# Ideas about a 16-pole, 3-phase axial flux permanent magnet generator for the VIRYA-3D2 windmill using 16 neodymium magnets size 50 * 15 * 15 mm

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## 1 Introduction

One of the most critical parts of a small wind turbine is the generator. As far as I know, simple and cheap direct drive 3-phase permanent magnet (PM) generators are not available on the market. For my current range of VIRYA windmills, I therefore 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 are described in public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking torque is not fluctuating because the armature poles are making a certain angle with the axis. This facilitates starting of the rotor at low wind speeds.

The sticking torque can be eliminated by using a generator with no iron in the coils. A 4-pole, 3-phase axial flux generator of this kind is described in public report KD 522 (ref. 2). This generator is meant for battery charging after rectification of the winding.

In report KD 530 (ref. 3) the rotor of the VIRYA-3D2 windmill is described. This windmill will be equipped with a 16-pole axial flux generator with no iron in the coils. The VIRYA-3D2 windmill is meant to be coupled to a 0.75 kW, 3-phase motor of a centrifugal pump. The axial flux generator has about the same mechanical construction as the construction of the 4-pole generator described in report KD 522 but the winding is different.

## 2 Description of the generator (see figure 1)

The generator is of the type ”axial flux” which means that the air gap in between rotor and stator is perpendicular to the generator shaft. So the direction of the magnetic flux in the air gap is parallel to the generator shaft.

The most simple 3-phase generator has a rotor with only two poles and a stator with only three coils. However, the frequency will be very low for this configuration if this generator is used as a direct drive windmill generator.

It is chosen to use 16 rotor poles, so the pole angle in between the rotor poles is 360 / 16 = 22.5°. The eight north poles are called N1 – N8. The eight south poles are called S1 – S8. It is chosen to use 15 stator poles, so the pole angle in between the stator poles is 360 / 15 = 24°. So the difference in between the stator pole angle and the rotor pole angle is 24° - 22.5° = 1.5°.

The three phases are called U, V and W. So there are five coils U1 – U5, five coils V1 - V5 and five coils W1 – W5. The orientation of the rotor poles with respect to the stator poles is given in figure 1 for the position that rotor pole N1 is just opposite stator pole U3.

For the magnets it is chosen to use neodymium magnets size ϕ 50 * 15 * 15 mm which are supplied by the Internet company www.supermagnete.de. These magnets have quality N48 and a remanence $B_r$ in between 1.37 T and 1.42 T. The current price is € 8.23 per magnet including VAT and excluding mailing costs for an order of 40 magnets, so the magnet costs for one generator are about € 132 which seems to be acceptable.

The generator consists of two square steel sheets with a height and width of 248 mm and a thickness of 6 mm. 32 sheets can be laser cut from a standard sheet of 1 * 2 m. The corners of the sheet are bevelled. The sheets are kept at a distance of 30 mm from each other by four stainless steel bushes with 15 mm diameter and 30 mm length.

The 16 magnets are glued to the backside of the front steel sheet. The pitch circle of the magnets is chosen 198 mm. The windmill rotor is mounted to the front side of the front square sheet by two stainless steel inner hexagon bolts M8 * 25 mm and one central nut M24. This nut is also used for connection of the front sheet to the generator shaft.

The back square sheet has the same outer dimensions as the front sheet but it has a 100 mm central hole which runs free from the bearing housing. The distance in between the front sheet and the back sheet is 30 mm. The thickness of the magnets is 15 mm, so the air gap for the magnetic flux is 15 mm.

The five coils of one phase are mounted close to each other. The coils are pored into an epoxy (or polyester) disk with an outside diameter of 266 mm, an inside diameter of 90 mm and a thickness of 12 mm. So the real air gap at both sides of the stator is 1.5 mm. The procedure how to determine the wire thickness and the number of turns per coil is given in chapter 5.

A stainless steel ring is cast together with the epoxy disk. The ring has an outside diameter of 90 mm, an inside diameter of 45 mm and a width of 12 mm. It has a groove at the outside for better fixation to the epoxy disk. The ring is connected to the bearing housing by four stainless steel inner hexagon bolts M10 * 30 mm at a pitch circle of 70 mm. A spring loaded oil seal size 35 * 45 * 7 mm is pressed in the centre of the stainless steel ring.

The stainless steel bearing housing is positioned at the back side of the stainless steel ring. The outside diameter is 90 mm and the length is 69 mm. The back side is closed. The back side is provided with four threaded holes M10 for connection of the generator to the head frame of the windmill.

The stainless steel shaft has a diameter of 25 mm. Two sealed bearings size 25 * 52 * 15 mm are used. A 30 mm long distance bush with an outer diameter of 35 mm separates both bearings. So the distance in between the hart of both bearings is 45 mm. The shaft has a flange at the back side and M24 thread at the front side. The shaft has a 14 mm inner hexagon hole at the front side to be able to tighten the central nut M24.

The bearing housing has an 7 mm deep chamber for the flange of the shaft. A 28.5 mm long stainless steel distance bush with an outside diameter of 35 mm is mounted in between the front bearing and the front square sheet.

A coil has an inside width of 15 mm, an inside length of 50 mm and rounded inside corners. A coil has an outside width of about 30 mm, an outside length of about 65 mm and a thickness of 12 mm. It is expected that this geometry is large enough to create a generator which is strong enough for the VIRYA-3D2 rotor. All five coils of one phase are connected in series. The three bundles of five coils are connected in star.

A flexible isolated cable with a yellow colour is soldered to the end of each winding. A flexible isolated cable with a black colour is soldered to the star point. The four isolated cables are coming out of the front side of the epoxy disk.

An external star point has as advantage that the star point can be short-circuited too if the generator is used as a brake by making short-circuit in between the three phases. The maximum braking torque will be larger if the start point is short-circuited too.

