Development of an alternative permanent magnet generator for the VIRYA-3 windmill using an Indian 4-pole, 3-phase, 2.2 kW asynchronous motor frame size 100 and 8 neodymium magnets size 50 * 25 * 10 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 with a low clogging torque 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 report KD 341 (ref. 1). These generators are very strong and have good characteristics. The clogging 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 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. An other problem is that for some generators, a Dutch motor housing with a lengthened stator stamping is used and motors with a lengthened stator stamping are not always available in other countries.

The idea is to design a new type of a small PM-generator which makes use of the original motor shaft and which can be used as an alternative if the correct local motor is available. The VIRYA-3 windmill has a rotor with two wooden blades. An alternative rotor with three wooden blades (VIRYA-3B3) is also available.

The current generator of the VIRYA-3 is made of a 4-pole, 2.5 kW, 3-phase asynchronous motor frame size 90 with lengthened stator and is provided with a modified 115/200 V winding. Modification of a standard 230/400 V winding into a modified 115/200 V winding is described in report KD 341. The generator is meant for 24 V battery charging if the winding is rectified in star. This generator has a 25 mm shaft and a tapered shaft end for connection of the rotor hub.

The new generator will be made of a 4-pole, 2.2 kW, 3-phase asynchronous motor frame size 100 and will also be provided with a modified 115/200 V winding. The original motor shaft can be used. This shaft has a diameter of 30 mm at the bearings but the shaft end is reduced to 28 mm and has a length of 60 mm. It is provided with a key groove. The original rotor hub has to be modified such that it has a 28 mm central hole and a 8 mm wide and 3 mm deep key groove. As the generator foot of frame size 100 is larger than that of frame size 90, the generator bracket of the head has to be modified too. The eccentricity e must stay the same (0.26 m), so the distance in between the centre of the head pin and the centre of the 45° plane at the end of the pipe has to be reduced by $\sqrt{2} * 10 = 14$ mm.

2 Description of the generator armature

It is chosen to make use of a motor housing of Indian manufacture because motors of Indian manufacture are a lot cheaper than motors of western manufacture. I have dimensions of stator stampings of manufacture Poggen-Amp from Ahmadabad. For a certain frame size, several stampings can be supplied. For a 4-pole motor frame size 100, the stamping 100F-4P is generally used in India. This stamping has configuration 165.00 * 95.00 * 33.50. 165.00 is the outside diameter of the stator in mm. 95.00 is the inside diameter of the stator in mm. 33.50 is the inside diameter of the armature in mm. The outside diameter of the armature is machined to 94.5 mm, so the air gap in between stator and armature is 0.25 mm. The length of the stator is 100 mm.

The stator has 36 slots, so also 36 stator poles. The armature has 28 slots and aluminium bars are cast into these slots. The steel part of the armature has also a length of 100 mm but aluminium disks are cast to both sides, making the total armature length a lot longer.

The idea is to use the original shaft. The original short-circuit armature has to be removed or one has to order a motor without armature. An aluminium bush is pressed onto this shaft. This aluminium bush prevents magnetic short-circuit at the inside of the rotor poles. The aluminium bush can be made from pipe ϕ 40 * 5 mm or from bar ϕ 40 mm if pipe isn't available. The bush has a length of 102 mm. The inside diameter of this bush must be turned to about 33.5 mm which is equal to the inside diameter of the original armature lamination. However, the iron of the armature lamination is very soft and will be deformed easily by the fine teething on the shaft. It might be that a little larger inside diameter than 33.5 mm has to be chosen for the aluminium bush to prevent a too large pressing force.

A mild steel bush is glued on the aluminium bush. The outside of the mild steel bush is turned after gluing it to the shaft with the required concentricity tolerance with respect to the bearing seats. The magnet grooves are made in the mild steel bush in a similar way as for the original VIRYA-3 generator. So the grooves must make a certain angle with the armature axis to prevent fluctuation of the clogging torque. It can be calculated that this angle must be 4.714° if there is just one stator pitch shift in between the left and the right side of the groove.

The mild steel bush has the same width as the width of the stator stamping, so 100 mm. Two neodymium magnets size 50 * 25 * 10 mm are glued in each groove in such a way that the same poles face each other in adjacent grooves. So two north and two south poles will be created in the remaining material of the armature. The poles are connected to each other by a small bridge which prevents that the armature falls apart during manufacture. A certain magnetic leak flux will be lost in each bridge but this is acceptable as the bridge has a height less than 1 mm. A side view and a cross section of the armature are given in figure 1.

