Ideas about a direct drive 34-pole permanent magnet generator for the VIRYA-3.3S windmill using the stator stamping of an Indian 6-pole, 3-phase, 2.2 kW asynchronous motor frame size 112 and 51 neodymium magnets size 40 * 10 * 5 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.

Strong fluctuation of the clogging torque can also be prevented by choosing a large pole number and if the number of stator poles differs only one from the number of armature poles. A 16-pole axial flux generator with no iron in the coils is described in report KD 531 (ref. 2). This generator has 15 stator coils wound around 15 stator poles and it has no preference positions because there is no iron in the stator. But if it would have iron in the stator, it would have 15 * 16 = 240 preference positions which will hardly be felt. In this report KD 560 it is investigated if this principle can also be used for a direct drive radial flux generator with a high pole number using the stator stamping of a standard asynchronous motor. However, in this case one can only use the number of stator poles for which standard stator stampings are available. Stator stampings of asynchronous motors have number of grooves and so number of stator poles which depend on the motor size and type. Standard stator pole numbers are: 24, 36, 48, 54 and 72.

A high armature pole number is needed if the generator is meant to generate a high voltage and frequency which is directly used to power an asynchronous motor of a pump. The generator is meant for the VIRYA-3.3S rotor, which is designed in report KD 576 (ref. 3). This rotor can be used in combination with a head which is derived from the head of the former VIRYA-3D windmill. A free standing tubular tower is designed for the VIRYA-3.3S.

A rotor with a diameter of 3 m needs a rotor shaft with a diameter of at least 28 mm. So a motor housing size 112 is chosen as this has a shaft end with a diameter of 28 mm and a length of 60 mm. It is not necessary to use a stainless steel shaft as it is the case for the normal VIRYA generators but it is possible to use the original motor shaft if the original short-circuit armature is removed.

2 Description of the generator

The minimum number of stator poles for a 3-phase winding is 3. The armature must have an even number of poles. If there is only a difference of one in between the number of stator poles and the number of armature poles it means that the number of stator poles must be odd. So the number of stator poles can be 3, 9, 15, 21, 27, 33, 39, 45, 51, 57, 63, 69, 75 etc. So none of these values matches with the available number of stator poles for standard stator stampings.

This problem can be solved by doubling the required number of stator and armature poles. The difference in between the number of stator poles and the number of armature poles must now be two. Doubling of the number of armature poles means that the number of armature poles is always even, also if the number of stator poles is even. In this case the required number of stator poles can be 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72 etc. So the numbers 24, 36, 48, 54 and 72 match with available numbers for standard stator stampings.

If the number of armature poles is two more than the number of stator poles it is respectively 26, 38, 50, 56 and 74. If the number of armature poles is two less than the number of stator poles it is respectively 22, 34, 46, 52 and 70.

The number of armature poles must be chosen rather high for the VIRYA-3.3S to realise an acceptable low design wind speed. It is chosen to take 36 stator poles and 34 armature poles. The rotational speed for a 2-pole generator is 3000 rpm for a frequency of 50 Hz. So for a 34-pole generator, the frequency is 50 Hz for a rotational speed of 3000 * 2 / 34 = 176.47 rpm or for 2.94 revolutions per second. In figure 4 of KD 576 it can be seen that n = 176.47 rpm results in a design wind speed of about 6.9 m/s which is a reasonable choice for a moderate wind regime.

For the 16-pole generator described in report KD 531 a coil is laid around each stator pole. Adjacent coils have a different winding direction. If this is done for an asynchronous motor it means that there will be two coils in one groove. In this case there will be room for only half a coil around each stator pole and adjacent coils must have an opposite winding direction. The coil configuration over 360° will be: 6 half coils U, 6 half coils W, 6 half coils V, 6 half coils U, 6 half coils W and 6 half coils V. However, it will be rather difficult to manufacture and mount this winding.

It is more elegant to position a full coil around a certain stator pole and no coil around the adjacent stator pole. An extra advantage of this option is that the winding direction of all coils will be the same. This would result in 3 coils of one phase in a row. So the coil configuration over 360° will be: 3 full coils U, 3 full coils W, 3 full coils V, 3 full coils U, 3 full coils W and 3 full coils V.

