Ideas about a 4-pole permanent magnet generator for the VIRYA-2S windmill using the housing of a 4-pole, 3-phase, 0.75 kW asynchronous motor frame size 80 and 4 neodymium magnets size 80 * 20 * 10 mm. Design report of the rotor (λ_d = 4.5, B = 3, stainless steel blades)

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1 Introduction

In my public report KD 341 (ref. 1), different types of permanent magnet (PM) generators for wind turbines are described. Every type has certain advantages and disadvantages. 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. The VIRYA-2.2S generator makes use of a motor housing of manufacture ROTOR frame size 80 with a special stator stamping which is lengthened up to 100 mm. This generator was already designed in 2000 and at that time I used rather expensive magnets of the Dutch supplier Bakker Magnetics. Recently I found a cheaper Polish supplier which supplies a magnet size 80 * 20 * 10 mm and the idea is to design a new PM-generator which makes use of four of these magnets. The motor housings of ROTOR have stator stampings which are not in accordance with the IEC norm so for this new generator it is chosen to use a 4-pole motor housing with a stator stamping according the IEC norm and with the standard width as used for a 0.75 kW, 4-pole motor frame size 80. This stator stamping is specified on the website of Kienle & Spiess. The generator is described in chapter 2.

The armature volume of this new PM-generator will be smaller than that of the VIRYA-2.2S generator and the torque level will therefore also be lower. So it is decided to use the generator in combination with a smaller rotor with a diameter of 2 m. This rotor will have the same stainless steel blades as the VIRYA-2.2S rotor but the hub plate will be smaller. The wind turbine with this smaller rotor is called the VIRYA-2S. The S is added after the name to distinguish it from the former VIRYA-2 with wooden blades. The VIRYA-2S will make use of the same head and tower as the VIRYA-2.2S. The description and calculations of the VIRYA-2S rotor are given in chapter 4 and 5.

2 Description of the 4-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). The manufacture of the motor housing is not yet chosen. 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. It is provided by a 230/400 V, 3-phase winding. The generator with this original winding is used for 24 V battery charging if the winding is rectified in delta and for 48 V battery charging if the winding is rectified in star.

The air gap in between armature and stator is chosen 0.25 mm, so the outside diameter of the armature is 69.5 mm. The short-circuit armature isn't used. The original motor shaft is also not used but replaced by a stainless steel shaft with a tapered shaft end. This shaft is made from round 25 mm bar. This bar is turned to a diameter of 24 mm at the position of the armature. It has 20 mm bearing seats at the same position as for the original motor shaft.

The armature is made from a mild steel bar with a diameter of 70 mm and a length of 80 mm. It is provided with an inside hole of 24.2 mm. The armature is glued to the shaft by epoxy glue or by anaerobe glue. This must be done for the shaft vertical to make that the glue is spread even along the whole shaft. The armature is turned in between centres to a diameter of 69.5 mm after gluing.

Four 10.2 mm wide grooves are milled in the armature under 90°. The grooves make an angle with the armature shaft which is that large that there is just one stator pitch overlap in between the left and the right side of the armature. This angle makes that the sticking torque is almost not fluctuating. It can be calculated that the angle must be 6.5° for a stator with 24 slots. The grooves have a depth of 21.75 mm measured from the outside of the armature. This means that the bridge in between the bottom of the groove and the inside of the 24.2 mm hole has a thickness of only 0.9 mm. One magnet size 80 * 20 * 10 mm is glued in each groove by anaerobe glue Threebond TB 1132. This type anaerobe glue hardens in a rather large air gap.

The magnets are supplied by the Polish company Enes Magnesy, website: www.enesmagnets.pl . The current price of one magnet is € 7.02 including VAT, excluding transport if a minimum quantity of 12 magnets is ordered. So the magnet costs for one generator are about € 28 which is rather low. The magnets have quality N35H which means that the remanence B_r is about 1.19 T.

The magnets are positioned such that two north and two south poles are created at the outside of the armature. So the magnets must be placed such that north poles of adjacent magnets are facing each other. The small thickness of the bridge at the bottom of each groove makes that only a limited part of the magnetic flux is lost because of magnetic short-circuit at this point. The shaft must be made of non magnetic stainless steel to prevent magnetic short-circuit through the shaft. Other advantages of using a stainless steel shaft are that there will be no rust at the seal and at the cone where the hub is connected to the shaft. A sketch of the generator armature is given in figure 1. A sketch with measures is given in appendix 1.

