Ideas about a 20-pole radial flux permanent magnet generator with a 3-phase, 1-layer stator winding with no iron in the coils

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 The generator has not yet been built and tested.

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1 Introduction

A 16-pole radial flux PM-generator with no iron in the coils is described in report KD 748 (ref. 1) for use in combination with the 2-bladed VIRYA-1.8W rotor. This generator makes use of 32 neodymium magnets size 40 * 15 * 5 mm. Magnets are used for the north and for the south poles. The generator has a special stator with a 1-layer, 3-phase 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 cogging torque. The only sticking torque is caused by the bearing friction and by the friction of the seal on the generator shaft. This low sticking torque results in a good starting behaviour for combination with a fast running rotor with a low starting torque coefficient. The square bearing covers are made out of aluminium strip size 120 * 20 mm. The outside diameter of the stator is 120 mm.

The idea is to design a bigger generator using the same principles but using square bearing covers which are made out of aluminium strip size 200 * 20 mm. The stator housing now gets a diameter of 200 mm. Neodymium magnets size 50 * 25 * 12 mm are chosen. Magnets are now only used for the north poles. The south poles are formed by the remaining material of the armature. It appears that a 20-pole armature is possible with these magnets.

The generator is used for 24 V battery charging if the winding is rectified in star. It is expected that this generator can be used in combination with the VIRYA-3B3 rotor for which the rotor calculations are given in report KD 484 (ref. 2). This rotor is originally meant to be coupled to a PM-generator which is made from an asynchronous motor and the generator bracket has to be modified for use with this alternative 20-pole generator. The rotor hub must also be modified as the 20-pole generator has a 30 mm shaft instead of a 25 mm shaft.

2 Description of the 20-pole PM-generator

2.1 Description of the armature and the shaft (see figure 1)

The flux density which can be realised for a stator without iron in the coils is much lower than for a stator with an iron stamping. To get a sufficient high maximum torque level, thick magnets have to be used, and the armature volume must be much larger than for the 16-pole generator. The 16-pole generator has an armature length of 80 mm and two 40 mm long magnets are used in one grove. For the 20-pole generator it is chosen to use only one 50 mm long magnet in one groove. However, the armature diameter is much larger and this makes that the armature volume is still much larger.

The armature diameter is chosen 169 mm and the armature width is chosen 50 mm. The armature is made from a mild steel bar width a diameter of 170 mm and a width of 51 mm. Ten grooves are made in the armature under an angle of 36°. The grooves have a width of 25.1 mm and a depth of 13 mm. A magnets size 50 * 25 * 12 mm is glued in each groove using epoxy or anaerobe glue. All north poles must point to the outside! To reduce the weight, a 20 mm deep chamber is made at both sides of the armature. The chambers have an outside diameter of 130 mm and an inside diameter of 50 mm.

So the distance in between the bottom of the groove and the shaft axis is 84.5 - 13 = 71.5 mm. A groove depth of 13 mm makes that the corners of the magnets don’t jut out of the south poles. At both sides of the magnet grove there is a 2.5 mm wide and 7 mm deep grove to prevent direct magnetic short-circuit in between the north and the south poles. These grooves makes that the south poles have a width of about 23 mm.

The stainless steel generator shaft has a diameter of 30 mm at the front bearing and a diameter of 25 mm at the back bearing. A rubber sealed ball bearing size 30 * 55 * 13 mm is used as front bearing. The SKF bearing code is: 6006-2RS1. A rubber sealed ball bearing size 25 * 52 * 15 mm is used as back bearing. The SKF bearing code is: 6205-2RS1. The reason that two different bearings are used is that an oil seal is needed at the generator shaft. An oil seal size 30 * 47 * 7 mm with an extra dust lip (type Rst) is chosen.

So the width of the front bearing and the oil seal is 13 + 7 = 20 mm which is just the same as the thickness of the front bearing cover. During mounting, grease has to be used in between the seal and the bearing and at the backside of the dust lip. The back bearing cover is closed. The front bearing has a dynamic load factor of 13300 N. The back bearing has a dynamic load factor of 14000 N which is a little higher but apart from the radial load, the back bearing also takes the axial load caused by the rotor thrust.

