Ideas about a 26-pole permanent magnet generator for the VIRYA-2.2 windmill using the housing of a 4-pole, 3-phase, 0.75 kW asynchronous motor frame size 80 and 26 neodymium magnets size 40 * 7 * 3 mm. Design report of the rotor (λ_d = 4.75, B = 2, galvanised steel blades)

ing. A. Kragten

May 2017
reviewed October 2017 (design report of the rotor included)

KD 632

 Anyone can use the described generator or the working principle. The generator has not yet been built and tested but some basic tests have been performed for a 22-pole generator frame size 71. The VIRYA-2.2 rotor has also not yet been tested.

Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

Contains page

1 Introduction

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

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

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

Recently the idea came up to design a small 26-pole PM-generator using the housing of a 4-pole, 0.75 kW motor frame size 80 and 26 neodymium magnets size 40 * 7 * 3 mm, so the same magnets as those which are also used for the 22-pole generator. An advantage of using these magnets for frame size 80 is that the armature length becomes the same as the stator length (80 mm) if two magnets are used in one groove. The 3-phase generator winding will be rectified in star and the windmill will be used for 24 V battery charging. Each phase has two bundles of two coils and the two bundles are connected in series for 24 V battery charging.

The two bundles can also be connected in parallel and in this case the generator can be used for 12 V battery charging. However, the maximum current in the cables in between the generator and the battery will be rather large for 12 V battery charging and copper wires with a large diameter will be required to limit the voltage losses in these cables. 12 V battery charging is therefore not advised.

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

A windmill rotor with a diameter of 2.2 m will be mounted directly to the generator shaft. The calculations of the VIRYA-2.2 rotor are given from chapter 5.

2 Description of the 26-pole PM-generator

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

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

The armature bush is provided with thirteen, 7 mm wide and 3.2 mm deep grooves parallel to the armature axis. Two magnets size 40 * 7 * 3 mm are glued in each groove. These 26 magnets are forming the 13 north poles which are called N1 – N13. The thirteen south poles are formed by the remaining armature material left in between the grooves. The south poles are called S1 – S13. So the armature has 26 poles. The armature pole angle is 360 / 26 = 13.8462°.

The stator has 24 grooves, so 24 poles. The stator pole angle is 360 / 24 = 15°. The difference in between the stator pole angle and the armature pole angle is 15° - 13.8462° = 1.1538°. Assume a preference position is created if an armature pole is just opposite a stator pole. This means that the number of preference positions per revolution is 360° / 1.1538 = 312. This is a large number so it can be expected that the fluctuation of the sticking torque is almost flattened. The number of preference positions can also be found by multiplying the number of armature poles times the number of stator poles and divide it by two as 26 * 24 / 2 = 312.

The stator winding is a very simple 3-phase, 1-layer winding with no crossing coil heads. A stator coil is wound around 1 armature spoke. The coil sequence is U1, U2, W3, W4, V1, V2, U3, U4, W1, W2, V3 and V4. All coils of one phase are connected in series for 24 V battery charging. A sketch of the armature and the stator is given in figure 1. The armature is positioned such that the north pole N1 is just opposite the middle of coil U1 and coil U2.

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

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

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

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

The air gap at the heart of the magnet is 0.5 mm. The air gap at the magnet edge is about 0.32 mm. The thickness of the glue layer in between magnet and groove is neglected. So the average air gap at a north pole is about 0.45 mm. The radius of the south pole is 69.4 / 2 = 34.7 mm and the air gap in between a south pole and the stator is 0.3 mm. During mounting of the armature in the stator, the armature will touch the stator and it will come free only when the bearing covers are tightened. But as the air gap at the south poles is smaller than the smallest air gap at the north poles, the magnets won’t touch the stator during mounting.

