Ideas about a 28-pole, 3-phase permanent magnet generator using the housing and winding of a 4-pole asynchronous motor frame size 80

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1 Introduction

One of the most critical parts of a small wind turbine is the generator. For my older range of VIRYA windmills, I have developed a range of PM-generators. These generators are derived from standard asynchronous 4-pole, 3-phase motors by replacing the original shaft and short-circuit armature by a stainless steel shaft and a mild steel armature which is provided by neodymium magnets. These generators (and several others types) are described in my public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking torque isn't fluctuating because the armature poles are making a certain angle with the axis. This facilitates starting of the rotor at low wind speeds.

The original shaft and armature is thrown away and a new stainless steel shaft and a new mild steel armature have to be made. Deep, inclined grooves have to be milled in the armature which needs special tools and is rather complicated and time consuming. 10 mm thick neodymium magnets have to be glued in the grooves. The whole generator is therefore rather difficult to manufacture and rather expensive.

I did several attempts to design a PM-generator which is simpler or cheaper and wrote KD-reports about every new idea. I have described radial flux and axial flux generators and generators with and without iron in the coils. The main disadvantage of a generator without iron in the coils is that this results in a big air gap. A big air gap reduces the magnetic flux flowing through the coils and therefore many thick and expensive magnets have to be used. The main disadvantage of a generator with iron in the coils is that this iron results in eddy currents and that the generator may have a strong peak on the sticking torque if the armature isn't designed properly. A large peak on the sticking torque results in a high starting wind speed if a fast running windmill rotor with a low starting torque coefficient is used.

There are several ways to reduce the peak on the sticking torque. I way to realise this for a 4-pole generator made from an asynchronous motor frame size 100 with 36 stator slots and using sixteen magnets size 40 * 15 * 5 mm, is described in report KD 718 (ref. 2). In this report KD 730 it is researched if a similar way can be used for a smaller generator with 24 stator slots using a housing of frame size 80 and smaller magnets. An advantage of a 4-pole generator is that the standard 230/400 V, 3-phase motor winding can be used for 24 V or 48 V battery charging if the winding is rectified.

A starting point for this generator is that it can be made from the housing of a standard 4-pole asynchronous motor frame size 80. This has as advantage that the housing and the bearing covers are rather cheap because they are already manufactured in large quantities. Another important advantage is that a housing of an asynchronous motor is water tight if the shaft is provided by an IP-55 seal. A generator of frame size 80 has a shaft diameter at the front bearing of 20 mm and a shaft end with a diameter of 19 mm, a length of 40 mm and a 6 mm wide key groove. It can be used for a direct drive windmill rotor with a diameter of about 1.8 m. A PM-generator made from an asynchronous motor has a magnetic flux which is radial at the air gap in between the armature and the stator stamping, so this generator will be of the type "radial flux".

2 Description of the 28-pole PM-generator

2.1 General

It is chosen to take an asynchronous motor in which a stator stamping of the German manufacture Kienle & Spiess is used. Information about dimension of stator stampings of this manufacture are given on the website: www.kienle-spiess.de. The chosen stator stamping has the code: IEC 80/4.70. The outside diameter is 120 mm, the inside diameter is 70 mm. This stamping is used for a 0.75 kW, 4-pole motor and the length of the stator stamping is 80 mm for this motor. The stamping has 24 slots, so in between these slots there are 24 stator poles.

The stamping has six 3.07 mm holes at a pitch circle of 115 mm. The manufacturer which uses this stamping of Kienle & Spiess for its 0.75 kW motor has not yet been selected. It is chosen to use this stamping for an armature with four magnetic poles. A 4-pole armature has normally two north and two south poles. The angle in between the heart of a north pole and the heart of a south pole is 90° for a 4-pole generator. This means that the optimum angle in between two legs of a stator coil is 90° too. However, it isn't possible to use this angle for all coils if the stator stamping has 24 slots. This problem is solved by using two coils which are lying within each other and for which the inner coil has an angle of 75° and for which the outer coil has an angle of 105°.

If the armature pole angle is chosen 90°, it means that the generator will normally get 24 preference positions per revolution. The armature will get a preference position when the magnetic flux in between armature and stator flows easiest. This is the case when there is a maximum overlap in between an armature pole and some of the stator poles.

