Ideas about a direct drive 46-pole PM-generator for the VIRYA-6.5 windmill meant for driving the 2.2 kW asynchronous motor of a centrifugal pump.

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January 2017
reviewed January 2024

KD 624

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1 Introduction

The VIRYA-6.5 windmill is described in report KD 578 (ref. 1) and KD 579 (ref. 2). It has a 3-bladed rotor with a diameter of 6.5 m and a design tip speed ratio of 6. The wooden blades are connected to each other by means of a welded spoke assembly. The rotor is mounted to the slow shaft of an accelerating gear box which drives a 4 kW, four pole asynchronous motor frame size 112 meant for grid connection. It might be possible to replace the gear box and the asynchronous motor by a 46-pole, direct drive PM-generator if the windmill is used for water pumping using a centrifugal pump with a 3-phase asynchronous motor.

The idea of using a multi pole generator was already described in report KD 614 (ref. 3) for the 34-pole VIRYA-5 generator coupled to a 1.1 kW asynchronous motor of a centrifugal pump. The VIRYA-6.5 with 46-pole PM-generator is primary designed to be directly coupled to the asynchronous motor of a centrifugal pump. The generator is made from the housing of an 8-pole, 11 kW asynchronous motor frame size 180 with stator lamination of manufacture Kienle & Spiess. The 46-pole generator is described in detail in chapter 3.

The VIRYA-6.5 has a design tip speed ratio of 6 in stead of 7 for the VIRYA-5 and a generator with 46 poles in stead of 34 poles. This combination results in a somewhat higher design wind speed and this makes that a pump motor with a nominal power of 2.2 kW can be used. The windmill is provided with the so called hinged side vane safety system and has a rated wind speed V_{rated} of about 11 m/s. This is also higher than for the VIRYA-5 which is realised by taking a thicker vane blade.

The VIRYA-6.5 has an about 17 m high free standing single pole tubular tower which is described in chapter 6 of KD 579.

In stead of direct coupling to the motor of a centrifugal pump, the windmill can also be used for battery charging if the generator is provided with a low voltage winding and if the winding is rectified in star. Rectification of the winding is described in report KD 340 (ref. 4).

2 Determination of the P-n curves, the optimum cubic line and the lines for constant f

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35 (ref. 5). One needs a C_p-λ curve of the rotor and a δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The P-n curves are determined in chapter 5 of report KD 578 and are given in figure 4 of KD 578. This figure is copied as figure 1 but the generator curves for two gear box ratios are removed. The optimum cubic line which can be drawn through the tops of the P-n curves is also given in figure 1.

The 46-pole generator has not yet been built and measured, so measured characteristics are not available. However, it is possible to derive the lines for which the frequency has a certain value. A 2-pole PM-generator has a frequency of 50 Hz for a rotational speed of 3000 rpm. So a 46-pole generator has a frequency of 50 Hz for a rotational speed of 3000 * 2 / 46 = 130.43 rpm. As the frequency is proportional to the rotational speed, the rotational speeds for other frequencies can be determined easily. It is found that:

n = 91.30 rpm for f = 35 Hz.
n = 104.35 rpm for f = 40 Hz.
n = 117.39 rpm for f = 45 Hz.
n = 130.43 rpm for f = 50 Hz.
n = 143.48 rpm for f = 55 Hz.
n = 156.52 rpm for f = 60 Hz.
n = 169.57 rpm for f = 65 Hz.

The lines for constant frequencies of 35, 40, 45, 50, 55, 60 and 65 Hz are also given in figure 1.

In figure 1 it can be seen that the line for f = 50 Hz is intersecting with the optimum cubic line at a power of about 3500 W. The available electrical power will be lower because of the generator efficiency. Assume the generator efficiency is 0.8, so the electrical power is about 2800 W. This power is generated at a wind speed of about 7.5 m/s. The wind speed for which the line for 50 Hz is intersecting with the optimum cubic line is called the design wind speed V_d. So V_d = 7.5 m/s.

A centrifugal pump with a 2.2 kW pump motor will generally be used below the nominal motor power. If it is used at a factor 0.95 of its nominal power and if the motor efficiency is 0.75, it will absorb an electrical power of about 2790 W. So a 2.2 kW pump motor seems an acceptable choice. So the working point will lie about on the optimum cubic line for a pump with a 2.2 kW motor used at a factor 0.95 of its nominal power for a frequency of 50 Hz.