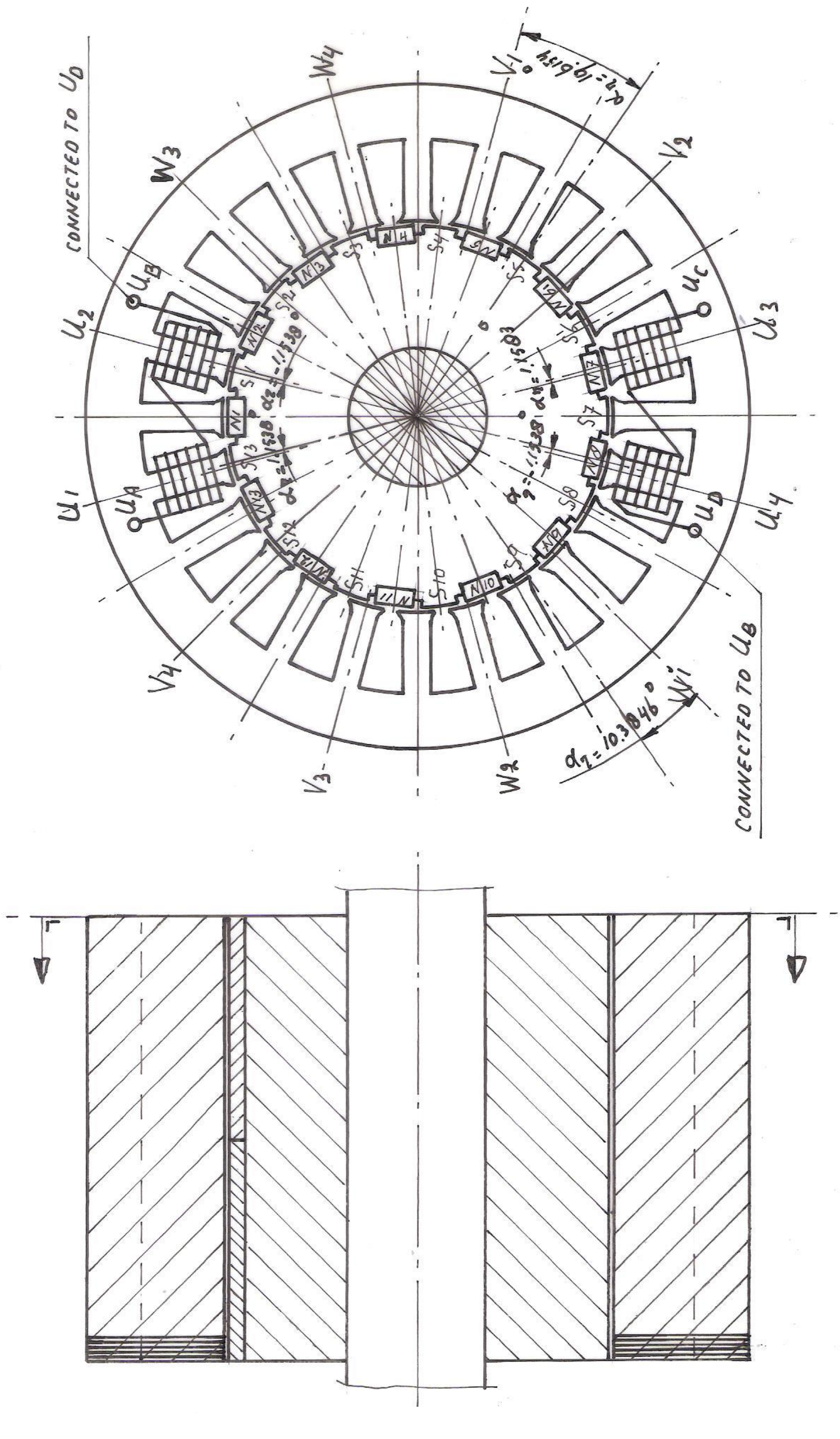

fig. 1 PM-armature of a 26-pole PM-generator frame size 80

3 Checking if a 3-phase current is generated

A 3-phase current has three phases called U, V and W. Normally the voltage U of each phase varies sinusoidal and the angle α in between the phases is 120°. The formulas for the voltage of each phase are:

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

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

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

The three curves are shown in figure 2.

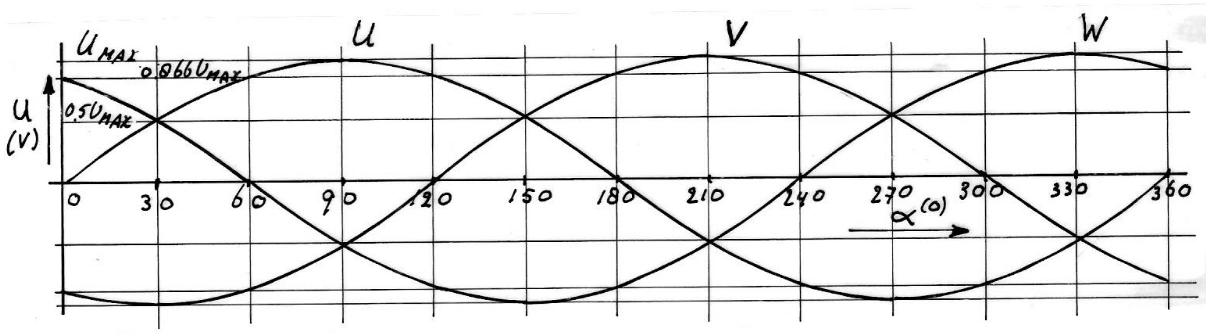

fig. 2 Three phases U, V and W

A pure sine wave is generated if a coil is rotating in a constant magnetic field because the magnetic field through the coil varies sinusoidal. If a permanent magnet is moving along a coil, the generated voltage may not be a pure sine wave, especially if the distance in between the magnets is large. But for the chosen generator configuration it is assumed that the generated voltage varies about sinusoidal.

If the rotor has two poles, the position of the rotor with respect to the stator will be the same if the rotor has rotated 360°. So the phase angle α is the same as the rotational angle α_r of the rotor. If the rotor has 26 poles this will be the case for 360 * 2 / 26 = 27.6923° rotation of the rotor. This results in the formula:

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

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

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

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

In figure 1 it can be seen that the coils U3 and U4 are not about opposite to south poles but that they are about opposite to the north poles N7 and N8. This means that the generated voltage in this bundle of coils will be opposite to the voltage as generated in the bundle of coils U1 – U2 if the coils have the same winding direction. It is decided to give all 12 coils the same winding direction and to connect all four coils of one phase in series for 24 V battery charging. 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. For 12 V battery charging (not advised because of high cable currents), 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.

The generator winding is very simple if compared to the winding of a normal 4-pole asynchronous motor. This is because all coils have the same shape and because there are no crossing coil heads. The strength of the magnetic field flowing through a coil will be the same for each coil and the generated voltage in each coil will therefore be the same too. This is not the case for a normal 4-pole winding as some coils have a different pitch. The coil heads are very small if compared to the length of the part of the coil lying in the grooves. A minimum amount of copper will therefore be used and the winding will have a relatively low resistance resulting in a high generator efficiency.

The angles in between the coils U3 – U4 and the poles N7 – N8 are the same as the angles in between the coils U1 – U2 and the poles S13 – S1.

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

Addition of sinusoidal voltages which are out of phase but which have the same frequency results in a voltage which is also sinusoidal. The total voltage U_{tot} for the four coils U1 – U4 is given by:

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

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

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

The winding can be rectified in star or in delta. However, rectification in delta has as disadvantage that the unloaded sticking torque is rising rather fast at low rotational speeds because higher harmonic currents circulate in the winding. This will result in a higher starting wind speed. Circulation of higher harmonic currents isn’t possible for star rectification and the sticking torque is therefore rising much less. So star rectification is preferred. If the generator is used as a brake, the star point should be short-circuited too because this gives a higher maximum braking torque.

4 Calculation of the flux density in the air gap and in the stator spoke

A calculation of the flux density in the air gap for the current VIRYA generators is given in chapter 5 of KD 341 (ref. 1).