If the armature poles are inclined with an angle such that there is just one stator pole pitch overlap in between the left and the right side of the armature pole, this problem is solved. However, inclined armature poles can only be gained if the magnets are placed in deep narrow grooves with the magnet area tangential and if there is magnetic isolation in between the north and the south poles. This procedure is used for the older VIRYA generators and the armature construction is explained in chapter 4 of report KD 341 (ref. 1).

2.2 Description of the armature

This new generator has an armature which is made from a 70 mm diameter and 80 mm long steel bush which is pressed on the original motor shaft. The bush is turned to a diameter of 69.4 mm after pressing. It is chosen that the magnets are positioned in fourteen 7 mm wide and 3.2 mm deep grooves with the magnet area radial and that the grooves are made in parallel to the armature axis. The angle in between the heart of the grooves is 360 / 14 = 25.714°. So a short and stiff 7 mm diameter cutter can be used. Two magnets size 40 * 7 * 3 mm are glued in each groove with epoxy or anaerobe glue. So totally 28 magnets are needed for one armature. In between each row of magnets there is a pole which is formed by the steel armature bush.

The magnets are glued in such a sequence that the armature works well in combination with the original 230/400 V, 3-phase, 4-pole stator motor winding. This is realised by using four rows of magnets with the north poles to the outside for one magnetic north pole and three rows of magnets with the south poles to the outside for one magnetic south pole. One magnetic north pole contains also three poles formed by the steel bush and so it has totally seven north poles. One magnetic south pole contains also four poles formed by the steel bush and so it has totally seven south poles. So mechanically, the armature has totally 28 poles. However, because seven rows of the same poles are lying against each other, physically it is still a 4-pole armature and so it can be used in combination with the winding of a 4-pole motor.

So the armature has totally 28 poles in the following sequence: N1, N2, N3, N4, N5, N6, N7, S1, S2, S3, S4, S5, S6, S7, N8, N9, N10, N11, N12, N13, N14, S8, S9, S10, S11, S12, S13 and S14. The odd pole numbers of the north poles and the even pole numbers of the south poles are formed by the magnets. The even pole numbers of the north poles and the odd pole numbers south poles are formed by the steel armature bush.

At each side of a 7 mm wide magnet groove there is a 0.8 mm wide and 2.2 mm deep groove to make that the poles which are formed by the armature bush also have a width of about 7 mm and to prevent magnetic short-circuit in between a north and a south pole at the sides of a magnet. These grooves can be made with an 8 mm cutter.

The stator has 24 slots so it has 24 poles and so the stator pole angle is 15°. The stator poles are numbered 1 – 24. The armature has 28 poles so the armature pole angle is 12.857°. So the difference in between the stator pole angle and the armature pole angle is 2.143°.

In figure 1, the armature is drawn such that the heart of north pole N1 is just opposite stator pole no. 1. The armature will therefore have a preference position for the drawn position. However, it will have a preference position for N2 if the armature has rotated 2.143° right hand. So the armature will have 360 / 2.143 = 168 preference positions per revolution. This seems enough to flatten the peak on the sticking torque up to an acceptable low value.

It might be possible to use a motor housing with a stator stamping of another manufacture. However, there is one important condition and that is that it isn't allowed to use a stator stamping with four outside grooves. Thin strips with bent ends, lying in these grooves, are used to connect all stampings together. These stampings are generally used in India. Four outside groves in the stator stamping make that the armature will get four strong preference positions per revolution for the position of the armature for which the magnetic flux in the stator is least hindered by the four outside grooves. The six 3.07 mm holes at a pitch circle of 115 mm in the stamping IEC 80/4.70 of Kienle and Spiess may cause six small extra preference positions per revolution. These preference positions can be prevented by placing of a mild steel rod with a diameter of 3 mm and a length of 80 mm in each hole.

The neodymium magnets are supplied by the Polish company Enes Magnets website: www.enesmagnets.pl. The magnets of this company are rather cheap if compared to magnets with the same volume of other magnet suppliers. The magnets size 40 * 7 * 3 mm have quality N38SH. The current price for one magnet is € 0.86 including VAT but excluding transport if at least 200 magnets are ordered. 28 magnets are needed for one generator, so the magnet costs for one generator are about € 25 which is rather cheap for this generator size.