The generator shaft has a diameter of 34 mm at the armature and a diameter of 35 mm in between the armature and the back bearing. The generator shaft has a tapered shaft end with a half cone angle of 5° and a central threaded hole M12 for connection of the hub. The length of the armature is only 46 mm at the shaft to prevent that the armature touches the bearing covers. The armature is pressed on the shaft using a press fitting.

The armature has twenty poles, so ten north poles and ten south poles. As the south poles are formed by the remaining material of the armature, only ten magnets are needed. The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl. The current price of one magnet is € 10.73 including VAT, excluding transport if a minimum quantity of 10 magnets is ordered. So the magnet costs for one generator are about € 110 including VAT which seems acceptable if the generator is strong enough for the VIRYA-3B3 and if it has a high efficiency and a low sticking torque.

Twenty magnetic loops are coming out of the armature. The direction of the magnetic field for ten loops is turning left hand and for the other ten loops it is turning right hand.

The armature volume is $\pi * 84.5^2 * 50 = 1121588 \text{ mm}^3$. The armature volume of the 16-pole generator as described in KD 748 is $\pi * 46.11^2 * 80 = 534355 \text{ mm}^3$. So the armature volume of the 20-pole generator is a factor 1121588 / 534355 = 2.01 larger than that of the 16-pole generator. The total thickness of the magnets in one magnetic loop is 2 * 5 = 10 mm for the 16-pole generator and it is 12 mm for the 20-pole generator. The flux density outside the armature is calculated in chapter 3. The original VIRYA-3B3 generator has an armature volume of 660449 mm^3 and so the armature volume of the 20-pole generator is a factor 1121588 / 660449 = 1.7 larger. It is expected that this larger armature volume compensates the smaller flux density in the coils.

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 10 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 12 * 25 mm sides. The magnets must be positioned such that the direction of the arrows points to the outside for all ten magnets! For mounting of the magnets, it is advised to use a clamp in which a magnet can be clamped at the 25 * 12 mm sides and which has a long handle which can be hold by both hands. 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! The magnets will be pulled in the armature and I think that no extra clamping is required. One has to check if the sides of the magnets coincide with the sides of the armature.

2.2 Description of the stator and the bearing covers (see figure 1)

The square bearing covers are made of aluminium strip size 200 * 20 mm. For large quantities, it seems also possible to cast the bearing covers. The maximum outside diameter of synthetic stator is 200 mm. The synthetic stator can be made on a 3D-printer. The length of the stator in between the bearing covers is 50 mm, so the total length of the generator housing is 50 + 2 * 20 = 90 mm. The stator is clamped in between the two bearing covers by four inner hexagon bolts M10 * 120 mm. These bolts are also used for connection of the generator to the generator bracket of the head. This generator bracket must be positioned at the back bearing cover in parallel to the rotor plane. This differs from the positioning of the generator bracket for an asynchronous motor of the VIRYA-3B3 which is positioned in parallel to the generator axis.

The pitch of the M10 bolts is 160 mm. The stator is provided with four 30 mm wide ears at 45° with the vertical and the M10 bolts are pushed through 10.5 mm holes in these ears. The length tolerances of the stator, the chambers in the bearing cover and the distance in between the bearings at the shaft have to be chosen such that the bearings don't get an axial load if the bolts are tightened. It is advised to make the chamber in the back bearing cover a little deeper than 15 mm to make that the shaft always has some axial clearance.

A 16 mm deep chamber with an inside diameter of 194 mm is made in each bearing cover. The stator has a 14 mm long rim with an outside diameter of 194 mm and an inside diameter of 190 mm at each side to centre the stator and to prevent that the coil heads can touch the bearing covers. The outside diameter of the bearing cover at the bearings is 70 mm.

The stator has a 1-layer, 3-phase winding. This means that it has 15 coils for a 20-pole armature. Five coils are of phase U, five coils are of phase V and five coils are of phase W. All five coils of one phase are connected in series. The sequence of the coils is U1, V1, W1, U2, V2, W2, U3, V3, W3, U4, V4, W4, U5, V5 and W5. The sequence of the poles is N1, S1, N2, S2, N3, S3, N4, S4, N5, S5, N6, S6, N7, S7, N8, S8, N9, S9, N10 and S10. A side view of the armature and stator and a top cross section are given in figure 1. The armature is drawn in that position that north pole N1 is opposite to coil U1.

The armature pole angle is 360 / 20 = 18°. This means that the optimum angle in between the left and the right leg of a coil is 18° too. Assume this angle is chosen. The stator pole angle is 360 / 15 = 24° This means that the angle in between the right leg of coil U1 and the left leg of coil V1 is 24° – 18° = 6°. It is chosen that these two legs are laid in one groove. As there are totally fifteen coils, this means that fifteen grooves are needed.

The grooves have a special triangular shape with a radius of 4 mm at the outside corners and a 60° inside taper. The pitch circle at the centre of the 4 mm radius is 182 mm. The coils have legs with a circular cross sectional area with a diameter of 8 mm. A 1.5 mm thick and 50 mm long synthetic strip with 30° bevelled sides is shifted in the grooves after mounting of the coils.

The bundle of five coils of one phase are wound outside the generator on a winding thorn. So all five coils of one phase are connected in series. A coil bundle has a beginning called A and an end called B. The three coil ends A are connected to each other and are forming the star point. The three coil ends B and the star point are guided outside the generator through a hole in the back bearing cover. The wires of the three phases are coloured red, yellow and blue. The wire of the star point is coloured black. The star point is also guided to the outside of the generator to make short-circuit possible in between the three phases and the star point as this gives the strongest braking torque. It might be needed to lacquer the winding after mounting it in the stator to prevent that the wires can vibrate along each other.

A 20-pole armature has the same magnetic position if it has rotated 36°. So a rotational angle β = 36° corresponds to a phase angle α = 360°. So β = 1° corresponds to α = 10°. The angle β in between N1 and U1 is 0° corresponding to α = 0°. The angle β in between N1 and V1 is 24° corresponding to α = 240°. The angle β in between N2 and coil W1 is 12° corresponding to α = 120°. So a 3-phase current is generated in between U1, V1 and W1.

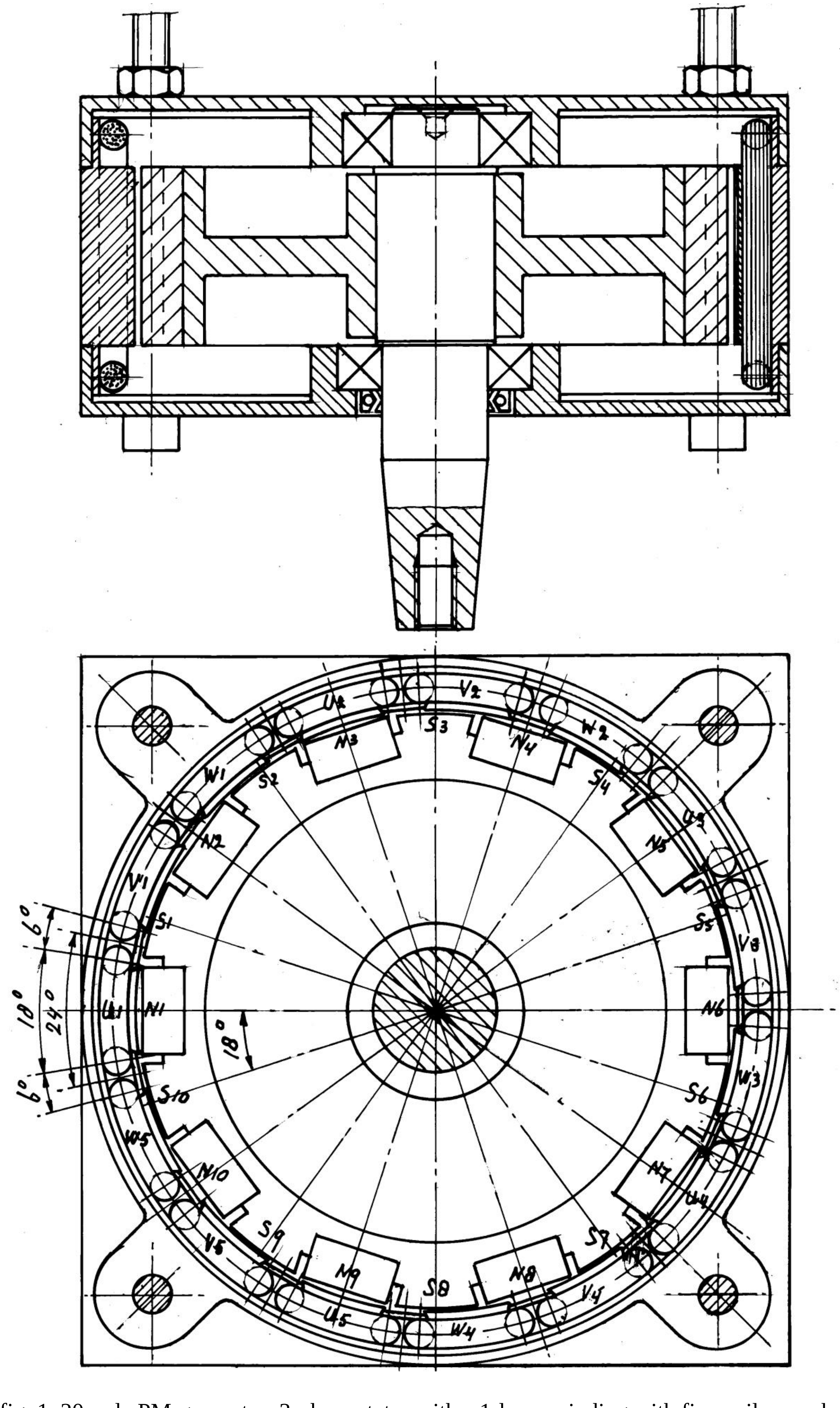

fig. 1 20-pole PM-generator, 3-phase stator with a 1-layer winding with five coils per phase

3 Determination of the flux density in the air gap

Twenty magnetic loops are coming out of a 20-pole armature. Ten poles are turning left hand and ten poles are turning right hand. The split in between a left hand and a right hand loop lies at the centre of a north pole. So there is a right hand loop in between the right side of N1 and the left side of S1 and a left hand loop in between the left side of N1 and the right side of S10. The length of the loop is maximal for the loop going through the centre of the poles and minimal for the loop going through the sides of the poles. The average length is obtained for the loop going through a point lying at ¼ of the magnet width from the side of a magnet. It is assumed that this loop is a part of a circle. It can be calculated that this average loop has a length t_2 of about 24 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 N38. The remanence B_r in a neodymium magnet with quality N38 is about 1.24 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 = 12 mm.

As the magnetic resistance of the iron can be neglected, the total magnetic resistance is only caused by the magnet 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 $t_1 + t_2 / t_1$. 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:

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

Substitution of B_r = 1.24 T, t_1 = 12 mm and t_2 = 24 mm in formula 1 results in $B_{r\,eff}$ = 0.413 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 7.5 mm at the edge of the magnet which means that the magnetic flux is concentrated by a factor 12.5 / 7.5 = 1.6. So the flux density in the armature becomes 1.6 * 0.413 = 0.66 T. Normal iron is saturated at about 1.6 T so the armature 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 0.413 / 0.9 = 0.46 of the flux density of a PM-generator which has a mild steel stator stamping. However, the armature volume of this 20-pole generator is rather large and this compensates the much lower flux density in the coils. If the generator is strong enough for the VIRYA-3B3 rotor has to be verified by making detailed drawings and building and testing of a prototype, but I won't do that.

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 50 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 stator. The winding is rectified in star by a 3-phase rectifier. Rectification of a 3-phase current is described in report KD 340 (ref. 3).

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 but this was done very long ago and this test rig is possibly no longer available. Next a series of measurements is executed for a range of DC voltages for instance 16, 20, 24, 28, 32 and 36 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 2 (see chapter 5). The optimum cubic line is also drawn in figure 2. 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 = 32 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 32 / 26 = 1.231 too high. So the number of turns per coil has to be decreased by a factor 26 / 32 = 0.813 and so it must be 0.813 * 50 = 41. The wire thickness must be increased by a factor $\sqrt{}$ (1 / 0.813) = 1.11 to get the same amount of copper in a groove. 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 32 V but it is good to measure the generator again for the modified winding.

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 2. At this moment, it is expected that the measured P_{mech}-n and P_{el}-n curves of the original 4-pole generator of the VIRYA-3B3 for 26 V star are the same as those of the 20-pole alternative generator for 26 V star. But once a prototype has been built and measured, real measured curves have to be used. The P_{el}-V curve for the original generator is also copied from KD 484 and is given in figure 3.

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 m/s. In the P_{el}-V curve it can be seen that the maximum power is 500 W and that supply of power starts already at a wind speed of 2.7 m/s ($V_{cut\ in}$ = 2.7 m/s). This is rather low and therefore the windmill can be used in regions with low wind speeds. The starting wind speed for the original generator is 2.7 m/s. For the new generator it might even be lower because there is absolutely no cogging torque.

In figure 2 it can be seen that the P_{mech}-n curve starts about at a rotational speed of 164 rpm. So if the alternative 20-pole generator would have the same P_{mech}-n curve, the open DC voltage should be 26 V at n = 164 rpm. This value might give a good impression about the number of turns per coil which has to be chosen for the first test winding.

I expect that the 20-pole generator has a higher efficiency at high powers than the original VIRYA-3B3 generator because the frequency is much higher and because the winding is optimised for 24 V battery charging. So the maximum power at high wind speeds might be larger than 500 W.

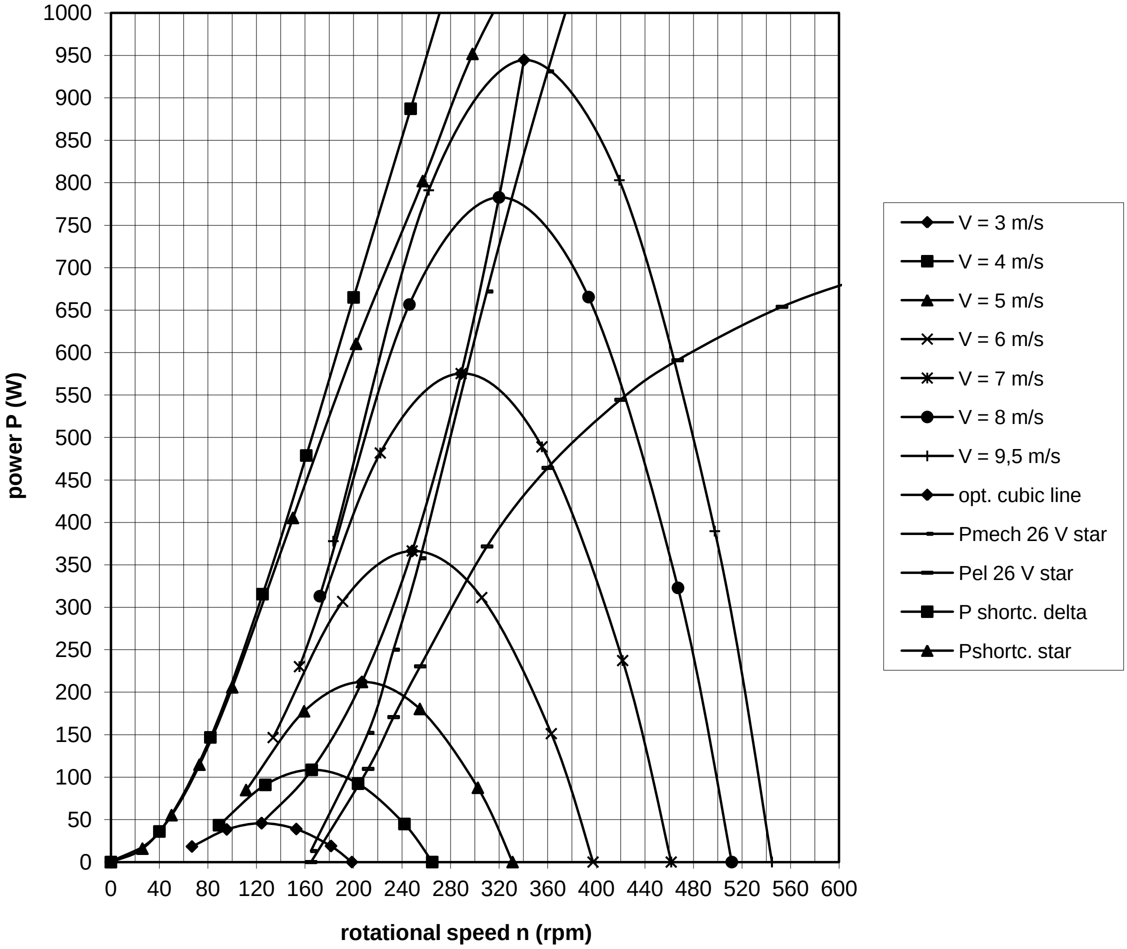

fig. 2 P-n curves of the VIRYA-3B3 rotor, optimum cubic line, measured P_{mech}-n and P_{el}-n curves for original PM-generator for 26 V star, measured P-n curves of the original generator for short-circuit is star and delta

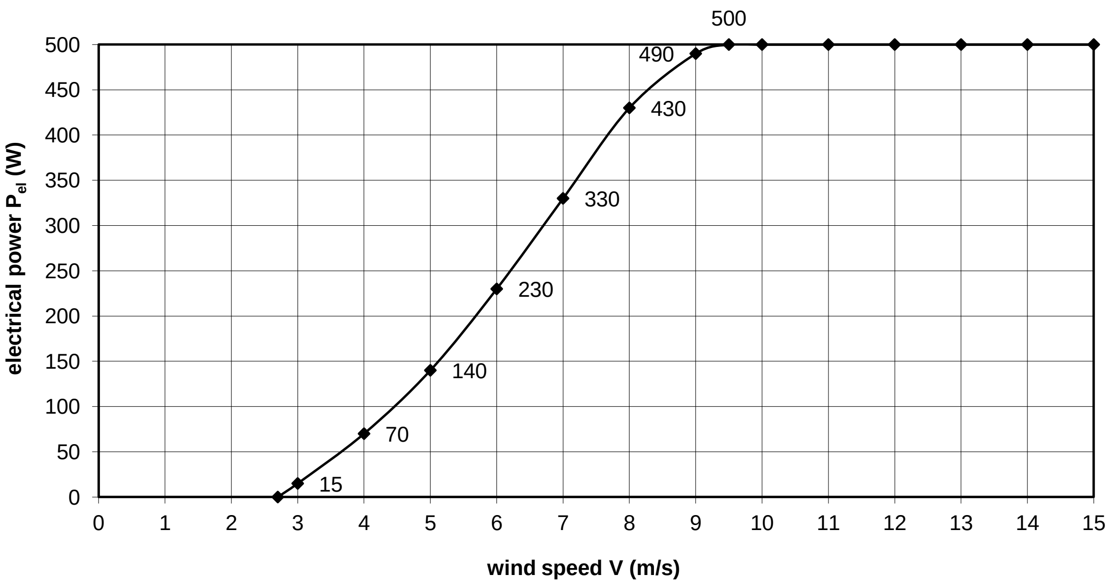

fig. 3 P_{el}-V curve VIRYA-3B3 for the original generator for 24 V battery charging

6 References

1 Kragten A. Ideas about a 16-pole, radial flux permanent magnet generator with a 3-phase, 1-layer stator winding with no iron in the coils, May 2023, free public report KD 748, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-3B3 windmill (λ_d = 6.5, wooden blades), February 2012, reviewed June 2023, free public report KD 484, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed January 2022, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode.