Ideas about a 12-pole permanent magnet generator using a motor housing frame size 100 and a stator with no iron in the coils for use in combination with the VIRYA-3B3 rotor

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November 2018

KD 667

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1 Introduction

The VIRYA-3B3 rotor is described in report KD 484 (ref. 1). It has three wooden blades which are coupled to each other by a stainless steel hub plate. The design tip speed ratio is 6.5. The VIRYA-3B3 is an alternative 3-bladed rotor for the 2-bladed VIRYA-3 rotor which has a design tip speed ratio of 7. Both rotors are used in combination with the same generator, head and tower. A photo of the drawing of the VIRYA-3B3 rotor is given in appendix 2 of KD 484.

A new type 8-pole radial flux PM-generator with no iron in the coils is described in report KD 644 (ref. 2) for the 2-bladed VIRYA-1.8W rotor. This generator makes use of eight neodymium magnets size 80 * 20 * 10 mm and it has a special stator with a 2-layers or a 1-layer winding. 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. This low sticking torque results in a good starting behaviour.

The idea is to design a bigger 12-pole generator for the VIRYA-3B3 rotor, using the same magnets size 80 * 20 *10 mm and a 1-layer winding. It is expected that the bearing friction of this generator is about 0.3 Nm. It can be calculated that the starting wind speed is about 2.3 m/s for this bearing friction if the generator is used in combination with the VIRYA-3B3 rotor. This allows the use of this wind turbine in regions with low wind speeds.

2 Description of the 12-pole PM-generator

2.1 General

The 8-pole generator of the VIRYA-1.8W makes use of the housing of an asynchronous motor frame size 71. Using the housing of an asynchronous motor for the 12-pole generator, means that a housing of frame size 100 is needed. The original VIRYA-3B3 generator uses a housing of a 4-pole motor frame size 90 but with a lengthened stator stamping. This generator has a 25 mm tapered shaft end. Measurements for the original VIRYA-3B3 generator are given in report KD 78 (ref. 3). It is expected that the original shaft from the frame size 100 motor can be used. This shaft has a diameter of 28 mm and a key groove. So the original hub of the VIRYA-3B3 rotor has to be modified to fit on the 28 mm shaft.

It is assumed that a motor housing is used in which stator stampings of Kienle and Spiess are used. These stator stampings all have an outside diameter of 150 mm for frame size 100. The inside diameter depends on the pole number and is 80 mm for 2-pole motors, 90 mm for 4-pole motors and 103 mm for 6-pole motors (8-pole motors are not taken into consideration). The length of the stator stamping depends on the power. It is 90 mm for a 3 kW, 2-pole motor, 90 mm for a 2.2 kW, 4-pole motor, 120 mm for a 3 kW, 4-pole motor and 120 mm for a 1.5 kW, 6-pole motor.

The length of the stamping part of the original motor armature is the same as the stator length. However, the real armature is much longer because of the aluminium short-circuit ring and the aluminium cooling fins. The total length is 47 mm longer than the length of the stamping part. So the maximum armature length is 120 + 47 = 167 mm. The diameter of the armature is 0.5 mm smaller than the inside diameter of the stator if the air gap is 0.25 mm.

2.2 Description of the armature

The flux density which can be realised for a stator without iron in the coils is much lower that for a stator with an iron stamping. To get a sufficient high maximum torque level, the armature volume must therefore be chosen as large as possible. Suppose the armature length is chosen 160 mm. This means that two 80 mm long magnets can be laid in one groove. The armature must have a diameter of about 90 mm for a 12-pole armature.

If a massive bush with a length of 160 mm and a diameter of 90 mm would be chosen, the armature would become rather heavy. Assume that one uses the armature of a 2-pole motor which has a length of the stamping part of 90 mm and a diameter of 79.5 mm. Assume one uses a piece of seamless mild steel pipe with an outside diameter of 90 mm, a length of 160 mm and a wall thickness of 6 mm. So the inside diameter of this pipe is 78 mm. Assume that the outside of the armature is turned to a diameter of 77.9 mm and that the steel bush is glued on the armature such that the bush juts out 35 mm at each side of the stamping part. If seamless pipe size 90 * 6 mm isn't available it might also be possible to use 3" welded steam pipe which has an outside diameter of 88.9 mm and a wall thickness of 4.85 mm. So the nominal inside diameter of this pipe is 79.2 mm. However this pipe may have a weld at the inside and the inside of welded pipe isn't round and smooth enough to glue it on the armature. So the inside of this pipe is turned to a diameter of 79.6 mm. But for the description of the armature it is assumed that seamless pipe size 90 * 6 mm is available.