Four 8 mm holes are drilled in the stainless steel ring and in the bearing housing at a pitch circle of 70 mm, just in between the four threaded holes M10. Each isolated cable is guided trough one of these holes. A prototype of the generator has to be built and tested to prove if the generator is strong enough for the VIRYA-3D2 rotor.

The same idea of a generator for which the number of stator coils differs only one from the number of rotor poles, is described for the VIRYA-3.9 generator in report KD 529 (ref. 4). This generator has 22 rotor poles and 21 stator coils. The VIRYA-3.9 is meant to be coupled to a 1.1 kW, 3-phase motor of a centrifugal pump.

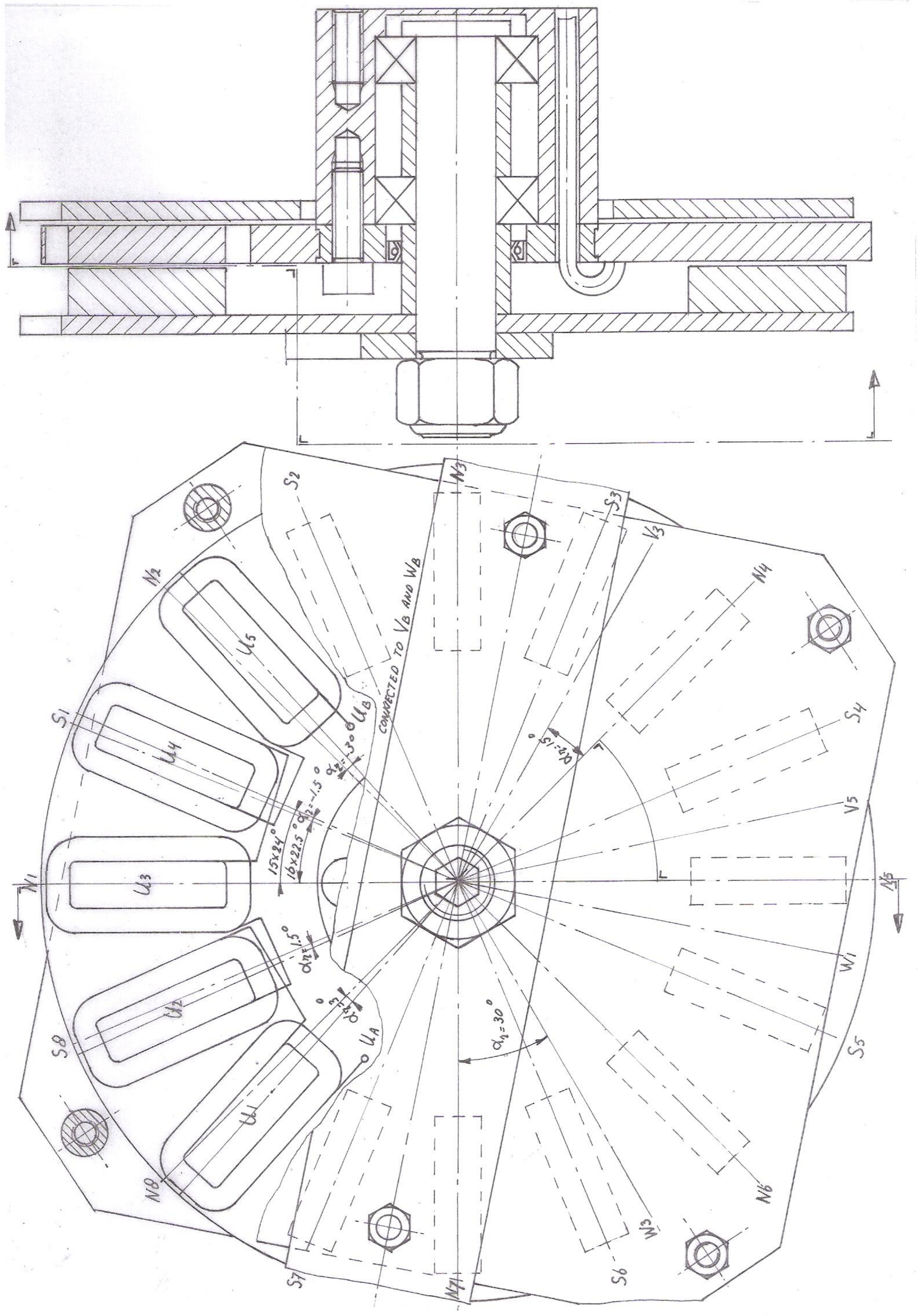

fig. 1  16-pole axial flux permanent magnet generator VIRYA-3D2

## 3 Mounting sequence of the generator and the rotor

1 The back bearing is pressed to the shaft.
2 The 30 mm long distance bush is shifted over the shaft.
3 The front bearing is pressed to the shaft.
4 The assembly of shaft and bearings is pushed in the bearing housing.
5 The oil seal is pressed in the stainless steel ring of the stator.
6 The four isolated cables are pushed through the four holes in the stainless steel ring and in the bearing housing.
7 The stator is bolted to the bearing housing using four inner hexagon bolts M10 * 30.
8 The 28.5 mm long distance bush is pushed over the shaft.
9 The 16 magnets are glued to the front square sheet such that eight north and eight south poles are created.
10 The four 30 mm long stainless steel studs are bolted to the corners of inside of the front sheet using four stainless steel bolts M8 * 20 mm.
11 The assembly of the front sheet, the magnets and the studs is shifted over the shaft and locked with the M24 nut. One needs an 8 mm auxiliary ring which is placed in between the nut and the front sheet.
12 The back square sheet is shifted over the bearing housing till it is pulled against the four studs. This pulling force will be very large so the front sheet must be connected to a solid structure and the back sheet should be lowered slowly by a hoist. The back sheet is connected to the studs by four stainless steel bolts M8 * 20 mm.
13 The two rotor blades are connected to the central strip using six bolts M10.
14 The rotor is balanced on a frictionless shaft at a windless place.
15 The generator housing is mounted in a vice with the shaft end upwards. The nut M24 and the auxiliary ring are removed.
16 The central strip is connected to the front square sheet using the nut M24 and two stainless steel inner hexagon bolts M8 * 25 mm and two self locking nuts M8.
17 The generator bracket of the head frame has a thickness of 8 mm. It has the same hole pattern as the bearing housing, so four 10.5 mm holes for the bolts M10 and four 8 mm holes for the isolated cables. The four isolated cables are shifted through the four 8 mm holes of the bracket.
18 The assembly of generator and rotor is bolted to the generator bracket of the head frame using four bolts M10 * 30 mm.
19 A terminal box with a 4-pole terminal is mounted to the back side of the generator bracket and the four isolated cables are connected to the terminal.

## 4 Checking if a 3-phase current is generated

A 3-phase current has three phases called U, V and W. Normally the voltage U of each phase varies sinusoidal and the angle $\alpha$ in between the phases is 120°. The formulas for the voltage of each phase are:

$$U_u = U_{max} * \sin\alpha \quad (V) \qquad (1)$$

$$U_v = U_{max} * \sin(\alpha - 120°) \quad (V) \qquad (2)$$

$$U_w = U_{max} * \sin(\alpha - 240°) \quad (V) \qquad (3)$$

The three curves are shown in figure 2.

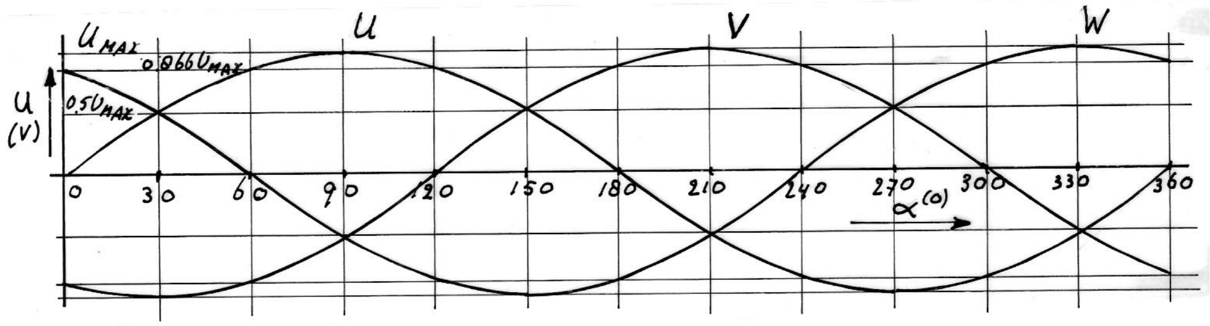


fig. 2 Three phases U, V and W

A pure sine wave is generated if a coil is rotating in a constant magnetic field because the magnetic field through the coil varies sinusoidal. If a permanent magnet is moving along a coil, the generated voltage may not be a pure sine wave, especially if the distance in between the magnets is large. But for the chosen generator configuration it is assumed that the generated voltage varies about sinusoidal. If the rotor has two poles, the position of the rotor with respect to the stator will be the same if the rotor has rotated 360°. So the phase angle $\alpha$ is the same as the rotational angle $\alpha_r$ of the rotor. If the rotor has 16 poles this will be the case for 360 * 2 / 16 = 45° rotation of the rotor. This results in the formula:

$\alpha = \alpha_r * p_r / 2$ (-) (4)

$\alpha$ is the phase angle, $\alpha_r$ is rotational angle of the rotor and $p_r$ is the number of rotor poles.

In figure 1 it can be seen that $\alpha_r$ = 0° in between N1 and U3, that $\alpha_r$ = 15° in between N4 and V3 and that $\alpha_r$ = 30° in between N7 and W3. Substitution of $\alpha_r$ = 15° and $p_r$ = 16 in formula 4 gives $\alpha$ = 120°. Substitution of $\alpha_r$ = 30° and $p_r$ = 16 in formula 4 gives $\alpha$ = 240°. So a 3-phase voltage is created in between the coils U3, V3 and W3.

In figure 1 it can be seen that there is an angle $\alpha_r$ = -1.5° in between S1 and U4 and an angle $\alpha_r$ = -3° in between N2 and U5. There is an angle $\alpha_r$ = 1.5° in between S8 and U2 and an angle $\alpha_r$ = 3° in between N8 and U1. So this means that the voltages generated in U1, U2, U4 and U5 are not in phase with the voltage which is generated in U3.

Substitution of $\alpha_r$ = 1.5° and $p_r$ = 16 in formula 4 gives $\alpha$ = 12°. Substitution of $\alpha_r$ = 3° and $p_r$ = 16 in formula 4 gives $\alpha$ = 24°. Substitution of $\alpha_r$ = -1.5° and $p_r$ = 16 in formula 4 gives $\alpha$ = -12°. Substitution of $\alpha_r$ = -3° and $p_r$ = 16 in formula 4 gives $\alpha$ = -24°.

Addition of sinusoidal voltages which are out of phase but which have the same frequency results in a voltage which is also sinusoidal. The total voltage $U_{tot}$ is given by:

$U_{tot} = U_{max} * \{\sin(\alpha - 24°) + \sin(\alpha - 12°) + \sin\alpha + \sin(\alpha + 12°) + \sin(\alpha + 24°)\}$ (V) (5)

It can be proven that this function has a maximum value for $\alpha$ = 90°.

Substitution of $\alpha$ = 90° in formula 5 gives:

$U_{tot\ max} = U_{max} * (\sin 66° + \sin 78° + \sin 90° + \sin 102° + \sin 114°) = 4.7834 * U_{max}$.

If the voltages U1, U2, U3, U4 and U5 would be exactly in phase, the resulting maximum voltage would be 5 * $U_{max}$.

So the difference in phase angle gives only a reduction of the total voltage by a factor 4.7834 / 5 = 0.957 and therefore also only a limited reduction of the generated power. So the shift in phase angles is allowed. The same counts for the coils V1, V2, V3, V4 and V5 and for the coils W1, W2, W3, W4 and W5.

