Ideas about a 26-pole permanent magnet generator for a small windmill using the housing of a 4-pole, 3-phase, 0.75 kW asynchronous motor frame size 80 and 26 neodymium magnets size 40 * 7 * 3 mm

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 Anyone can use the described generator or the working principle. The generator has not yet been built and tested but some basic tests have been performed for a 22-pole generator frame size 71.

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1 Introduction

In my public report KD 341 (ref. 1), three different types of permanent magnet (PM) generators for wind turbines are described. The type which is used in my older VIRYA wind turbines make use of a 4-pole asynchronous motor for which the short-circuit armature is replaced by a 4-pole armature with radial positioned neodymium magnets. Most of the recent designs of small free VIRYA designs make use of an axial flux generator with only one armature sheet with magnets. For use of the windmill in combination with the asynchronous motor of a centrifugal pump, I have designed some rather large multi pole PM-generators with tangential positioned magnets. Every type has certain advantages and disadvantages.

The main advantage of the multi pole PM-generator is the high frequency which makes use in combination with an asynchronous motor possible but for this use the generator must be rather large. Other advantages are the small fluctuation of the sticking torque, the low magnet volume and so the low magnet costs, the shallow magnets grooves in the armature, the fact that the original motor shaft can be used and the simple 1-layer stator winding with very short coil heads resulting in minimal use of copper.

The first experiments with a multi pole PM-generator are described in report KD 553 (ref. 2) for a 22-pole PM-generator which makes use of an Indian motor housing frame size 71 and 22 neodymium magnets size 40 * 7 * 3 mm. A prototype of the armature has been made and the measured fluctuation of the sticking torque is rather low. This report wasn’t made public because it was written for an Indian company which finally decided not start production. A 34-pole PM-generator is described in public report KD 560 (ref. 3) for the VIRYA-3.3S windmill. This generator makes use of a motor housing frame size 112 and 51 neodymium magnets size 40 * 10 * 5 mm.

Recently the idea came up to design a small 26-pole PM-generator using the housing of a 4-pole, 0.75 kW motor frame size 80 and 26 neodymium magnets size 40 * 7 * 3 mm, so the same magnets as those which are also used for the 22-pole generator. An advantage of using these magnet for frame size 80 is that the armature length becomes the same as the stator length (80 mm) if two magnets are used in one groove. A windmill rotor with a diameter of about 2 m will be mounted directly to the generator shaft. The 3-phase generator winding will be rectified and the windmill will be used for 12 V or 24 V battery charging.

The low fluctuation of the sticking torque is realised if the number of armature poles is two less or two more than the number of stator groves which is 24 for frame size 71 and 80. The fluctuation of the sticking torque decreases if the number of fluctuations per revolution increases. The number of fluctuations per revolution for a 26-pole armature is 26 * 24 / 2 = 312 (see explanation chapter 2). It is 22 * 24 / 2 = 264 for a generator with 22 armature poles. So the fluctuation of the sticking torque of a 26-pole generator is less than for the tested 22-pole generator for which is was already rather low.

2 Description of the 26-pole PM-generator

It is chosen to use a motor housing with an IEC stator stamping of manufacture Kienle & Spiess (see website www.kienle-spiess.de). It is chosen to use a stator stamping of a 4-pole, 0.75 kW motor frame size 80. This stamping has an outside diameter 120 mm, an inside diameter of 70 mm and a length of 80 mm. The stator has 24 slots, so also 24 stator poles.

The air gap in between armature and stator is chosen 0.3 mm, so the outside diameter of the armature is chosen 69.4 mm. The short-circuit armature has an inside hole of 25 mm but is not used. However, the original motor shaft is used. It has a fine teething in the length direction. A mild steel bush with a length of 80 mm and a central inside hole of 25.1 mm is pressed onto the shaft. So the length of the armature is the same the length of the stator.

The armature bush is provided with thirteen, 7 mm wide and 3.2 mm deep grooves parallel to the armature axis. Two magnets size 40 * 7 * 3 mm are glued in each groove. These 26 magnets are forming the 13 north poles which are called N1 – N13.