The armature has twelve poles, so six north and six south poles. Twelve 20 mm wide and 2 mm deep grooves are milled in the pipe at an angle of 30° in parallel to the shaft axis. The bottom of the groove lies 43 mm from the shaft axis. Two magnets size 80 * 20 * 10 mm are 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 € 160 including VAT which is rather high but it seems acceptable if the generator has a high efficiency and a low sticking torque.

Twelve magnetic loops are coming out of the armature. The direction of the magnetic field for six loops is turning left hand and for the other six 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 armature.

The radius at the heart of the outer side of a magnet is 43 + 10 = 53 mm. It can be calculated that the radius at the corner of a magnet is 53.94 mm. If the air gap in between the corner of a magnet and the inside of the stator is chosen 1.06 mm, it means that the stator must have an inside diameter of 2 * (53.94 + 1.06) = 110 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 24 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 six 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 six south poles in between the twelve magnets of the six 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 twelve magnets of the 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.

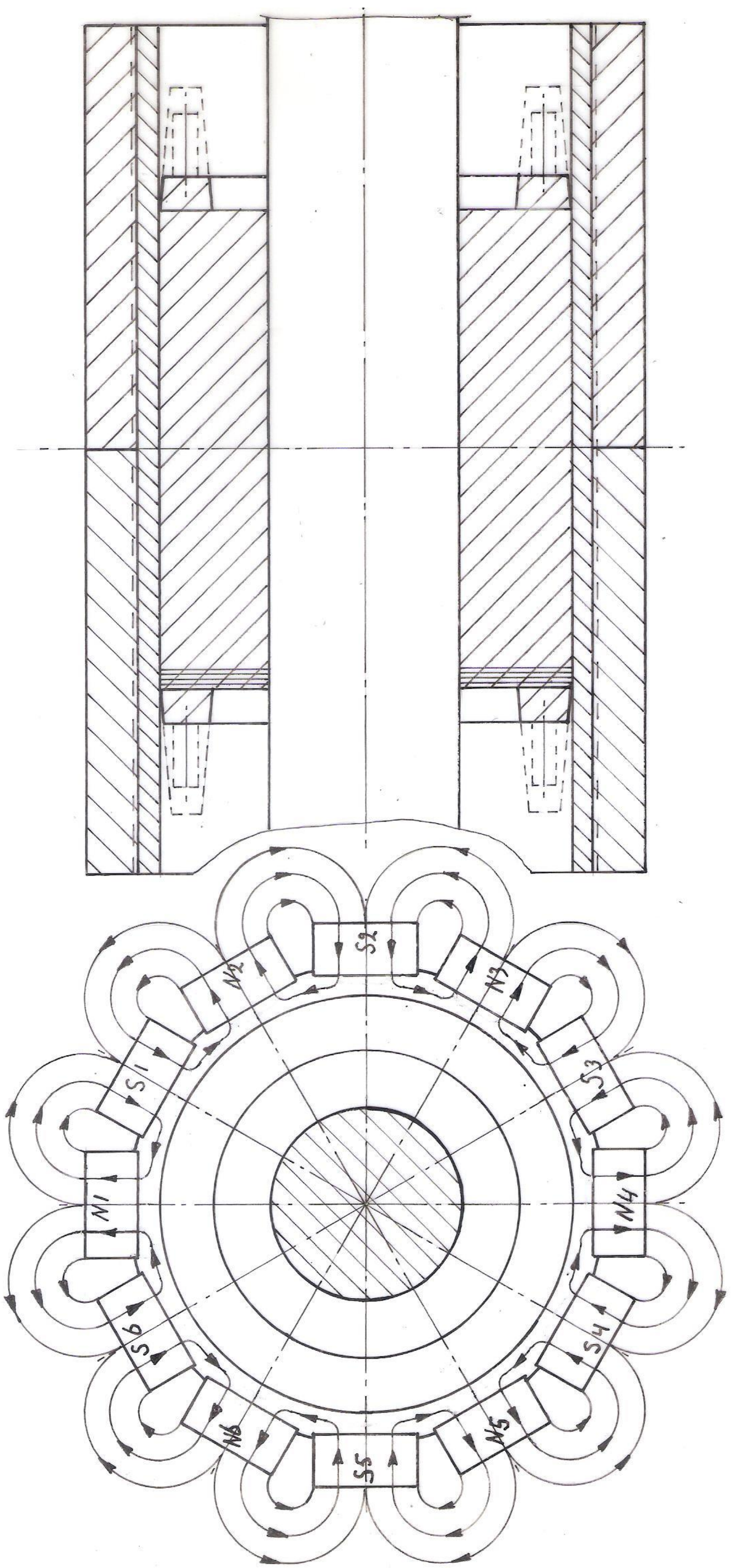

fig. 1 12-pole armature with 24 neodymium magnets size 80 * 20 * 10 mm.

2.3 Description of the stator and the housing

If the stator construction of the 8-pole generator would also be used for this 12-pole generator it means that a piece of Delrin bar with a diameter of 150 mm and a length of 160 + 30 = 190 mm would be needed. This piece of this Delrin bar will be rather expensive but it might be the only option for a prototype. For serial production it must be possible to order special Delrin pipe with an outside diameter of 150 mm and an inside diameter of 110 mm.

For the 8-pole generator, two different windings are described. Figure 2 of KD 644 shows a 2-layers winding. Figure 3 of KD 644 shows an alternative 1 layer winding. The average distance of the coil with respect to the magnets of the armature is smallest for a 2-layers winding and therefore the highest voltage will be generated in one turn of a coil for a certain rotational speed. But mounting of the coils is much easier for a 1-layer winding as there are no crossing coil heads. As the grooves can be made much wider, much more space is available for the coils. So a 1-layer winding is chosen for the 12-pole PM-generator.

