Ideas about a 38-pole permanent magnet generator for the VIRYA-3B3 windmill using the housing of a 6-pole, 3-phase, 1.5 kW asynchronous motor frame size 100 and 57 neodymium magnets size 40 * 7 * 3 mm

ing. A. Kragten

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Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

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1 Introduction

One of the most critical parts of a small wind turbine is the generator. For my current 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 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 expensive, especially if a housing of western manufacture is used.

I did several attempts to design PM-generators which are simpler or cheaper and which also have no fluctuating sticking torque. The last years I wrote several reports about PM-generators for which the number of armature poles is two less or two more than the number of stator slots. The most recent public report is KD 632 (ref. 2). This report describes a 26-pole generator frame size 80 using the stator of a 4-pole motor with 24 slots. The original motor shaft is used for the PM-armature. The used magnets have size 40 * 7 * 3 mm. Magnets are only used for the north poles. The south poles are formed by the remaining material of the armature. The idea came up to design a similar bigger 38-pole PM-generator using the housing and the shaft of a motor with frame size 100 which has a stator with 36 slots and to use an armature with the same magnets size 40 * 7 * 3 mm.

The direction of the magnetic flux in the air gap for the generator described in chapter 2, is perpendicular to the cylindrical armature and the generator is therefore of the type ”radial flux”. This kind of generator is relatively long and has a small diameter and that's why it is possible to use the housing of a standard asynchronous motor. This has as advantage that the housing, the bearing covers and the shaft will be 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 with an IP-55 seal.

The generator is meant for the 3-bladed VIRYA-3B3 rotor which has a design tip speed ratio of 6.5 and three wooden blades with a constant chord and a constant blade angle which are connected to each other by a stainless steel hub plate. The rotor calculations are given in report KD 484 (ref. 3). The VIRYA-3B3 originally uses a 4-pole PM-generator which is made from a 2.5 kW asynchronous motor with frame size 90 and a lengthened stator stamping. This generator has a 25 mm stainless steel shaft with a tapered shaft end. The original 230/400 V winding is modified into a 115/200 V winding for 24 V battery charging and rectification in star by connecting the first and the second layer in parallel. The measurements of this generator for the original 230/400 V winding are given in report KD 78 (ref. 4).

The shaft of a motor housing frame size 100 has a 28 mm cylindrical shaft with a length of 60 mm and an 8 mm key groove. So the hub of the VIRYA-3B3 rotor has to be modified to fit onto a 28 mm cylindrical shaft. If the VIRYA-3B3 head frame is used, the generator bracket should also be modified to fit with the hole spacing of a motor with frame size 100 and to maintain the eccentricity e in between the rotor axis and the tower axis at 0.26 m.

2 Description of the generator

It is chosen to use a motor housing with an IEC stator stamping of the German manufacture Kienle & Spiess (see website www.kienle-spiess.de). It is chosen to use a stator stamping of a 6-pole, 3-phase, 1.5 kW motor frame size 100. This stamping has an outside diameter of 150 mm, an inside diameter of 103 mm and a length of 120 mm. The stator has 36 slots, so also 36 stator poles. The length of the wound stator is much longer because the coil heads of a 6-pole winding are rather large. The winding of this new type 38-pole generator has much smaller coil heads because there are no crossing coil heads and because the coil pitch is much smaller. So a longer stator is possible but this isn't done as a longer stator isn't standard.

The original short-circuit armature has an outside diameter of 102.4 mm after machining, an inside diameter of 36 mm and an effective length of 120 mm but both sides are provided with aluminium disks with cooling fans and the total armature length is therefore much longer. The armature of the new 38-pole generator will also have a length of 120 mm, so the same as the stator length.

The original short-circuit armature can't be used to glue the magnets in because it is provided with cast aluminium bars which guide a magnetic field very poorly. So the original armature is removed from the shaft. A steel bush with a width of 120 mm and an outside diameter of at least 103 mm and an inside diameter of about 36.2 mm is pressed on the shaft. The shaft is provided with a fine teething to improve the press fitting. The original armature has an inside diameter of 36 mm but the lamination is rather soft. A little larger inside diameter might therefore be needed for a massive steel bush. After pressing, this bush is turned to an outside diameter of 102.4 mm with perfect concentricity with respect to the bearing seats on the shaft. As an alternative it might be possible to use a 120 mm long piece of seamless pipe size 105 * 7.5 mm. The original short-circuit armature is turned to a diameter of about 89.8 mm and the steel pipe is glued to it by epoxy. The whole is turned to an outside diameter of 102.4 mm after hardening of the glue.

Nineteen 7 mm wide grooves are milled in the bush parallel to the shaft axis. The groove depth is 3.2 mm at the heart of the groove. So the bottom of the groove is lying 48 mm from the shaft axis. A 2.2 mm deep and 1.5 mm wide groove is made at each side of the 7 mm groove. Three magnets size 40 * 7 * 3 mm are glued in each groove with the north pole to the outside. So for one armature, 57 magnets are needed. The south poles are formed by the remaining material of the armature. The 1.5 mm wide grooves at each side of a magnet prevent magnet short-circuit in between the sides of the magnets and make that the south poles also have a width of about 7 mm. A side view of the armature and the stator is given in figure 1. The armature is drawn in the position for which N1 is opposite to U2.

The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl . The current price of one magnet is € 0.70 including VAT, excluding transport if a minimum quantity of 40 magnets is ordered. So the magnet costs for one generator are about € 40 which is rather low for a PM-generator of frame size 100.

The radius at the heart of the outer side of a magnet is 48 + 3 = 51 mm. It can be calculated that the radius at the corner of a magnet is 51.12 mm. The radius of a south pole is 102.4 / 2 = 51.2 mm so at the sides, the magnets are lying 0.08 mm below the south poles. This means that the magnets won't touch the stator when the armature is mounted in the stator.

The stator has 36 grooves, so 36 poles. The stator pole angle is 360° / 36 = 10°. The armature has 38 poles, so the armature pole angle is 360° / 38 = 9.4737°. The difference in between the stator pole angle and the armature pole angle is 10° – 9.4737° = 0.5263°. Assume a preference position is created if an armature pole is just opposite a stator pole. This means that the number of preference positions per revolution is 360° / 0.5263 = 684. This is a large number so it can be expected that the fluctuation of the sticking torque is almost flattened. The number of preference positions can also be found by multiplying the number of armature poles times the number of stator poles and divide it by two as 38 * 36 / 2 = 684.

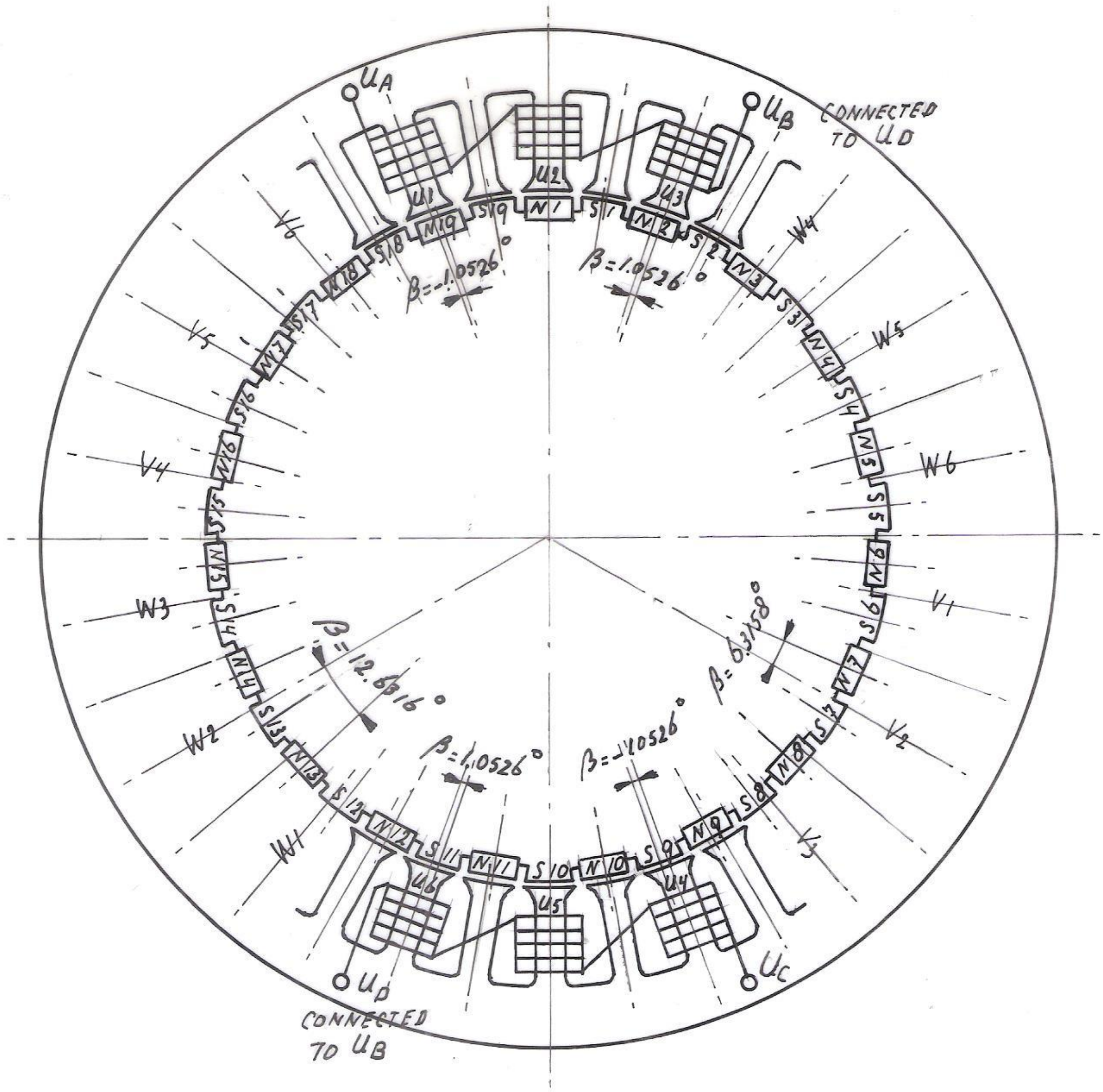

fig. 1 38-pole PM generator with a 1-layer, 3-phase winding

The stator winding is a very simple 3-phase, 1-layer winding with no crossing coil heads. A stator coil is wound around one armature spoke. The coil sequence is U1, U2, U3, W4, W5, W6, V1, V2, V3, U4, U5, U6, W1, W2, W3, V4, V5 and V6. All coils of one phase are connected in series for 24 V battery charging.

The air gap at the heart of the magnet is 0.5 mm. The air gap at the magnet edge is about 0.38 mm. The thickness of the glue layer in between magnet and groove is neglected. So the average air gap at a north pole is about 0.45 mm. The air gap in between a south pole and the stator is 0.3 mm.

3 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 α in between the phases is 120°. The formulas for the voltage of each phase are:

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

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

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

The three curves are shown in figure 2.

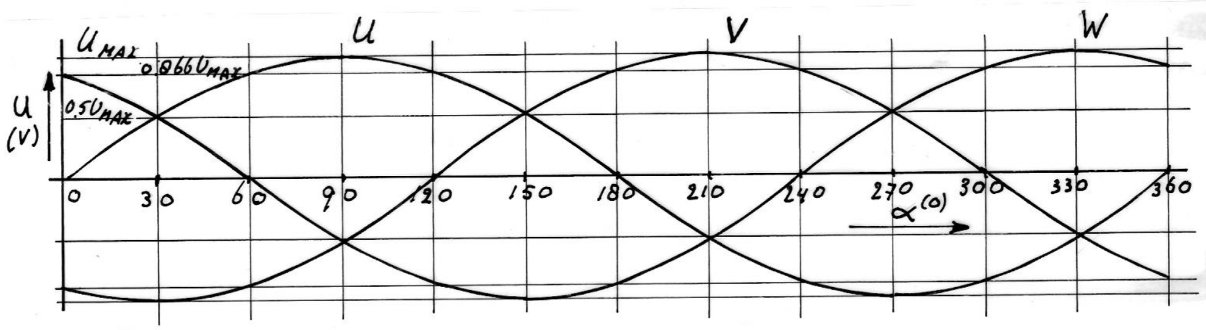

fig. 2 Three phases U, V and W

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 α is the same as the rotational angle β of the rotor. If the rotor has 38 poles this will be the case for 360 * 2 / 38 = 18.9474° rotation of the rotor. This results in the formula:

$\alpha = \beta * p / 2$ (-) (4)

α is the phase angle, β is rotational angle of the armature and p is the number of armature poles.