In figure 1 it can be seen that the mechanical power at a wind speed of 9 m/s and a frequency of 50 Hz is about 5300 W. If the generator efficiency is still 0.8, the electrical power will be about 4240 W. If a centrifugal pump with a pump motor of 3 kW is used at a factor 0.95 of its nominal power and if the motor has an efficiency of 0.75, the required electrical power will be about 3800 W which is even lower than 4240 W. So it is also possible to use a pump with a 3 kW pump motor but this results in a design wind speed which lies in between 8 m/s and 9 m/s.

In figure 1 it can be seen that the maximum power at a wind speed of 11 m/s is 7400 W if the optimum cubic line is followed. The rotational speed is about 168 rpm and the frequency is about 64 Hz which are rather high values. But the load characteristic of a centrifugal pump at higher frequencies than 50 Hz is probably not a cubic line and the assumption, that the optimum cubic line is followed for a centrifugal pump as load, seems too optimistic.

The pump torque for a multi stage centrifugal pump used in deep wells is proportional to the pressure difference over the set of pump fans. The pressure difference has a static part which is caused by the static water height H_{stat} and a dynamic part H_{dyn} which is caused by the friction of the water when it passes the fans and the pressure line of the pump. If H_{stat} is large, H_{dyn} will be only a limited part of the total height. So if H_{dyn} is neglected, the pomp requires a constant torque for every rotational speed. A constant torque means that the power is increasing linear to the rotational speed. This means that the P_{mech}-n curve of the pump is a straight line through the origin from the working point n = 130.43 rpm and P = 3500 W. In reality H_{dyn} can’t be neglected which means that the real P_{mech}-n curve will rise faster than for a straight line through the origin but it won’t rise that fast as for a cubic line. This means that the maximum rotational speed will certainly be larger than 168 rpm.

There is another aspect which has an influence on the maximum rotational speed. A multi stage centrifugal pump with an asynchronous motor is designed for a grid frequency of 50 Hz and it has a maximum efficiency for the design water height H. So this means that the product of the flow q and the height H is maximal for this height. If the pump is used for higher or lower water heights, the efficiency will be lower and the product of q * H will be lower too. Above a certain height, the flow will be zero. Every centrifugal pump has a certain q-H curve for a frequency of 50 Hz. For higher frequencies, the q-H curve will lie higher and for lower frequencies the q-H curve will lie lower. For a frequency of about 35 Hz, the pump can’t even supply the design water height H. However, the real water height isn’t constant but it depends on the water level in the well. After long periods of rain, the water level may have risen a lot and this means that the required generator power for 50 Hz will be a lot lower than 2800 W. If the working point at 50 Hz lies below the optimum cubic line of the rotor, it will certainly lie much lower at wind speeds of 11 m/s and higher.

So there are several reasons why the maximum rotational speed may be a lot higher than 168 rpm and it is uncertain if the pump and the pump motor will survive frequencies and rotational speeds which are much higher than the frequency and the rotational speed for which they were designed. It might be possible to solve this problem by adding a voltage controller and a dump load which limits the phase voltage up to 240 V.

As the pump motor will be connected in star, the three phases are rectified in star. The effective DC-voltage for rectification in star is given by formula 14 of KD 340 (ref. 4). Substitution of U_{eff} = 240 V in formula 14 of KD 340 gives U_{DCeff} = 560 V. The P_{mech}-n curve for U_{DCeff} = 560 V will be a rather steep line and the maximum rotational speed will therefore be limited sharply. One needs a controller with dump load similar to the battery charge controllers as designed for the battery charging VIRYA-windmills. Only the voltage must be much higher. It must be prevented that the dump load is connected earlier than the pump motor. So the pump motor must be connected at a somewhat lower voltage, assume 230 V AC. If the winding is chosen such that the open AC voltage is 280 V at 50 Hz, it will be 230 V at 41 Hz, so at about 107 rpm. This rotational speed will be reached for an unloaded rotor at a rather low wind speed of about 3.9 m/s.