The thirteen south poles are formed by the remaining armature material left in between the grooves. The south poles are called S1 – S13. So the armature has 26 poles. The armature pole angle is 360 / 26 = 13.8462°.

The stator has 24 grooves, so 24 poles. The stator pole angle is 360 / 24 = 15°. The difference in between the stator pole angle and the armature pole angle is 15° - 13.8462° = 1.1538°. 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° / 1.1538 = 312. 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 26 * 24 / 2 = 312.

The stator winding is a very simple 3-phase, 1-layer winding with no crossing coil heads. A stator coil is wound around 1 armature spoke. The coil sequence is U1, U2, W3, W4, V1, V2, U3, U4, W1, W2, V3 and V4. A sketch of the armature and the stator is given in figure 1. The armature is positioned such that the north pole N1 is just opposite the middle of coil U1 and coil U2.

A 1.4 mm wide and 1.7 mm deep groove is made at each side of a magnet groove. These grooves make that an armature south poles also has a width of about 7 mm. The grooves also prevent magnetic short-circuit in between the sides of the magnets.

The magnets are mounted radial, with the largest area to the outside of the armature. As the magnet is flat, the air gap in between the heart of the magnet and the stator is larger at the heart of the magnet than at the side of the magnet but this is acceptable because the width of the used magnets is rather small (7 mm).

Some research has done to neodymium magnets which are standard supplied by Internet companies. The Polish Internet company www.enesmagnets.pl supplies magnets size 40 * 7 * 3 mm. The price of this magnet including VAT but excluding the costs of transport is € 0.70 for an ordered quantity of 40 pieces. So this results in magnet costs for one generator of 26 * € 0.70 = € 18.20 which seems acceptable. The magnets have quality N38SH which means that the remanence B_r is about 1.24 T and that they can be used up to a very high temperature of 150°.

Each groove must have a depth which is such that the magnet edges don’t jut out of the armature. It has been calculated that the groove depth must be 3.2 mm which means that the distance in between the bottom of the groove and the heart of the shaft is 31.5 mm for an armature diameter of 69.4 mm.

The air gap at the heart of the magnet is 0.5 mm. The air gap at the magnet edge is about 0.32 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 radius of the south pole is 69.4 / 2 = 34.7 mm and the air gap in between a south pole and the stator is 0.3 mm. During mounting of the armature in the stator, the armature will touch the stator and it will come free only when the bearing covers are tightened. But as the air gap at the south poles is smaller than the smallest air gap at the north poles, the magnets won’t touch the stator during mounting.

