Ideas about a 22-pole permanent magnet generator for the VIRYA-2.7 windmill using a 4-pole, 3-phase, 1.5 kW asynchronous motor frame size 90 and 27 ½ neodymium magnets size 40 * 10 * 4 mm

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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 are described in chapter 4 of my public report KD 341 (ref. 1). These generators are very strong and have good characteristics. The sticking 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.

The idea is to design a new type of a small PM-generator which makes use of the original motor shaft and for which the shallow magnet grooves are in parallel to the generator shaft. The generator will be used for a small windmill with a diameter of about 2.7 m.

It is decided to use a motor housing of a 1.5 kW, 4-pole motor frame size 90 and to use a motor which is provided with a stator stamping of the German supplier Kienle & Spiess type IEC 90/4.824. This stator stamping has 24 stator slots so 24 stator poles. The generator armature differs strongly from the normal 4-pole VIRYA-generators as it will have 22 poles. So the number of armature poles is two less than the number of stator poles. In chapter 2 it will be shown that this results in only a very small fluctuation of the sticking torque.

Already in 2014, I have designed and built a 22-pole PM-generator. This generator is described in report KD 553 (ref. 2). This report isn’t public as it was written for an Indian company. This generator makes use of an Indian motor housing frame size 71. A disadvantage of Indian stator stampings is that these stampings have four outside grooves in which four strips are used to bind the sheets together. However, these grooves result in a non homogeneous density of the magnetic flux in the stator which causes extra preference positions. Stator stampings of Kienle & Spiess don’t have large outside grooves and this is one of the reasons why this manufacture is chosen. Another reason is that a very large range is available and that all measures can be found on the website: www.kienle-spiess.de.

2 Description of the generator armature and stator

The 1.5 kW, 4-pole motor frame size 90 of Kienle & Spiess makes use of a stamping type IEC 90/4.824. The outside diameter of the stator stamping is 135 mm. The inside diameter of the stator stamping is 80 mm. The length of the stator stamping is 100 mm for a 1.5 kW motor (and 75 mm for a 1.1 kW motor).

The original short-circuit armature stamping is pressed on the shaft. The armature stamping has an inside diameter of 30 mm and an outside diameter of 80 mm but the outside diameter is turned to 79.4 mm after pressing. So the air gap in between the armature and the stator is 0.3 mm. The shaft is provided with a fine teething to guarantee a strong press fitting. The original short-circuit armature isn’t used so it is removed from the shaft if an existing motor is used for a prototype. The original 4-pole winding is removed from the stator. For serial production one should use only bare shafts and a stator stamping without a winding.

The short-circuit armature is replaced by a mild steel bush with an outside diameter of 80 mm and a length of 100 mm. So the length of the armature is the same as the length of the stator stamping. The inside diameter is chosen 0.1 mm larger than that of the stator stamping because a massive bush is less flexible that a bunch of sheets. So the inside diameter is 30.1 mm. This bush is turned to a diameter of 79.4 mm after pressing on the shaft.

Eleven grooves with a width of 10 mm and a depth of 4.35 mm are made in the armature. The angle in between the heart of the grooves is 360° / 11 = 32.7273°. Two and a half neodymium magnets size 40 * 10 * 4 mm are glued in each groove by epoxy glue or anaerobe glue such that the north poles of all magnets are pointing to the outside. A whole magnet can be broken in two 20 mm long halves if a deep scratch is made in the middle. The half magnet is mounted in between two whole ones. These 27 ½ magnets are forming the eleven north poles which are called N1 – N11. The eleven south poles are formed by the remaining material left in between the grooves. The south poles are called S1 – S11. So the armature has 22 poles. The armature pole angle is 360° / 22 = 16.3636°.

As the coil heads are very small, there is place for a 120 mm long stator stamping (if available). In this case one can use a 120 mm long armature with three magnets size 40 * 10 * 4 mm per groove.

So the north poles are formed by the magnets and the south poles are formed by the remaining material in between the armature grooves. At each side of a 10 mm magnet groove there is a 1.3 mm wide and 3.35 mm deep groove which make that the width of a south pole is also 10 mm. The air gap at the south poles is 0.3 mm. The air gap is about 0.3 + 0.35 = 0.65 mm at the heart of the north pole and about 0.34 mm at the side of a north pole. The average air gap at a north pole is about 0.55 mm.

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 16.3636 - 15° = 1.3636°. Assume that 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° / 1.3636 = 264. 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 22 * 24 / 2 = 264.