The stator pole angle for 36 stator poles is 360° / 36 = 10°. The angle in between the coils is the double value so 360 / 18 = 20°. The armature pole angle for 34 armature poles is 360° / 34 = 10.5882°. The angle between two north poles is the double value so 360 / 17 = 21.1765°. The difference in between the stator pole angle and the armature pole angle is 10.5882° - 10° = 0.5882°. 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° / 0.5882 = 612. This is a very large number so it can be expected that the fluctuation of the clogging torque can be neglected. The number of preference positions can also be found by multiplying the number of armature poles and stator poles and divide it by two as 34 * 36 / 2 = 612.

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 motor frame size 112, stampings with 36 stator poles are available for 2-pole, 4-pole and 6-pole motors. Assume the 6-pole stamping 112F-6P for a 2.2 kW motor with configuration 180 * 120 * 33.5 mm is chosen. The first value is the outside diameter of the stator stamping. The second value is the inside diameter of the stator stamping. The third value is the inside diameter of the armature stamping. The standard stator length for a 2.2 kW motor isn't known to me but it is assumed that there is enough place for the coil heads if a stator length of 120 mm is chosen. The armature length is chosen the same, so also 120 mm. The air gap in between stator and armature is assumed 0.4 mm, so the armature diameter is 119.2 mm.

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 * 10 * 5 mm and size 20 * 10 * 5 mm. Size 40 * 10 * 5 mm is chosen for a stator length of 120 mm. The current price (including VAT, excluding transport) is € 1.81 per magnet for 40 magnets. For larger quantities it will be cheaper and it is assumed that the price per magnet is about € 1.6.

The armature is made from a mild steel cylinder with a diameter of 119.2 mm and a length of 120 mm. In this cylinder 17, 10 mm wide and 5.3 mm deep grooves are made parallel to the axis. Three magnets are glued in each groove, so 51 magnets are needed for one armature. The magnet costs are about € 82 which seems acceptable. All magnets are glued with the north pole to the outside.

The south poles are formed by the remaining material in between the grooves. A 1 mm wide and 3.3 mm deep groove is made at each side of a magnet. This groove makes that a south pole also has a width of about 10 mm and that there is no magnetic short-circuit in between the sides of the magnets. The 17 north poles are called N1 – N17. The 17 south poles are called S1 – S17. A picture of armature and stator is given in figure 1. The position of the armature in figure 1 is drawn such that north pole N1 is just opposite coil U2.