A PM-generator is normally designed such that the magnetic field in the stator is saturated or almost saturated. For this condition, the generator has its maximum torque level and this means that it can supply the maximum electrical power for a certain rotational speed. The stator can be saturated at the narrowest cross section of the spokes in between the stator slots but it can also be saturated at the bridge in between the bottom of the stator slots and the outside of the stator stamping. The stator stamping is originally designed for a 4-pole motor and for a 4-pole motor there is a large magnetic flux in the bridge. The magnetic flux in the bridge for a 26-pole PM-generator is very low because only half the flux coming out of one stator pole is flowing through the bridge. So only the magnetic flux in the spokes is critical. The stator is about saturated if the calculated flux density in the air gap is 0.9 T or higher.

The remanence B_r (magnetic flux) in a neodymium magnet supplied by www.enesmagnets.pl with quality N38SH is in between 1.22 T and 1.26 T, if the magnet is short-circuited with a mild steel arc which is not saturated. Assume that B_r = 1.24 T. However, an air gap in the arc reduces the magnetic flux because it has a certain magnetic resistance. The resistance to a magnetic flux for the magnet itself is about the same as for air. The magnet thickness is called t_1. The magnetic resistance of the iron of the armature can probably be neglected. The magnetic resistance of the iron in the stator can't be neglected if the stator is close to saturation. However, this is complicating the calculation a lot and so the magnetic resistance of the iron in the stator is also neglected. So the total magnetic resistance is only caused by the magnet itself and by the air gaps.

The air gap t_2 in between a south pole and the stator is 0.3 mm. The average air gap t_3 in between a north pole and the stator is somewhat larger because the magnet is flat and because the depth of a magnet groove is chosen 3.2 mm. It is assumed that t_3 = 0.45 mm. So the magnetic resistance is increased by a factor $(t_1 + t_2 + t_3) / t_1$ because of the two air gaps. This means that the remanence in the air gap is reduced by a factor $t_1 / (t_1 + t_2 + t_3)$. The effective remanence in the air gap $B_{r\,eff}$ is given by:

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

Substitution of B_r = 1.24 T, t_1 = 3 mm, t_2 = 0.3 mm and t_3 = 0.45 mm in formula 6 results in $B_{r\,eff}$ = 0.992 T. This is higher than 0.9 T so the stator will probably be saturated. The flux density in a spoke can be calculated if the spoke width is known. The spoke has a minimum width of about 5 mm. A magnet has a width of 7 mm and the length of the armature is the same as the length of the stator. So the magnetic flux is concentrated by a concentration factor k = 7 / 5 = 1.4. So the magnetic flux in a spoke can be calculated to be 0.992 * 1.4 = 1.39 T. This is smaller than 1.6 T so the spokes are probably not saturated but I still believe that the chosen magnets are rather optimal for the chosen stator stamping.

I think that it is worth wile to make a prototype of a stator and an armature according to the geometry as given in figure 1 and chapter 2 and to test if the generator will have acceptable characteristics. The matching in between rotor and generator can only be checked if a certain windmill rotor is designed. The design of the VIRYA-2.2 rotor is given from chapter 5. The optimum winding is the winding for which the P_{mech}-n curve of the generator for the chosen load is lying close to the optimum cubic line of the rotor.

5 Description of the VIRYA-2.2 head, tower and rotor

The VIRYA-2.2 windmill is developed for 24 V battery charging. The VIRYA-2.2 is meant for use in Western countries but also for use in developing countries. The VIRYA-2.2 has a simple 2-bladed rotor with galvanised steel blades. A 2-bladed rotor has been tested in the VIRYA-1.25 windmill for more than ten years.

The head geometry is the same as the head geometry of the 3-bladed VIRYA-2.2S windmill. The VIRYA-2.2S head is completely made out of stainless steel but one can use normal steel for the VIRYA-2.2 head except for the head bearing pin. The tower is identical to the tower of the VIRYA-2.2S windmill. The VIRYA-2.2 has a 1 mm galvanised steel vane blade and the rated wind speed for this vane blade is about 11 m/s.

The 2-bladed rotor of the VIRYA-2.2 windmill has a diameter D = 2.2 m and a design tip speed ratio $\lambda_d = 4.75$. Advantages of a 2-bladed rotor are that no welded spoke assembly is required and that the rotor can be balanced and transported easily.

The rotor has blades with a constant chord and a constant blade angle and is provided with a 7.14 % cambered airfoil. A blade is made of a strip with dimensions of 2 * 208 * 830 mm and 18 blades for nine windmills can be cut out of a standard sheet of 1.25 * 2.5 m. Because the blade is cambered, the chord c is a little less than the blade width, resulting in c = 205 mm = 0.205 m. The blade press for making the camber can be derived from the blade press of the VIRYA-2.2S windmill.

The blades are connected to each other by a central strip size 4 * 138 * 620 mm and 36 strips can be cut out of a sheet of 1.25 * 2.5 m. The overlap in between blade and strip is 40 mm resulting in a rotor diameter of 2200 mm = 2.2 m. The central strip is cambered over 40 mm at each end with the same radius as for the blade camber. The next about 80 mm is used for transition of camber to flat. The next part till the edge of the hub is non cambered but twisted to give the blade the correct angle at the blade root. This non cambered part makes the blade rather flexible which is necessary to prevent vibrations due to the gyroscopic moment. A blade is connected to the central strip using three bolts M8 * 35 mm. The pitch in between the bolts is 50 mm. The free blade length is 790 mm which is expected to be short enough in combination with a sheet thickness of 2 mm to prevent flutter at high rotational speeds.

The hub is made out of a piece of stainless steel bar with a diameter of 50 mm and a length of 40 mm and with a 19 mm central hole with a 6 mm key groove for connection to the generator shaft. The central strip is bolted to the hub by four bolts M6 * 60 mm at a pitch circle of 35 mm and a central bolt M6 * 20 mm to prevent that the hub can come loose from the generator shaft.

The total mass of the rotor is about 8.6 kg which is rather low for a steel rotor with a diameter of 2.2 m. The rotor is balanced by grinding so much from the heaviest blade tip till it is just in balance. After balancing, blades and strip are marked to get the correct blade at the correct side of the central strip. A sketch of the VIRYA-2.2 rotor is given in figure 3.