The armature is made of an 80 mm long mild steel bush with an outer diameter of 70 mm. The armature is pressed on the original motor shaft such that the sides of the armature coincide with the sides of the stator stamping. The bearings and the original short-circuit armature have to be removed first from the shaft if an original motor shaft is used. The original short-circuit armature has an inner diameter of 25 mm. The original motor shaft is provided with small grooves in the direction of the axis to guarantee a strong press fitting. As the original stator stamping is made of very soft steel, it might be required to give the new armature an inside diameter which is a little larger than 25 mm, so for instance 25.1 mm, otherwise the required pressing force may be too high. The armature is turned to a diameter of 69.4 mm after pressing it on the shaft. This must be done such that the outside is exactly concentric to the two bearing seats. So the air gap in between the poles which are formed by the armature bush and the stator becomes (70 – 69.4) / 2 = 0.3 mm.

The 7 mm wide grooves for the magnets are made that deep that the distance in between the bottom of the groove and the axis of the shaft is 31.5 mm. This means that the depth of the groove measured from the outside of the armature is 34.7 – 31.5 = 3.2 mm. The magnets are not jutting out of the armature for this groove depth. The average air gap at the magnets is somewhat larger than the air gap at the poles formed by the armature bush but this is no problem.

The front bearing cover at the shaft side has an oil seal. No fan is needed and so the back bearing cover is closed and the back bearing cover therefore has no seal. The shaft has to be shortened if the back bearing cover is closed. The bearings have an internal rubber seal at both sides. The space in between the front bearing and the shaft seal is filled with grease to create an extra barrier against the entrance of water and dust. So the original motor shaft can be used and stainless steel isn't needed for its anti magnetic qualities as it is the case for the older VIRYA generators with inclined magnet grooves. A cross section and a side view of the generator armature are given in figure 1 at chapter 2.3.

Instead of removing the complete original short-circuit armature, one can also use a bush made of seamless steel pipe size 70 * 6. This pipe has a nominal inside diameter of 58 mm. The armature is turned to about 57.8 mm and an 80 mm long bush is glued to the pipe by anaerobe glue. The outside is turned to 69.4 mm.

2.3 Description of the stator

The stator stamping is pressed in the aluminium generator housing. The stator stamping has 24 slots in which the coils are laid. In between the 24 slots we have 24 stator poles which are numbered 1 – 24.

Two slots are used for one coil, so 12 coils can be laid in 24 slots. Every phase has four coils for a 3-phase winding. The slots are provided with a thin slot isolation. After mounting of the coils, a slot cap is shifted in each slot to prevent that the coils can come out of the slots and touch the rotating armature. It will be needed so soak the whole assembly of coils in liquid lacquer to prevent vibration of the wires if a new winding is laid. In chapter 2.1 it was already explained that two coils of one phase are positioned within each other.

The winding is a so called 2-layers winding. This means that the three bundles of three coils U1 and U2, V1 and V2 and W1 and W2 are laid in the first layer. The coil heads of these six coils are bent to the outside to make place for the six coils of the second layer U3 and U4, V3 and V4 and W3 and W4. The two coils of a certain phase in one layer are always connected in series because the voltage generated in each of the coils isn't the same. The two coils of the first layer can be connected in series with the two coils of the second layer or they can be connected in parallel. But all four coils of a standard 230 / 400 V winding are normally connected in series.

The two coils of a coil bundle of one phase are made outside the generator. The first layer with two coils has an end labelled A and an end labelled B. The second layer with two coils has an end labelled C and an end labelled D. So the ends B and C are normally soldered to each other. The soldering point is isolated and is lying somewhere on the coil heads. The both ends A and D of each phase are connected to a terminal with six tags in a way as this is normally done for a 3-phase winding.

The winding can be connected in star or in delta. For star connection, the three coil ends labelled A are connected to each other by brass strips and are forming the star point. The three coil ends labelled D are guided to the three contacts of a 3-phase rectifier. It is also possible to connect the winding in delta by using three brass strips in parallel and this reduces the voltage by a factor $\sqrt{3}$.

Which way of rectification has to be used depends on the choice of the windmill rotor and the battery voltage. A standard 230 / 400 V winding will give a rather high voltage already at low rotational speeds and so it won't be possible to use the generator for 12 V battery charging for the original winding. The original winding might be useful for 24 V battery charging if the winding is rectified in delta and for 48 V battery charging if the winding is rectified in star.