Below a frequency of about 35 Hz, belonging to a rotational speed of 91.30 rpm, the pump is no longer able to produce the static water height, so no water will be pumped. Probably it is necessary to disconnect the generator and the pump motor by a 3-phase switch below a frequency of about 35 Hz. This makes that the rotor will always start unloaded at low wind speeds. If the connection is broken at f = 35 Hz for a running rotor, this results in acceleration of the rotor until the connection is made again at an open DC voltage of 230 V, so at a frequency of 41 Hz belonging to a rotational speed of about 107 rpm. This means that even at low wind speeds, there will be some intermittent output.

A short-circuit switch to stop the rotor connects the three phases to the star point. The short-circuit switch, the rectifier and the controller are placed at the tower foot. From here, a 3-phase cable goes to the pump motor.

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 in this case water is not pumped intermittently if the wind speed is just above 3.9 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 generator winding must be chosen such that the loaded voltage is 230 V at a frequency of 50 Hz. This means that the unloaded voltage at 50 Hz must be a lot higher. I expect about 280 V but this must be tested for a prototype of the generator.

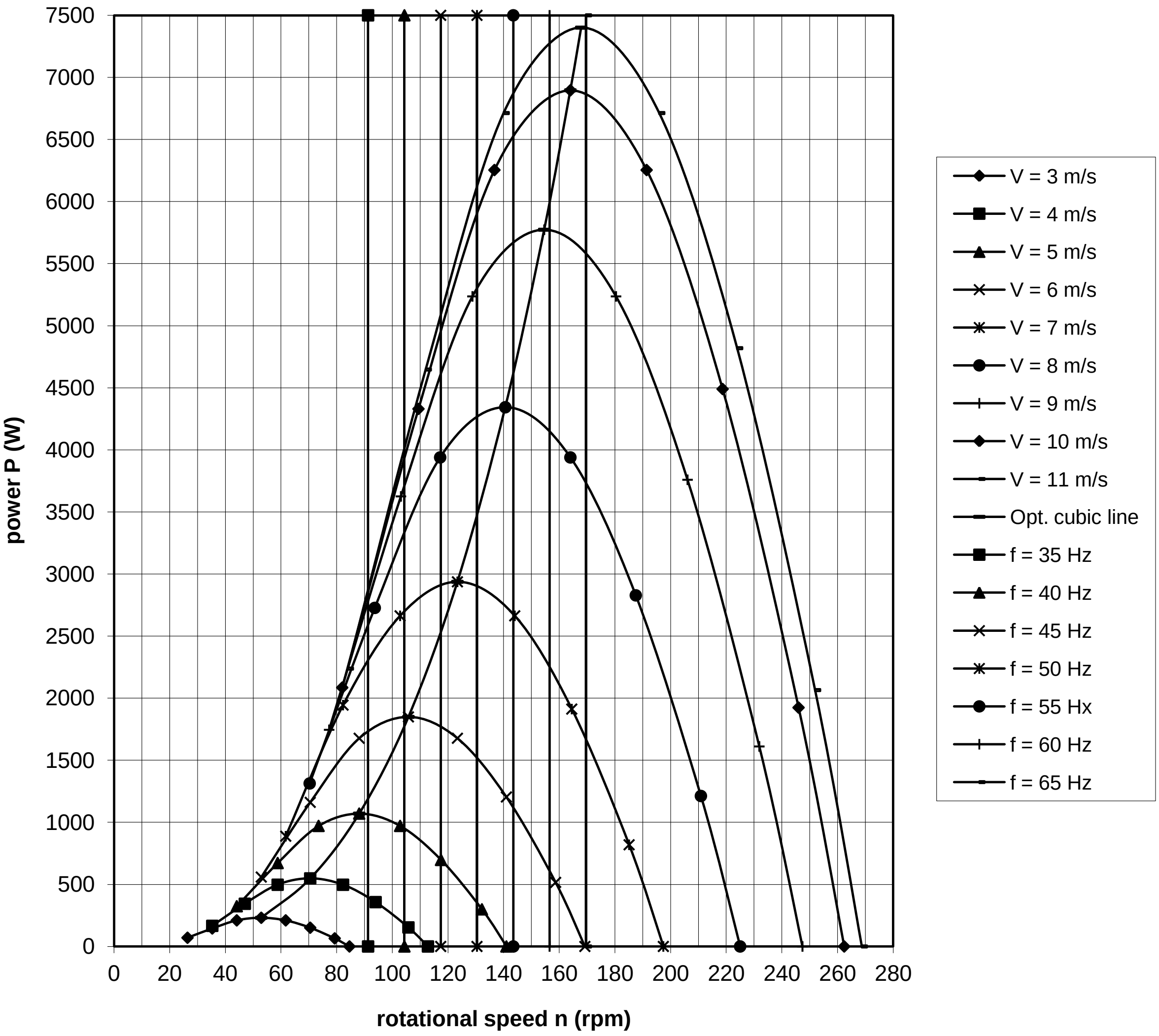

fig. 1 P-n curves of the VIRYA-6.5 rotor, optimum cubic line and line for frequencies f of 35, 40, 45, 50, 55, 60 and 65 Hz