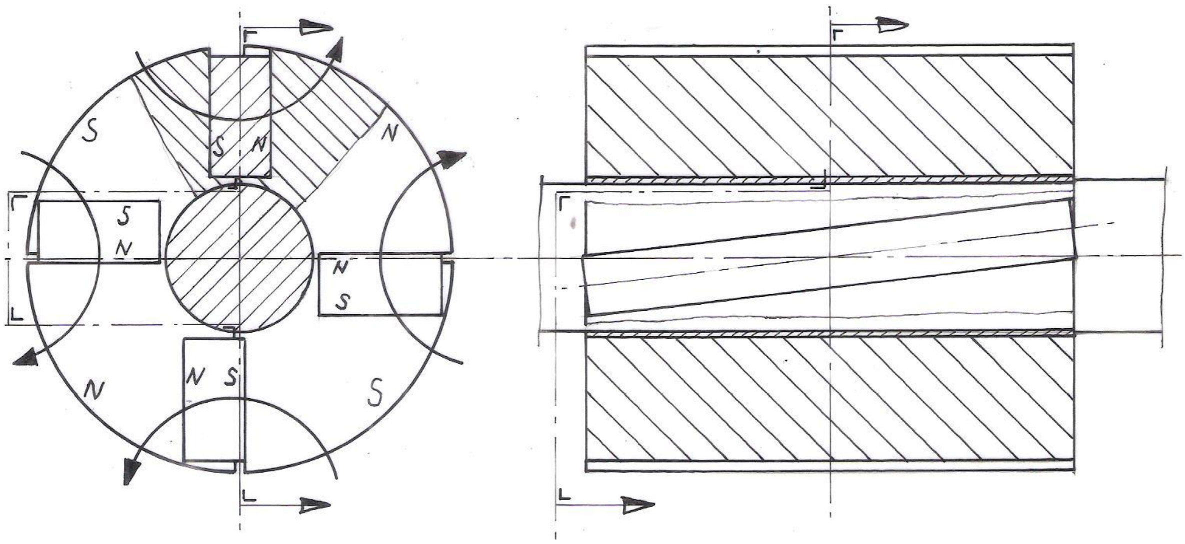

fig. 1 PM-armature of a 4-pole PM-generator frame size 80

3 Calculation of the flux density in the air gap

A calculation of the flux density in the air gap for the older 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. If the stator is close to saturation at these points, the flux density in the air gap in between armature and stator will be about 0.9 Tesla (T). The flux density in the air gap B_l (T) is given by formula 5 of KD 341 (ref. 1). This formula is copied as formula 1.

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

In this formula, B_r is the remanence which is about 1.19 T for the chosen magnets. t_1 is the magnet thickness and t_1 = 10 mm. n is the number of magnets per groove and n = 1. L_m is the magnet length and L_m = 80 mm. H is the magnet height and H = 20 mm. L_b is the stator length and L_b = 80 mm. t_2 is the glue gap at the magnet size and t_2 = 0.1 mm for a 10.2 mm wide groove. t_3 is the air gap in between the armature and the stator and t_3 = 0.25 mm.

D is the armature diameter and D = 69.5 mm. p is the number of armature poles and p = 4. Substitution of these values in formula 1 gives that B_l = 0.95 T. So the calculated value of B_l is larger than 0.9 T and this means that the stator stamping will be saturated. This means that the generator will have the maximum possible torque level for the chosen frame size.

4 Description of the VIRYA-2S rotor

The VIRYA-2S rotor has a 3-bladed rotor with cambered stainless steel blades. Each blade is made of a strip size 2 * 125 * 833 mm and 30 blades can be cut from a standard sheet size 1.25 * 2.5 m without waste material. Each blade is 7.14 % cambered over the whole blade length. The chord is a little smaller than the strip width because of this camber and it is found that c = 123.3 mm = 0.1233 m. The blades have the same geometry as the VIRYA-2.2S blades and can be made with the same hydraulic blade press given on drawing 9905-01/A.

The blades are connected to each other by a hub plate which is made from 3 mm stainless steel sheet. The bigger hub plate of the VIRYA-2.2S rotor is made of 4 mm stainless steel sheet, so VIRYA-2S hub plate is much lighter. The hub plate has three 125 mm wide and 192 mm long ears under an angle of 120°. The end of the hub plate ears are cambered with about the same camber as for the blades. The hub plate ears are twisted 12° right hand to make that a blade has the correct blade angle at the blade root. The overlap in between a blade and a hub plate ear is 25 mm. A blade is connected to the hub plate by three stainless steel bolts M6 * 30 and three self-locking nuts M6. Enough washers for M6 are placed under the nuts to make that the nuts don’t touch the cylindrical part of the bolts. In stead of these washers, one can also connect balancing weight at the position of the bolts.

The holes in the blades and in the hub plate have a diameter of 6 mm to minimise clearance. The pitch distance for the holes in the blades is exactly 50 mm. The pitch distance for the holes in the hub plate is exactly 50.57 mm, so a little larger. This is done because the bending radius at the heart of the blade is 220 mm but the bending radius at the heart of a hub plate ear is 222.5 mm.

The hub plate is bolted to a stainless steel hub with an outside diameter of 60 mm and a thickness of 38 mm. It has a tapered central hole with a halve taper angle of 5° and a maximum hole diameter of 20 mm. It has three 8.5 mm holes at a pitch circle of 40 mm. The hub plate is connected to the hub by three stainless steel bolts M8 * 50 and three self-locking stainless steel nuts M8. The hub plate also has a central 8.5 mm hole. The hub plate is pulled on the tapered generator shaft by one stainless steel bolt M8 * 25.

The VIRYA-2S makes use of the same head and tower as used for the VIRYA-2.2S. The head has a vane blade made out of 1 mm stainless steel sheet. The rated wind speed for this vane blade is about 11 m/s. A sketch of the VIRYA-2S rotor is given in figure 2.

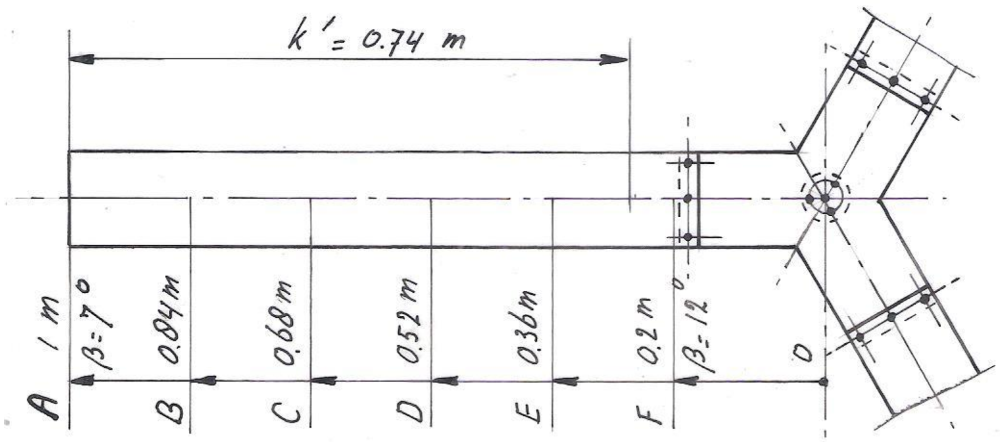

fig. 2 Sketch VIRYA-2S rotor

5 Calculation of the geometry of the VIRYA-2S rotor

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 2). This report (KD 690) has its own formula numbering. Substitution of λ_d = 4.5 and R = 1 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 4.5 * r$ (-) (2)