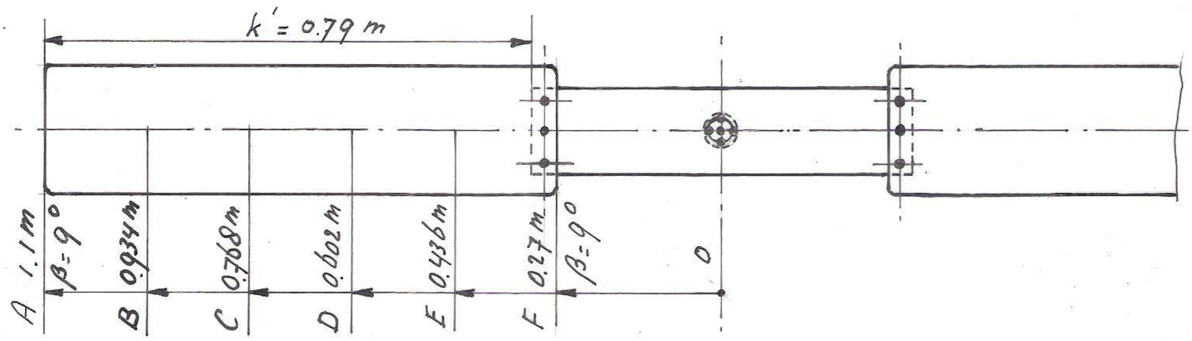

fig. 3 Sketch of the VIRYA-2.2 rotor

6 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 4). This report (KD 632) has its own formula numbering. Substitution of λ_d = 4.75 and R = 1.1 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 4.3182 * r$ (-) (7)

Formula's (5.2) and (5.3) of KD 35 stay the same so:

$\beta = \phi - \alpha$ (°) (8)

$\phi = 2/3 \arctan 1 / \lambda_{r\,d}$ (°) (9)

Substitution of B = 2 and c = 0.205 m in formula (5.4) of KD 35 gives:

$C_l = 61.299\ r\ (1 - \cos\phi)$ (-) (10)

Substitution of V = 5 m/s and c = 0.205 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.684 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (11)

The blade is calculated for six stations A till F which have a distance of 0.166 m of one to another. Station F corresponds to the blade root. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root. First the theoretical values are determined for C_l, α and β and next β is linearised such that the blade angle is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of a 7.14 % cambered airfoil are given in report KD 398 (ref. 5). The Reynolds values for the stations are calculated for a wind speed of 5 m/s because this is a reasonable wind speed for a windmill with V_{rated} = 11 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	1.1	4.75	7.9	0.205	0.64	0.56	3.28	3.4	-0.7	-1.1	8.6	9.0	0.055
B	0.934	4.033	9.3	0.205	0.75	0.77	2.80	2.5	0.2	0.3	9.1	9.0	0.036
C	0.768	3.316	11.2	0.205	0.89	0.94	2.31	2.5	1.7	2.2	9.5	9.0	0.032
D	0.602	2.600	14.0	0.205	1.10	1.13	1.84	1.7	4.5	5.0	9.5	9.0	0.048
E	0.436	1.883	18.6	0.205	1.40	1.42	1.37	1.2	9.0	9.6	9.6	9.0	0.098
F	0.27	1.166	27.1	0.205	1.81	1.27	0.92	1.2	-	18.1	-	9.0	0.29

table 1 Calculation of the blade geometry of the VIRYA-2.2 rotor

No value for α_{th} and therefore for β_{th} is found for station F because the required C_l value can't be generated. The theoretical blade angle β_{th} varies only in between 8.6° and 9.6°. If a constant blade angle of β_{lin} = 9° is chosen, the linearised blade angles β_{lin} and the linearised angles of attack α_{lin} are lying close to the theoretical values for the most important outer part of the blade. A constant blade angle prevents the need for twisting of the blade. The transition part of the central strip is twisted 9° right hand to get the correct blade angle at the blade root.

7 Determination of the C_p-λ and the C_q-λ curves

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the most important outer part of the blade is about 0.04. Figure 4.6 of KD 35 (for B = 2) and λ_{opt} = 4.75 and C_d/C_l = 0.04 gives $C_{p\ th}$ = 0.41. The blade is stalling at station. Therefore not the whole blade length k = 0.83 m, but only the part up to 0.04 m outside station F is used for the calculation of the C_p. This gives an effective blade length k' = 0.79 m. Substitution of $C_{p\ th}$ = 0.41, R = 1.1 m and blade length k = k' = 0.79 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.38. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.38 / 4.75 = 0.08.
Substitution of $\lambda_{opt} = \lambda_d$ = 4.75 in formula 6.4 of KD 35 gives λ_{unl} = 7.6.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R – ½k) * C_l * c * k / \pi R^3 \quad (-) \qquad (12)$$

The blade angle is 9° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 9° = 81°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 81° it can be read that C_l = 0.3. The whole blade is stalling during starting and the central strip is also contributing somewhat to the starting torque. Therefore now a blade length k* = 0.9 m is taken for the calculation of $C_{q\ start}$.
Substitution of B = 2, R = 1.1 m, k = k* = 0.9 m, C_l = 0.3 and c = 0.205 m in formula 12 gives that $C_{q\ start}$ = 0.013. For the ratio in between the starting torque and the optimum torque we find that it is 0.013 / 0.08 = 0.16. This is acceptable for a rotor with a design tip speed ratio of 4.75.

The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3}\right)} \quad (m/s) \qquad (13)$$

As the generator has not yet been built and tested, the sticking torque Q_s isn't known but it is estimated to be 0.3 Nm if the shaft is not rotating. Substitution of Q_s = 0.3 Nm, $C_{q\ start}$ = 0.013, ρ = 1.2 kg/m^3 and R = 1.1 m in formula 13 gives that V_{start} = 3 m/s. This is acceptable low for a 3-bladed rotor with a design tip speed ratio of 4.75. The generator is rectified in star for 24 V battery charging and the unloaded Q-n curve is rising only a little at increasing rotational speeds. The Q-n curve of the rotor is rising rather fast for a rotor with cambered blades and therefore the real starting wind speed will be about the same as the calculated value.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing a S-shaped line which is horizontal for λ = 0.

Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 6). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a 7.14 % cambered sheet airfoil is used. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-2.2 rotor are given in figure 4 and 5.

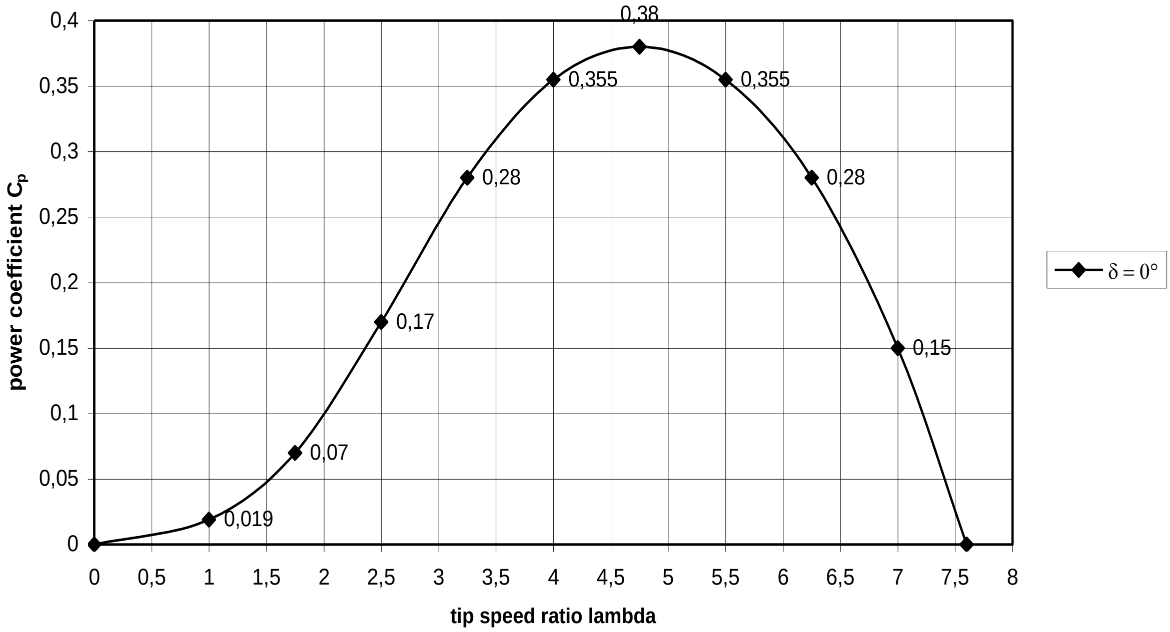

fig. 4 Estimated C_p-λ curve for the VIRYA-2.2 rotor for the wind direction perpendicular to the rotor (δ = 0°)

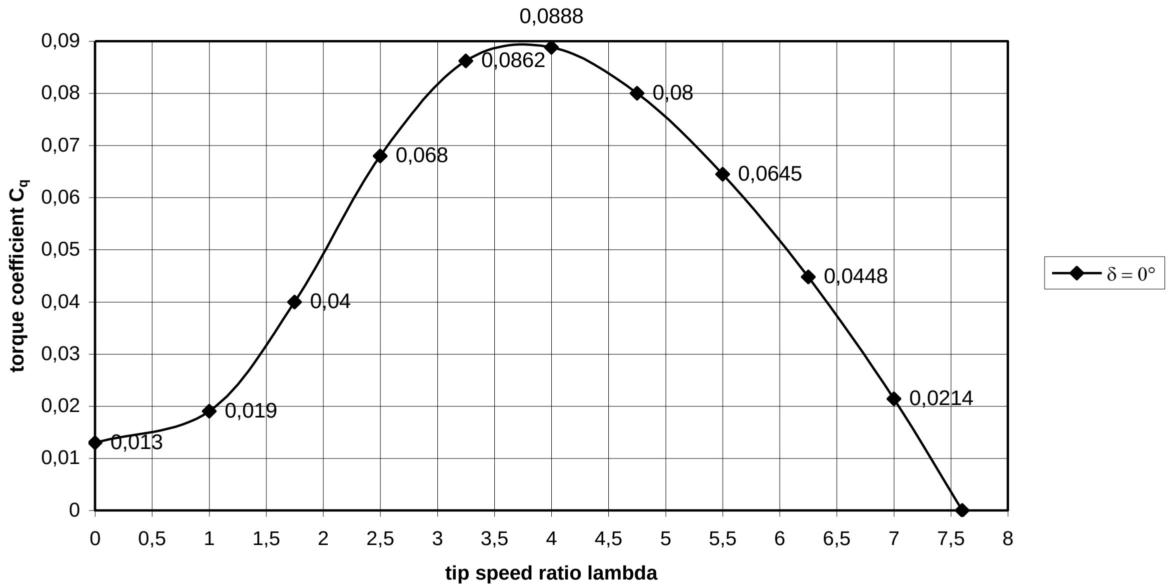

fig. 5 Estimated C_q-λ curve for the VIRYA-2.2 rotor for the wind direction perpendicular to the rotor (δ = 0°)

8 Determination of the P-n curves, the optimum cubic line and the P_{el}-V curve

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. 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 C_p-λ curve is given in figure 4. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 1 mm galvanised steel sheet. This vane blade gives a rated wind speed V_{rated} of about 11 m/s. The estimated δ-V curve is given in figure 3. In report KD 223 (ref. 7) a method is given to check the estimated δ-V curve and the estimated δ-V curve of the VIRYA-3.3D windmill is checked as an example. The estimated curve is given in figure 6.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 11 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 11 m/s will therefore also be valid for wind speeds higher than 11 m/s.