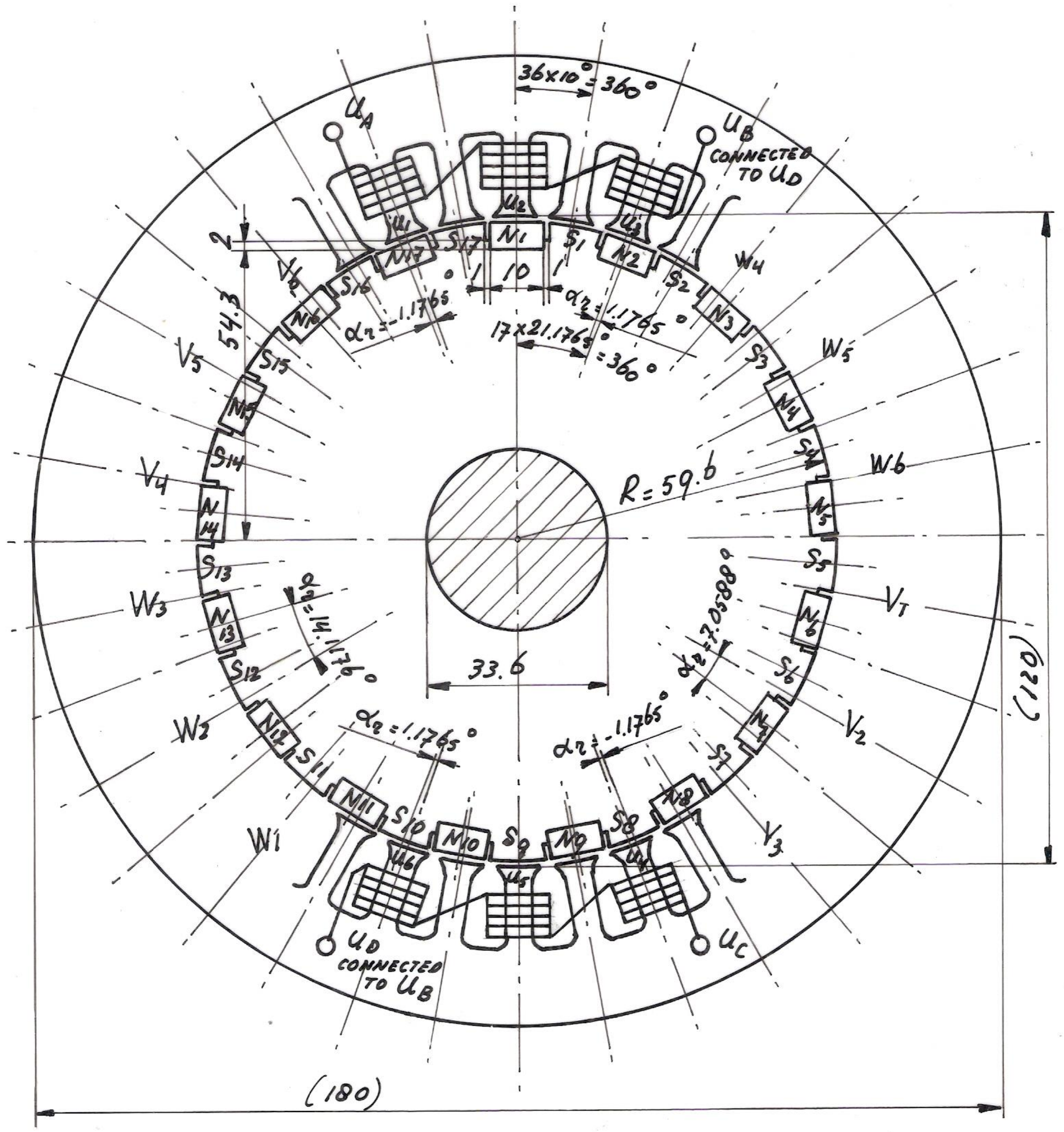

figure 1 34-pole armature and 36-pole stator for housing size 112F-6P, 180 * 120 * 33.5 mm

The shaft can be made using the original motor shaft. So the shaft will also get a fine teething. The armature is pressed over the teething. The original armature stamping has a hole with a diameter of 33.5 mm. As the lamination is rather soft, a little larger inside diameter has to be used for the mild steel bush of the armature, other wise the required pressing force will be too high. It is expected that this must be 33.6 mm.

Detailed drawings of the VIRYA-3.3S windmill have been made. The drawing number of the generator is 1404-02.

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.

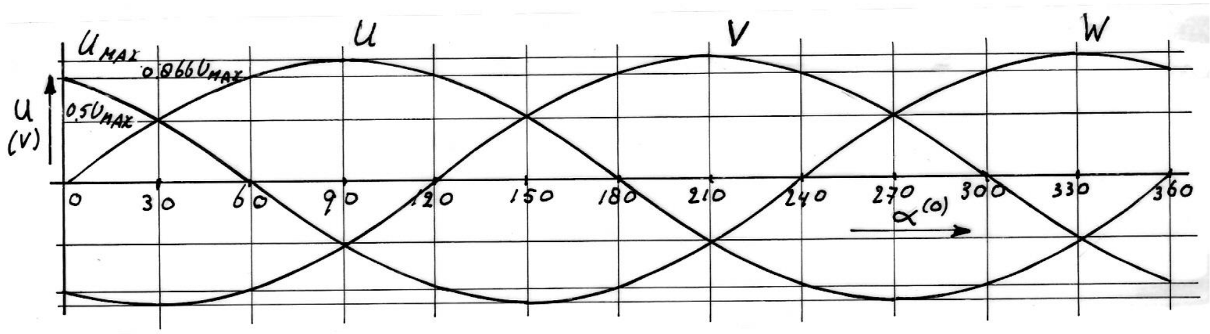

fig. 2 Three phases U, V and W

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 34 poles this will be the case for 360 * 2 / 34 = 21.1765° 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 $\alpha_r = 0°$ in between N1 and U2, that $\alpha_r = 7.0588°$ in between N7 and V2 and that $\alpha_r = 14.1176°$ in between N13 and W2. Substitution of $\alpha_r = 0°$ and $p_r = 34$ in formula 4 gives $\alpha = 0°$. Substitution of $\alpha_r = 7.0588°$ and $p_r = 34$ in formula 4 gives $\alpha = 120°$. Substitution of $\alpha_r = 14.1176°$ and $p_r = 34$ in formula 4 gives $\alpha = 240°$. 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 $\alpha_r = -1.1765°$ in between N17 and U1 and that $\alpha_r = 1.1765°$ in between N2 and U3. So this means that the voltages generated in U1 and U3 are not in phase with the voltage generated in U2.