For a 3-phase winding of a 12-pole generator, nine coils are needed, so three coils for each phase. The pitch angle in between the poles of a 12-pole generator is 30°. The optimum pitch angle in between the heart of two legs of a stator pole is also 30° 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. As there is 360 / 9 = 40° available for each coil, the angle in between the heart of two adjacent coil arms of two different phases must be about 40° - 30° = 10°.

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 and W3. All coils are made identical. The three coils of one phase are connected in series. The three coils of one phase are made together on a winding thorn, so there are no soldering points in the wires which connect the coils.

A coil has two straight legs which have a length of 160 mm. The coil heads can be very small for a 1-layer winding as there are no crossing coil heads and as there are no coil heads which are lying within each other as it is the case for a normal 3-phase, 4-pole winding. The coil legs can therefore be much longer than the coil legs of a 3-phase motor with a 120 mm long stator without the risk that the coil heads may touch the bearing covers.

The generator will be used for 24 V battery charging if the winding is rectified in star. Each bundle of three coils has a beginning end labelled A and an ending end labelled B. The totally six coil ends of the three phases are guided to the terminal housing positioned at the top of the generator. This terminal housing contains a terminal with six terminals and the coils are connected to the terminal in the same way as for a normal 3-phase winding. This means that the winding can be connected in star or in delta using brass strips. For star connection the points U_A, V_A and W_A are connected together.

Delta connection can be used for 12 V battery charging but the currents for 12 V battery charging will be very high and this requires thick lines in between the generator and the batteries. As an alternative, it is also possible to choose a winding which is good for 48 V battery charging for star rectification and for 24 V battery charging for delta rectification. But the efficiency for delta rectification will be lower than for star rectification as higher harmonic currents circulate in the winding for delta rectification. A low voltage winding is therefore preferred if the nominal battery voltage is 24 V. So at this moment such winding is chosen.

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.

The angle in between the heart of the legs of adjacent phases is 10°. This means that the corresponding grooves would come very close to each other if every leg has its own groove. So it is decided to make nine 20 mm wide and 18.5 mm deep grooves in the outside of the Delrin bush and to lie the arms of two adjacent coils in one groove.