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

$\beta = \phi - \alpha$ (°) (3)

$\phi = 2/3 \arctan 1 / \lambda_{r\,d}$ (°) (4)

Substitution of B = 3 and c = 0.1233 m in formula (5.4) of KD 35 gives:

$C_l = 67.945\ r\ (1 - \cos\phi)$ (-) (5)

Substitution of V = 5 m/s and c = 0.1233 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.411 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (6)

The blade is calculated for six stations A till F which have a distance of 0.16 m of one to another. Station F lies 8 mm outside the end of a hub plate ear. 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 twist 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. 3). 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	4.5	8.4	0.1233	0.72	0.79	1.87	1.7	0.7	1.4	7.7	7	0.048
B	0.84	3.78	9.9	0.1233	0.85	0.84	1.58	1.7	2.0	1.9	7.9	8	0.040
C	0.68	3.06	12.1	0.1233	1.02	1.00	1.29	1.2	3.3	3.1	8.8	9	0.030
D	0.52	2.34	15.4	0.1233	1.27	1.20	1.00	1.2	6.2	5.4	9.2	10	0.041
E	0.36	1.62	21.1	0.1233	1.64	1.43	0.72	1.2	-	10	-	11	0.105
F	0.2	0.9	32.0	0.1233	2.07	1.26	0.46	1.2	-	20	-	12	0.34

table 1 Calculation of the blade geometry of the VIRYA-2S rotor

No value for α_{th} and therefore for β_{th} is found for stations E and F because the required C_l values can't be generated. The theoretical blade angle β_{th} varies in between 7.7° and 9.2°. If a blade angle of 7° is chosen for the blade tip and 12° is chosen for the blade root, 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. So the blade twist is 5° which is the same as for the VIRYA-2.2S blades. So the VIRYA-2S and the VIRYA-2.2S blades are identical.

6 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 4.7 of KD 35 (for B = 3) and λ_{opt} = 4.5 and C_d/C_l = 0.04 gives $C_{p\ th}$ = 0.43. The blade is stalling at station F. Therefore not the whole blade length k = 0.83 m, but only the part up to 0.06 m outside station F is used for the calculation of the C_p. This gives an effective blade length k' = 0.74 m. Substitution of $C_{p\ th}$ = 0.43, R = 1 m and blade length k = k' = 0.74 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.4. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.4 / 4.5 = 0.0889.
Substitution of $\lambda_{opt} = \lambda_d$ = 4.5 in formula 6.4 of KD 35 gives λ_{unl} = 7.2.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \quad (-) \qquad (7)$$

The average blade angle is 9.5°. For a non rotating rotor, the average angle of attack α is therefore 90° - 9.5° = 80.5°. The estimated C_l-α curve for large values of α is given as figure 5 of KD 398. For α = 80.5° it can be read that C_l = 0.31. The whole blade is stalling during starting. Therefore the real blade length k* = 0.833 m is taken for the calculation of $C_{q\ start}$.
Substitution of B = 3, R = 1 m, k = k* = 0.833 m, C_l = 0.31 and c = 0.1233 m in formula 7 gives that $C_{q\ start}$ = 0.0133. The real starting torque coefficient is a little lower because we have used the average blade angle. Assume $C_{q\ start}$ = 0.013. For the ratio in between the starting torque and the optimum torque we find that it is 0.013 / 0.0889 = 0.146. This is acceptable for a rotor with a design tip speed ratio of 4.5.

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

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3}\right)} \quad (m/s) \qquad (8)$$

As the generator has not yet been built and tested, the sticking torque Q_s isn't known. However, the sticking torque at stand still position is only determined by the friction of the bearings and the seal on the generator shaft. The VIRYA-2S shaft has the same diameter as the VIRYA-2.2S shaft (20 mm) so it is assumed that the sticking torque at stand still position is the same. This torque has been measured for the VIRYA-2.2S generator and it was found that Q_s = 0.38 Nm for a new seal. It is assumed that the sticking torque is reduced to about 0.25 Nm when the seal has run in. Substitution of Q_s = 0.25 Nm, $C_{q\ start}$ = 0.013, ρ = 1.2 kg/m^3 and R = 1 m in formula 8 gives that V_{start} = 3.2 m/s. This is acceptable low for a 3-bladed rotor with a design tip speed ratio of 4.5. The generator is rectified in delta for 24 V battery charging and the unloaded Q-n curve is rising at increasing rotational speeds. The Q-n curve of the rotor is rising rather fast for a rotor with 7.14 % 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. 4). 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-2S rotor are given in figure 3 and 4.

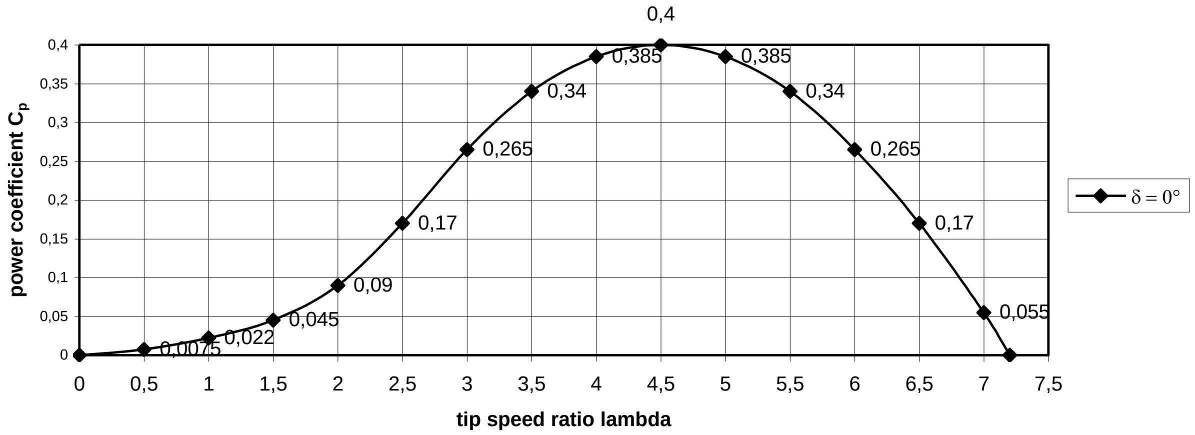

fig. 3 Estimated C_p-λ curve for the VIRYA-2S rotor for the wind direction perpendicular to the rotor (δ = 0°)