In figure 1 it can be seen that coil U3 is opposite to north pole N1. Coils U2 and U4 are almost opposite to respectively south poles S8 and S1. Coils U1 and U5 are almost opposite to respectively north poles N8 and N2. This means that if coils U1, U3 and U5 are wound right hand, coils U2 and U4 must be wound left hand to make that the voltages of all five coils strengthen each other!

The five coils of one phase are wound together on a five steps winding thorn. It is easy if the winding direction of all five coils is the same so it is chosen to wind all five coils right hand. To realise the alternate winding direction in the stator, the coils with an even coil number are flipped over 180°. The wire connection for this method is given in figure 1.

A bundle of five coils U has two wire ends which are labelled $U_A$ and $U_B$. The five coils V have wire ends $V_A$ and $V_B$. The five coils W have wire ends $W_A$ and $W_B$. The wire ends $U_B$, $V_B$ and $W_B$ are connected to each other and are forming the star point.

If a 1-phase current is needed, one can make a stator with 16 instead of 15 coils.

## 5 Calculation of the flux density in the air gap and the rotor sheet

A calculation of the flux density in the air gap for the current VIRYA generators is given in chapter 5 of KD 341 (ref. 1). However, the magnet configuration of this new type PM-generator is completely different and so the formulas out of KD 341 can’t be used.

A radial flux PM-generator with a laminated stator is normally designed such that the magnetic field in the stator is just saturated. For this condition, the generator has its maximum torque level and this means that it can supply the maximum electrical power for a certain rotational speed. However, for this new axial flux generator it is not allowed that the rotor sheets are saturated because saturated rotor sheets will reduce the magnetic flux in the air gap. Saturation has to be checked for the front and for the back square sheet. The iron of a mild steel sheet is saturated at a flux density of about 1.6 Tesla (T).

The remanence $B_r$ (magnetic flux) in a neodymium magnet supplied by Supermagnete with quality N 48 is about 1.395 T if the magnet is short-circuited with a mild steel arc which is not 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 $t_1$. The magnetic resistance of the iron of the rotor sheets can be neglected if there is no saturation. So the total magnetic resistance is only caused by the magnet itself and by the air gap. For each magnet there is one 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 the effective remanence $B_{r\,eff}$. $B_{r\,eff}$ is given by:

$$B_{r\,eff} = B_r * t_1 / (t_1 + t_2) \qquad \text{(T)} \qquad (6)$$

Substitution of $B_r$ = 1.395 T, $t_1$ = 15 mm and $t_2$ = 15 mm in formula 6 results in $B_{r\,eff}$ = 0.7 T.

Next it is checked if the iron of the front square sheet is not saturated. Both sheets have the same thickness of 6 mm but the back square sheet has a 100 mm central hole which will have almost no influence on the magnetic flux in the back sheet. Let’s look at magnet N1.

Half of the magnetic flux coming out of magnet N1 will bend to the left and will flow to magnet S8. The other half will bend to the right and will flow to magnet S1. It is assumed that almost no magnet flux is flowing in the radial direction.

So the sheet area $A_{sh}$ through which the total magnetic flux has to pass is given by: $A_{sh} = 2 * 50 * 6 = 600\ mm^2$. $A_{mag}$ is called the magnet area and $i_1$ is called the concentration ratio in between $A_{mag}$ and $A_{sh}$.

$i_1 = A_{mag} / A_{sh}$ (-) (7)

Substitution of $A_{mag} = 50 * 15 = 750\ mm^2$ and $A_{sh} = 600\ mm^2$ in formula 7 gives $i_1 = 1.25$. The fact that $A_{mag}$ is larger than $A_{sh}$ results in concentration of the magnetic flux in the sheet $B_{r\ sh}$ with a factor $i_1$. So $B_{r\ sh}$ is given by:

$B_{r\ sh} = B_{r\ eff} * i_1$ (T) (8)

Substitution of $B_{r\ eff} = 0.7$ T and $i_1 = 1.25$ in formula 8 gives $B_{r\ sh} = 0.875$ T. This is much smaller than 1.6 T, so the rotor sheet is not saturated. The same counts for the back square sheet opposite the position of the magnets. Concerning the need to prevent saturation of the magnetic flux in the rotor, the sheets can be much thinner. However, it is thought that a sheet thickness of 6 mm is required to make the rotor sheets stiff enough. It must be prevented that the rotor sheets touch the stator if the rotor sheets are bent. It will also be much more difficult to realise the required flatness for a thinner sheet. The sheet material which is normally used for laser cutting is specially flattened.

At this moment I don't know if I will make a prototype of this new axial flux PM-generator. As there is no iron in the coils, the generator will have no clogging torque. The only torque will be caused by the bearing friction and by the friction of the oil seal but this torque will be very low. For this reason this generator can be used in combination with a rotor with a rather high design tip speed ratio and a rather low starting torque coefficient.

If it comes to realisation, first a stator will be made with a test winding of one phase with for instance 100 turns per coil. The wire thickness will be chosen such that the coil has the chosen volume belonging to the described coil geometry. The generator should have a loaded phase voltage of 230 V at a frequency of 50 Hz, so at a rotational speed of 375 rpm. The open phase voltage must be a lot higher because the current results in a certain voltage drop in the winding. Assume the open voltage must be 300 V at 50 Hz.

Assume an open phase voltage of 200 V is measured for n = 375 rpm. This means that the number of turns per coil has to be increased by a factor 300 * 200 = 1.5 to realise an open voltage of 300 V. So the number of turns per coil must be 1.5 * 100 = 150. The wire thickness has to be reduced such that a coil has the chosen coil geometry.

Next a stator is made with a complete 3-phase winding. First the generator is tested for a range of loads formed by three resistors for which the ohmic value can be varied. This will gives an impression what maximum power can be supplied at what efficiency. Next the generator is coupled to a 0.75 kW, 3-phase asynchronous motor for which the mechanical load can be varied. The motor is loaded up to a factor of maximum 0.9 of the nominal power so to maximum 675 W. This motor needs an electrical power of about 938 W at the nominal power. It is checked if the generator can supply this power for a loaded voltage of about 230 V.

This procedure requires an accurate test rig which is available at the University of Technology Eindhoven and which can be hired at a certain fee. I have used this test rig for my current VIRYA generators. If the laboratory tests are promising, one should test the generator in combination with a real centrifugal pump with a 0.75 kW motor and a water height such that the pump motor supplies a mechanical power of about 675 W.

## 6 Checking the bearings and the generator shaft

In figure 1 it can be seen that two ball bearings size 25 * 52 * 15 mm are chosen which are mounted at a distance of 30 mm from each other. So the distance e in between the hart of the bearings is 45 mm. The static load factor of this type of bearing $C_{stat}$ = 6950 N. The dynamic load factor C = 14000 N. The static radial load is caused by the sum of the weight of the rotor and the two square sheets which is only about 170 N. The distance in between the centre of gravity and the hart of the front bearing is about 42 mm. The distance in between the centre of gravity and the hart of the back bearing is about 87 mm. This results in an upwards reaction load on the front bearing of 170 * 87 / 42 = 352 N and a downwards reaction load on the back bearing of 352 - 170 = 182 N. These loads are very low so the static load can be neglected. The dynamic load has to be checked.

The axial load is caused by the rotor thrust. The maximum rotor thrust on one blade has been calculated in report KD 530 (ref. 2) to be 129 N, so the thrust on the two blades of the whole rotor is 258 N. This load is taken by the back bearing. A load of 258 N is a very low value. The allowable axial load is even larger than the allowable radial load because all balls take an axial load but only one ball takes a radial load. So the axial load can be neglected.

The rotor thrust will cause no bending moment in the shaft if there is no aerodynamic imbalance. It is assumed that the rotor mass is balanced perfectly so also no bending moment is caused by mass imbalance. The only bending moment is caused by the gyroscopic moment $M_{gyr}$. The maximum gyroscopic moment for one blade $M_{gyr\ bl\ max}$ has been calculated in report KD 530 and it was found that $M_{gyr\ bl\ max}$ = 31700 Nmm for a rotation speed n = 387 rpm. The maximum gyroscopic moment of the whole rotor is double this value, so $M_{gyr\ max}$ = 63400 Nmm. The maximum radial bearing load $F_{max}$ is given by:

$F_{max} = M_{gyr\ max} / e$ (N) (9)

Substitution of $M_{gyr\ max}$ = 63400 Nmm and e = 45 mm in formula 8 gives $F_{max}$ = 1409 N.

This force is much lower than the static load factor $C_{stat}$ = 6950 N so the bearing can certainly have this load for a short moment. For the lifetime of the bearing the dynamic load factor C has to be used.

The lifetime for ball bearings L, is given by the formula (from the SKF catalogue):

$L = 10^6 * (C / P)^3 / (60 * n)$ (hour) (10)

Substitution of C = 14000 N, P = $F_{max}$ = 1409 N and n = 387 rpm in formula 10 gives L = 42246 hour or about 4.82 year. This is rather long. The maximum gyroscopic moment and the corresponding rotational speed occur only during very short times at very high wind speeds so it is not realistic to calculate the lifetime of the bearings for the peak load.

The average gyroscopic moment and the average rotational speed are much lower. Assume that the average values are half the peak values which is certainly a pessimistic assumption. So assume $F_{av}$ = 705 N and $n_{av}$ = 194 rpm. Substitution of these values in formula 10 gives L = 672766 hour or about 77 year. So it can be concluded that the bearings are strong enough. Generator bearings normally don't fail because of the load but because of wear of the seals and penetration of water. Wear of the oil seal and the internal seals of the front bearing can be minimised if the space in between the seal and the front bearing is filled with grease.

The maximum bending moment in the generator shaft is caused by the gyroscopic moment $M_{gyr\ max}$. The bending stress σ for a shaft with a diameter d is given by:

$\sigma = 32\ M / (\pi * d^3)$ ($N / mm^2$) (11)

Substitution of M = $M_{gyr\ max}$ = 63400 Nmm and d = 25 mm in formula 11 gives $\sigma$ = 41.3 N/mm$^2$. This is a low stress so the shaft is strong enough for the rotor of the VIRYA-3B2 windmill equipped with the hinged side vane safety system. This safety system strongly limits the maximum angular velocities of rotor and head and therefore it strongly limits the maximum gyroscopic moment.

## 7 Functioning of the generator with the VIRYA-3D2 rotor

The P-n curves for different wind speeds for the VIRYA-3D2 rotor are given in figure 4 of report KD 530 (ref. 3). This figure is copied as figure 3.

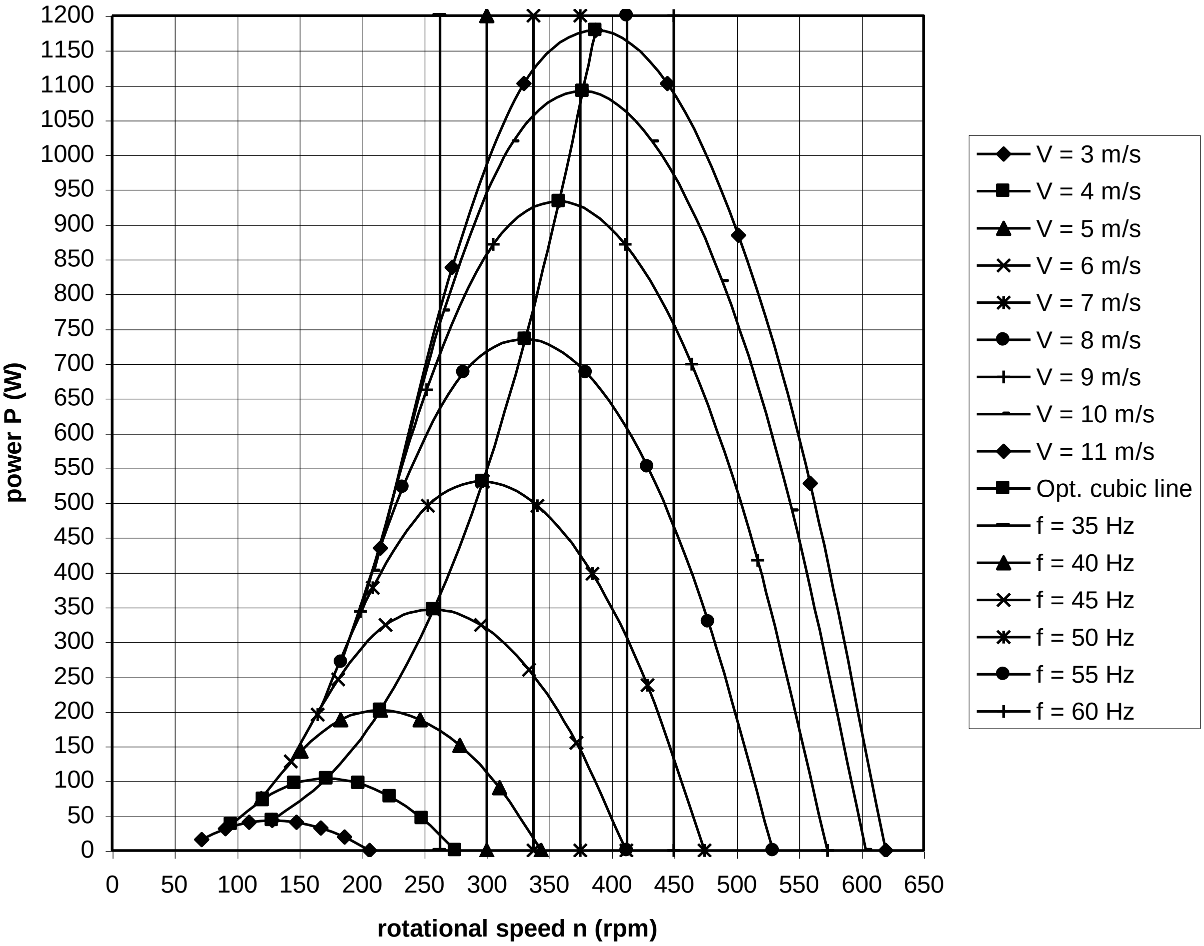


fig. 3 P-n curves of the VIRYA-3D2 rotor for $V_{rated}$ = 11 m/s, optimum cubic line and lines for 35, 40, 45, 50, 55 and 60 Hz

The optimum cubic line and the lines for a frequencies from 35 up to 60 Hz are also given in figure 3. The design point is the point where the line for f = 50 Hz intersects with the optimum cubic line. This point corresponds to a mechanical power of about 1060 W. This power is generated for a wind speed of about 9.8 m/s (see figure 4) so the design wind speed is 9.8 m/s which seems a reasonable choice for a good wind regime.

The 16-pole generator will have a high efficiency because it has no iron losses. Assume the efficiency is 0.9 at f = 50 Hz, so the electrical power is about 954 W at 50 Hz. It is assumed that the 3-phase asynchronous pump motor has a nominal mechanical power of 0.75 kW = 750 W and that it is used at a factor 0.9 of the nominal power, so at 675 W. If the pump motor has an efficiency of 0.72, the required electrical power is 938 W. This power can be generated by the generator at the design wind speed of 9.8 m/s.

A centrifugal pump has about a cubic $P_{mech}$-n curve which means that the optimum cubic line of the windmill will be followed for higher and for lower wind speeds than the design wind speed of 9.8 m/s. Below a frequency of about 35 Hz, belonging to a rotational speed of 262.5 rpm, the pump is no longer able to produce the static water height so no water will be pumped. So the connection in between the generator and the pump motor can be broken. This results in acceleration of the rotor. The connection can be made at a frequency of 46 Hz belonging to a rotational speed of 345 rpm. This frequency will be reached for an unloaded rotor for a wind speed of about 5 m/s. So the windmill will supply water intermittently if the wind speed is just above 5 m/s. For continue water supply, the wind speed must be that high that the loaded rotational speed is not becoming lower than 262.5 rpm. This is the case for wind speeds above about 6.1 m/s.

If the pump is a centrifugal pump, the system will probably also work if there is no 3-phase switch which disconnects the generator and the pump motor but then there will be no output for wind speeds just above 5 m/s. A switch will certainly be needed for a positive displacement pump as such pump demands a torque directly from stand still position.

The maximum rotational speed will be 387.2 rpm if the optimum cubic line is followed for high wind speeds. This rotational speed corresponds to a frequency of 51.6 Hz which seems acceptable for the pump motor and for the pump.

## 8 Alternatives

The first idea of this axial flux generator has been discussed with several people. Although I still believe that the original design will work, some alternatives came out of these discussions and will be given in this chapter. One has to argue oneself if an alternative is better than the original idea.

### 8.1 Iron in the stator

The magnetic flux through the coils can be increased if an iron core is used in each stator coil. The total air gap is now reduced from 15 mm up to 3 mm. Using formula 6 it can be calculated that the effective remanence $B_{r\ eff}$ increases from 0.7 T up to 1.16 T. So it increases by a factor 1.66. The flux density in the steel sheets also increases by this factor so it becomes 1.66 * 0.875 T = 1.45 T. This is still lower than 1.6 T so the steel sheets aren’t saturated. The voltage, the torque and the power at a certain rotational speed will increase by about the same factor 1.66. However, putting iron in the coils has some negative side effects.

The first side effect is that eddy currents will flow in the iron because of the changing direction of the magnetic field. The stator will heat up by these eddy currents and the generator efficiency will drop somewhat because of these losses. So it is not allowed to use massive iron coil cores. The eddy currents can be minimised if laminated iron is used. The laminated sheets must be isolated electrically from each other and the direction of the sheets must be parallel to the direction of the magnetic flux. This is a common solution for almost all electric motors but laminated iron in the needed shape is something special and may be difficult to obtain.

The second side effect is that the generator will get a sticking torque and that it will have preference positions. The difference in between the pole angle and the coil angle is 1.5°. Assume that a preference position exists if a pole is just opposite a coil, so for the position as given in figure 1. If the armature has rotated 1.5° right hand, magnet S1 is opposite to coil U4. So again this is a preference position. So there are 360 / 1.5 = 240 preference position in one revolution. The same number is found if the number of armature poles is multiplied by the number of coils. 240 preference positions in one revolution is very high and I expect that the fluctuation of the sticking torque will be rather small and that the starting wind speed will therefore be acceptable low. But the fluctuation of the torque may give some vibration and therefore some noise production at high rotational speeds.

**8.2 Choosing a smaller coil angle**

In chapter 4 it has been calculated that the voltage of the five coils of one phase is a factor 4.7834 times and not a factor 5 times the voltage of the central coil. This is because the voltage generated in the outer coils is slightly out of phase compared to the voltage generated in the central coil. This can be prevented by making the coil angle identical to the pole angle of 22.5°. However, the angle in between the three coils U3, V3 and W3 must be maintained at 120° otherwise no 3-phase voltage will be generated. This results in increase of the coil angle in between two adjacent coils of different phases from 24° up to 30°. But as all coils must be identical, this larger angle can't be filled with more copper. So this modification gives a little higher voltage but there is less room for each coil and therefore thinner thread has to be used which will reduce the efficiency. So it is better to maintain the original coil angle of 24°.

**8.3 Choosing a serpentine winding**

A voltage is generated in a coil if the magnetic flux in the coil is varying. However, a voltage is also generated in a wire if the wire is moving perpendicular to a standstill magnetic field or if a magnetic field is moving perpendicular to a standstill wire. This second principle can be used for a serpentine winding. This winding has a number of sections with radial positioning. The number of sections must be even because for each loop, a connection wire must connect both outer sections. This means that a serpentine winding is not possible for five sections.

The best choice seems to be six sections per phase if the armature has 16 poles. Six sections per phase means that three phases have totally 18 sections and the section angle is therefore 360° / 18 = 20°. The armature pole angle is 22.5° so the difference is 2.5°. This difference is larger than the 1.5° for the original option with five coils and a coil angle of 24°. So the voltage generated in the six radial sections will be more out of phase than for five coils. The voltage reduction factor will therefore be lower than 0.957. A picture of a serpentine winding of phase U with six radial sections is given in figure 4.

The six sections of phase U are called U1 – U6. It is assumed that the voltage generated in one section is maximal if the hart of the section is opposed the hart of a magnet. The position of the magnets with respect to the sections is chosen such in figure 4 that the pattern of six sections is symmetrical to the pattern of five magnets. The maximum total voltage will be generated for this position. The voltage reduction factor can be determined as follows.

In figure 4 it can be seen that there is an angle $\alpha_r$ = 1.25° in between S1 and U4, an angle $\alpha_r$ = 3.75° in between N2 and U5 and an angle $\alpha_r$ = 6.25° in between S2 and U6. There is an angle $\alpha_r$ = -1.25° in between N1 and U3, an angle $\alpha_r$ = -3.75° in between S8 and U2 and an angle $\alpha_r$ = -6.25° in between N8 and U1. So this means that all voltages generated in U1 - U6 are out of phase with each other.

Substitution of $\alpha_r$ = 1.25° and $p_r$ = 16 in formula 4 gives $\alpha$ = 10°. Substitution of $\alpha_r$ = 3.75° and $p_r$ = 16 in formula 4 gives $\alpha$ = 30°. Substitution of $\alpha_r$ = 6.25° and $p_r$ = 16 in formula 4 gives $\alpha$ = 50°. Substitution of $\alpha_r$ = -1.25° and $p_r$ = 16 in formula 4 gives $\alpha$ = -10°. Substitution of $\alpha_r$ = -3.75° and $p_r$ = 16 in formula 4 gives $\alpha$ = -30°. Substitution of $\alpha_r$ = -6.25° and $p_r$ = 16 in formula 4 gives $\alpha$ = -50°.

Addition of sinusoidal voltages which are out of phase but which have the same frequency results in a voltage which is also sinusoidal. The total voltage $U_{tot}$ is given by:

$$U_{tot} = U_{max} * \{\sin(\alpha - 50°) + \sin(\alpha - 30°) + \sin\alpha\ (\alpha - 10°) + \sin(\alpha + 10°) + \sin(\alpha + 30°) + \sin(\alpha + 50°\} \quad \text{(V)} \qquad (12)$$

It can be proven that this function has a maximum value for $\alpha$ = 90°.

Substitution of $\alpha$ = 90° in formula 12 gives:

$U_{tot\ max} = U_{max} * (\sin 40° + \sin 60° + \sin 80° + \sin 100° + \sin 120° + \sin 140°) = 4.9872 * U_{max}$.

If the voltages U1, U2, U3, U4, U5 and U6 would be exactly in phase, the resulting maximum voltage would be 6 * $U_{max}$. So the difference in phase angle gives a reduction of the total voltage by a factor 4.9872 / 6 = 0.831. This is substantial lower than the factor 0.957 which was found in chapter 4 for the five coils. The negative effect of the lower voltage factor may be compensated by the fact that there is more space to lie the winding as there are no coil cores. On the other hand, six radial sections of a certain wire thickness and a certain number of turns per coil contain much less copper than five coils with the same wire thickness and the same number of turns per coil. So I expect that the total power which can be generated by a serpentine winding with six radial sections is less than for a winding with five separate coils.

Another point is that not all wires of a section can be placed at the ideal position. So for some wires $\alpha_r$ will be smaller and for other wires $\alpha_r$ will be larger than the values as given in figure 4. But for the total voltage this effect will be averaged.

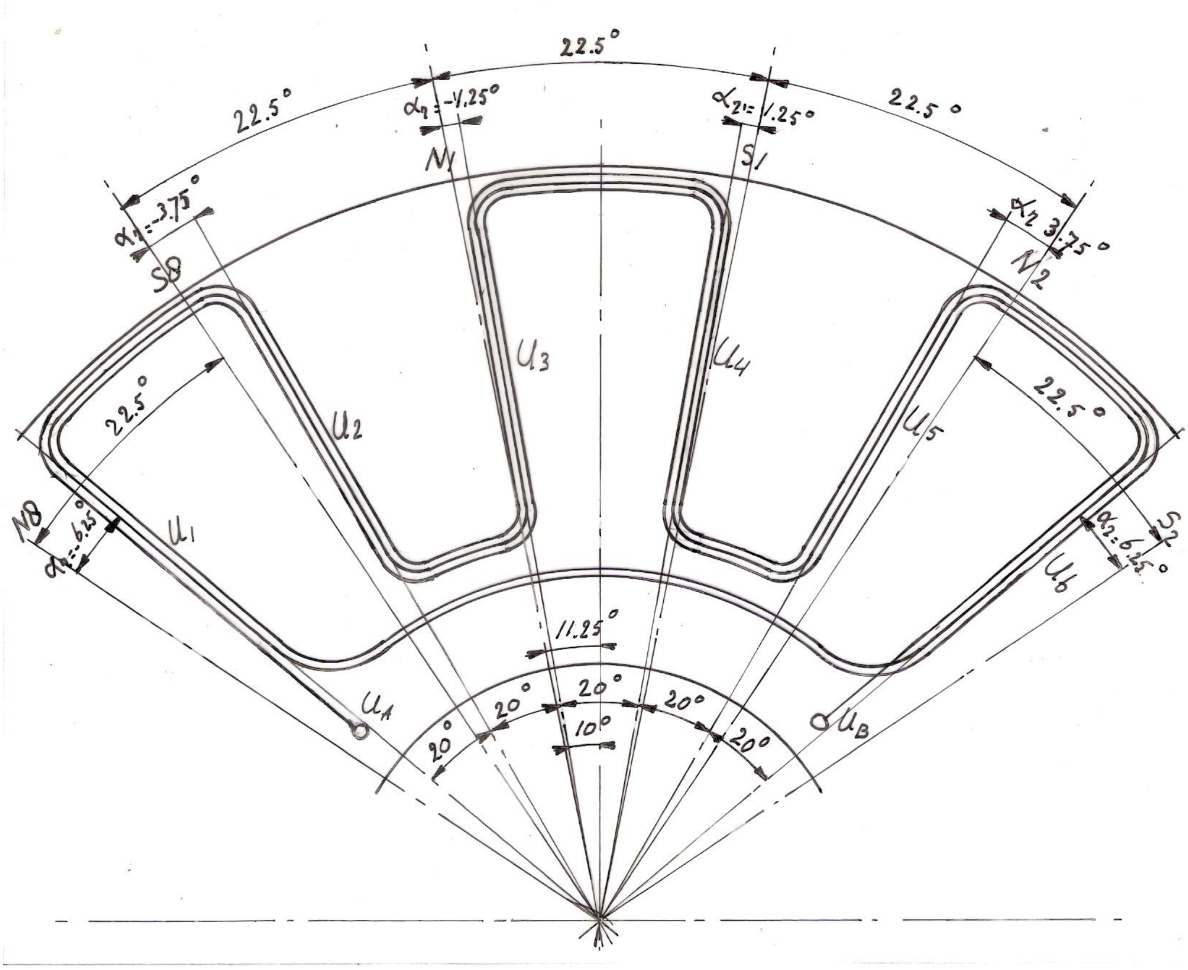

fig. 4  Serpentine winding of phase U with six radial sections

The serpentine winding can be made in two different ways. The winding can be made in the final shape which requires a lot of variation of the winding direction during lying of the winding. One needs a jig with six outer pins and six inner pins around which the winding is laid. A disadvantage is that one gets crossing wires in between the outer and inner pins.

Another way is to make one circular coil and to deform this coil such that it has three fingers and so six radial sections. This second option has no crossing wires and seems the most promising if a deformation tool can be developed.

The idea of a serpentine winding is very logic for a 1-phase winding with 16 radial section over 360°. The angle in between the radial sections is the same as the pole angle, so 22.5°. A generator with a 1-phase winding can be coupled to a 1-phase asynchronous motor which is general for low powers. In reality a 1-phase motor is a 2-phase motor and the second phase is created by a large capacitor.

### 8.4 Choosing a windmill rotor made of Roofmate and glass fibre

The axial flux generator was originally designed to be used in combination with the 2-bladed steel VIRYA-3D2 rotor which is described in report KD 530. As an alternative, the much lighter 2-bladed VIRYA-3.1L7 rotor has been designed which is described in report KD 532 (ref. 5). This rotor is made of Roofmate and glass fibre soaked in epoxy.

## 9 References


1 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Ideas about a 4-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1.5 windmill using square neodymium magnets size 30 * 30 * 15 mm and no iron in the stator, free public report KD 522, June 2013, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Calculations executed for the 2-bladed rotor of the VIRYA-3D2 windmill ($\lambda_d$ = 6.75, steel blades) using a 16-pole axial flux PM-generator for coupling to a pump motor, September 2013, report KD 530, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Ideas about a 22-pole, 3-phase axial flux permanent magnet generator for the VIRYA-3.9 windmill using 22 neodymium magnets size 50 * 15 * 15 mm, report KD 529, August 2013, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Calculations executed for the rotor of the VIRYA-3.1L7 windmill ($\lambda_d$ = 7, Gö 623 airfoil), with 2-bladed rotor made of Roofmate and glass fibre, September 2013, report KD 532, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.