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 S8, S9 and S10. 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 and U3 if the coils have the same winding direction. It is decided to give all 18 coils the same winding direction and to connect all six coils of one phase in series. The coil ends of the bundle of the three coils U1, U2 and U3 are called U_A and U_B. The coil ends of the bundle of the three coils U4, U5 and U6 are called U_C and U_D. The first bundle of 3 coils of phase U has to be connected such to the second bundle of 3 coils, that the generated voltages in both bundles are strengthening each other. This is realised if coil end U_B is connected to U_D.

The generator winding is very simple if compared to the winding of a normal 6-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 6-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 S8 – S10 are the same as the angles in between the coils U1 – U3 and the poles N17 – N2.

Coil U1 and U4. Substitution of $\alpha_r = -1.1765°$ and $p_r = 34$ in formula 4 gives $\alpha = -20°$.
Coil U3 and U6. Substitution of $\alpha_r = 1.1765°$ and $p_r = 34$ 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:

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

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 - 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 = 0.960 and therefore also a small reduction of the generated power. A factor 0.960 is certainly acceptable, so the given shift of the phase angles in between the three coils of a bundle U is allowed. The same counts for the coils V and W.

Probably a 3-phase relay in between the generator and the pump motor is needed to realise that the windmill starts unloaded. The relay is activated by the generator frequency.

In stead of use in combination with a pump motor it is possible to use the generator for high voltage battery charging. If the voltage for the standard winding is too high, the voltage is halved if the bundle of three coils of one phase is connected in parallel to the other bundle of three coils of the same phase. 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. For 24 V battery charging, one will need a special winding with a much lower number of turns per coil and a much larger wire thickness.

Rectification in star will give the lowest sticking torque because higher harmonic currents can’t circulate in the winding. If the generator is used as a brake, the star point should be short-circuited too because this gives a higher maximum braking torque. Because the frequency is high, it might be required to make short-circuit over a resistor to create a torque which is high enough at normal rotational speeds.

4 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 (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 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 34-pole PM-generator is very low because only half the flux coming out of one a 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 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 1.305 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 0.4 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 5.3 mm. It is assumed that t_3 = 0.6 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 = 1.305 T, t_1 = 5 mm, t_2 = 0.4 mm and t_3 = 0.6 mm in formula 6 results in $B_{r\,eff}$ = 1.088. 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 width is estimated to be 6 mm. As a magnet has a width of 10 mm, the magnetic flux is concentrated by a concentration factor k = 10 / 6 = 1.667. So the magnetic flux in a spoke can be calculated to be 1.667 * 1.088 = 1.81 T. This is higher than 1.6 T so the spokes are saturated and the maximum possible torque level will be realised.

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 optimum number of windings per coil and the wire thickness are found by try and error. The open phase voltage must be a lot higher than 230 V for a frequency of 50 Hz as the loaded phase voltage must be about 230 V. A frequency of 50 Hz is realised for a rotational speed of 176.47 rpm.

First a half winding with three coils of one phase is laid with a thin wire with for instance 100 windings per coil. Assume one measures an open AC voltage of 100 V for f = 50 Hz. So the voltage for a whole winding with six coils would be 200 V. Assume an open voltage of 280 V at 50 Hz is needed. So the number of windings has to be increased by a factor 280 / 200 = 1.4 and becomes 140 windings per coil.

Next one selects the maximum wire thickness for which 140 windings can be laid in a groove and one manufactures a complete 3-phase winding with this wire thickness. Next the generator is measured in combination with a loaded pump motor and it is investigated if the loaded phase voltage is about 230 V at 50 Hz.

At high wind speeds, the generator and the pump motor will run at higher frequencies than 50 Hz and it should be tested if this is allowed for the generator, for the pump motor and for the pump. If the maximum rotational speed is too high, a lighter vane blade has to be used to reduce the rated wind speed. In KD 576 it is assumed that a centrifugal pump with a 0.55 kW pump motor can be chosen so it has to be checked if this is possible for a prototype of the VIRYA-3.3S windmill.

5 References

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