The stator winding is a very simple 3-phase, 1-layers 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.

Some research has done to Neodymium magnets which are standard supplied by Internet companies. The Polish company www.enesmagnets.pl supplies several magnets with a width of 10 mm. Finally the magnet size 40 * 10 * 4 mm was chosen. The current price of this magnet including VAT but excluding transport is € 0.91 for an ordered quantity of 250 pieces. So this results in magnet costs for one generator of only about € 28 including transport and VAT which is rather low compared to the magnet costs of an axial flux PM-generator of the same torque level. The magnets have quality N38 which means that the remanence B_r is about 1.24 T.

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 4.35 mm which means that the distance in between the bottom of the groove and the heart of the shaft is 35.35 mm for an armature diameter of 79.4 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.

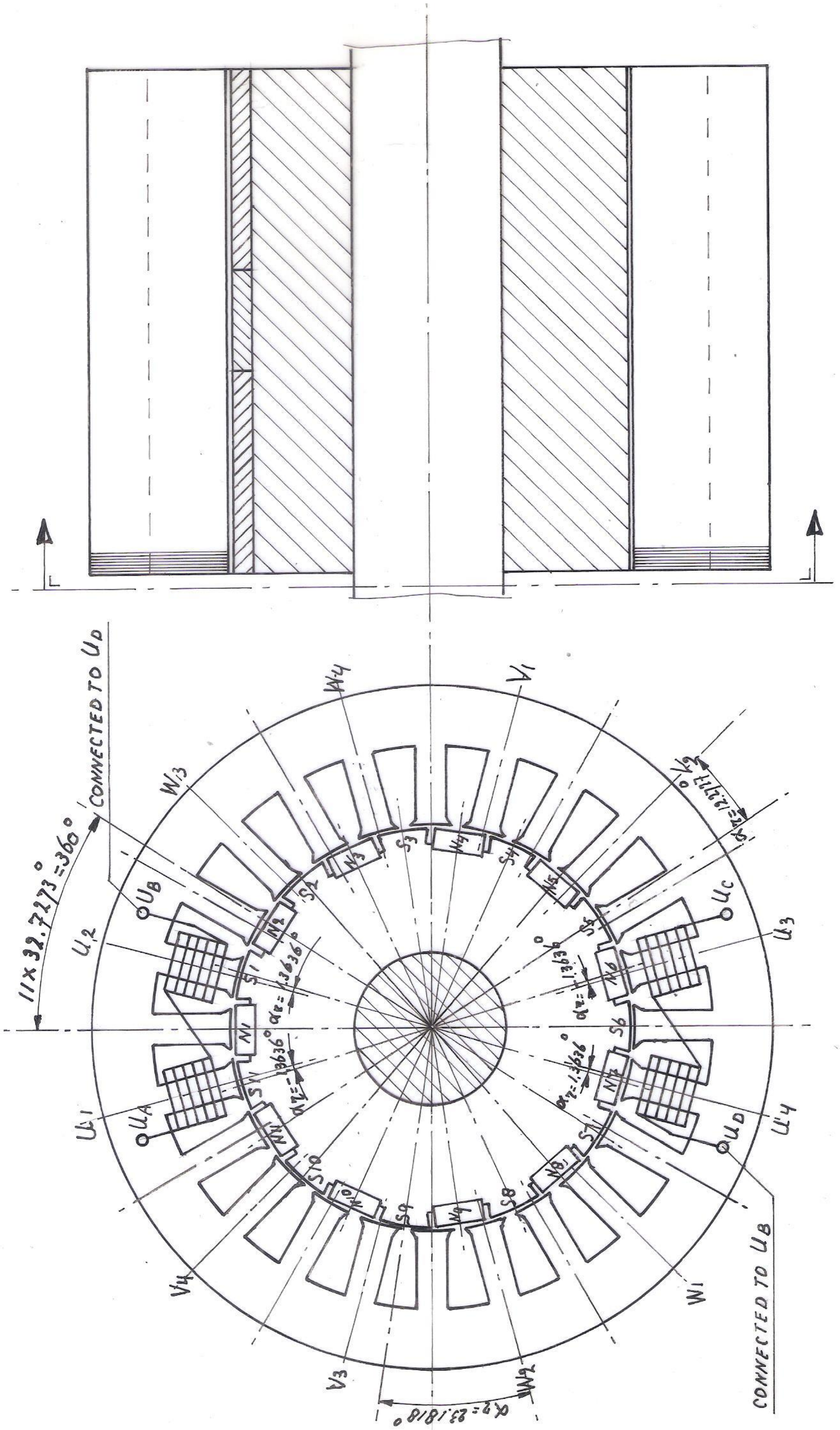

fig. 1 22-pole PM-armature and stator with twelve coils

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:

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

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

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

The three curves are shown in figure 2.