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 and 9.5 mm wide 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 aluminium housing. Therefore a 2 mm wide and 2 mm deep slot is made at each side of the groove and a synthetic strip size 24 * 2 mm is shifted in each slot. As this strip has a length of 190 mm, it also prevents that the coil heads may touch the aluminium housing. It must also be prevented that the coil heads may touch the armature when it is mounted and a 2 mm thick and 15 mm wide rim is therefore made at both sides of the Delrin stator. This rim also prevents that the wires, which connect the three coils of one phase, may contact the armature. It might be needed to lacquer the winding after mounting in the Delrin bush to bind all the wires of a coil together such preventing that wires can vibrate along each other.

The main magnetic flux outside the armature will flow in the space in between the armature and the aluminium housing because the distance in between the armature and the aluminium housing is rather large (about 21 mm). However, a little part of the magnetic flux will flow through the aluminium housing and this flux will cause small eddy currents in the aluminium. 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, the stator with the 1-layer winding and the armature 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 aluminium housing. Pressing of the 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 nine stainless steel hexagon socket head cap screws M8 * 25. This option requires drilling of nine holes in the aluminium housing and one should look at the chosen housing if this is possible. The best position seems to be three holes at the bottom, three holes at 120° left from the bottom holes and three holes at 120° right from the bottom holes. These bolts are drawn in figure 2. The 15 mm holes for the bolt heads must be machined that deep that there is a distance of 5 mm in between the inside diameter of the housing and the bolt head.

The aluminium housing is drawn with a cylindrical outside with a diameter of 166 mm. In reality, the housing has cooling fins, a foot at the bottom and a terminal box at the top. Only if the housing is known, an accurate cross section of the housing can be drawn.

