Ideas about a 16-pole radial flux permanent magnet generator with a 3-phase, 1-layer stator winding with no iron in the coils

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1 Introduction

An 8-pole radial flux PM-generator with no iron in the coils is described in report KD 644 (ref. 1) for use in combination with 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 cogging 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 for combination with a fast running rotor with a low starting torque coefficient.

The prices of neodymium magnets have increased a lot in recent years and the current price for one magnet is € 13.96 including VAT, excluding transport if a minimum quantity of 30 magnets is ordered. So the magnet costs for one generator are about € 112 including VAT which is rather high. So it is investigated if it is possible to design a generator with thinner and cheaper magnets. The generator out of KD 644 makes use of a motor housing of an asynchronous motor from which the iron stator stamping and the standard winding are removed and replaced by a synthetic stator stamping in which a new winding is laid. So if an existing motor housing is used, a valuable part of the motor is wasted.

The idea is to design a 16-pole generator using cheaper magnets size 40 * 15 *5 mm and a synthetic stator which is cast or 3D-printed. The stator will be provided by a 3-phase, 1-layer winding which is rectified. The generator is used for 12 V battery charging if the winding is rectified in series. This generator can be used in combination with the VIRYA-1.8W rotor for which the rotor calculations and the drawings are given in report KD 664 (ref. 2). This rotor is originally meant to be coupled to an axial flux generator and the central strip and the hub have to be modified for use with the 16-pole generator. It is possible to use the head and tower of the former VIRYA-1.8 windmill if the generator bracket is modified. Drawings of the head and the tower are given in the manual of the VIRYA-1.81.

2 Description of the 12-pole PM-generator

2.1 General

The 8-pole generator as described in KD 644 (ref. 1) has a stator with outside grooves. This facilitates mounting of the coils. The winding is protected because the stator is mounted in the aluminium motor housing. For this new 16-pole generator, no motor housing is used and the stator is clamped in between two aluminium bearing covers. To protect the winding, the stator grooves must now be made at the inside of the stator. But the stator has a rather large inside diameter and mounting of the coils of the winding isn’t very difficult.

2.2 Description of the armature

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 for rather thin 5 mm thick magnets, the armature volume must be larger than for the 8-pole generator. Suppose the armature length is chosen 80 mm. This means that two 80 mm long magnets are laid in one groove. The armature must have a diameter of 85 mm for a 16-pole armature using magnets size 40 * 15 * 5 mm.

The stainless steel generator shaft has a diameter of 17 mm at the bearings and a tapered shaft end with a half cone angle of 5° and a central threaded hole M8 for connection of the hub. The shaft diameter at the armature is 21 mm. The shaft diameter of the part in between the armature and the back bearing is 22 mm. If a massive bush with a length of 80 mm and a diameter of 85 mm would be chosen, the armature would become rather heavy. The weight is reduced by turning chambers at each side of the armature.

The length of the armature is only 76 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 sixteen poles, so eight north poles and eight south poles. Sixteen 15 mm wide and 2 mm deep grooves are milled in the armature at an angle of 22.5° in parallel to the shaft axis. The bottom of the groove lies 40.5 mm from the shaft axis. Two magnets size 40 * 15 * 5 mm are glued in each groove using epoxy or anaerobe glue. Sixteen magnets are positioned with the north pole to the outside and sixteen magnets are positioned with the south pole to the outside. So for one armature, 32 magnets are needed. The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl. The current price of one magnet is € 2.88 including VAT, excluding transport if a minimum quantity of 150 magnets is ordered. So the magnet costs for one generator are about € 92 including VAT which is still rather high but lower than for the 8-pole generator as described in KD 644. The magnet costs seem acceptable if the generator has a high efficiency and a low sticking torque.

Sixteen magnetic loops are coming out of the armature. The direction of the magnetic field for eight loops is turning left hand and for the other eight loops it is turning right hand. The radius at the heart of the outer side of a magnet is 40.5 + 5 = 45.5 mm. It can be calculated that the radius at the corner of a magnet is 46.11 mm. If the air gap in between the corner of a magnet and the inside of the stator is chosen 0.39 mm, it means that the stator must have an inside diameter of 2 * (46.11 + 0.39) = 93 mm.

The armature volume is $\pi * 46.11^2 * 80 = 534355$ mm^3. The armature volume of the 8-pole generator as described in KD 644 is $\pi * 36.4^2 * 80 = 332999$ mm^3. So the armature volume of the 16-pole generator is a factor 534355 / 332999 = 1.59 larger than that of the 8-pole generator. It is assumed that this much larger armature volume compensates the less strong magnetic flux because of using 5 mm thick instead of 10 mm thick magnets.

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 32 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 5 * 15 mm sides. The magnets must be positioned such that the direction of the arrows alternates for adjacent poles. It is assumed that the arrow points in the direction of the north pole.

So first eight north poles are made and the arrows of these magnets are pointing to the outside. Mounting of these sixteen 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 40 * 5 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 sixteen magnets of the eight south poles in between the 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 sixteen magnets of the south poles until the glue of the 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 sixteen 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.

It is chosen to use sealed ball bearings size 17 * 40 * 12 mm. The SKF bearing code is 6203-2RS1. Although these bearings have a rubber seal at both sides, this seal isn’t good enough to prevent entrance of water if a long lifetime is wanted. So an extra oil seal size 17 * 35 * 7 mm is used at the shaft side. This seal also has a dust lip type RST. The space in between the oil seal and the front bearing is filled with grease to create an extra barrier for the penetration of water in the front bearing. The back bearing cover is closed.

2.3 Description of the stator and the bearing covers

The square bearing covers are made of aluminium strip size 120 * 20 mm. For large quantities, it seems also possible to cast the bearing covers. The maximum outside diameter of synthetic stator is 120 mm. The length of the stator in between the bearing covers is 80 mm. so the total length of the generator housing is 80 + 2 * 20 = 120 mm. The stator is clamped in between the two bearing covers by four bolts M8 * 140 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-1.8 which is positioned in parallel to the generator axis.

The pitch of the M8 bolts is 95 mm. The stator is provided with four 20 mm wide ears at 45° with the vertical and the M8 bolts are pushed through 8.5 mm holes in these ears. The length tolerances of the stator, the cambers in the bearing cover and 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 12 mm to make that the shaft always has some axial clearance.

A 16 mm deep chamber with an inside diameter of 114 mm is made in each bearing cover. The stator has a 14 mm long rim with an outside diameter of 114 mm and an inside diameter of 110 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 50 mm.

The stator has a 1-layer, 3-phase winding. This means that it has 12 coils for a 16-pole armature. Three coils are of phase U, three coils are of phase V and three coils are of phase W. The sequence of the coils is U1, V1, W1, U2, V2, W2, U3, V3, W3, U4, V4 and W4. The sequence of the poles is N1, S1, N2, S2, N3, S3, N4, S4, N5, S5, N6, S6, N7, S7, N8 and S8. A side view of the armature and stator is 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 / 16 = 22.5°. This means that the optimum angle in between the left and the right leg of a coil is 22.5° too. Assume this angle is chosen. This means that the angle in between the right leg of coil U1 and the left leg of coil V1 is 7.5°. It is chosen that these two legs are laid in one groove. As there are totally twelve coils, this means that twelve grooves are needed. The grooves are positioned such that there is a groove at each side of the ear for the M8 connecting bolt.

The grooves have a special triangular shape with a radius of 3.5 mm at the outside corners and a 60° inside taper. The pitch circle at the centre of the 3.5 mm radius is 103 mm. The coils have legs with a circular cross sectional area with a diameter of 7 mm. A 1.5 mm thick and 80 mm long synthetic strip with 30° bevelled sides is shifted in the grooves after mounting of the coils.

The bundle of four coils of one phase are wound outside the generator on a winding thorn. 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 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 16-pole armature has the same magnetic position if it has rotated 45°. So a rotational angle β = 45° corresponds to a phase angle α = 360°. So β = 1° corresponds to α = 8°. The angle β in between N1 and U1 is 0° corresponding to α = 0°. The angle β in between N1 and V1 is 30° corresponding to α = 240°. The angle β in between N2 and coil W1 is 15° corresponding to α = 120°. So a 3-phase current is generated in between U1, V1 and W1.

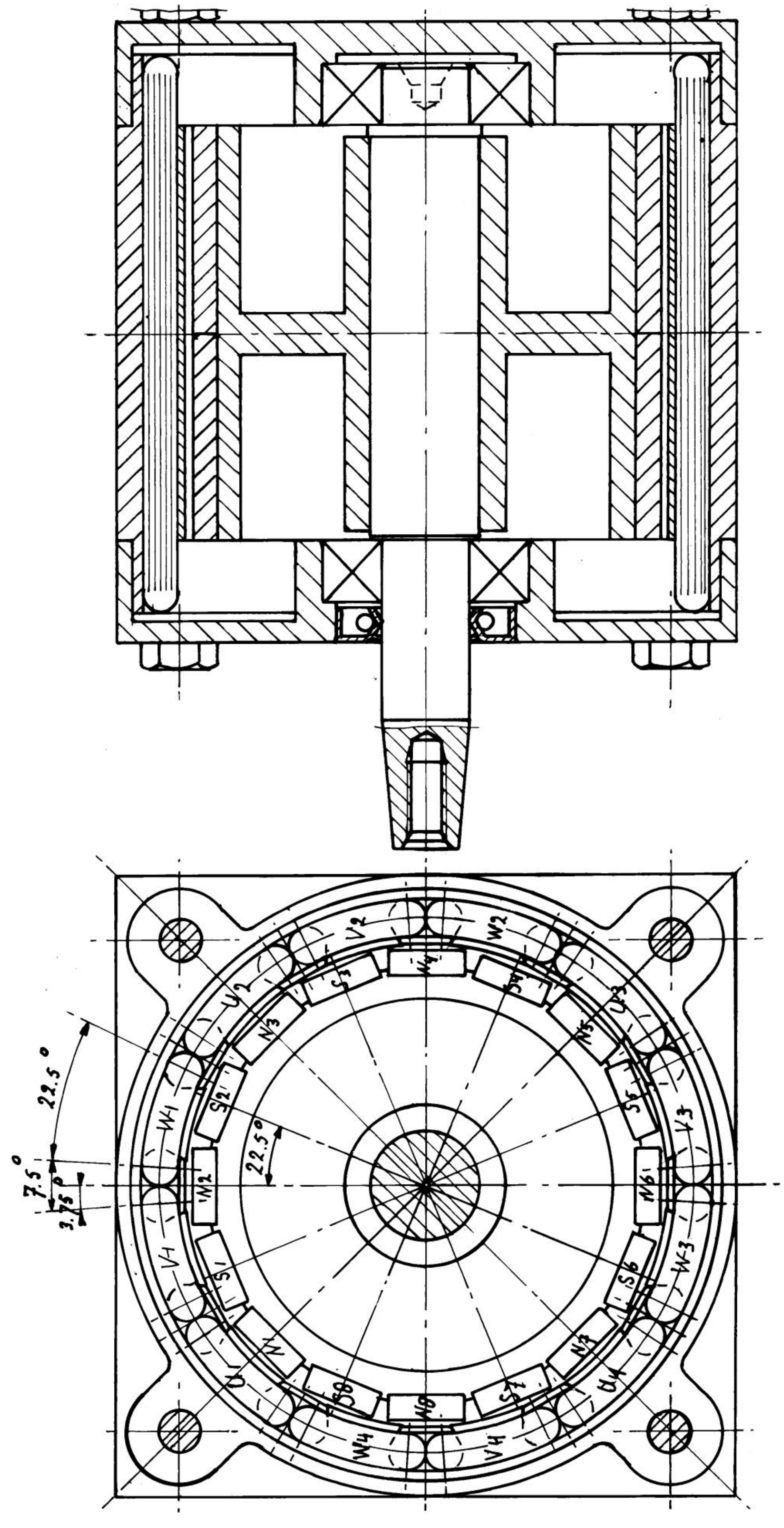

fig. 1 16-pole PM-generator, 3-phase stator with a 1-layer winding with four coils per phase

3 Determination of the flux density in the air gap

Sixteen magnetic loops are coming out of a 16-pole armature. Eight poles are turning left hand and eight 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 S8. The length of the loop is maximal for the loop going through the centre of the magnets and minimal for the loop going through the sides of the magnets. 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 19 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 = 5 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:

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

Substitution of B_r = 1.24 T, t_1 = 5 mm and t_2 = 19 mm in formula 1 results in $B_{r\ eff}$ = 0.43 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 4 mm at the edge of the magnet which means that the magnetic flux is concentrated by a factor 7.5 / 4 = 1.88. So the flux density in the armature becomes 1.88 * 0.43 = 0.81 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 0.43 / 0.9 = 0.48 of the flux density of a PM-generator which has a mild steel stator stamping. However, the armature volume of this 16-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-1.8W 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 8, 10, 12, 14, 16 and 18 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-1.8W 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 = 16 V. Assume that the generator is used for 12 V battery charging. This means that the average charging voltage is about 13 V. So the voltage of the test winding is a factor 16 / 13 = 1.231 too low. So the number of turns per coil has to be increased by a factor 16 / 13 = 1.231 and so it must be 1.23 * 50 = 62. The wire thickness must be reduced by a factor $\sqrt{(1 / 1.231)}$ = 0.9 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 13 V, as the curves of the test winding for 16 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-1.8W rotor for different wind speeds are determined in chapter 5 of KD 464 and are given in figure 4 of KD 464. This figure is copied as figure 2 but the estimated P_{mech}-n and P_{el}-n curves of the 8-pole generator for 26 V star are replaced by the estimated P_{mech}-n and P_{el}-n curves of the 16-pole generator for 13 V star. It is assumed that the P_{el}-n curve for 13 V star starts at a rotational speed of 250 rpm. So in this case, the generator winding has to be chosen such that the open DC-voltage is 13 V at n = 250 rpm. It is assumed that the efficiency is 85 % for n = 350 rpm and that it is 60 % for n = 650 rpm.

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 3). The charging voltage at high powers will be somewhat higher than the average charging voltage of 13 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 m/s. In the P_{el}-V curve it can be seen that the maximum power is 230 W and that supply of power starts already at a wind speed of 2.6 m/s ($V_{cut\ in}$ = 2.6 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 if the sticking torque of the generator is 0.08 Nm. So for this sticking torque, there is no hysteresis in the P_{el}-V curve.

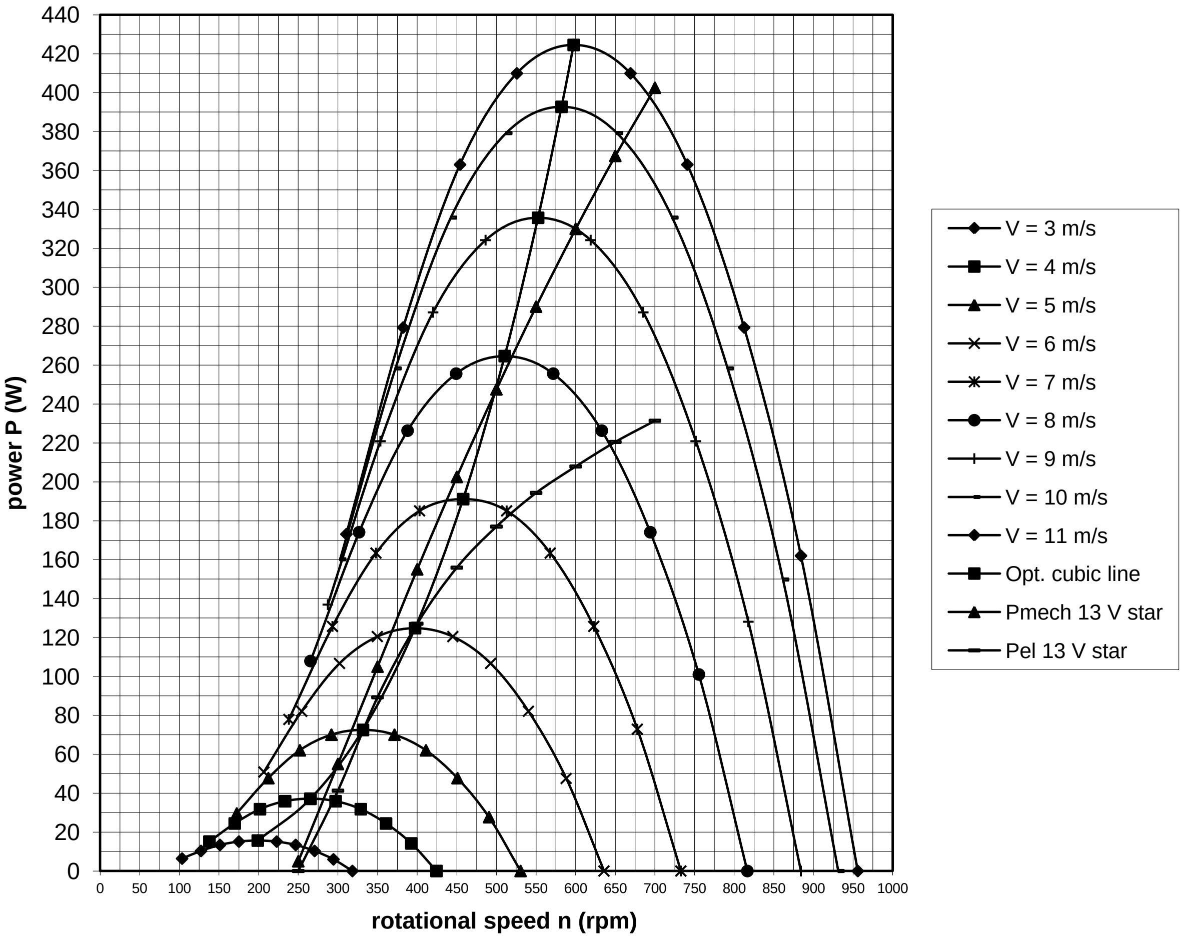

fig. 2 P-n curves of the VIRYA-1.8W rotor, optimum cubic line, estimated P_{mech}-n and P_{el}-n curves of the 16-pole PM-generator for 13 V star

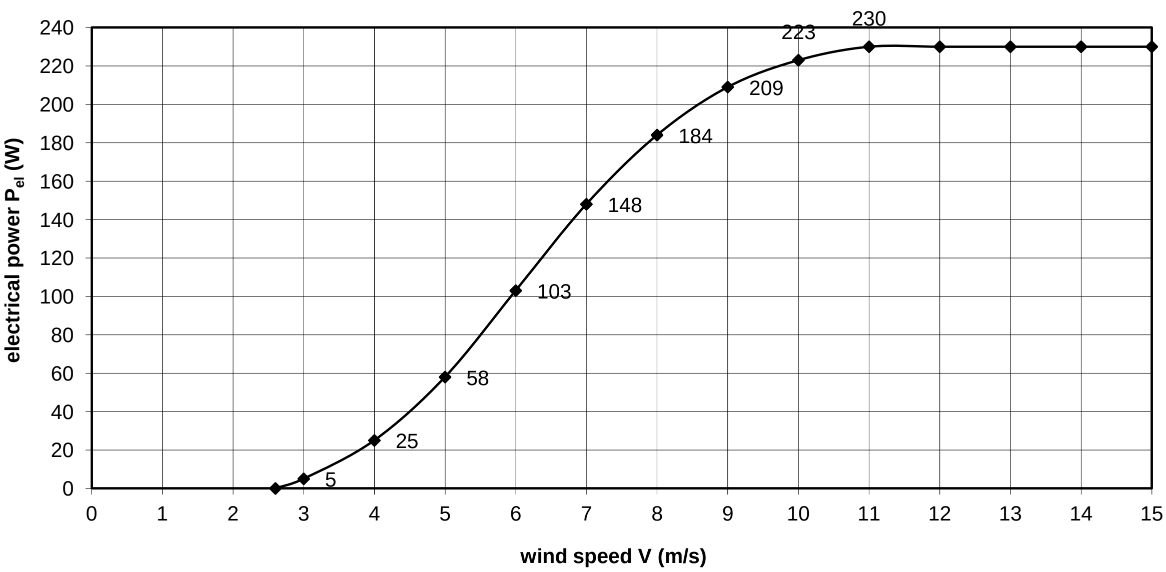

fig. 3 Estimated P_{el}-V curve VIRYA-1.8W for 12 V battery charging

6 References

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