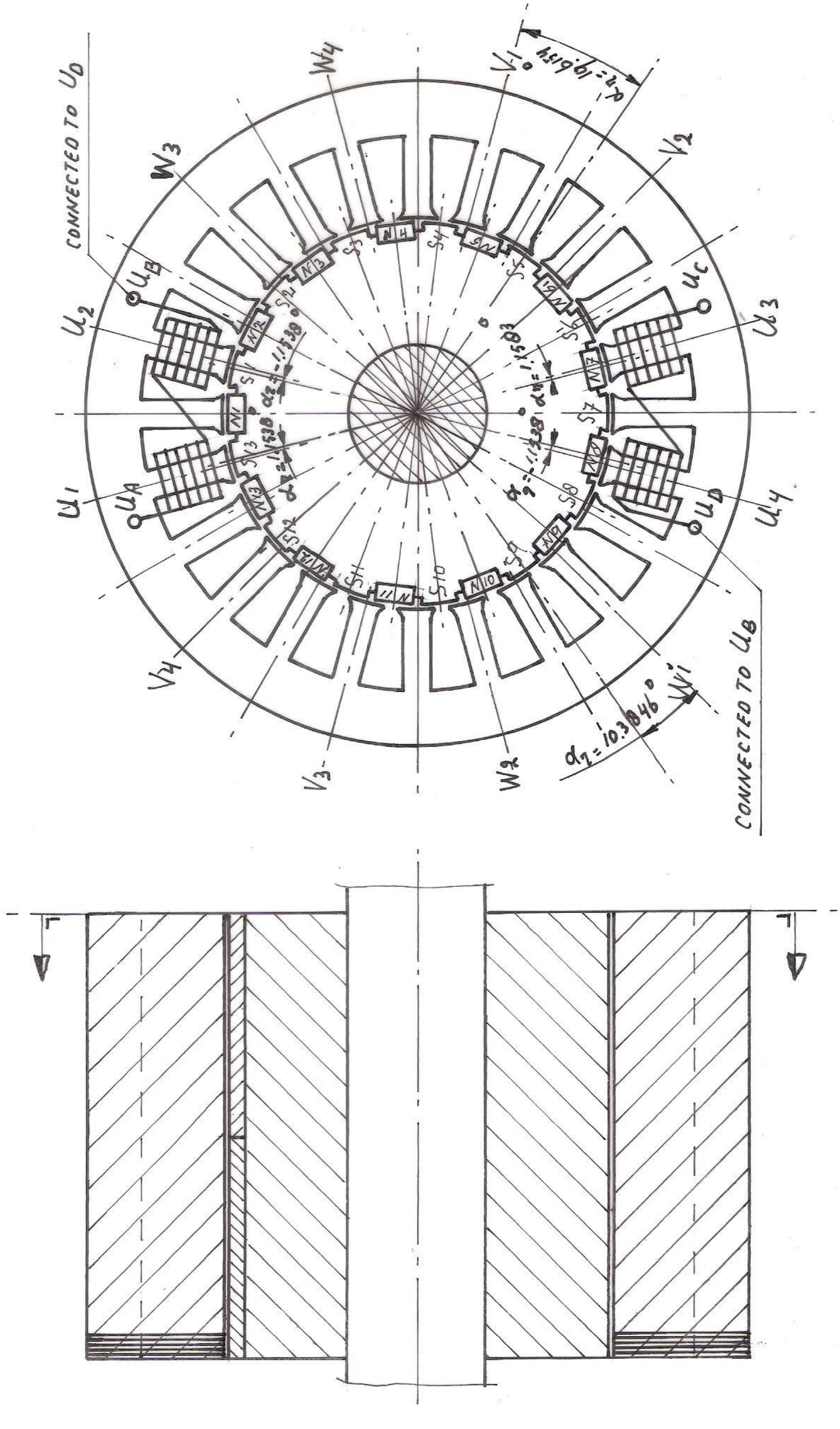

fig. 1 PM-armature of a 26-pole PM-generator frame size 80

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.

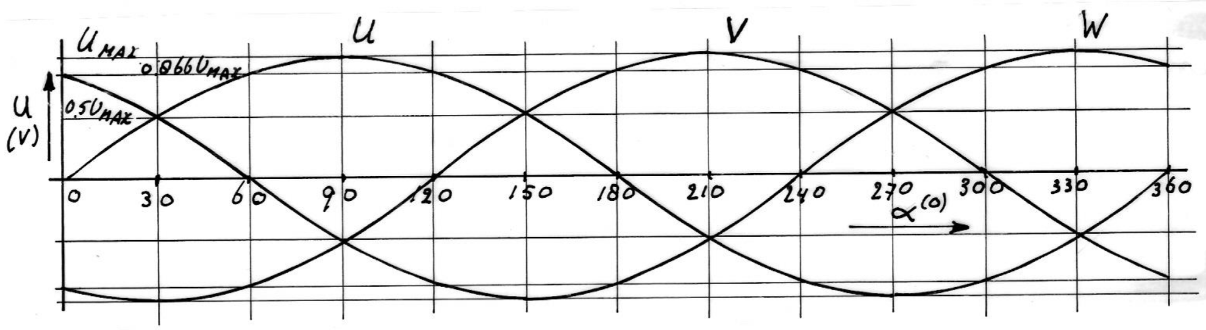

fig. 2 Three phases U, V and W

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 α_r of the rotor. If the rotor has 26 poles this will be the case for 360 * 2 / 26 = 27.6923° rotation of the rotor. This results in the formula:

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

α is the phase angle, α_r is rotational angle of the rotor and p_r is the number of rotor poles.