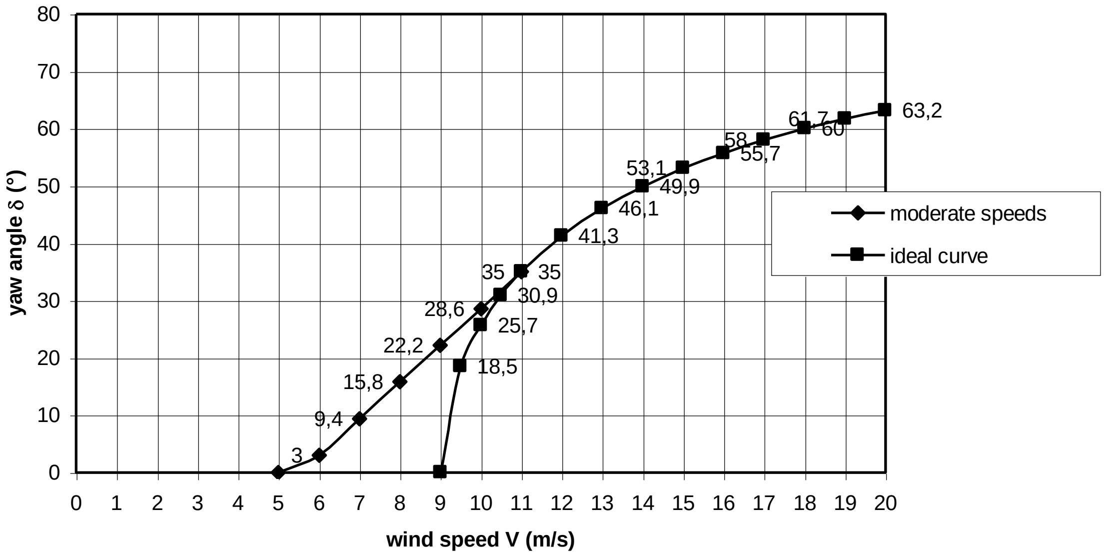

fig. 6 Estimated δ-V curve for a 1 mm galvanised steel vane blade

The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10, and 11 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 1.1 m in formula 7.1 of KD 35 gives:

$n_\delta = 8.6812 * \lambda * \cos\delta * V$ (rpm) (14)

Substitution of $\rho = 1.2$ kg / m^3 and R = 1.1 m in formula 7.10 of KD 35 gives:

$P_\delta = 2.2808 * C_p * \cos^3\delta * V^3$ (W) (15)

The P-n curves are determined for C_p values belonging to λ is 2.5, 3.25, 4, 4.75, 5.5, 6.25, 7 and 7.6 (see figure 1). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 14 and 15 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 6, is taken into account. The result of the calculations is given in table 2.

		V = 3 m/s δ = 0°		V = 4 m/s δ = 0°		V = 5 m/s δ = 0°		V = 6 m/s δ = 3°		V = 7 m/s δ = 9.4°		V = 8 m/s δ = 15.8°		V = 9 m/s δ = 22.2°		V = 10 m/s δ = 28.6°		V = 11 m/s δ = 35°	
λ (-)	C_p (-)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2.5	0.17	65.1	10.5	86.8	24.8	108.5	48.5	130.0	83.4	149.9	127.7	167.1	176.9	180.8	224.3	190.5	262.4	195.6	283.7
3.25	0.28	84.6	17.2	112.9	40.9	141.1	79.8	169.1	137.4	194.8	210.3	217.2	291.3	235.1	369.5	247.7	432.2	254.2	467.2
4	0.355	104.2	21.9	138.9	51.8	173.6	101.2	208.1	174.2	239.8	266.7	267.3	369.3	289.4	468.5	304.9	548.0	312.9	592.4
4.75	0.38	123.7	23.4	164.9	55.5	206.2	108.3	247.1	186.4	284.8	285.5	317.4	395.3	343.6	501.5	362.0	586.6	371.6	634.1
5.5	0.355	143.2	21.9	191.0	51.8	238.7	101.2	286.1	174.2	329.7	266.7	367.5	369.3	397.9	468.5	419.2	548.0	430.2	592.4
6.25	0.28	162.8	17.2	217.0	40.9	271.3	79.8	325.1	137.2	374.7	210.3	417.7	291.3	452.1	369.5	476.4	432.2	488.9	467.2
7	0.15	182.3	9.2	243.1	21.9	303.8	42.8	364.1	73.6	419.7	112.7	467.8	156.1	506.4	198.0	533.5	231.5	547.6	250.3
7.6	0	197.9	0	263.9	0	329.9	0	395.3	0	455.6	0	507.9	0	549.8	0	579.3	0	594.5	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-2.2 rotor

The calculated values for n and P are plotted in figure 7. The optimum cubic line which is going through the tops of the P-n curves is also given in figure 7.