The standard 230 / 400 V winding can be modified into a 115 / 200 V winding if the coil bundles of the first and second layer of a certain phase are connected in parallel in stead of in series. So coil end C is connected to coil end A and coil end D is connected to coil end B. This procedure is explained in detail in report KD 341 (ref. 1). A modified 115 / 200 V winding can be used for 24 V battery charging if the winding is rectified in star and for 12 V battery charging if the winding is rectified in delta. But a 12 battery voltage will result in rather large maximum currents and so in high cable losses in between the generator and the battery if thin and long wires are used. So 12 V battery charging is only advised if cables with a sufficient copper area are used. The losses are minimal if the rectifier is placed at the tower foot because then a 2-phase cable can be used.

A prototype of the generator has to be measured and a windmill rotor with the correct rotor diameter and design tip speed ratio has to be chosen for correct matching (see chapter 4).

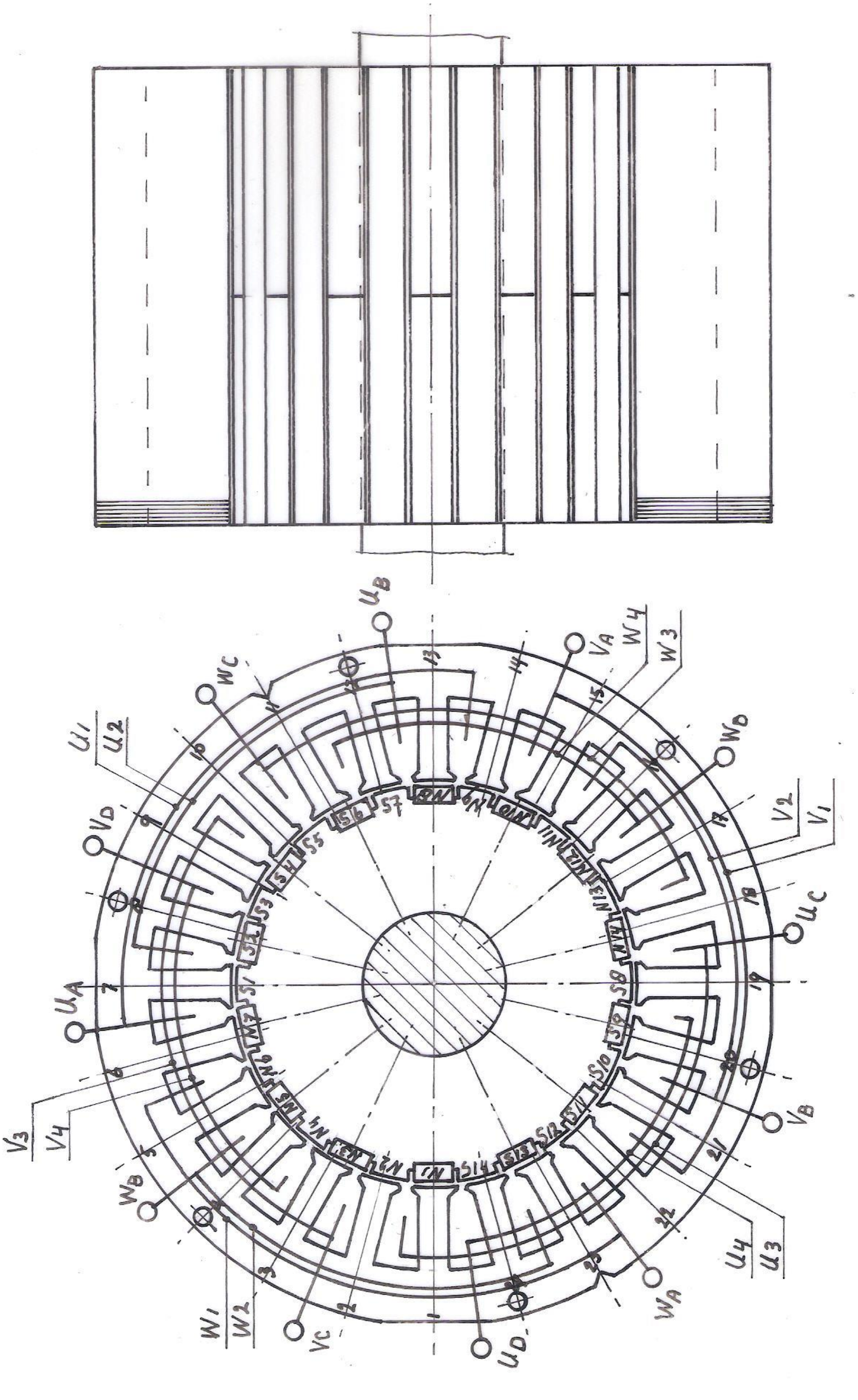

fig. 1 28-pole, 3-phase PM-generator with a 4-pole, 2-layers, 230/400 V, 3-phase winding

3 Determination of the flux density in the air gap

A part of a magnetic loop is flowing inside the armature and a part is flowing inside the stator. Four magnetic loops are coming out of a normal 4-pole armature. Two loops are turning left hand and two loops are turning right hand. However, sixteen magnetic loops are coming out of this special 28-pole armature. Eight loops are turning left hand and eight loops are turning right hand. Four left hand turning loops will be followed.

