144 mm. A groove with a depth of 9 mm and a width of 9 mm is made all around. So the core has 1.5 mm thick flanges. A 10 mm hole is made in the heart of each half circle of the oval. The pitch in between the holes is 108 mm, so the heart of a threaded hole M10 is lying at 9 mm from the inside of a bearing cover.

If the generator supplies a torque, a certain force will work on the wire of a coil. So it must be prevented that the straight part of a wire can move tangentially out of the groove. This can be prevented by using some epoxy after each layer of the winding and so make that the wires become one with the Delrin core. It might also be possible to press a strip with a 20° key angle in between the flanges of two adjacent cores.

The radius of the armature at the corner of a magnet is 105.48 mm so the diameter at the corners is 210.96 mm. The distance in between two opposite cores is 212 mm so the minimum gap in between a magnet and a core is (212 – 210.96) /2 = 0.52 mm. A picture of the core is given in figure 3.

The six coils of one phase are connected in series for the high voltage winding for connection to the asynchronous motor of a centrifugal pump. For separate coils, it is possible to connect certain coils in parallel. So the open voltage at a certain rotational speed is reduced by a factor 2 if two coil bundles of three coils are connected in parallel, is reduced by a factor 3 if three coil bundles of two coils are connected in parallel and is reduced by a factor six if all six coils are connected in parallel.

This alternative stator isn’t water tight by itself but it can be made water tight by putting silicone sealant in between the coil cores and around the coil heads.

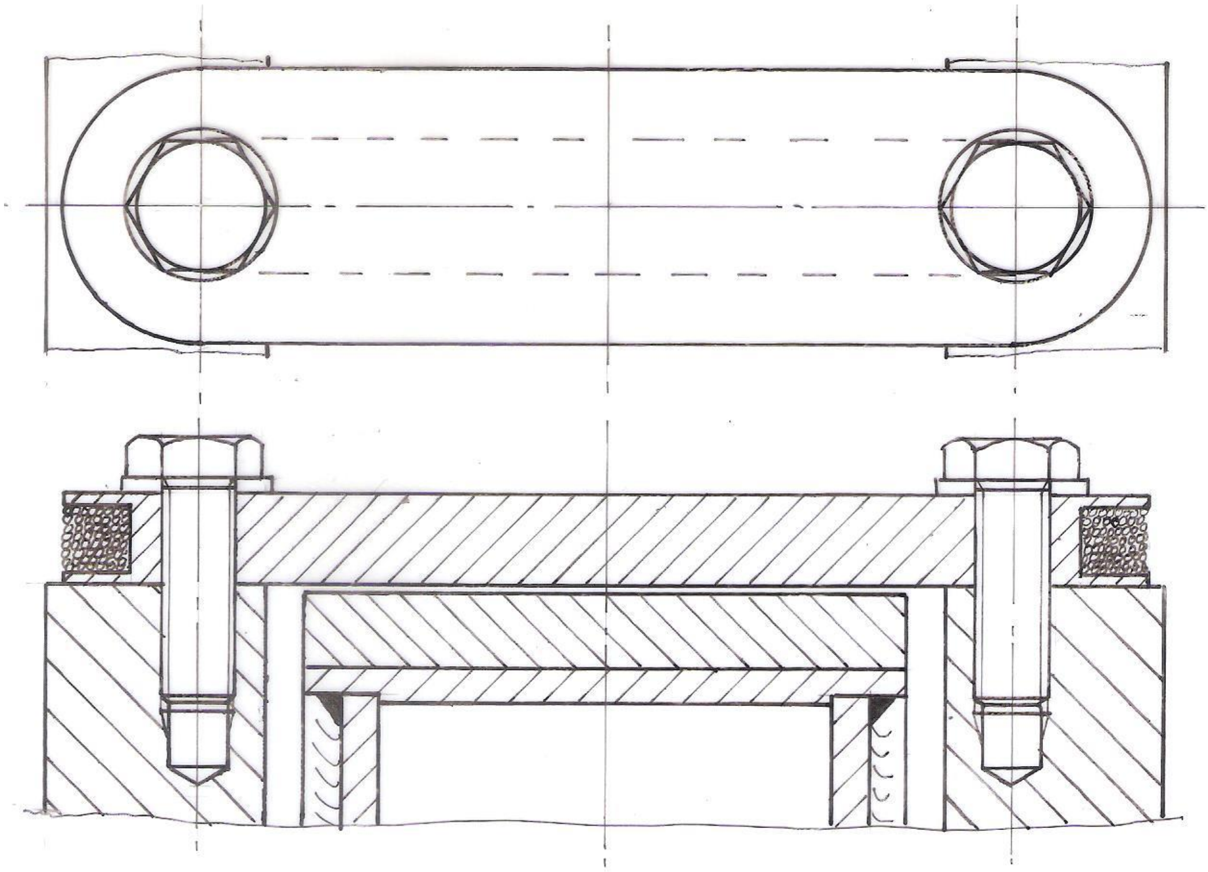

fig. 3 Alternative stator with 18 separate coils

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