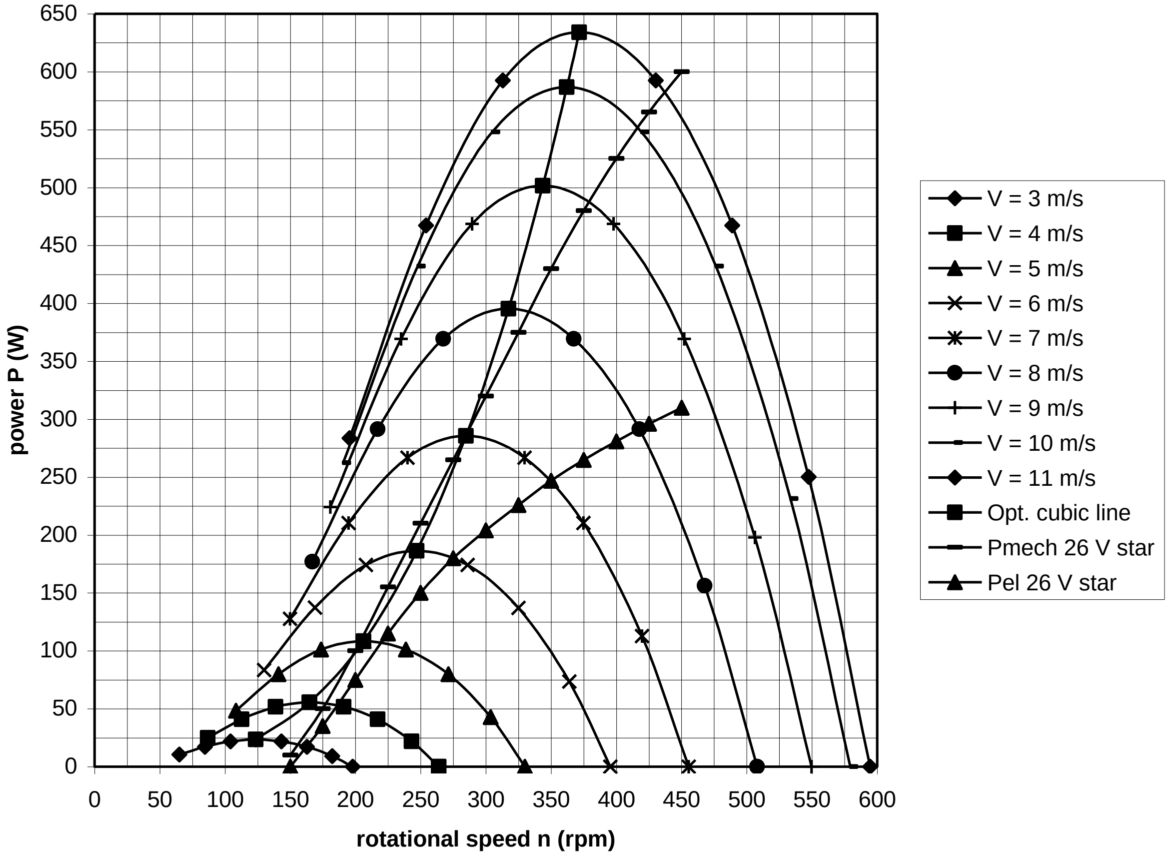

fig. 7 P-n curves and optimum cubic line of the VIRYA-2.2 rotor, estimated P_{mech}-n and P_{el}-n curves for 26 V star

The 26-pole generator of the VIRYA-2.2 windmill has not yet been built and tested so measured P_{mech}-n and P_{el}-n curves are not yet available. These curves are therefore estimated for 24 V battery charging based on measured curves of other VIRYA generators. The average charging voltage for 24 V battery charging is about 26 V. So the P_{mech}-n and P_{el}-n curves are estimated for 26 V star. It is assumed that the number of turns per coil are chosen such that and open DC voltage of 26 V is generated at a rotational speed of 150 rpm. This means that the P_{mech}-n and P_{el}-n curves start at 150 rpm.

The generator efficiency depends very much on the current and is maximal for a rather low rotational speed. The shape of the P_{el}-n curve is determined by assuming a realistic η-n curve. It is assumed that the efficiency η is 0.75 for n = 200 rpm and that it is 0.52 for n = 450 rpm. The estimated P_{mech}-n and P_{el}-n curves are also given in figure 7.

The point of intersection of the P_{mech}-n curve for 26 V of the generator with the P-n curve of the rotor for a certain wind speed, gives the working point for that wind speed. The electrical power P_{el} for that wind speed is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve. The values of P_{el} found this way for all wind speeds, are plotted in the P_{el}-V curve (see figure 8).

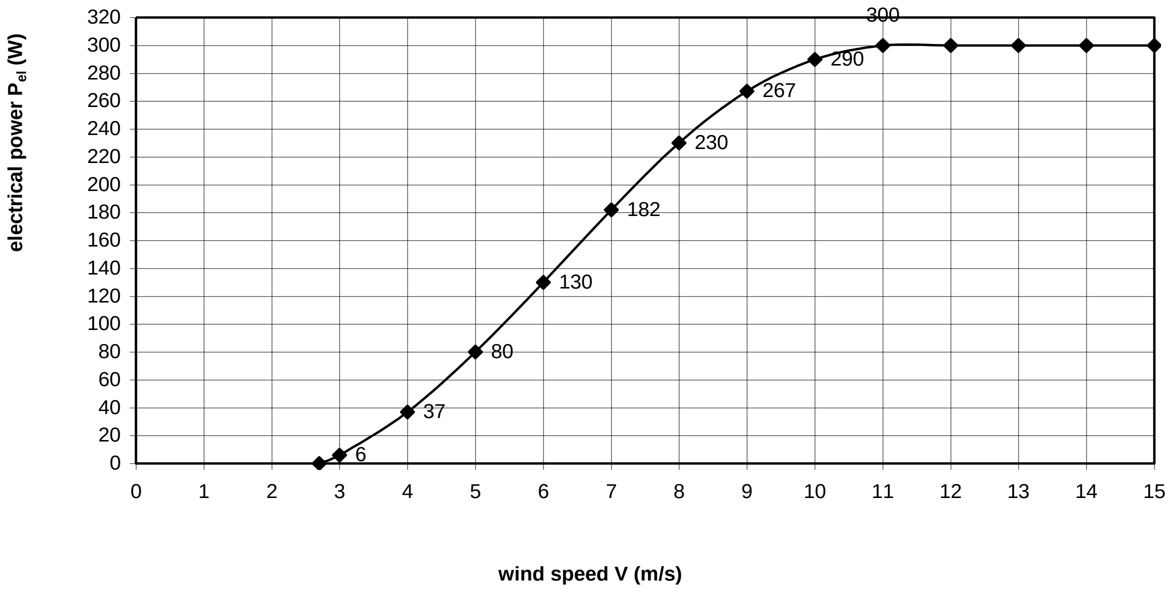

fig. 8 P_{el}-V curve of the VIRYA-2.2 windmill with V_{rated} = 11 m/s for 24 V battery charging

In figure 8 it can be seen that the P_{el}-V curve starts at a wind speed V = 2.7 m/s so $V_{cut\ in}$ = 2.7 m/s. In chapter 7 it was calculated that V_{start} = 3 m/s so there is some hysteresis in the P_{el}-V curve for 2.7 < V < 3 m/s. The maximum power is 300 W which is good for a rotor diameter of 2.2 m.