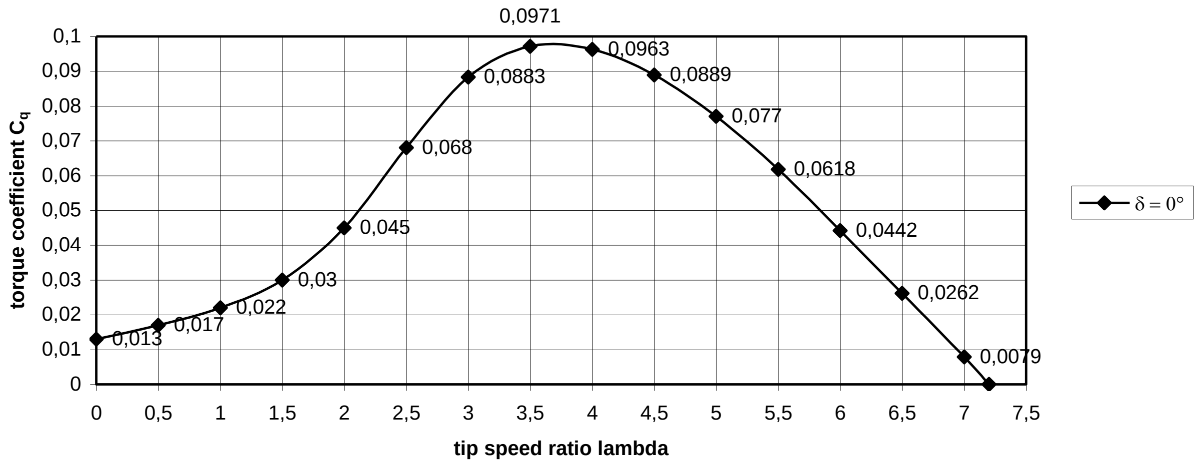

fig. 4 Estimated C_q-λ curve for the VIRYA-2S rotor for the wind direction perpendicular to the rotor (δ = 0°)

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

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 3. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 1 mm stainless steel sheet. This vane blade gives a rated wind speed V_{rated} of about 11 m/s. In report KD 223 (ref. 5) 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 δ-V curve is given in figure 5.

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.

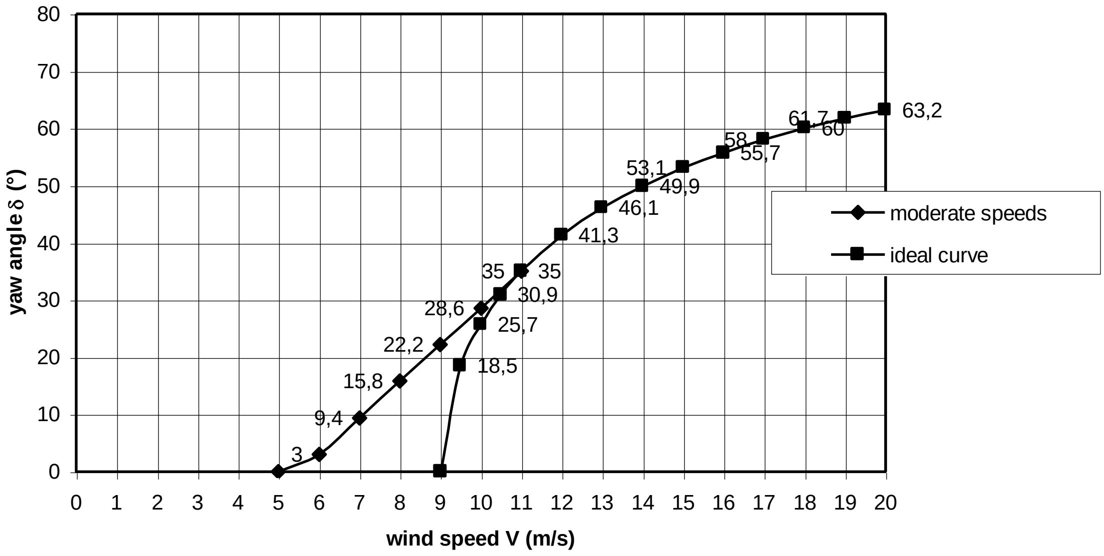

fig. 5 Estimated δ-V curve for a 1 mm stainless steel vane blade

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 m in formula 7.1 of KD 35 gives:

$n_\delta = 9.5493 * \lambda * \cos\delta * V$ (rpm) (9)

Substitution of $\rho = 1.2$ kg / m^3 and R = 1 m in formula 7.10 of KD 35 gives:

$P_\delta = 1.885 * C_p * \cos^3\delta * V^3$ (W) (10)