The magnetic flux coming out of the magnet of north pole N1 flows through the large air gap t_3 into the stator stamping. Next it makes a left hand bend. Next it flows through the small air gap t_2 and enters the south pole S14. Next it flows into the steel armature bush, making a left hand bend and enters the magnet of the north pole N1 again. So this magnetic loop flows through one magnet and the two air gaps t_2 and t_3.

The magnetic flux coming out of north pole N2 flows through the small air gap t_2 into the stator stamping. Next it makes a left hand bend. Next it flows through the large air gap t_3 and enters the magnet of south pole S13. Next it flows into the steel armature bush, making a left hand bend and enters the north pole N2 again. So also this magnetic loop flows through one magnet and the two air gaps t_2 and t_3. The only difference is that this second loop is longer than the first one as it lies around the first one.

The magnetic flux coming out of the magnet of north pole N3 flows through the large air gap t_3 into the stator stamping. Next it makes a left hand bend. Next it flows through the small air gap t_2 and enters the south pole S12. Next it flows into the steel armature bush, making a left hand bend and enters the magnet of the north pole N3 again. So also this magnetic loop flows through one magnet and the two air gaps t_2 and t_3. This third loop is even longer than the second one.

Only half of the north pole N4 and one half of the south pole S11 is used for a left hand loop. The magnetic flux coming out of half the north pole N4 flows through the small air gap t_2 into the stator stamping. Next it makes a left hand bend. Next it flows through the large air gap t_3 and enters the half the magnet of south pole S11. Next it flows into the steel armature bush, making a left hand bend and enters the north pole N4 again. So also this magnetic loop flows through one magnet and the two air gaps t_2 and t_3. However, as only half of the poles N4 and S11 are used for this fourth left hand loop, this fourth loop is less strong than the other three loops. The other half of the poles N4 and S11 are used for right hand loops.

A magnet has a thickness t_1 = 3 mm. As the glue layer is very thin, it is assumed that there is no air gap in between the inside of the magnet and the bottom of the groove.

The stator stamping has an inside diameter of 70 mm. It is assumed that the armature is turned at a diameter of 69.4 mm at the south poles. So the air gap at the poles which are formed by the armature bush t_2 = 0.3 mm. The air gap opposed to the magnets is maximal at the heart of the magnet and minimal at both sides. The groove depth is chosen such that there is a distance of 31.5 mm from the bottom of the groove up to the shaft axis. This means that the air gap at the heart of the 3 mm thick magnet is 35 – (31.5 + 3) = 0.5 mm. The air gap at the sides of the magnet is about 0.31 mm so the magnets don’t jut out of the armature. The average air gap is more than half the mathematical average because the air gap is moon shaped. Assume that the average air gap at the north poles t_3 = 0.45 mm.

The flux density in the air gap is calculated by formula 5 from report KD 341 for a PM-generator with tangential orientation of the magnets. A simpler formula can be derived for this PM-generator with radial orientation of the magnets if the magnetic resistance of the iron is neglected and if it is assumed that the magnetic resistance of the magnets is the same as for air. Formula 1 of KD 341 changes into:

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

For radial positioning of the magnets, the pole area is the same as the magnet area. So it isn't necessary to compare the magnet area with the pole area as it is required for tangential positioning of the magnets. So formula 1 can be used directly to calculate the flux density in the air gap. The used magnets with quality N38SH have a remanence B_r of about 1.24 T. Substitution of B_r = 1.24 T, t_1 = 3 mm, t_2 = 0.3 mm and t_3 = 0.45 mm in formula 1 gives that $B_{r\ eff}$ = 0.99 T.

In KD 341 it is assumed that the stator stamping is saturated if the calculated flux density in the air gap is larger than 0.9 T. So it can be expected that the generator is saturated and so the maximum possible torque level is gained. The stator stamping can be saturated at the spokes in between the slots or at the bridge in between the bottom of the slots and the outside of the stamping. The stamping is designed for a 4-pole motor and it is used for a generator with a 4-pole winding. So if the stator stamping is saturated, it can be saturated at the spokes, at the bridge or at both.