In figure 1 it can be seen that the north pole N1 is opposite to coil U2, so β = 0° for this position. It is assumed that α = 0° for β = 0°. In figure 1 it can be seen that β = 6.3158° in between N7 and V2. Substitution of β = 6.3158° and p = 38 in formula 4 gives α = 120°. In figure 1 it can be seen that and that β = 12.6316° in between N13 and W2. Substitution of β = 12.6316° and p = 38 in formula 4 gives α = 240°. The difference in between the phase angles is 120° and so a 3-phase voltage is created in between the coils U2, V2 and W2.

In figure 1 it can be seen that β = -1.0526° in between N19 and U1 and that β = 1.0526° in between N2 and U3. So this means that the voltages generated in U1, U2 and U3 are not in phase with each other. In figure 1 it can be seen that the coils U4, U5 and U6 are not about opposite to north poles but that they are about opposite to the south poles S9, S10 and S11. This means that the generated voltage in this bundle of coils will be opposite to the voltage as generated in the bundle of coils U1 – U3 if the coils have the same winding direction.

It is decided to give all eighteen coils the same winding direction and to connect all six coils of one phase in series for 24 V battery charging. The coil ends of the bundle of three coils U1 - U3 are called U_A and U_B. The coil ends of the bundle of three coils U4 – U6 are called U_C and U_D. The first bundle of three coils of phase U has to be connected such to the second bundle of three coils, that the generated voltages in both bundles are strengthening each other. This is accomplished if coil end U_B is connected to coil end U_D.

The generator winding is very simple if compared to the winding of a normal 4-pole asynchronous motor. This is because all coils have the same shape and because there are no crossing coil heads. The strength of the magnetic field flowing through a coil will be the same for each coil and the generated voltage in each coil will therefore be the same too. This is not the case for a normal 4-pole winding as some coils have a different pitch. The coil heads are very small if compared to the length of the part of the coil lying in the grooves. A minimum amount of copper will therefore be used and the winding will have a relatively low resistance resulting in a high generator efficiency.

The angles in between the coils U4 – U6 and the poles S9 – S11 are the same as the angles in between the coils U1 – U3 and the poles N19 – N2.

Coil U1 and U4. Substitution of $\beta = -1.0526°$ and $p = 38$ in formula 4 gives $\alpha = -20°$.
Coil U3 and U6. Substitution of $\beta = 1.0526°$ and $p = 38$ in formula 4 gives $\alpha = 20°$.

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} for the six coils U1 – U6 is given by:

$$U_{tot\ max} = U_{max} * 2 * \{\sin(\alpha - 20°) + \sin\alpha + \sin(\alpha + 20°)\} \quad \text{(V)} \qquad (5)$$

It can be proven that this function has a maximum value for $\alpha = 90°$. Substitution of $\alpha = 90°$ in formula 5 gives: $U_{tot\ max} = U_{max} * 2 * (\sin 70° + \sin 90° + \sin 110°) = 5.7588 * U_{max}$.

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 small reduction of the total voltage by a factor 5.7588 / 6 = 0.96 and therefore also a small reduction of the generated power. A factor 0.96 is acceptable, so the given shift of the phase angles in between the six coils U is allowed. The same counts for the coils V and for the coils W.

The winding can be rectified in star or in delta. However, rectification in delta has as disadvantage that the unloaded sticking torque is rising rather fast at low rotational speeds because higher harmonic currents can circulate in the winding. This will result in a higher starting wind speed. Circulation of higher harmonic currents isn’t possible for star rectification and the sticking torque is therefore rising much less. So star rectification is preferred. If the generator is used as a brake, the star point should be short-circuited too because this gives a higher maximum braking torque.

4 Determination of the flux density in the air gap and in the stator spoke

A PM-generator is normally designed such that the magnetic field in the stator is saturated or almost 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. The stator can be saturated at the narrowest cross section of the spokes in between the stator slots but it can also be saturated at the bridge in between the bottom of the stator slots and the outside of the stator stamping. The stator stamping is originally designed for a 6-pole motor and for a 6-pole motor there is a large magnetic flux in the bridge.