For a company which manufactures electric motors and which also manufactures the shaft, it is an option to cancel the aluminium or stainless steel bush and to make the shaft from 40 mm stainless steel bar. In this case one cane also chose for a tapered shaft end in stead of a cylindrical shaft end with a key groove.

Some research has been done to neodymium magnets which are standard supplied by Internet companies and which can be used for this new generator type. The company www.supermagnete.de supplies magnets size 40 * 20 * 10 mm and size 50 * 25 * 10 mm. Size 50 * 25 * 10 mm is chosen. The current price (including VAT, excluding transport) is € 8.27 per magnet for 30 magnets, so the magnet costs for one armature are about € 70 which seems acceptable.

The original VIRYA-3 generator makes use of eight magnets size 67 * 20 * 10 mm. The supplier is Bakker Magnetics. I have paid € 14 per magnet already in 2003 which is € 112 per armature. At this moment these magnets will certainly be more expensive. I expect about € 140 per armature. So the choice of magnets size 50 * 25 * 10 mm makes the magnet costs of the armature about a factor two lower.

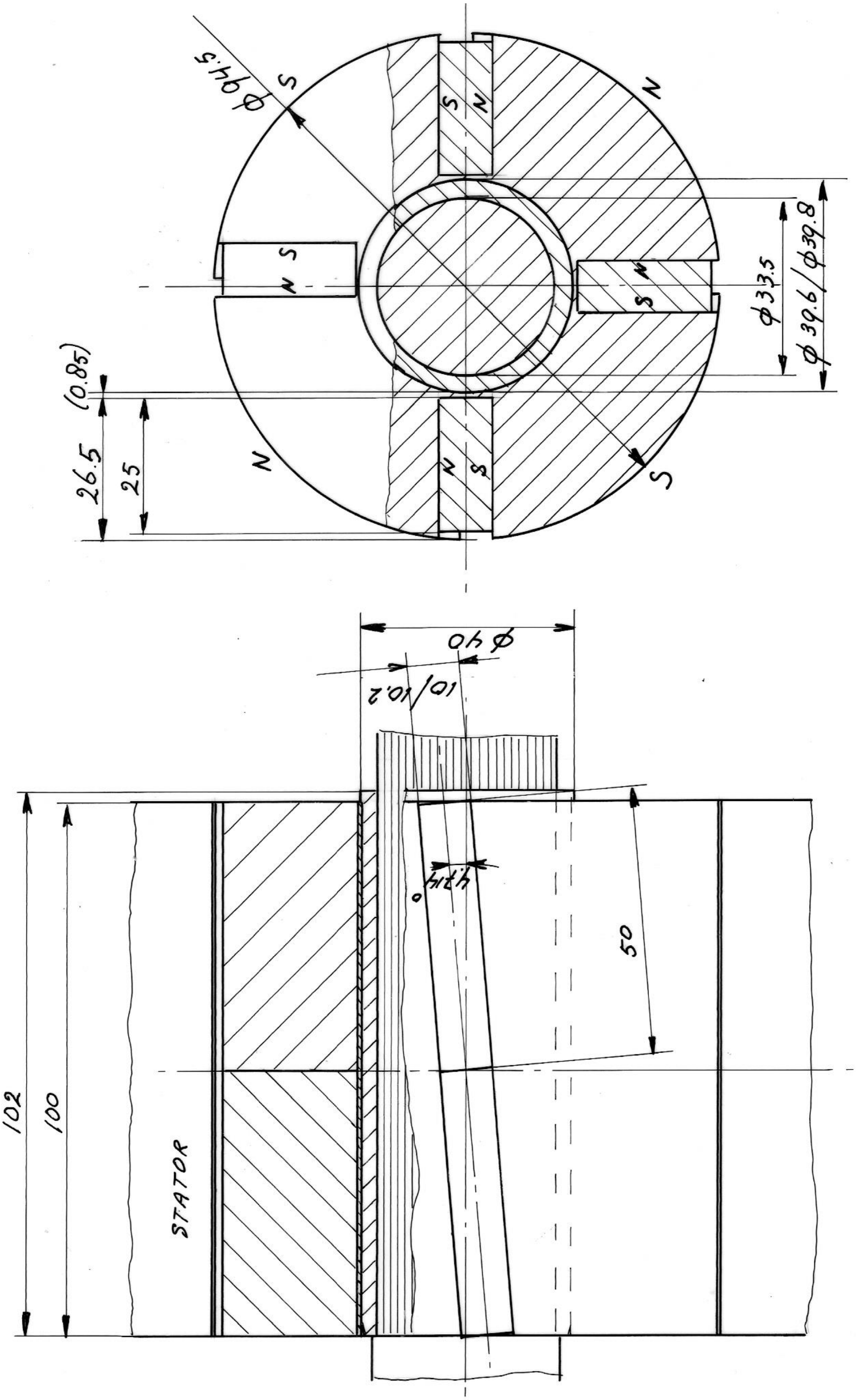

Figure 1 Side view and cross section of 4-pole armature for housing size 100F-4P

3 Calculation of the flux density in the air gap

A calculation of the flux density in the air gap for the current VIRYA generators is given in chapter 5 of KD 341.

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 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 Supermagnete with quality N 42 is in between 1.29 T and 1.32 T, if the magnet is short-circuited with a mild steel arc which is not saturated. Assume it is 1.3 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 the side of the magnet and the side of the magnet groove is about 0.1 mm (for a groove width of 10.2 mm). The air gap t_3 in between the armature and the stator is 0.25 mm. Formula 5 of KD 341 (ref. 1) gives the magnetic flux B_l in the air gap in between armature and stator. This formula is copied as formula 1.

$$B_l = \frac{2\, B_r * t_1 * n * L_m * (H - 1)}{L_b * (t_1 + 2\, t_2 + 2\, t_3) * (\pi * D/p - t_1)} \quad \text{(T)} \qquad (1)$$

Substitution of B_r = 1.3 T, t_1 = 10 mm, n = 2, L_m = 50 mm, H = 25 mm, L_b = 100 mm, t_2 = 0.1 mm, t_3 = 0.25 mm, D = 94.5 mm and p = 4 in formula 1 results in $B_{r\,eff}$ = 0.908 T. This is just a little higher than 0.9 T so the stator will be saturated. For the original VIRYA-3 generator it was calculated that B_l = 0.846 T, so somewhat lower.