9 Determination of the winding

The estimated P_{el}-n curve given in figure 7 starts at a rotational speed of 150 rpm. This means that the generated unloaded DC voltage must be equal to the open battery voltage at this rotational speed. It is assumed that the average charging voltage is 26 V. So the winding must be such that the open DC voltage is 26 V for n = 150 rpm. In this case the starting point of the real P_{el}-n curve will be the same as for the estimated P_{el}-n curve. However, the remaining part of the real P_{el}-n curve can only be found by building and measuring of a generator prototype.

The generated effective AC voltage U_{eff} of one phase for a certain stator and armature geometry is proportional to the rotational speed n and proportional to the number of turns per coil. Star rectification of a 3-phase current is explained in chapter 3.2.1 of report KD 340 (ref. 8). The relation in between the effective DC voltage U_{DCeff} and the effective AC voltage U_{eff} is given by formula 13 of KD 340 if the voltage drop over the rectifier U_{rect} is neglected. Formula 13 of KD 340 is copied as formula 16.

$$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff} \quad \text{(V)} \quad \text{(star rectification)} \qquad (16)$$

U_{eff} is the effective AC voltage of one complete phase. One complete phase has two coil bundles of two coils in series for the chosen winding and for 24 V battery charging.

Formula 16 can be written as:

$U_{eff} = 0.427 * U_{DCeff}$ (V) (star rectification) (17)

The voltage drop over the rectifier U_{rect} depends on the current. It can be neglected for the very small current flowing through a digital volt meter if the open DC voltage is measured. But for medium up to large currents, the voltage drop U_{rect} is about 1.4 V for a 3-phase rectifier with silicon diodes and the value of U_{DCeff} has to be reduced by 1.4 V to find the loaded voltage. The voltage drop over the rectifier can be reduced up to about 0.4 V if a rectifier is used which has so called Schottky diodes. However, I could not find a 3-phase bridge rectifier provided with these diodes of enough power and therefore a rectifier with normal diodes is specified on the drawings. But one can make a rectifier with six separate Schottky diodes and this will reduce the power loss in the rectifier.

Substitution of U_{DCeff} = 26 V in formula 17 gives that U_{eff} = 11.1 V. So the effective AC voltage of one complete phase winding must be 11.1 V at n = 150 rpm. If only the two coils of one coil bundle are laid, this coil bundle must have an effective AC voltage of 5.55 V at n = 150 rpm.

One starts with making one coil bundle of two coils using a rather thin wire. Assume that enamelled copper wire with a thickness of 1 mm is available and that it is possible to lie 100 turns per coil for maximum filling of the available space. Next the effective open AC voltage is measured for a rotational speed of 150 rpm. Assume that it is measured that U_{eff} = 3.7 V. So this means that the number of turns per coil has to be increased by a factor 5.55 / 3.7 = 1.5 and becomes 1.5 * 100 = 150.

The wire must be thinner for 150 turns per coil. It is assumed that at least the same total cross sectional area of all wires together can be realised for the thinner wire. So the wire thickness has to be reduced by a factor $\sqrt{(1 / 1.5)}$ = 0.816. So it should become 0.816 * 1 = 0.82 mm. The available closest standard wire diameter is 0.8 mm so this wire diameter is chosen. The final number of turns per coil is chosen a little higher because of the voltage drop over the rectifier. Assume that the final number of turns per coil is 155.

Next a complete winding has to be made with this wire thickness and this number of turns per coil and the open DC voltage has to be measured for 150 rpm. If it is about 26 V for star rectification, the P_{mech}-n and P_{el}-n curves have to be measured for a real 24 V battery as load or for a battery charge controller adjusted at 26 V. If the curves are almost the same as the estimated curves in figure 7, the generator is ready.

If the matching of the P_{mech}-n curve with the optimum cubic line of the rotor isn't well, one has to measure the generator again for a higher or for a lower voltage. Assume that now the matching is optimal for a voltage of 22 V. This means that the number of turns per coil has to be increased by a factor 26 / 22 = 1.182 and becomes 1.182 * 155 = 183. However, for a wire diameter of 0.8 mm, it won't be possible to lie 183 turns per coil. So one has to take one size lower and chose a wire diameter of 0.71 mm. With this new wire diameter and this new number of turns per coil, a complete new winding is laid. It can now be expected that the matching will be good for 26 V star.

So finding of the optimum number of turns per coil and the optimum wire diameter is a lot of work and one needs a sophisticated test rig to measure the P_{mech}-n and P_{el}-n curves for the correct load. I have extensively measured a PM-generator with frame size 90 on a test rig of the University of Technology Eindhoven. The test rig and the measurements are described in report KD 78 (ref. 9).

10 References

1 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, reviewed May 2017, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Development of a simple 22-pole permanent magnet generator for a small windmill using the housing of an Indian 4-pole, 3-phase, 0.37 kW asynchronous motor frame size 71 and 22 neodymium magnets size 40 * 7 * 3 mm, April 2014, reviewed February 2017, report KD 553, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. 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, May 2014, reviewed December 2014, free public report KD 560, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, reviewed February 2017, free public rapport KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. The 7.14 %, 10 % and 12.5 % cambered plate as airfoil for windmill rotor blades, Aerodynamic characteristics, geometry, moment of inertia I and moment of resistance W, November 2008, free public report KD 398, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Determination of C_q for low values of λ. Deriving the C_p-λ and C_q-λ curves of the VIRYA-1.8D rotor, July 2002, free public report KD 97, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Kragten A. Method to check the estimated δ-V curve of the hinged side vane safety system and checking of the δ-V curve of the VIRYA-3.3D windmill (7.14 % cambered steel blades), February 2005, free public report KD 223, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Rectification of 3-phase VIRYA windmill generators May 2007, reviewed May 2017, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

9 Kragten A. Measurements performed on a generator with housing RN90L04V and a 4-pole armature equipped with neodymium magnets, March 2011, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.