4 Checking if the standard winding can be used

The standard winding of a 4-pole motor is meant for a 3-phase 230 / 400 V grid with a frequency of 50 Hz. It might be possible to use the PM-generator with this standard winding for 24 V or for 48 V battery charging. To verify this, one needs a test rig with which it is possible to measure the torque, the rotational speed, the voltage and the current. I have used a sophisticated test rig of the University of Technology Eindhoven for measuring my older VIRYA generators but this was done long ago. I have also developed a simple private test rig for very small axial flux generators but this test rig is too small for this 4-pole generator. I will not perform measurements for this new generator.

First the generator is connected in star and the P_{mech}-n and P_{el}-n curves are determined for a 48 V battery of sufficient capacity or for a battery charge controller which is adjusted at a constant voltage of 52 V. A voltage of 52 V is about the average charging voltage for a 48 V battery. Next the generator is connected in delta and the P_{mech}-n and P_{el}-n curves are determined for a 24 V battery of sufficient capacity or for a battery charge controller which is adjusted at a constant voltage of 26 V. A voltage of 26 V is about the average charging voltage for a 24 V battery. Rectification of a 3-phase winding is explained in KD 340 (ref. 3).

Next the P-n curves of the chosen windmill rotor are determined for different wind speeds and these curves are drawn in a P-n graph. A windmill rotor has a certain optimum cubic line which can be drawn through the tops of the P-n curves of the rotor for different wind speeds. The formula for the optimum cubic line is given in chapter 8 of report KD 35 (ref. 4). The optimum cubic line is also drawn in the P-n graph with the generator measurements. If the correct parameters have been chosen for the windmill rotor, the P_{mech}-n curve of the generator for 52 V star and for 26 V delta will have a good matching with the optimum cubic line of the chosen rotor. Good matching means that both curves have two points of intersection which are not lying far apart. If there is no good matching for none of the P_{mech}-n curves of the generator, one has to change the parameters of the windmill rotor (matching is explained in chapter 8 of report KD 35 ref. 4).

Already in 2000 I have built and measured a 4-pole PM-generator made from a 0.6 kW asynchronous motor frame size 71 (with lengthened stator stamping). This motor was of manufacture ROTOR and the stator stamping differs from the stampings of Kienle & Spiess. This generator was used for the VIRYA-1.8 and the VIRYA-1.75 windmills. Use of the new 28-pole generator for these windmills requires change of the hub and the generator bracket.

The armature diameter is 65 mm and the armature length is 71 mm. This gives an armature volume of 235600 mm^3. The armature volume of the 28-pole generator is 302621 mm^3, so a factor 1.284 larger. However, four strong magnets size 67 * 20 * 10 mm were used for the 4-pole generator and the maximum torque level might therefore still be about the same as for this new 28-pole generator. The generator measurements of the 4-pole generator are given in report KD 54 (ref. 5). This report is not public as it is not digital.

However, new digital P_{mech}-n and P_{el}-n curves can be made in Excel using the original measuring points for 13 V delta, 26 V delta and 52 V delta. A voltage of 13 V is about the average charging voltage for a 12 V battery. The curves have been measured up to 1000 rpm but the curves are only given up to 500 rpm in figure 2. The generator should not be used at high rotational speeds because the efficiency will be very low, especially for 13 V delta. It is expected that the curves for this new 28-pole generator are about the same.