The armature volume within the stator for the original VIRYA-3 generator is calculated to be 660449 mm^3. The armature volume of this new generator within the stator iron is $\pi/4 * 94.5^2 * 100 = 701380\ mm^3$, so a factor 1.06 higher. The maximum torque level is proportional to the armature volume for a certain flux density in the air gap. So as the new generator has a higher armature volume and a higher flux density, the maximum torque level of the new generator will probably lie somewhat higher. It is expected that this will not result in problems with matching or starting if this new generator is combined with the VIRYA-3 or the VIRYA-3B3 rotor. However, one can only be sure if a prototype of the new generator is tested on a test rig and if the measured characteristics are compared.

The magnetic loop coming out of halve an armature north pole is flowing through 4 ½ stator spokes, then bending right hand and flowing through the bridge formed by the distance in between the bottom of the stator slots and the outside of the stator, then bending right hand again and flowing through 4 ½ other stator spokes, then flowing through half the south pole, then bending right hand again and then flowing through the armature, then bending right hand again and flowing through halve the armature north pole.

The magnetic flux through the bridge is normally hindered by four grooves at every 90° in the outside of the stator. In each groove a strip is laid for which the ends are bent inwards. These strips are used to connect all stator laminations.

If the armature is positioned such that the heart of a south pole coincides with the heart of an outside stator groove, the grooves will be just at the point where one loop bends right hand and one loop bends left hand. The groove will therefore give almost no reduction to the magnetic flux and the magnetic flux will therefore be larger resulting in a certain preference position at every 90° of the armature. This preference position will be flattened by the inclination angle of the magnet grooves but some peak may remain and this peak will result in increase of the starting wind speed. This problem can be reduced if the stator stamping is provided with only three outside grooves. There might be manufacturers of stator lamination which can supply laminations with three grooves or with no grooves at all and connecting the lamination is done otherwise.

So I think that it is worth wile to make a prototype of an armature according to the geometry as given in figure 1 and to test if the generator will have acceptable characteristics. It is assumed that the 3-phase current is rectified in star by a 3-phase rectifier. The characteristic which can easy be determined, is the open DC voltage for rectification is star as a function of the rotational speed for the original 230/400 V winding.