3 Description of the 46-pole PM-generator (see figure 2)

The number of stator poles for a 3-phase winding must be dividable by 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. None of these values matches with the available number of stator poles for standard stator stampings of asynchronous motors. 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-6.5 to realise an acceptable low design wind speed. It is chosen to take 48 stator poles and 46 armature poles. The rotational speed for a 2-pole generator is 3000 rpm for a frequency of 50 Hz. So for a 46-pole generator, the frequency is 50 Hz for a rotational speed of 3000 * 2 / 46 = 130.43 rpm or for 2.17 revolutions per second. In figure 1 it can be seen that n = 130.43 rpm results in a design wind speed of about 7.5 m/s which is a reasonable choice for a moderate wind regime.

The coil configuration of the VIRYA-6.5 generator is chosen about the same as for the VIRYA-5 generator. But as the VIRYA-6.5 generator has 48 stator grooves and as every coil takes two grooves, it will have 24 coils, so 8 coils for each phase. So the coil configuration over 360° will be: 4 coils U, 4 coils W, 4 coils V, 4 coils U, 4 coils W and 4 coils V. A coil is wound around one stator spoke so every coil makes use of two adjacent stator grooves. All 24 coils are identical and are lying in one cylinder shaped plane, so there are no crossing coil heads

The stator pole angle for 48 stator poles is 360° / 48 = 7.5°. The angle in between the coils is the double value so 360 / 24 = 15°. The armature pole angle for 46 armature poles is 360° / 46 = 7.8261°.

The angle between two north poles is the double value so 360 / 23 = 15.6522°. The difference in between the stator pole angle and the armature pole angle is 7.8261° - 7.5° = 0.3261°. 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° / 0.32609 = 1104. 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 46 * 48 / 2 = 1104.

Provisionally it is chosen to make use of a motor housing which makes use of a stator stamping of manufacture Kienle and Spiess. The manufacturer which uses stampings of Kienle and Spiess for their motors has not yet been chosen. Information about the geometry of these stampings is given on the website: www.kienle-spiess.de. Stator stampings with 48 stator grooves are used for 8-pole motors. It is chosen to use a stamping for an 11 kW, 8-pole motor. This stamping has frame size 180. The shaft diameter of this frame size is 48 mm which seems just enough for a rotor with a diameter of 6.5 m. This stator stamping has an inside diameter of 190 mm, an outside diameter of 270 mm and a length of 240 mm. The armature stamping has an inside diameter of 65 mm but the armature stamping is not used. The armature diameter is chosen 189.2 mm, so the air gap in between armature and stator is 0.4 mm. The armature length is chosen the same as the stator length, so 240 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.enesmagnets.pl supplies magnets size 30 * 10 * 8 mm with quality N40H. The tolerance on the width is ± 0.1 mm and so the groove width must be chosen 10.2 mm to guarantee that the magnets always fit. The current price (January 2017, including VAT, excluding transport) is € 1.43 per magnet for 140 magnets.

The armature is made from a mild steel cylinder with a diameter of 189.2 mm and a length of 240 mm. In this cylinder 23, 10.2 mm wide and 8.3 mm deep grooves are made parallel to the axis. Eight magnets are glued in each groove, so 184 magnets are needed for one armature. The magnet costs are about € 263 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 2.8 mm wide and 5.2 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 23 north poles are called N1 – N23. The 23 south poles are called S1 – S23. A picture of armature and stator is given in figure 8. The position of the armature in figure 8 is drawn such that south pole S2 is just opposite the empty stator pole in between coil U2 and coil U3.

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 sheets of the original armature stamping have a central hole with a diameter of 65 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 65.2 mm.

For small series, the armature must be made from massive bar. However, for big series it might be possible to make the armature also from sheet lamination which is already provided with the pattern of the grooves for the magnets.