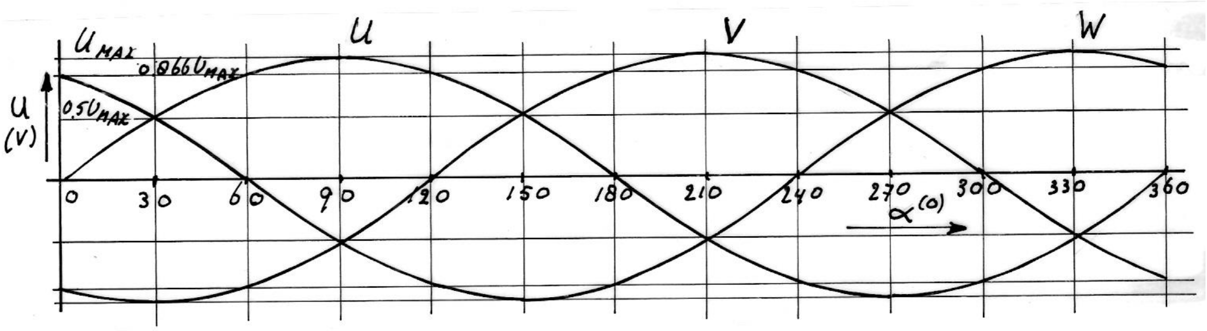

fig. 2 Three phases U, V and W

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 armature has two poles, the position of the armature with respect to the stator will be the same if the armature has rotated 360°. So the phase angle α is the same as the rotational angle α_r of the armature. If the armature has 22 poles this will be the case for 360 * 2 / 22 = 32.7273° rotation of the armature. This results in the formula:

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

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

In figure 1 it can be seen that $\alpha_r = 1.3636°$ in between S1 and U2, that $\alpha_r = 12.2727°$ in between S5 and V2 and that $\alpha_r = 23.1818°$ in between S9 and W2. Substitution of $\alpha_r = 1.3636°$ and $p_r = 22$ in formula 4 gives $\alpha = 15°$. Substitution of $\alpha_r = 12.2727°$ and $p_r = 22$ in formula 4 gives $\alpha = 135°$. Substitution of $\alpha_r = 23.1818°$ and $p_r = 22$ in formula 4 gives $\alpha = 255°$. 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 $\alpha_r = -1.3636°$ in between S11 and U1 and that $\alpha_r = 1.3636°$ 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 N6 and N7. 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 N6 – N7 are the same as the angles in between the coils U1 – U2 and the poles S11 – S1.

Coil U1 and U3. Substitution of $\alpha_r = -1.3636°$ and $p_r = 22$ in formula 4 gives $\alpha = -15°$.
Coil U2 and U4. Substitution of $\alpha_r = 1.3636°$ and $p_r = 22$ 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:

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

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 winding has to be rectified in delta. However, rectification in delta has as disadvantage that the unloaded sticking torque is rising faster at low rotational speeds. This is because higher harmonic currents can circulate in the winding for delta connection and this will result in a somewhat lower efficiency and a somewhat higher starting wind speed.

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 22-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 the chosen neodymium magnet with quality N38 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 it $B_r = 1.24$ 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 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 4.35 mm. It is assumed that $t_3 = 0.55$ 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, $t_1 = 4$ mm, $t_2 = 0.3$ mm and $t_3 = 0.55$ mm in formula 6 results in $B_{r\ eff} = 1.023$ 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 5.7 mm. A magnet has a width of 10 mm. So the magnetic flux is concentrated by a concentration factor $k = 10 / 5.7 = 1.754$. So the magnetic flux in a spoke can be calculated to be 1.023 * 1.754 = 1.79 T. This is larger than 1.6 T so the spokes are saturated and the maximum possible torque level will therefore be realised, even for a magnet thickness of only 4 mm.

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.