The magnetic flux in the bridge for a 38-pole PM-generator is very low because only half the flux coming out of one stator spoke is flowing through the bridge. So only the magnetic flux in the spokes is critical. The stator is about saturated if the calculated flux density in the air gap is 0.9 T or higher.

The remanence B_r (magnetic flux) in a neodymium magnet supplied by www.enesmagnets.pl with quality N38SH is in between 1.22 T and 1.26 T, if the magnet is short-circuited with a mild steel arc which is not saturated. Assume that B_r = 1.24 T. 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 armature can be neglected. The magnetic resistance of the iron in the stator can't be neglected if the stator is close to saturation. However, this is complicating the calculation a lot and so the magnetic resistance of the iron in the stator is neglected too. So it is assumed that the total magnetic resistance is only caused by the magnet itself and by the two air gaps.

The air gap t_2 in between a south pole and the stator is 0.3 mm. The average air gap t_3 in between a north pole and the stator is somewhat larger because the magnet is flat and because the depth of a magnet groove is chosen 3.2 mm. It is assumed that t_3 = 0.45 mm. So the magnetic resistance is increased by a factor $(t_1 + t_2 + t_3) / t_1$ because of the two air gaps. This means that the remanence in the air gap is reduced by a factor $t_1 / (t_1 + t_2 + t_3)$. The effective remanence in the air gap $B_{r\,eff}$ is given by:

$$B_{r\,eff} = B_r * t_1 / (t_1 + t_2 + t_3) \quad \text{(T)} \qquad (6)$$

Substitution of B_r = 1.24 T, t_1 = 3 mm, t_2 = 0.3 mm and t_3 = 0.45 mm in formula 6 results in $B_{r\,eff}$ = 0.992 T. This is higher than 0.9 T so the stator will probably be saturated. The flux density in a spoke can be calculated if the spoke width is known. The spoke has a width of 4.4 mm. A magnet has a width of 7 mm and the length of the armature is the same as the length of the stator. So the magnetic flux is concentrated by a concentration factor k = 7 / 4.4 = 1.59. So the magnetic flux in a spoke is 0.992 * 1.59 = 1.58 T. This is very close to1.6 T so the spokes are very close to saturation. So the chosen magnets are rather optimal for the chosen stator stamping.

I think that it is worth wile to make a prototype of a stator and an armature according to the geometry as given in figure 1 and chapter 2 and to test if the generator will have acceptable characteristics. However, I won't do that. The matching in between rotor and generator can only be checked if a certain windmill rotor is chosen.

5 Determination of the number of turns per coils

The required number of turns per coil and the maximum allowable wire thickness can be determined by try and error. First one makes a certain choice, assume 100 turns per coil and one makes a prototype of the stator with the largest wire thickness possible. The winding is rectified in star by a 3-phase rectifier. Rectification of a 3-phase current is described in report KD 340 (ref. 5).

Next the generator is placed on a test rig with which it is possible to measure the torque, the rotational speed, the voltage and the current. I have used a test rig of the University of Technology Eindhoven for measuring my normal VIRYA generators. Next a series of measurements is executed for a range of voltages for instance 8, 12, 16, 20, 24, 28 and 32 V star. 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. This is done in figure 4 of KD 484 (ref. 3). 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. 6). The optimum cubic line is also drawn in figure 4 of KD 484.

All measured P_{mech}-n curves are drawn in the same graph. One curve will have the best matching. This means that it has two points of intersection with the optimum cubic line, which are lying not very far apart.

Assume that the best matching is realised for the P_{mech}-n curve which belongs to V = 20 V. Assume that the generator is used for 24 V battery charging. This means that the average charging voltage is about 26 V. So the voltage of the test winding is a factor 20 / 26 = 0.769 too low. So the number of turns per coil has to be increased by a factor 26 / 20 = 1.3 and so it must be 1.3 * 100 = 130. The wire thickness must be reduced by a factor √ (1 / 1.3) = 0.877 to get the same amount of copper in a slot. The modified winding should have the same P_{mech}-n and P_{el}-n curves for 26 V, as the curves of the test winding have for 20 V but to be sure, the generator with the final winding should be measured again for 26 V star.

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