The P-n curves are determined for C_p values belonging to λ is 2.5, 3.5, 4.5, 5.5, 6.5 and 7.2 (see figure 2). For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 9 and 10 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 5, 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	71.6	8.7	95.5	20.5	119.4	40.1	143.0	68.9	164.9	105.5	183.8	146.2	198.9	185.4	209.6	216.9	215.1	234.4
3.5	0.34	100.3	17.3	133.7	41.0	167.1	80.1	200.3	137.9	230.8	211.1	257.3	292.3	278.5	370.8	293.4	433.8	301.2	468.9
4.5	0.4	128.9	20.4	171.9	48.3	214.9	94.3	257.5	162.2	296.8	248.3	330.8	343.9	358.1	436.3	377.3	510.3	387.2	551.6
5.5	0.34	157.6	17.3	210.1	41.0	262.6	80.1	314.7	137.9	362.7	211.1	404.3	292.3	437.7	370.8	461.1	433.8	473.3	468.9
6.5	0.17	186.2	8.7	248.3	20.5	310.4	40.1	371.9	68.9	428.7	105.5	477.8	146.2	517.2	185.4	545.0	216.9	559.3	234.4
7.2	0	206.3	0	275.0	0	343.8	0	412.0	0	474.8	0	529.3	0	572.9	0	603.7	0	619.5	0

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

The calculated values for n and P are plotted in figure 6. The optimum cubic line which is going through the tops of the P-n curves is also given in figure 6.

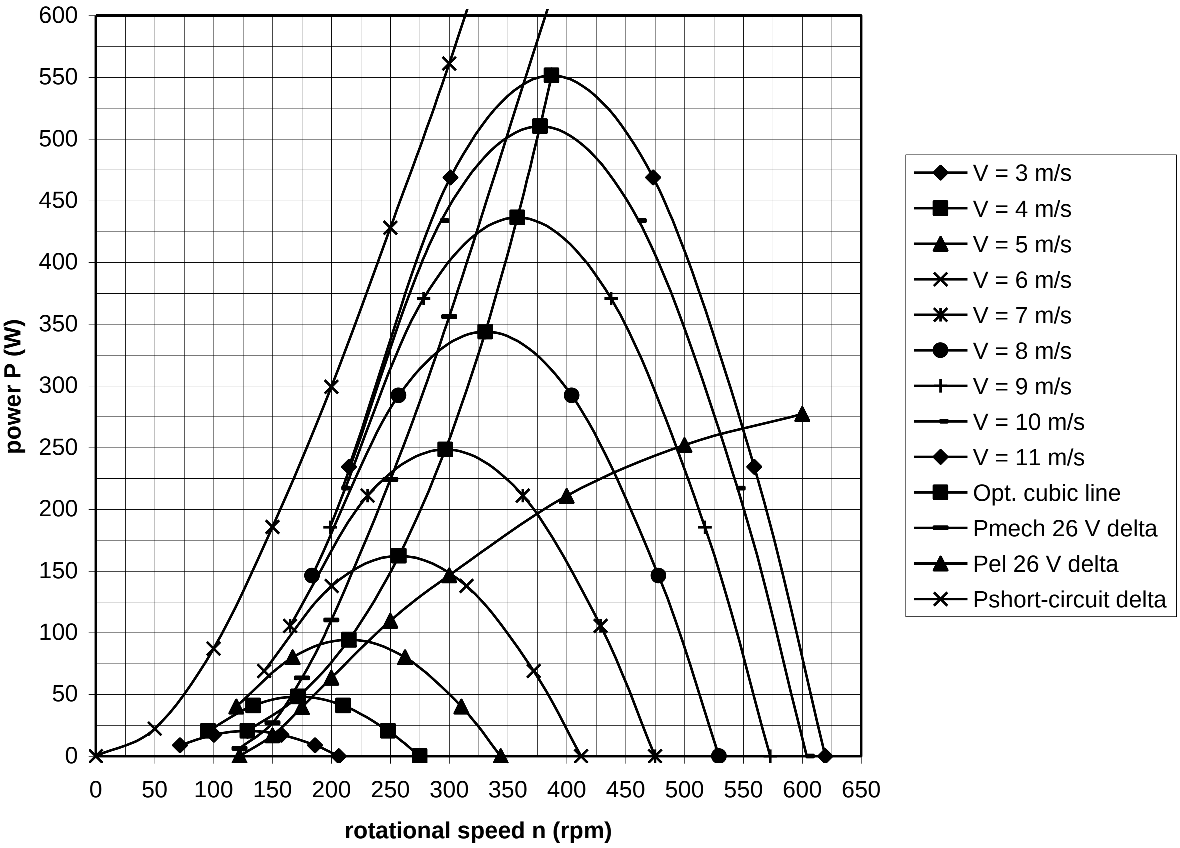

fig. 6 P-n curves and optimum cubic line of the VIRYA-2S rotor, estimated P_{mech}-n and P_{el}-n curves for 26 V delta, estimated P-n curve for short-circuit in delta

The VIRYA-2S generator has not yet been built and tested so measured P_{mech}-n and P_{el}-n curves for a 24 V battery load are not yet available. However, it is assumed that the torque level of the VIRYA-2S generator is reduced by the reduction of the armature volume lying within the stator. The VIRYA-2.2S generator has an armature diameter of 75 mm and a stator length of 100 mm. The VIRYA-2S generator has an armature diameter of 69.5 mm and a stator length of 80 mm. It can be calculated that the armature volume of the VIRYA-2S generator is a factor 0.687 smaller than that of the VIRYA-2.2S generator. The generator measurements for the VIRYA-2.2S generator are given in the report KD 55 from 2000 (ref. 6). This report was made on a Brother typewriter and so it isn't available digital.

But the measuring points for 26 V delta are given in table 3 up to a rotational speed n = 600 rpm. The average charging voltage for a 24 V battery is about 26 V. The torque level is proportional to the armature volume for a certain flux density in the air gap. So it is assumed that the torque level of the VIRYA-2S generator is a factor 0.687 than that of the VIRYA-2.2S generator. This means that the power at a certain rotational speed is also a factor 0.687 lower. It is also assumed that the power supply starts at the same rotational speed. So the P_{mech} and P_{el} values for the VIRYA-2S generator can be found by multiplying of all values of the VIRYA-2.2S generator by a factor 0.687.