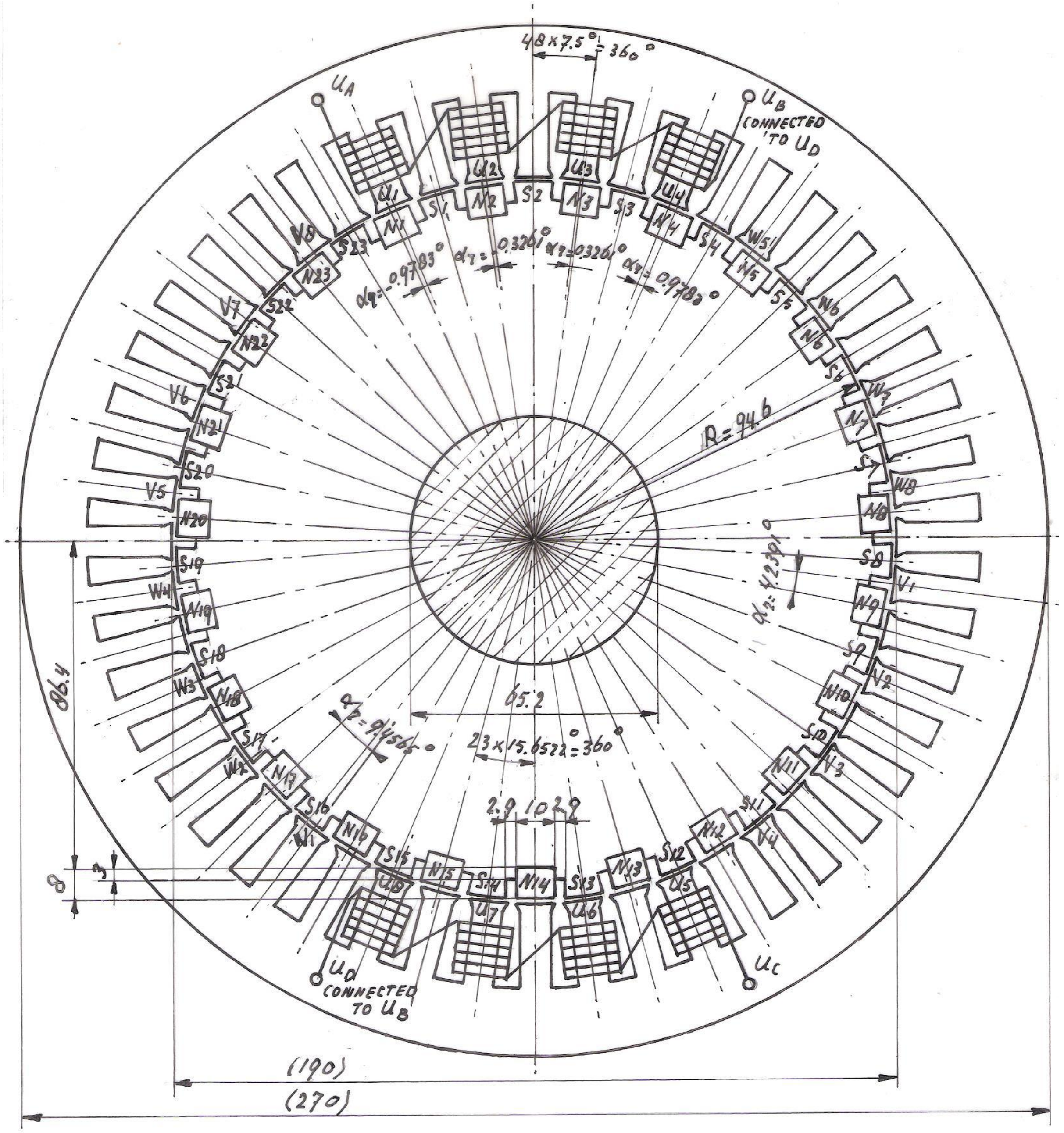

fig. 2 46-pole armature and 48-pole stator for housing size 180L, 270 * 190 * 65 mm

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 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 3.