In figure 1 it can be seen that α_r = 1.1538° in between S13 and U1, that α_r = 19.6154° in between S5 and V1 and that α_r = 10.3846° in between S9 and W1. Substitution of α_r = 1.1538° and p_r = 26 in formula 4 gives α = 15°. Substitution of α_r = 19.6154° and p_r = 26 in formula 4 gives α = 255°. Substitution of α_r = 10.3846° and p_r = 26 in formula 4 gives α = 135°. The difference in between the phase angles is 120° and so a 3-phase voltage is created in between the coils U1, V1 and W1.

In figure 1 it can be seen that α_r = 1.1538° in between S13 and U1 and that α_r = - 1.1538° in between S1 and U2. So this means that the voltages generated in U1 and U2 are not in phase with each other.

In figure 1 it can be seen that the coils U3 and U4 are not about opposite to south poles but that they are about opposite to the north poles N7 and N8. 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 – U2 if the coils have the same winding direction. It is decided to give all 12 coils the same winding direction and to connect all four coils of one phase in series. The coil ends of the bundle of two coils U1 – U2 are called U_A and U_B. The coil ends of the bundle of two coils U3 – U4 are called U_C and U_D. The first bundle of 2 coils of phase U has to be connected such to the second bundle of 2 coils, that the generated voltages in both bundles are strengthening each other. This is realised 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 U3 – U4 and the poles N7 – N8 are the same as the angles in between the coils U1 – U2 and the poles S13 – S1.

Coil U1 and U3. Substitution of $\alpha_r = 1.1538°$ and $p_r = 26$ in formula 4 gives $\alpha = 15°$.
Coil U2 and U4. Substitution of $\alpha_r = -1.1538°$ and $p_r = 26$ in formula 4 gives $\alpha = -15°$.

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 four coils U1 – U4 is given by:

$$U_{tot\ max} = U_{max} * 2 * \{\sin(\alpha - 15°) + \sin(\alpha + 15°)\} \qquad \text{(V)} \qquad (5)$$

It can be proven that this function has a maximum value for $\alpha = 90°$. Substitution of $\alpha = 90°$ in formula 5 gives:
$U_{tot\ max} = U_{max} * 2 * (\sin 75° + \sin 105°) = 3.8637 * U_{max}$.

If the voltages U1, U2, U3 and U4 would be exactly in phase, the resulting maximum voltage would be 4 * U_{max}. So the difference in phase angle gives a small reduction of the total voltage by a factor 3.8637 / 4 = 0.966 and therefore also a small reduction of the generated power. A factor 0.966 is certainly acceptable, so the given shift of the phase angles in between the four coils U is allowed. The same counts for the coils V and for the coils W.

The winding with all four coils of one phase connected in series and rectified in star is meant for 24 V battery charging. The windmill can also be used for 12 V battery charging but in this case the two bundles of two cores have to be connected in parallel. In this case coil end U_A has to be connected to coil end U_D and coil end U_B has to be connected to coil end U_C. An alternative for 12 V battery charging might be to use the 24 V winding with all four coils connected in series but to rectify the winding in delta. However, rectification in delta has as disadvantage that the unloaded sticking torque is rising faster at low rotational speeds and this will result in a higher starting wind speed.

Rectification in star will give the lowest sticking torque because higher harmonic currents can’t circulate in the winding 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 Calculation of the flux density in the air gap and in the stator spoke

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).

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 4-pole motor and for a 4-pole motor there is a large magnetic flux in the bridge. The magnetic flux in the bridge for a 26-pole PM-generator is very low because only half the flux coming out of one stator pole 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 probably 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 also neglected. So the total magnetic resistance is only caused by the magnet itself and by the 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:

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

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 minimum width of about 5 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 / 5 = 1.4. So the magnetic flux in a spoke can be calculated to be 0.992 * 1.4 = 1.39 T. This is smaller than 1.6 T so the spokes are probably not saturated but I still believe that 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. The matching in between rotor and generator can only be checked if a certain rotor is designed. Rotor design is explained in public report KD 35 (ref. 4). Matching is explained in chapter 8 of KD 35. The optimum winding is the winding for which the P_{mech}-n curve of the generator for the chosen load is lying close to the optimum cubic line of the rotor.

5 References

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