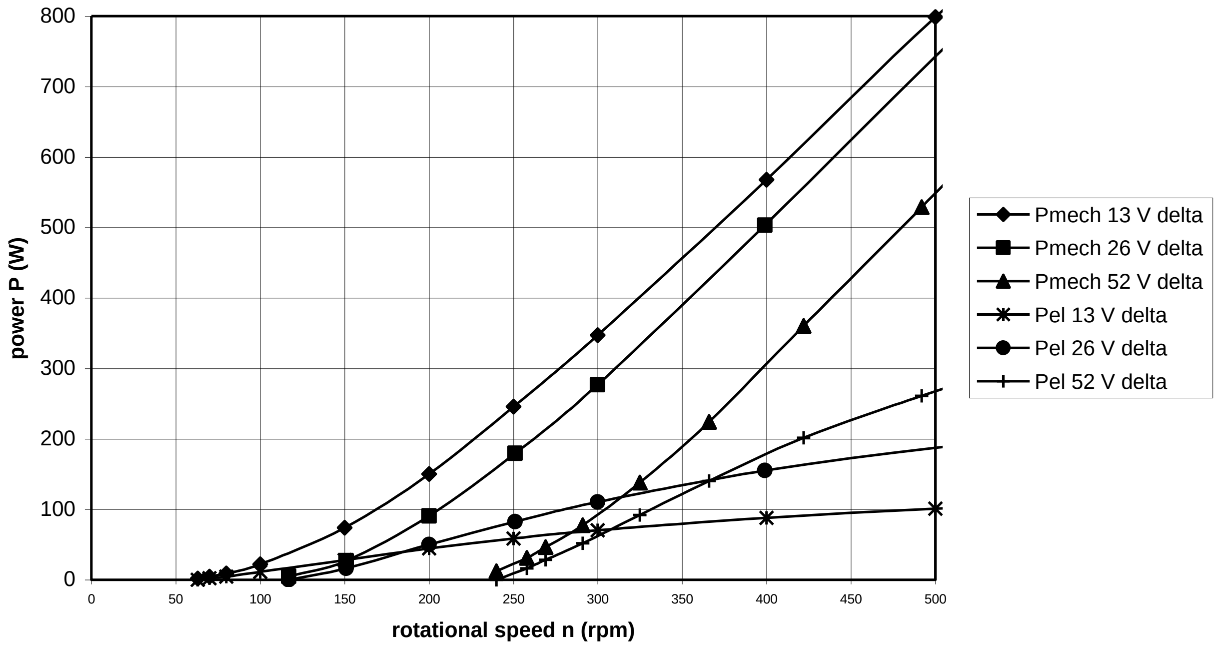

fig. 2 Estimated mechanical power P_{mech} and electrical power P_{el} as a function of n for U = 13 V, U = 26 V and U = 52 V rectified in delta for rotational speeds up to 500 rpm

5 Alternative 4-pole winding with coils piled up like roof tiles

The winding as given in figure 1 is most common for a small 4-pole, 3-phase asynchronous motor. The advantage of this winding is that one can lay first the three coil bundles of the coils U1 + U2, V1 + V2 and W1 + W2 in the first layer and then the three coil bundles of the coils U3 + U4, V3 + V4 and W3 + W4 in the second layer. However, this winding has some disadvantages. The first disadvantage is that the outer coil of a coil bundle is longer than the inner coil. The second disadvantage is that the angle in between the legs of a coil isn't 90°. The angle is 75° for the inner coil and 105° for the outer coil. As the armature pole angle is 90°, this means that only a part of the magnetic flux of the armature is flowing through a coil. For the inner coil this results in a reduction of the voltage by about a factor 75 / 90 = 0.833. If a north pole is just opposite to an outer coil, at both sides of the coil there will also be a small part of the south pole. The reduction of the voltage for the outer coil is therefore also about a factor 0.833. The third disadvantage is that the coil heads of the inner layer are crossing the coil heads of the outer layer.

There is an alternative winding possible for which all coils have the same length and for which there are no crossing coil heads. This winding is given in figure 3. The coil heads are now piled up like roof tiles. However, this winding has as disadvantage that now all twelve coils have to be laid together and this is very difficult for a small armature. So piling up like roof tiles, is normally only used for bigger stator stampings. The coils are laid in the following sequence: U1, U2, V1, V2, W1, W2, U3, U4, V3, V4, W3 and W4. A problem with coils U1 and U2 is that the left legs can only be pushed in the slots after coils W3 and W4 are laid.

Both coils in one coil bundle now have the ideal pitch of 90° in between the left and the right leg. However, both coils are shifted 15° with respect to each other in the stator.

This means that the voltage generated in coil U1 is out of phase to the voltage generated in coil U2. The armature has the same magnetic position if it has rotated 180°. So an angle $\beta = 180°$ at the stator corresponds to a phase angle $\alpha = 360°$. So an angle $\beta = 15°$ at the stator corresponds to a phase angle $\alpha = 30°$. Two sinusoidal voltages which have a phase shift with respect to each other result in one sinusoidal voltage if they are added. The resulting voltage U is given by:

$$U = U_{max} \sin(\alpha - 15°) + U_{max} \sin(\alpha + 15°) \quad \text{(V)} \qquad (2)$$