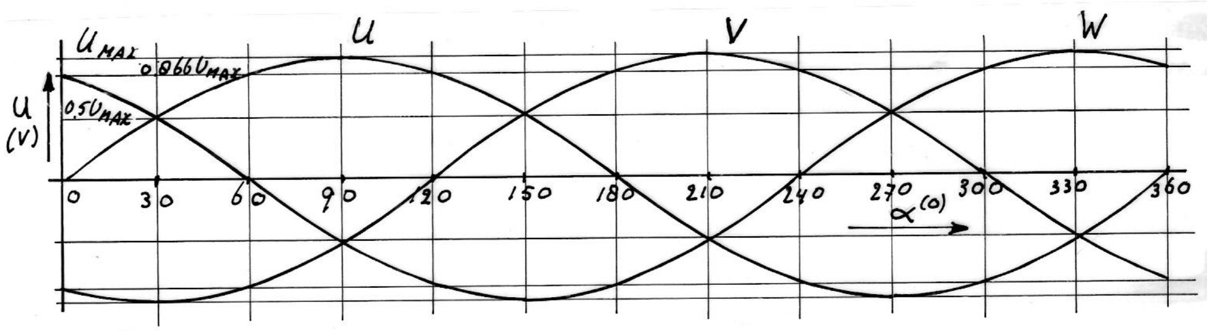

fig. 3 Three phases U, V and W

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 46 poles this will be the case for 360 * 2 / 46 = 15.6522° 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 2 it can be seen that α_r = -0.9783° in between N1 and U1, that α_r = 4.2391° in between N9 and V1 and that α_r = 9.4565° in between N17 and W1. Substitution of α_r = -0.9783° and p_r = 46 in formula 4 gives α = -22.5°. Substitution of α_r = 4.2391° and p_r = 46 in formula 4 gives α = 97.5°. Substitution of α_r = 9.4565° and p_r = 46 in formula 4 gives α = 217.5°. 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 2 it can be seen that α_r = -0.9783° in between N1 and U1, that α_r = -0.3261° in between N2 and U2, that α_r = 0.3261° in between N3 and U3 and that α_r = 0.9783° in between N4 and U4. So this means that the voltages generated in U1, U2, U3 and U4 are not in phase.

In figure 2 it can be seen that the coils U5, U6, U7 and U8 are not about opposite to north poles but that they are about opposite to the south poles S12, S13, S14 and S15. 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, U3 and U4 if the coils have the same winding direction. It is decided to give all 24 coils the same winding direction and to connect all eight coils of one phase in series. The coil ends of the bundle of the four coils U1, U2, U3 and U4 are called U_A and U_B. The coil ends of the bundle of the four coils U5, U6, U7 and U8 are called U_C and U_D. The first bundle of four coils of phase U has to be connected such to the second bundle of four 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 8-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 8-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 U5 – U8 and the poles S8 – S10 are the same as the angles in between the coils U1 – U4 and the poles N1 – N4.

Coil U1 and U5. Substitution of $\alpha_r = -0.9783°$ and $p_r = 46$ in formula 31 gives $\alpha = -22.5°$.
Coil U2 and U6. Substitution of $\alpha_r = -0.3261°$ and $p_r = 46$ in formula 31 gives $\alpha = -7.5°$.
Coil U3 and U7. Substitution of $\alpha_r = 0.3261°$ and $p_r = 46$ in formula 31 gives $\alpha = 7.5°$.
Coil U4 and U8. Substitution of $\alpha_r = 0.9783°$ and $p_r = 46$ in formula 31 gives $\alpha = -22.5°$.

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 eight coils U1 – U8 is given by:

$$U_{tot} = U_{max} * 2 * \{\sin(\alpha - 22.5°) + \sin(\alpha - 7.5°) + \sin(\alpha + 7.5°) + \sin(\alpha + 22.5°)\} \quad \text{(V)} \quad (5)$$

It can be proven that this function has a maximum value for $\alpha = 90°$. Substitution of $\alpha = 90°$ in formula 5 gives:
$U_{tot\ max} = U_{max} * 2 * (\sin 67.5° + \sin 82.5° + \sin 97.5° + \sin 112.5) = 7.6613 * U_{max}$.

If the voltages U1 – U8 would be exactly in phase, the resulting maximum voltage would be $8 * U_{max}$. So the difference in phase angle gives a small reduction of the total voltage by a factor 7.6613 / 8 = 0.958 and therefore also a small reduction of the generated power. A factor 0.958 is certainly acceptable, so the given shift of the phase angles in between the four coils of a bundle U is allowed. The same counts for the coils V and W.