The calculated values for the VIRYA-2S generator are also given in table 3. The generator efficiency η_{gen} (%) is also given in table 3. The generator efficiency depends very much on the current and is maximal for a rather low rotational speed. The maximum efficiency is about 64 % for a rotational speed in between 150 and 175 rpm. The main reason for the rather low maximum efficiency is that a high voltage winding is used at a low voltage and at a low rotational speed. Another reason is that the efficiency in delta is lower than in star because higher harmonic currents can circulate in the winding. The power and the efficiency can be increased by using the generator for 48 V battery charging rectified in star. Rectification in star and delta is explained in report KD 340 (ref. 7).

	VIRYA-2.2S generator		VIRYA-2S generator		
n (rpm)	P_{mech} (W)	P_{el} (W)	P_{mech} (W)	P_{el} (W)	η_{gen} (%)
122	9.2	0	6.3	0	0
150	39.27	24.44	27.0	16.8	62.2
175	91.99	57.72	63.2	39.7	62.7
200	160.22	92.3	110.1	63.4	57.6
250	325.94	159.64	223.9	109.7	49.0
300	518.36	213.46	356.1	146.6	41.2
400	950.86	306.94	653.2	210.9	32.3
500	1361.36	366.97	935.3	252.1	27.0
600	1746.73	403.51	1200.0	277.2	23.1

table 3 Measured values of P_{mech} and P_{el} for the VIRYA-2.2S generator for 26 V delta. Estimated values for P_{mech} and P_{el} for the VIRYA-2S generator

The estimated P_{mech}-n and P_{el}-n curves for the VIRYA-2S generator for 26 V delta are also given in figure 6. It can be seen that the P_{mech}-n curve of the generator for 26 V star is lying at the left side of the optimum cubic line. So the matching isn’t optimal but certainly acceptable. The point of intersection of the P_{mech}-n curve for 26 V delta 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 7).

The VIRYA-2.2S generator has only been measured for short-circuit in star (before the rectifier). However, it has been measured for 13 V delta. The Q-n curve for short-circuit in delta can be found by shifting the Q-n curve for 13 V delta that much to the left that it coincides with the Q-n curve for short-circuit in star at low rotational speeds. Next, the P-n curve for short-circuit in delta can be derived from the Q-n curve. The P-n curve for short-circuit in delta for the VIRYA-2S generator can now be determined from the P-n curve for short-circuit in delta for the VIRYA-2.2S generator, by multiplying all values by a factor 0.687. This has been done and the estimated P-n curve for short-circuit in delta is also given in figure 6. It can be seen that this curve is lying left from the P-n curve of the rotor for V = 11 m/s, so the rotor can be stopped at any wind speed by making short-circuit.

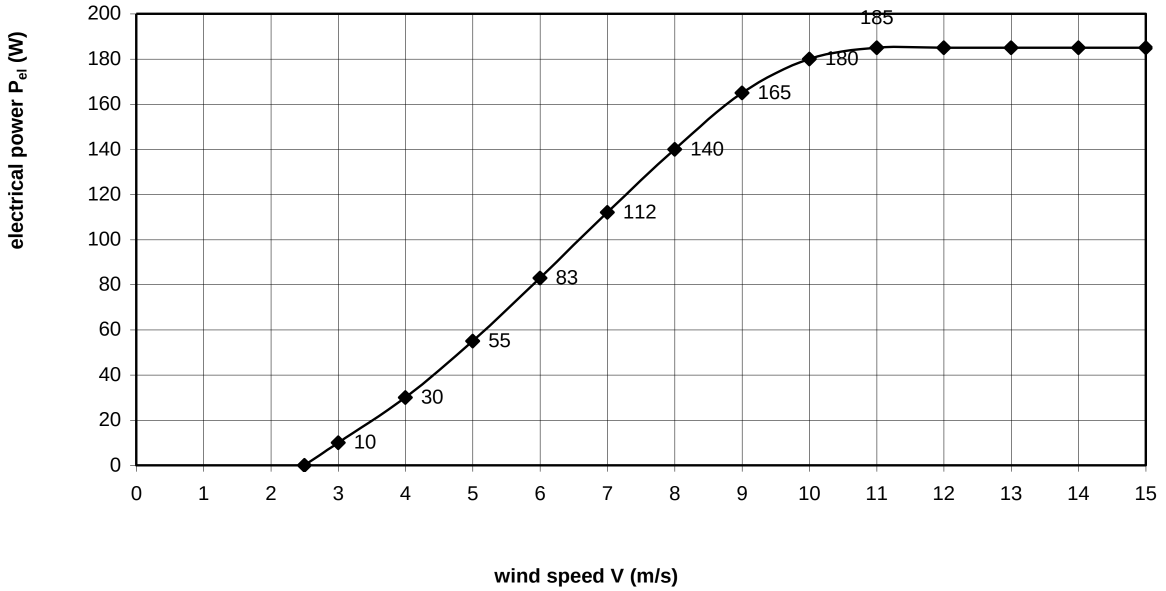

fig. 7 P_{el}-V curve of the VIRYA-2S windmill with V_{rated} = 11 m/s for 26 V delta

In figure 7 it can be seen that the P_{el}-V curve starts at a wind speed V = 2.5 m/s so $V_{cut\ in}$ = 2.5 m/s. In chapter 6 it was calculated that V_{start} = 3.2 m/s so there is some hysteresis in the P_{el}-V curve for 2.5 < V < 3.2 m/s. The maximum power is 185 W which is acceptable for a rotor diameter of 2 m.

The matching can be made better if the generator is used for 48 V battery charging and if the winding is rectified in star. The same procedure is now followed to transfer the characteristics for 52 V star for the VIRYA-2.2S generator to the characteristics for the VIRYA-2S generator. The result of the calculations is given in table 4.