The original VIRYA-3 generator has a modified 115/200 V winding. However, the generator measurements as given in report KD 78 (ref. 2) are performed for the original 230/400 V winding, so the voltage is a factor two higher than for a 115/200 V winding. The open U-n curve for rectification is star is given as figure 1 in KD 78. If the measured U-n curve for star rectification for the alternative generator is compared to curves of original generator given in figure 1 of KD 78, it gives a good impression of the strength of the magnetic flux which is realised. If both U-n curves are identical, it can be expected that the other curves will also be almost identical.

Determination of the P_{el}-n curve for 26 V star is rather simple. Determination of the P_{mech}-n curves for 26 V star requires a test rig with which the torque can be measured. The P_{mech}-n curve is required to check the matching of the generator with the VIRYA-3 rotor.

4 Alternative IEC stator

The Indian stator has no dimensions according the IEC norm. Another disadvantage of Indian stator stampings is that normally they have four outside groves and these grooves cause four preference positions per revolution. Stator stampings according to the IEC norm are described on the website of Kienle & Spiess: www.kienle-spiess.de . These stampings don’t have four outside grooves and therefore don’t have four preference positions per revolution.

Stator stampings for frame size 100 are used for 2.2 kW and 3 kW, 4-pole motors. The outside diameter of the stator stamping is 150 mm. The inside diameter of the stator stamping is 90 mm, so 5 mm smaller than for the Indian stator stamping. The length is 90 mm for the 2.2 kW motor and 120 mm for the 3 kW motor. The inside diameter of the armature stamping is 36 mm. The outside diameter of the short-circuit armature is chosen 89.5 mm so the air gap is 0.25 mm. Assume a 2.2 kW motor is chosen, so the length of the stator stamping is 90 mm. This is 10 mm shorter than for the Indian stator stamping.

Assume the length of the armature is chosen 100 mm. So the armature juts out 5 mm at each side of the stator stamping. As the inside armature diameter of an IEC stator stamping is 5 mm smaller than that of an Indian stator stamping, it is no longer possible to use the original motor shaft covered with an aluminium bush. So a new stainless steel shaft has to be made.

Assume that this shaft is made from bar round 35 mm. This bar is turned to a diameter of 34 mm at the position of the armature. A mild steel bush with an outer diameter of 90 mm, an inside diameter of 34.2 mm and a length of 100 mm is glued to the shaft by epoxy glue or anaerobe glue. This bush is turned to an outside diameter of 89.5 mm after gluing.

Instead of magnets size 50 * 25 * 10 mm supplied by Supermagnete it is also possible to use magnets size 50 * 25 * 12 mm supplied by Enesmagnesi website: www.enesmagnets.pl . These magnets have quality N38 and a remanence B_r = 1.24 T. The current price (December 2019) = € 7.27 including VAT but excluding costs of transport if 30 magnets are ordered.

So the total magnet costs are about € 58 which is certainly acceptable. Although these magnets are thicker, they are even cheaper than the thinner magnets of Supermagnete. The advantage of thicker magnets is that now a 12 mm finger cutter can be used to make the grooves in the armature. A thicker cutter will bend less and so the groove width tolerance can also be realized for the bottom of the groove.

Four 12.2 mm wide and 26.75 mm deep grooves are milled in the armature. It can be calculated that the inclination angle of the grooves must be 4.96° for an armature diameter of 89.5 mm and a stator with 36 slots and length of 90 mm. Two magnets are glued in each groove by anaerobe glue Threebond TB 1132 such that two north and two south poles are created.

In a housing frame size 100, bearings are used with an inside diameter of 30 mm. So if a new stainless steel shaft is made, this shaft can have a tapered shaft with a maximum shaft diameter of 30 mm and a half taper angle of 5°. So the inside tapered hole of the original hub of the VIRYA-3B3 rotor has to be enlarged from 25 mm up to 30 mm.

As the generator foot of frame size 100 is larger than that of frame size 90, the generator bracket of the head has to be modified too. The eccentricity e must stay the same (0.26 m), so the distance in between the centre of the head pin and the centre of the 45° plane at the end of the pipe has to be reduced by $\sqrt{2} * 10 = 14$ mm. The VIRYA-3B3 rotor is described in report KD 484 (ref. 3).

5 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. Measurements performed on a generator with housing 5RN90L04V and armature equipped with neodymium magnets, March 2001, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-3B3 rotor ($\lambda_d = 6.5$, wooden blades), February 2012, reviewed November 2018, free public report KD 484, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.