5 Choosing of the test winding and the final winding

It is not possible at this moment to specify a winding for which the generator will have a good matching with a certain rotor. To check the matching with the rotor, first a certain rotor has to be chosen. The generator shaft has a diameter of 25 mm at the front bearing but a diameter of 24 mm at the shaft end and a grinding groove at the change. The rotor diameter should therefore be chosen not larger than about 2.7 m. As the generator will have a certain sticking torque, also caused by the seal on the rotor shaft, one must use a rotor with an acceptably high starting torque coefficient. So the design tip speed ratio λ_d of the rotor should be not too high. I expect that it should be about 5.5.

Assume that the 3-bladed VIRYA-3B3 rotor is chosen but that the blades are shortened by 0.15 m such that the rotor diameter D = 2.7 m. So the windmill with this new rotor is called the VIRYA-2.7. The geometry calculations of the VIRYA-3B3 rotor are given in public report KD 484 (ref. 3). A photo of the original rotor drawing with drawing number 1201-01 is given in appendix 2 of KD 484. This rotor has a diameter of 3 m, a design tip speed ratio $\lambda_d = 6.5$ and a maximum C_p of 0.4. It has three wooden blades with a Gö 623 or a Gö 711-12% airfoil, a constant chord of 150 mm and a constant blade angle $\beta = 7°$. The three blades are connected to each other by a stainless steel hub plate with 7° twisted ears (on drawing 1201-01 it is mentioned 6° but this should be 7°). The hub plate is connected to a stainless steel hub with a diameter of 70 mm.

If the blade length is shortened by 0.15 m, it is assumed that the optimum tip speed ratio λ_d is reduced from 6.5 up to 5.5 but that the optimum blade angle β is maintained at 7°. So the hub plate isn't changed. It is assumed that the maximum C_p is still 0.4. I have checked these values but to prove that these assumptions are correct, a new design report of the VIRYA-2.7 rotor has to be made. The optimum cubic line of the VIRYA-2.7 rotor can be determined using formula 8.1 of public report KD 35 (ref. 4).

The hub has to be changed such that it fits to a cylindrical shaft with a diameter of 24 mm, a length of 40 mm and provided with a 8 mm wide key. It seems possible to use this VIRYA-2.7 rotor in combination with the head and tower of the VIRYA-2.68 windmill with two stainless steel, 7.14 % cambered blades.

The procedure to find the optimum winding is as follows. One starts with a 3-phase test winding using copper wire of 1 mm diameter and using as many turns per coil as possible in the available space of a stator slot. Assume 50 turns per coil can be laid.

The generator will be used for 24 V battery charging if the winding is rectified in star and for 12 V battery charging if the winding is rectified in delta. The average charging voltage of a 24 V battery is about 26 V and of a 12 V battery it is about 13 V.

The generator will be measured for star rectification for a range of DC voltages. Measuring of the mechanical power requires a test rig for which it is possible to measure the torque. If such a test rig isn't available, at least the electrical power must be measured for a range of rotational speeds. So P_{el}-n curves will be available for a range of DC voltages of for instance 12 V, 16 V, 20 V, 24 V, 28 V and 32 V. The corresponding P_{mech}-n curves will be estimated for an estimate η-n curve based on measurements of other VIRYA generators. Extensive measurements are given in public report KD 78 (ref. 5).

The estimated P_{mech}-n curves are compared with the optimum cubic line of the rotor. That curve which gives the best matching with the optimum cubic line of the rotor shows the optimum voltage for the test winding. The best matching means that the P_{mech}-n curve of the generator is just touching the optimum cubic line of the rotor. Assume the best matching is realised for 20 V star. This means that the final winding must have a number of turns per coil which is a factor 26 / 20 = 1.3 higher to get the same P_{mech}-n curve. So the final winding must have 1.3 * 50 = 65 turns per coil. The wire thickness must be reduced such that the same total copper area is used in a stator slot.

So the cross sectional copper area must be reduced by a factor 1.3. The wire diameter therefore has to be reduced by a factor √ 1.3 = 1.14 and becomes 1 / 1.14 = 0.877 mm.

The generator should be measured again but now with the final winding for 26 V star and for 13 V delta. The P_{mech}-n curve for 13 V delta will lay somewhat more to the left than the P_{mech}-n curve for 26 V star. So the matching for 13 V delta will also be acceptable if the P_{mech}-n curve for 26 V star is just touching the optimum cubic line of the rotor. It is advised to also measure the Q-n curve for short-circuit in delta to check if the torque Q is strong enough at low rotational speeds to use the generator as a brake.

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