	VIRYA-2.2S generator		VIRYA-2S generator		
n (rpm)	P_{mech} (W)	P_{el} (W)	P_{mech} (W)	P_{el} (W)	η_{gen} (%)
143	14	0	9.6	0	0
152	16.71	8.84	11.5	6.1	52.9
171	47.45	36.4	32.6	25.0	76.7
195	104.55	73.84	71.8	50.7	70.6
211	152.46	100.88	104.7	69.3	66.2
227	201.58	126.36	138.5	86.8	62.7
258	310.70	173.68	213.5	119.3	55.9
307	497.66	239.2	341.9	164.3	48.1
344	643.02	284.44	441.8	195.4	44.2
411	912.44	353.6	626.8	242.9	38.8
513	1267.82	426.4	871.0	292.9	33.6

table 4 Measured values of P_{mech} and P_{el} for the VIRYA-2.2S generator for 52 V star. Estimated values for P_{mech} and P_{el} for the VIRYA-2S generator

If table 4 is compared to table 3 it can be seen that the efficiencies for 52 V star are higher than for 26 V delta. The maximum efficiency is now about 77 % which is acceptable. Figure 6 is now copied as figure 8 but the generator characteristics for 26 V delta are replaced by the characteristics for 52 V star as given in table 4.

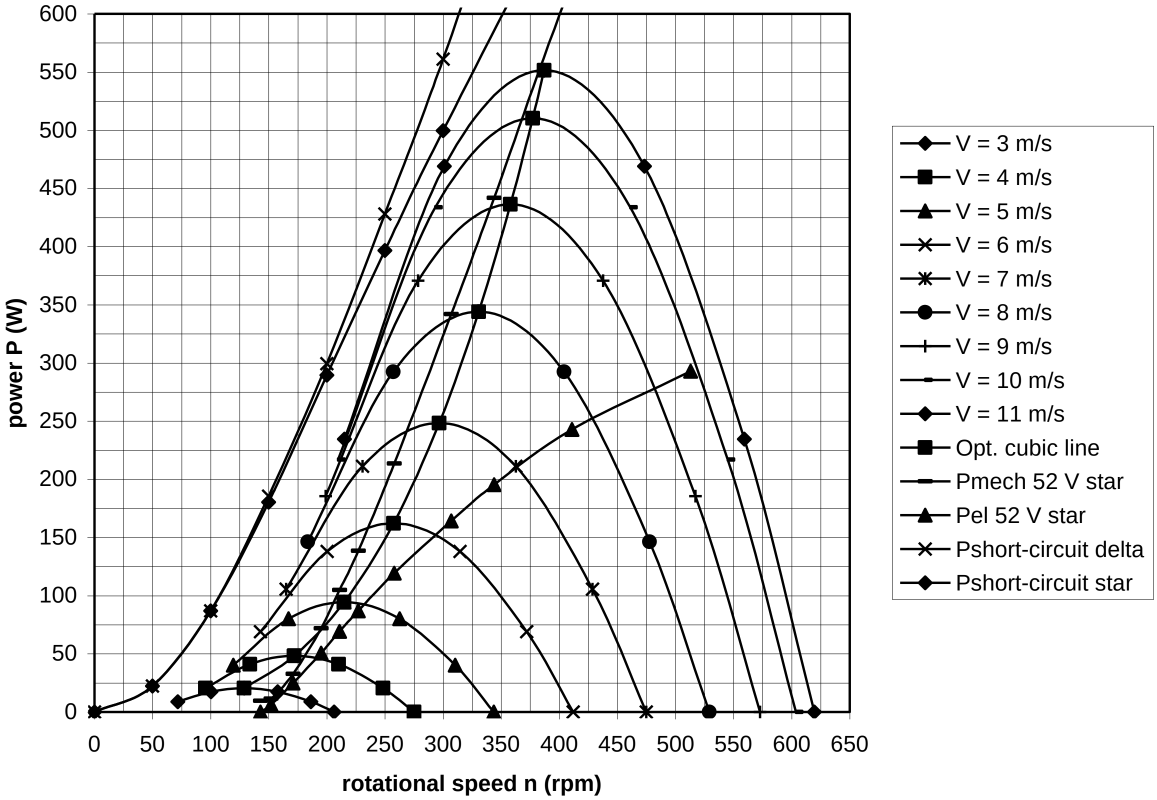

fig. 8 P-n curves and optimum cubic line of the VIRYA-2S rotor, estimated P_{mech}-n and P_{el}-n curves for 52 V star, estimated P-n curves for short-circuit in delta and in star

The estimated P-n curve for short-circuit in star is also given in figure 8. It can be seen that this curve is lying more to the right at high rotational speeds than the P-n curve for short-circuit in delta. The distance in between this curve and the P-n curve of the rotor for V = 11 m/s is therefore smaller. So it seems just possible to stop the rotor by making short-circuit in star but it is better to stop the rotor by making short-circuit in delta. Short-circuit in star is the same as short-circuit in delta if the star point is short-circuited too. However, this requires an extra line from the star point to the short-circuit switch and the short-circuit switch must have three switch contacts. The hinges of the switch contacts are connected to each other and the star point is connected to the combined hinges.

If figure 8 is compared to figure 6 it can be seen that the P_{mech}-n curve for 52 V star is lying more to the right than the P_{mech}-n curve for 26 V delta. So the matching for 52 V star is better. The P_{el}-V curve for 52 V star is derived in the same way as it was done for 26 V delta. The result is given in figure 9.