U_{max} is the maximum voltage of one phase. It can be proven that this function has a maximum for $\alpha = 90°$. This gives for the total maximum voltage $U_{max\ tot}$ that:

$$U_{max\ tot} = U_{max} \{\sin 75° + \sin 105°\} = 1.932 * U_{max} \quad \text{(V)} \qquad (3)$$

If the voltages generated in coils U1 and U2 would be exactly in phase, it would be valid that $U_{max\ tot} = 2 * U_{max}$. So the fact that both voltages are not in phase, results in reduction of the voltage by a factor 1.933 / 2 = 0.966. This factor is much higher than the factor of 0.833 which was found for the winding of figure 1. Another advantage is that the coil heads are shorter than the coil heads of the outer coils of figure 1 and so the ohmic losses are also somewhat lower. So a winding for which the coils are piled up like roof tiles is more efficient. But the difficult procedure to mount the coils makes that the winding of figure 1 is more common for small stator stampings.

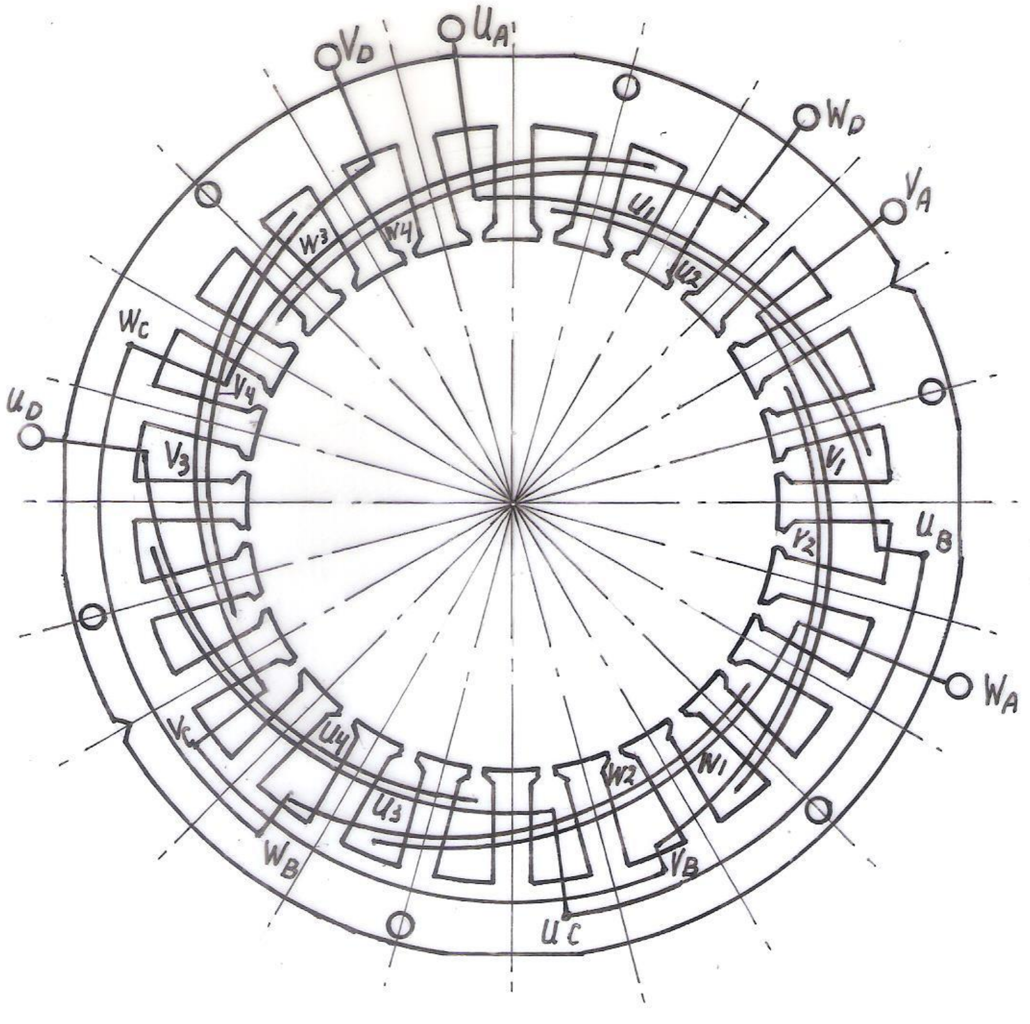

fig. 3 Alternative 4-pole winding with coils piled up like roof tiles

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