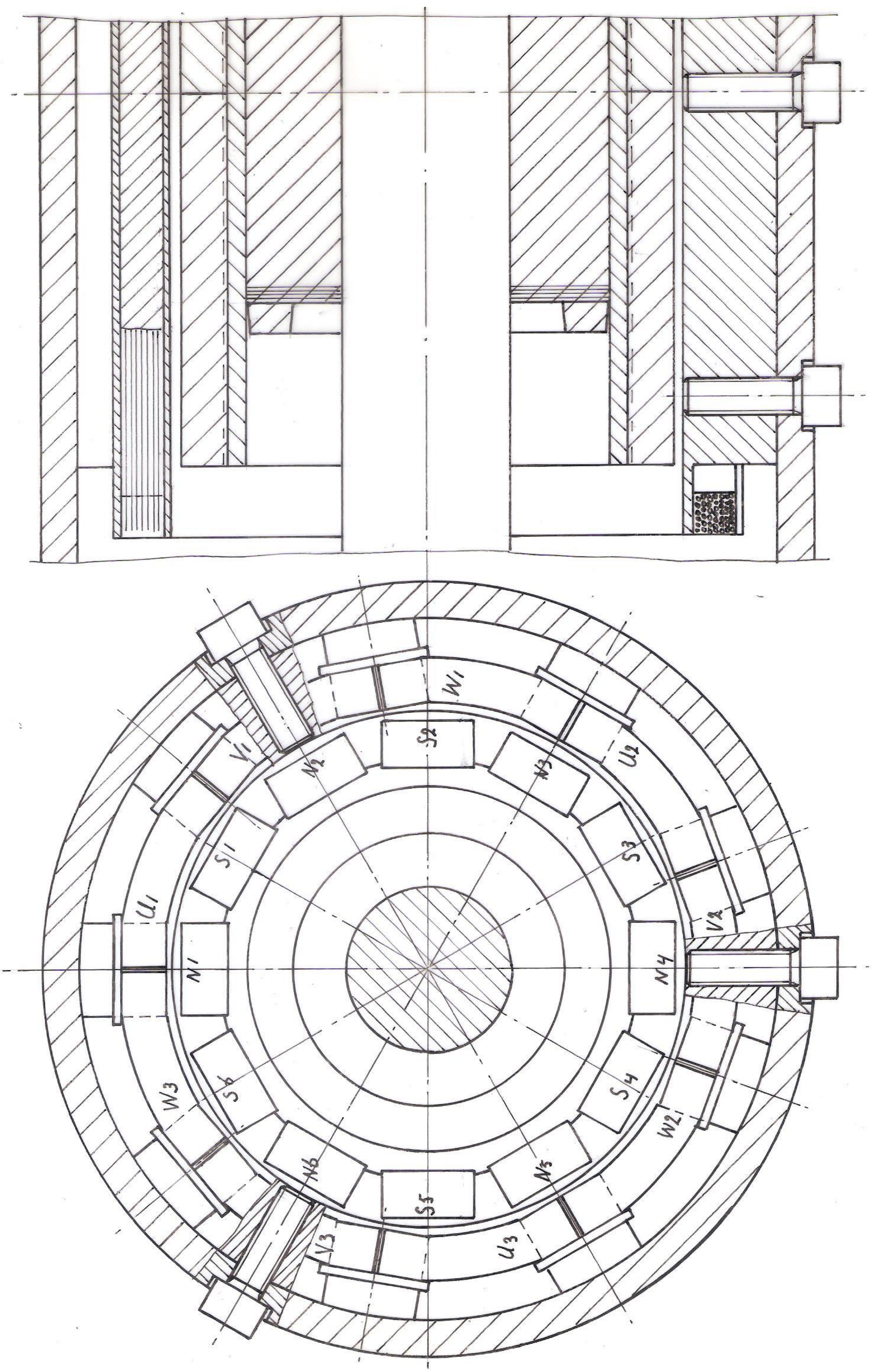

fig. 2 12-pole PM-generator, 3-phase stator with a 1-layer winding with three coils per phase

3 Determination of the flux density in the air gap

In figure 1, field lines are drawn for each magnetic loop. A part of a magnetic loop is flowing outside the armature and a part is flowing inside the armature. Three loops of different diameter are drawn outside the armature. The middle loop is also drawn in the magnets and in the armature. It can be seen that the length of the outer loop through air is much longer than the length of the inner loop through iron. The length of the middle loop through air has a length which is about the average of the three drawn loops. 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 33 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 $t_2 = 33$ mm in formula 1 results in $B_{r\ eff} = 0.45$ 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 * 0.45 = 0.9 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 0.45 / 0.9 = 0.5 of the flux density of a PM-generator which has a mild steel stator stamping. However, the armature volume of this 12-pole generator is more than a factor 2 larger than that of the original 4-pole generator and the stator has no iron losses and it 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

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 grooves in 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. 4).

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 DC voltages for instance 8, 12, 16, 20, 24, 28 and 32 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 VIRYA-3B3 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 = 20 V. Assume that the generator is used for 24 V battery charging. This means that the average charging voltage is about 26 V. So the voltage of the test winding is a factor 20 / 26 = 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 $\sqrt{(1 / 1.3)}$ = 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 26 V, as the curves of the test winding for 20 V.

This is the best method but one has to make a test winding and a final winding which is a lot of work. To simplify the procedure, one also can assume that the estimated P_{mech}-n and P_{el}-n curves as given in figure 3 are right. This means that the winding must be such that the open DC voltage is 26 V at n = 160 rpm. To find the number of turns per coil for which this is realised, it is necessary to make a test winding with only one complete coil for each phase and to measure the DC voltage for this test winding at 160 rpm. The voltage for three coils per phase will then be a factor three higher and in this way it is rather easy to determine the required number of turns per coil. To make the generator as strong as possible, next one choses the maximum wire thickness for which coils with the required number of turns per coil can be laid in the available space in the grooves of the Delrin bush. The stator with this winding then has to be measured to verify if the real P_{mech}-n and P_{el}-n curves are lying close to the estimated ones. If this is the case, the winding is OK. If this is not the case, the winding should be modified and the modified winding should be measured again. If no test rig is available with which the P_{mech}-n curve can be measured one at least has to measure the P_{el}-n curve for a constant DC voltage of 26 V. For measuring of the P_{mech}-n curve one has to measure the torque Q and this requires a rather sophisticated test rig.

5 Determination of the P-n curves, the optimum cubic line and the P_{el}-V curve

The P-n curves and the optimum cubic line of the VIRYA-3B3 rotor for different wind speeds are determined in chapter 5 of KD 484 and are given in figure 4 of KD 484. This figure is copied as figure 3 but the P_{mech}-n and P_{el}-n curves of the original 4-pole generator for 26 V star are removed.

The P_{mech}-n and P_{el}-n curves of the 12-pole PM-generator are estimated and are also given in figure 3. It is assumed that the P_{el}-n curve for 26 V star starts at a rotational speed of 160 rpm. So the generator winding has to be chosen such that the open DC-voltage is 26 V at n = 160 rpm. It is assumed that the efficiency is 0.9 for n = 200 rpm and that it is 0.645 for n = 360 rpm.

It is assumed that the P-n curve for short-circuit in delta is the same as for the original generator and this curve is also given in figure 3. Short-circuit in delta is the same as short-circuit in star if the star point is short-circuited too.

The point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The electrical power P_{el} for that wind speed is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 4). The charging voltage at high powers will be somewhat higher than the average charging voltage of 26 V and therefore the generator efficiency will be somewhat higher too. This results in a somewhat higher electrical power. The P_{el}-V curve is corrected for this effect for high wind speeds.

The matching of rotor and generator is very good because the P_{mech}-n curve of the generator is lying close to the optimum cubic line for wind speeds in between 4 and 9.5 m/s. In the P_{el}-V curve it can be seen that the maximum power is 610 W and that supply of power starts already at a wind speed of 2.5 m/s ($V_{cut\ in}$ = 2.5 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. The starting wind speed is 2.3 m/s, so there is no hysteresis in the P_{el}-V curve.

The P-n curve for short-circuit in delta is lying left from the P-n curve of the rotor for V = 9.5 m/s and higher. This means that the rotor will slow down to almost stand still for every wind speed if short-circuit in delta is made.