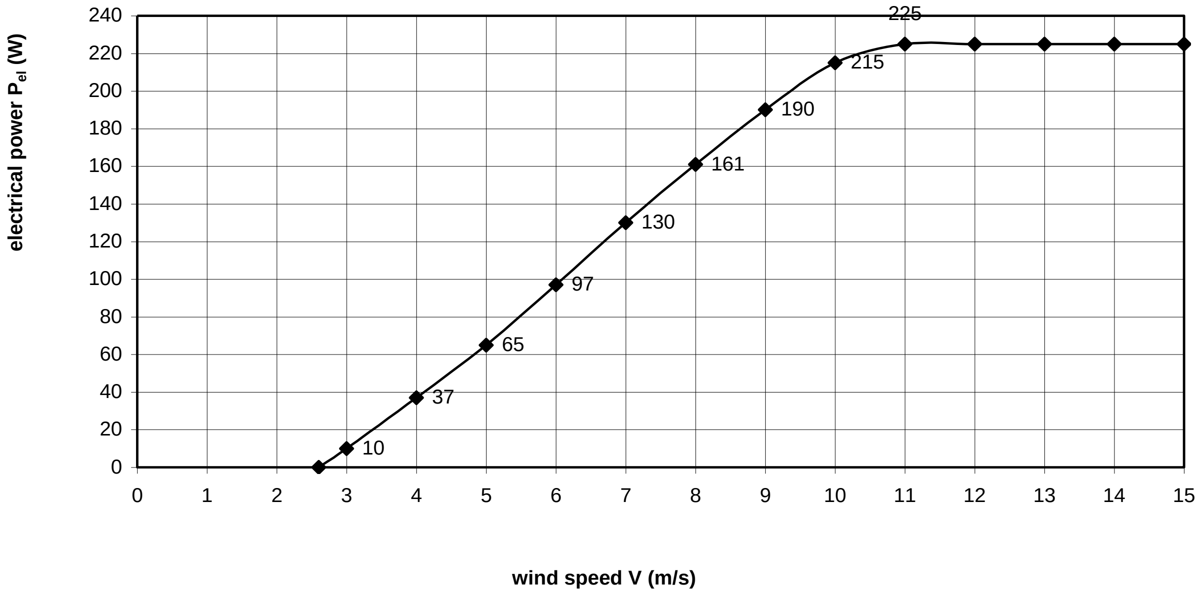

fig. 9 P_{el}-V curve of the VIRYA-2S windmill with V_{rated} = 11 m/s for 52 V star

If figure 9 is compared to figure 7 it can be seen that the cut-in wind speed is 2.6 m/s in stead of 2.5 m/s but that the P_{el}-V curve for 52 V star is lying higher than for 26 V delta for wind speeds higher than 3 m/s. The maximum power is 225 W for 52 V star and only 185 W for 26 V delta. The higher power is partly caused by the better matching but mainly caused by the higher generator efficiency for star rectification.

The original 230/400 V winding can be modified into a 115/200 V winding by connecting the first and the second layer of the winding in parallel in stead of in series. This procedure is described in report KD 341 (ref. 1). The voltage halves and the current doubles by this procedure. So the P_{el}-V curve of figure 7 is valid for 12 V battery charging if the winding is modified and the P_{el}-V curve of figure 9 is valid for 24 V battery charging if the winding is modified.

8 References

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Appendix 1 Sketch of the armature with essential measures

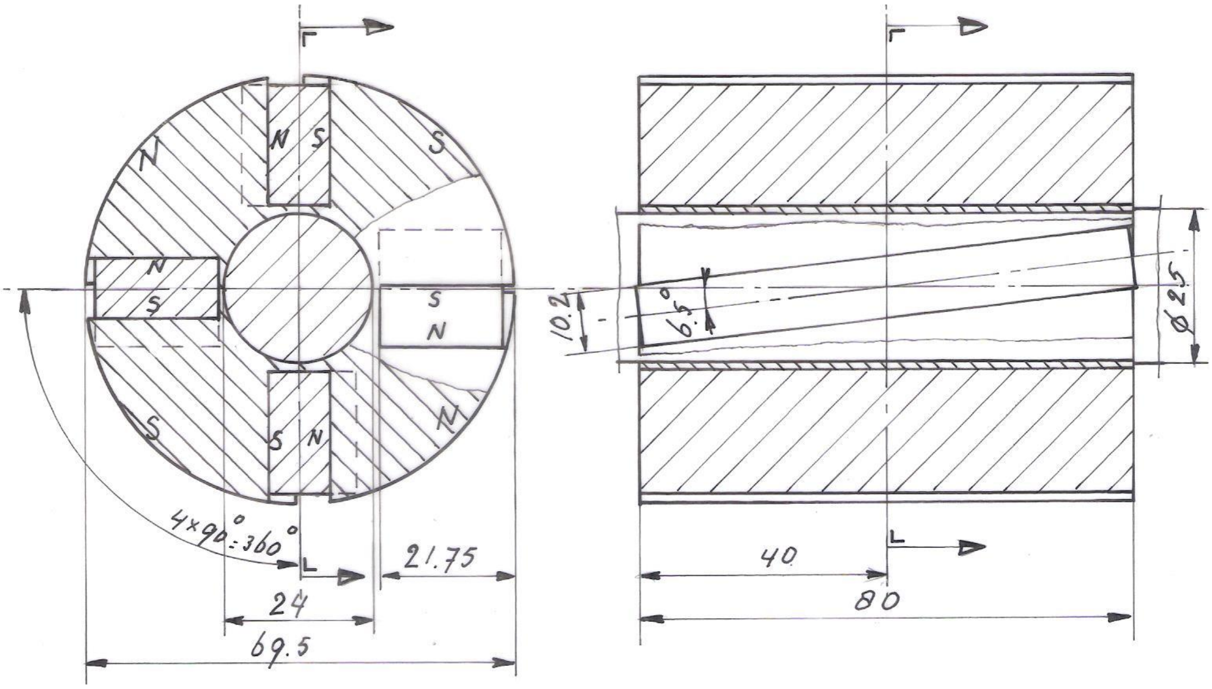

fig. 10 PM-armature of a 4-pole PM-generator frame size 80 with essential measures