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 four coils of one phase is connected in parallel to the other bundle of four 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 or 48 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.

5 Calculation of the flux density in the air gap and the stator spokes

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 an 8-pole motor and for a 8-pole motor there is a large magnetic flux in the bridge. The magnetic flux in the bridge for a 46-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 Enes with quality N40H is in between 1.26 T and 1.29 T, if the magnet is short-circuited with a mild steel arc which is not saturated. Assume it is 1.275 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 8.2 mm. It is assumed that t_3 = 0.5 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:

$$B_{r\ eff} = B_r * t_1 / (t_1 + t_2 + t_3) \quad \text{(T)} \qquad (33)$$

Substitution of B_r = 1.275 T, t_1 = 8 mm, t_2 = 0.4 mm and t_3 = 0.5 mm in formula 33 results in $B_{r\ eff}$ = 1.146. 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 about 8 mm. As a magnet has a width of 10 mm, the magnetic flux is concentrated by a concentration factor k = 10 / 8 = 1.25. So the magnetic flux in a spoke can be calculated to be 1.25 * 1.146 = 1.43 T. This is lower than 1.6 T so the spokes are not saturated but I still think that the used magnets are strong enough..

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 2 and chapter 3 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 130.43 rpm.

First a half winding with four 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 eight 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.

6 Using 138 neodymium magnets size 40 * 10 * 10 mm

In January 2017, when the first version of this report was made, magnets size 30 * 10 * 8 mm where the thickest magnets with a width of 10 mm which were supplied by Enes Magnets. In January 2024, Enes Magnets also supplies magnets size 40 * 10 * 10 mm. The quality of these magnets is N38 which means that the remanence B_r is about 1.24 T, so a little lower than the value of 1.275 T which was used in chapter 5 for the calculation of the flux density in the air gap for the magnets size 30 * 10 * 8 mm.

The current price (January 2024) of magnets size 30 * 10 * 8 mm is € 1.71 if 120 magnets are ordered. The magnet volume is 2.4 cm^3. So the magnet costs are € 0.713 / cm^3. The current price of magnets size 40 * 10 * 10 mm is € 1.89 if 100 magnets are ordered. The magnet volume is 4 cm^3. So the magnet costs are € 0.473 / cm^3. So the magnet costs per cm^3 are much lower for magnets size 40 * 10 * 10 mm than for magnets size 30 * 10 * 8 mm.

Assume than the eight magnets size 30 * 10 * 8 mm in one groove are replaced by six magnets size 40 * 10 * 10 mm. So the total magnet length is 240 mm for both magnet sizes. As there are 23 grooves, now 6 * 23 = 138 magnets are needed. So the total magnet costs are 138 * € 1.89 = € 260.82. The total magnet costs of 184 magnets size 30 * 10 * 8 mm are 184 * € 1.71 = € 314.64. So the total magnets costs for magnets size 40 * 10 * 10 mm are € 53.82 lower, even if thicker magnets are used.

The remanence B_r of magnets size 40 * 10 * 10 mm is a little lower than for magnets size 30 * 10 * 8 mm, but as the thickness is 2 mm more, the calculated flux density in the air gap is about the same. So the generator armature will have about the same magnetic strength.

As the magnets now have a thickness of 10 mm, the 10.2 mm wide grooves must now have a depth of 10.3 mm. The 2.8 mm wide grooves at both sides of a magnet groove must now have a depth of 7.2 mm.

A problem with magnets for which the height is the same as the width, is that the magnets can be mounted with a side facing to the outside. So all magnets have to be marked with two N’s at the north side of the magnet and after mounting of a magnet, these two N’s should be visible on all 138 magnets. It is advised to use a tool in which a magnet can be hold firmly when it is mounted in a groove. This tool should clamp a magnet on both long sides and the clamping area should be that high, that the magnet can be pushed up to the bottom of the groove.

Another point of change is that the manufacturer of the stator stamping Kienle & Spiess has recently changed its name into Feintool. Information about the dimensions of stator and armature stampings of asynchronous motors can be found following the path: www.feintool.com – Online catalogue industry – Products – Induction Machines. One has to make an account with an e-mail address and a password to get access to the catalogue.

7 References

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2 Kragten A. Extended calculations executed for the grid connected VIRYA-6.5 windmill, March 1015, reviewed June 2023, free public report KD 579, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

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