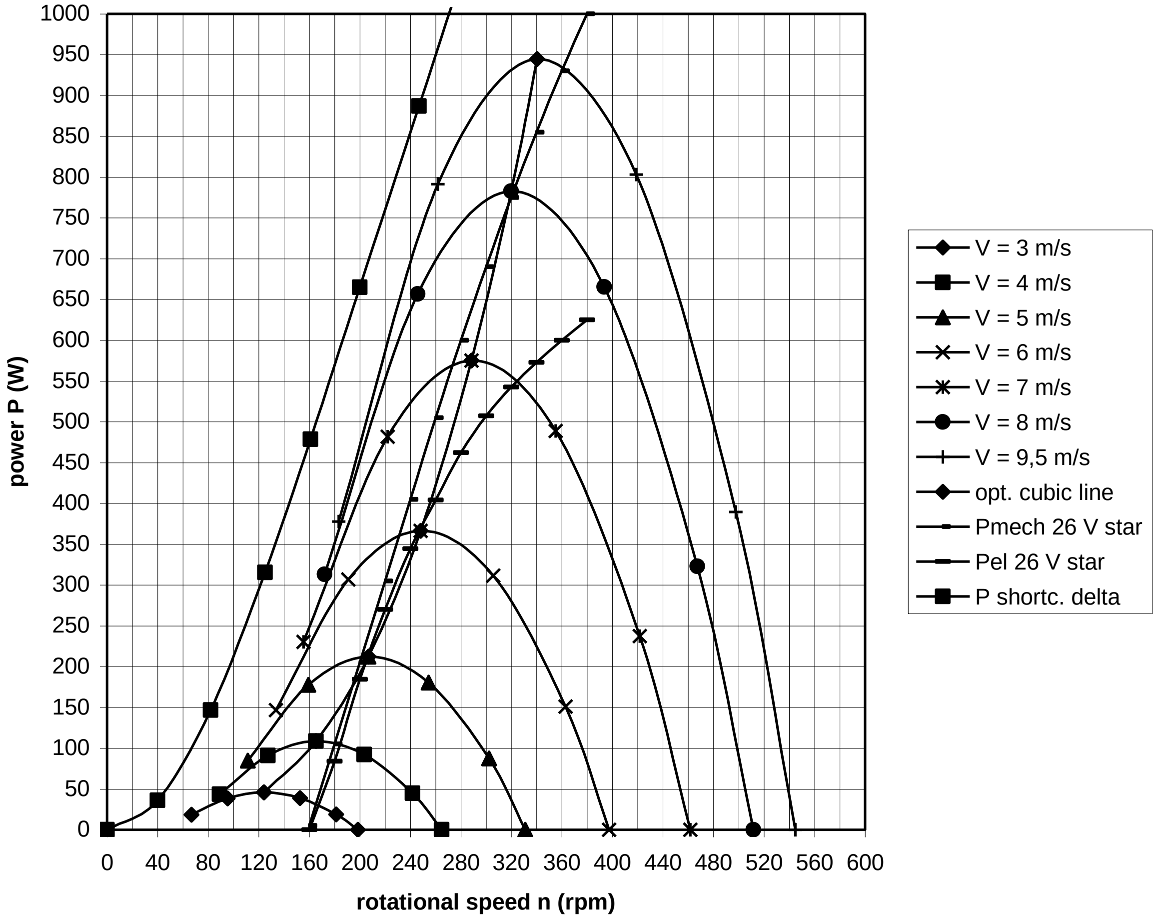

fig. 3 P-n curves of the VIRYA-3B3 rotor for V_{rated} = 9.5 m/s, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves of the 12-pole PM-generator for 26 V star, estimated P-n curve of the generator for short-circuit in delta.

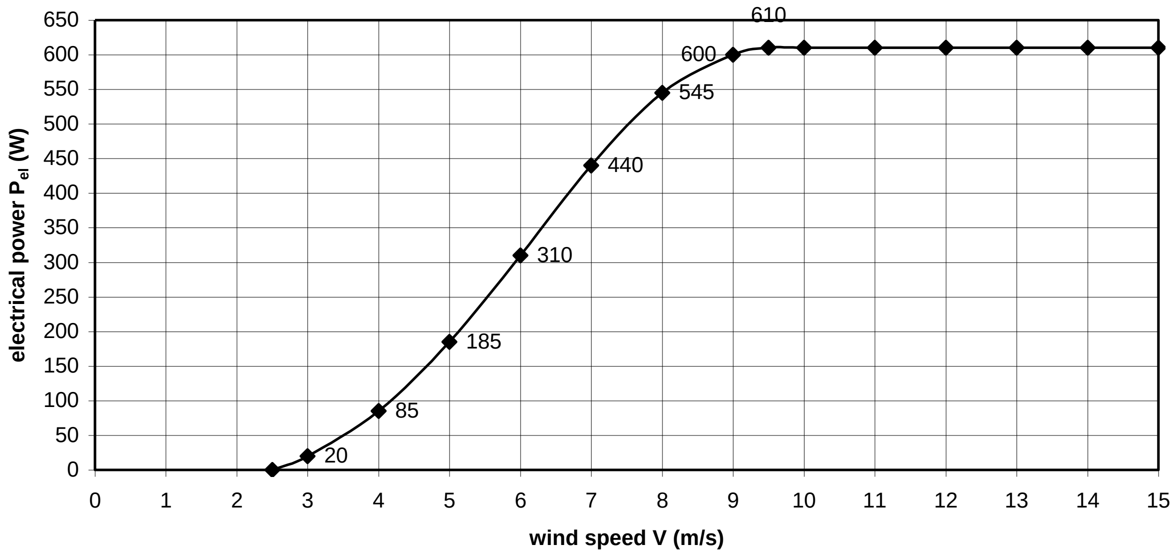

fig. 4 Estimated P_{el}-V curve VIRYA-3B3 for 24 V battery charging

The whole P_{el}-V curve is better than the P_{el}-V curve of the original generator given in figure 5 of KD 484 but this curve is based on real generator measurements and therefore more reliable. If a prototype of the generator is available, it should be measured for a constant voltage of 26 V according to the method as described in chapter 4 and it should be verified if the measured curves are about the same as the estimated ones. The generator should also be measured for short-circuit in star and in delta. The measured P-n curve of the generator for short-circuit in delta should also be drawn in figure 3 and if this curve is not intersecting with the P-n curve of the rotor for V = 9.5 m/s, it means that the rotor can be stopped for every wind speed by making short-circuit in delta.

6 References

1 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-3B3 windmill (λ_d = 6.5, wooden blades). February 2012, reviewed November 2018 , free public report KD 484, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Ideas about an 8-pole, 3-phase permanent magnet generator with a stator without iron in the coils, using eight neodymium magnets size 80 * 20 * 10 mm and a housing of an asynchronous motor with frame size 71. November 2017, reviewed November 2018, free public report KD 644, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Measurements performed on a generator with housing 5RN90L04V and a 4-pole armature equipped with neodymium magnets, March 2001, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed October 2014, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode.