Calculations executed for the 3-bladed rotor of the VIRYA-3.6 windmill (λ_d = 4.75, stainless steel blades) driving the PM-generator of Magnetic Innovations type 260-25 HS for 48 V battery charging or water pumping

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KD 794

It is allowed to copy this report for private use. As manufacture of the blades requires an expensive blade press, making of the VIRYA-3.6 rotor is only advised for serial manufacture by a professional company. The generator characteristics as given in chapter 10 are estimated and measured characteristics are preferred to check if the matching in between rotor and generator is acceptable. The rotor is not tested. Kragten Design accepts no responsibility for possible failures.

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1 Introduction

Recently I was informed about the existence of a very compact radial flux PM-generator of the Dutch company Magnetic Innovations. Originally this is a PM-motor to drive a fan. It has a housing diameter of 261 mm and is available in three different thicknesses and two different nominal rotational speeds. The low speed version has LS and the high speed version has HS in the type number. I have chosen the smallest type: 260-25 HS because I think that this type can be used as a PM-generator in combination with a 3-bladed rotor with stainless steel blades, a rotor diameter of 3.6 m and a design tip speed ratio $\lambda_d = 4.75$. It is expected that the standard winding can be used for 48 V battery charging. The wind turbine is called the VIRYA-3.6. The generator is described in chapter 7.

The VIRYA-3.6 will use a head and tower which are derived from the head and tower of the VIRYA-3.5. The head has drawing number 1501-03. The tower has drawing number 0507-04 and is also used for other windmills. It is also possible to use the tubular tower of the VIRYA-3.3S. The VIRYA-3.3S tower has drawing number 1404-04. The wind turbine is provided with the so called hinged side vane safety system which limits the rotational speed and thrust at high wind speeds. This safety system is described in report KD 213 for the VIRYA-4.2 (ref. 1). This safety system results in a rated wind speed of about 10 m/s.

The mass of the whole rotor is about 24 kg which seems reasonable for a steel rotor with a diameter of 3.6 m. The mass of the generator is 15 kg and so the total mass of rotor and generator is about 39 kg. A rather expensive blade press is needed for manufacture of the blades and the VIRYA-3.6 is therefore only suitable for serial manufacture by a professional company. The existing drawings of the head and the tower of the VIRYA-3.5, the tower of the VIRYA-3.3S and the blade press of the VIRYA-4.1 are available at certain conditions. May be I will also make detailed drawings of the VIRYA-3.6 rotor if a serious company has interest in the VIRYA-3.6.

2 Description of the rotor of the VIRYA-3.6 windmill

The 3-bladed rotor of the VIRYA-3.6 windmill has a diameter D = 3.6 m and a design tip speed ratio $\lambda_d = 4.75$. Advantages of a 3-bladed rotor are that the gyroscopic moment in the rotor shaft isn't fluctuating and that a 3-bladed rotor looks better than a 2-bladed one.

The rotor has stainless steel blades made out of a sheet size 3 * 200 * 1500 mm. Fifteen sheets for five rotors can be made from a standard sheet size 1.5 * 3 m. The sheet is 7.14 % cambered. It is possible to use the blade press with drawing number 0508-01 which was designed for the VIRYA-4.1. Information about cambered sheet airfoils is given in report KD 398 (ref. 2). The camber radius r_c can be derived from chapter 5.1 of KD 398 and it is found that $r_c = 352$ mm for b = 200 mm. The chord c is somewhat smaller than the width of the sheet and it is found that c = 197.3 mm = 0.1973 m. The whole blade length is cambered and no blade twist is used. So the blade has a constant chord c and a constant blade angle β.

The three blades are connected to each other by a spoke assembly. Every spoke is made out of a stainless steel strip size 8 * 120 * 600 mm. The strips are welded together at the centre under an angle of 120°. The 300 mm long outer part of a spoke is cambered with a camber radius of 347 mm. A blade is connected to a spoke by six bolts M10 * 40 and six self locking nuts M10. The spokes are twisted 8° right hand (see chapter 3).

The whole generator housing is rotating. The front side of the generator has six threaded rods M8 at a pitch circle of 196 mm. It has a centring collar with a diameter of 170 mm but this centring collar isn't used. Six aluminium bushes with a thickness of 15 mm and a diameter of 25 mm are used in between the spoke assembly and the mounting plane of the generator. The original threaded rods M8 have to be replaced by threaded rods which are 20 mm longer. The spoke assembly is connected to the generator by six self locking nuts M8. The rotor is balanced by weights which are connected under the nuts M10. A picture of the rotor is given in figure 1.

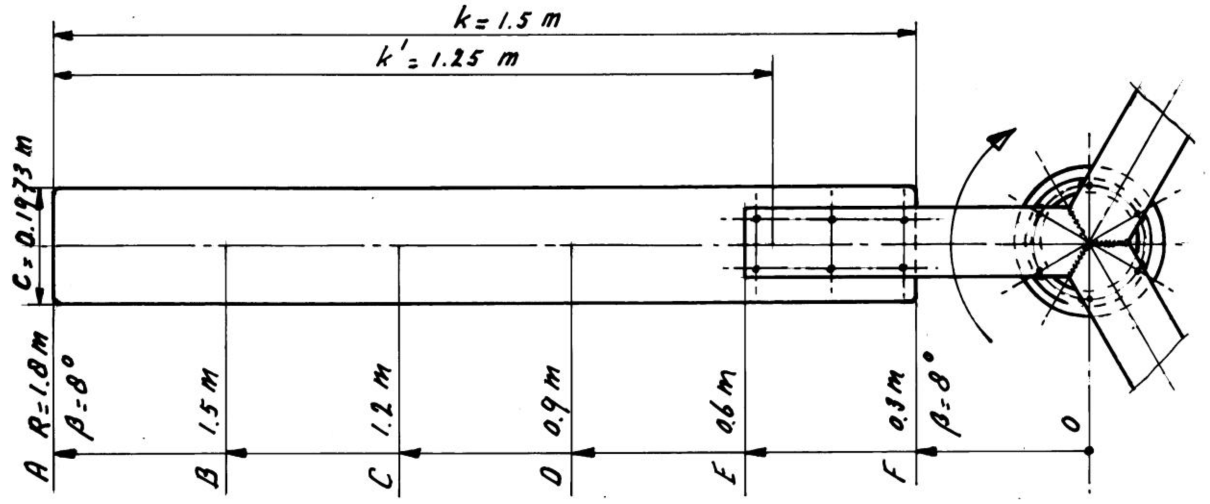


fig. 1 Front view of the VIRYA-3.6 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 3). This report (KD 794) has its own formula numbering. Substitution of $\lambda_d = 4.75$ and R = 1.8 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 2.639 * r$ (-) (1)

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

$\beta = \phi - \alpha$ (°) (2)

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

Substitution of B = 3 and c = 0.1973 m in formula (5.4) of KD 35 gives:

$C_l = 42.461 * r\,(1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.1973 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.658 * 10^5 * \sqrt{}\,(\lambda_{r\,d}^2 + 4/9)$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.3 m of one to another. Station E corresponds to the end of a spoke. 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 lift coefficient is low at the blade tip and high at the blade root. First the theoretical values are determined for C_l, α and β. Next β is linearized such that a certain constant β_{lin} matches best with β_{th}. This results in new values α_{lin} and $C_{l\,lin}$. The result of the calculations is given in table 1.

The aerodynamic characteristics of cambered airfoils are given in report KD 398 (ref. 2). 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} = 10 m/s. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

sta- tion	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	1.8	4.75	7.9	0.1973	0.73	0.75	3.16	3.4	-0.3	-0.1	8.2	8.0	0.041
B	1.5	3.958	9.5	0.1973	0.86	0.88	2.64	2.5	1.1	1.5	8.4	8.0	0.032
C	1.2	3.167	11.7	0.1973	1.06	1.09	2.13	2.5	3.5	3.7	8.2	8.0	0.039
D	0.9	2.375	15.2	0.1973	1.34	1.32	1.62	1.7	7.4	7.2	7.8	8.0	0.09
E	0.6	1.583	21.5	0.1973	1.78	1.34	1.13	1.2	-	13.5	-	8.0	0.2
F	0.3	0.792	34.4	0.1973	2.23	-	0.68	1.2	-	26.4	-	8.0	-

table 1 Calculation of the blade geometry of the VIRYA-3.6 rotor

No value of α_{th} is found for station E and F because the required value of $C_{l\ th}$ can't be generated. The value of β_{th} varies in between 8.4° and 7.8° for station A up to D. If a value β_{lin} = 8° is chosen for the whole blade, the values of β_{lin}, α_{lin} and $C_{l\ lin}$ are lying close to the theoretical values for the most important outer part of the blade.

4 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} = 4.75 and C_d/C_l = 0.04 gives $C_{p\ th}$ = 0.43 (interpolation in between the curves for C_d/C_l = 0.03 and C_d/C_l = 0.05).

The blade is stalling in between station E and F. For the calculation of the maximum C_p therefore not the whole blade length k = 1.5 m is taken into account but only the part up to 0.25 m outside station F. This gives an effective blade length k' = 1.25 m.
Substitution of $C_{p\ th}$ = 0.43, R = 1.8 m and effective blade length k' = 1.3 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.39. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.39 / 4.75 = 0.0821.
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:

$$C_{q\ start} = 0.75 * B * (R - \tfrac{1}{2}k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (6)$$

The blade angle is 8° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 8° = 82°. The aerodynamic characteristics for the 7.14 % cambered airfoil aren't given in KD 398 for large angles of α. However, it is assumed that the characteristics of the 10 % cambered airfoil can be used for large angles of α. The C_l-α curve for large angles of α for the 10 % cambered airfoil is given in figure 5 of KD 398. In this figure it can be read that C_l = 0.27 for α = 82°. The whole blade is stalling during starting and therefore now the whole blade length k = 1.5 m is taken.
Substitution of B = 3, R = 1.8 m, k = 1.5 m, C_l = 0.27 and c = 0.1973 m in formula 6 gives that $C_{q\ start}$ = 0.0103. For the ratio between the starting torque and the optimum torque we find that it is 0.0103 / 0.0821 = 0.126. This is acceptable for a rotor with λ_d = 4.75. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * \tfrac{1}{2}\rho * \pi R^3} \right)} \qquad (m/s) \qquad (7)$$

The VIRYA-3.6 generator has 32 armature poles and 30 stator poles. This makes than only two armature poles are exactly opposite to a stator pole at a certain time. If this situation causes a preference position, it can be calculated that the generator has 460 small preference positions per revolution. It has been measured that the peak on the cogging torque is only 0.54 Nm (see chapter 9). Substitution of $Q_s = 0.54$ Nm, $C_{q\ start} = 0.0103$, $\rho = 1.2$ kg/m^3 and R = 1.8 m in formula 7 gives that $V_{start} = 2.2$ m/s. This is very low for a 3-bladed rotor with a design tip speed ratio of 4.75. The generator is used in star for 48 V battery charging and the Q-n curve of the rotor for V = 2.2 m/s is rising faster than unloaded Q-n curve of the generator. So once the rotor is started, it will accelerate.

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 an S-shaped line which is horizontal for $\lambda = 0$. 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 about straight and horizontal for low values of λ if a 7.14 % cambered airfoil is used. A scale model of a three bladed rotor with constant chord and blade angle and with a design tip speed ratio $\lambda_d = 6$ has been measured in the wind tunnel already on 20-11-1980. It has been found that the maximum C_p was more than 0.4 and that the C_q-λ curve for low values of λ was not horizontal but somewhat rising. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-3.6 rotor are given in figure 2 and 3.

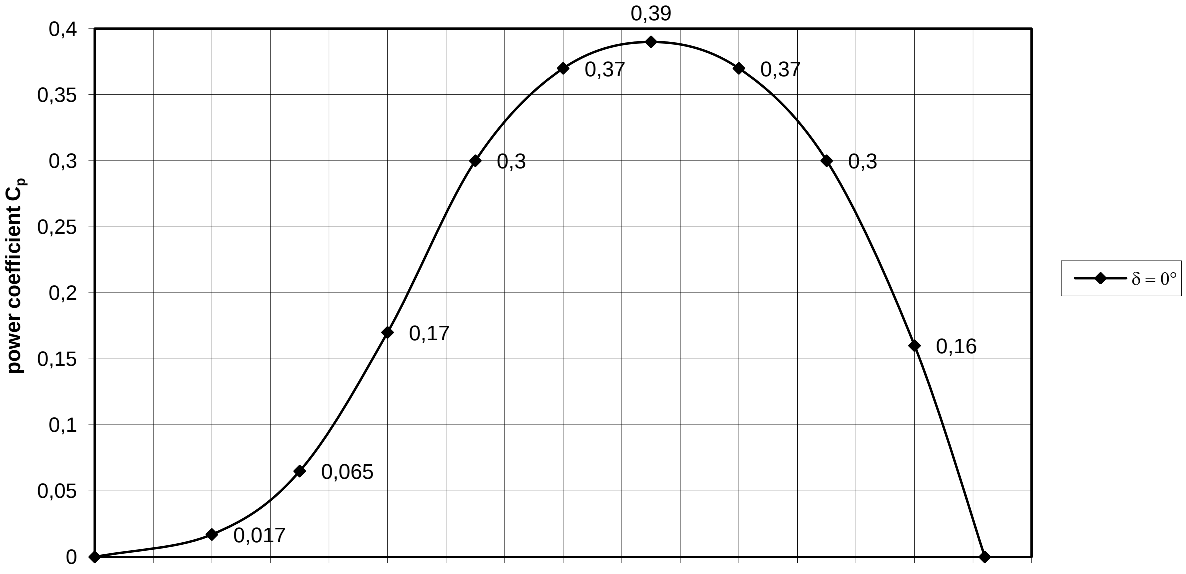


fig. 2 Estimated C_p-λ curve for the VIRYA-3.6 rotor for the wind direction perpendicular to the rotor ($\delta = 0$

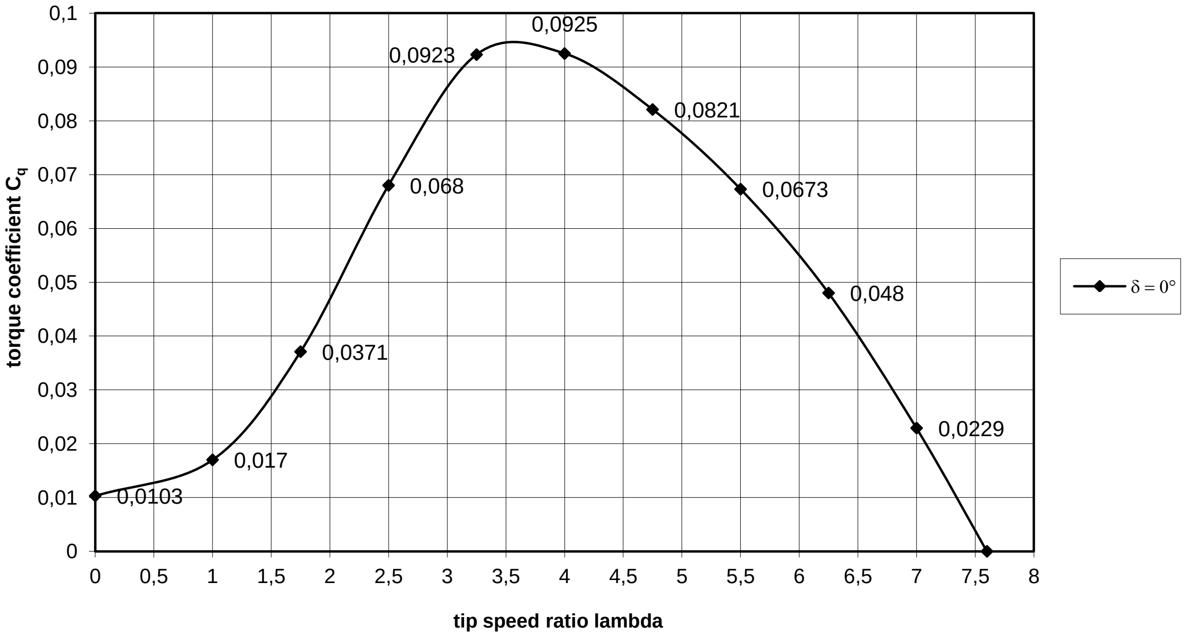


fig. 3 Estimated C_q-λ curve for the VIRYA-3.6 rotor for the wind direction perpendicular to the rotor (δ = 0°)

5 Determination of the P-n curves and the optimum cubic line

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 2. The δ-V curve of the safety system depends on the vane blade mass per area. The vane blade of the VIRYA-3.5 is made of 9 mm meranti waterproof plywood with a density of about $0.6 * 10^3$ kg/m^3. This vane blade gives a rated wind speed V_{rated} of about 10 m/s. The vane blade of the VIRYA-3.6 is also made of 9 mm meranti and so the rated wind speed is also about 10 m/s. The estimated δ-V curve is given in figure 4. The head starts to turn away at a wind speed of about 6 m/s. For wind speeds above 10 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 10 m/s will therefore also be valid for wind speeds higher than 10 m/s.

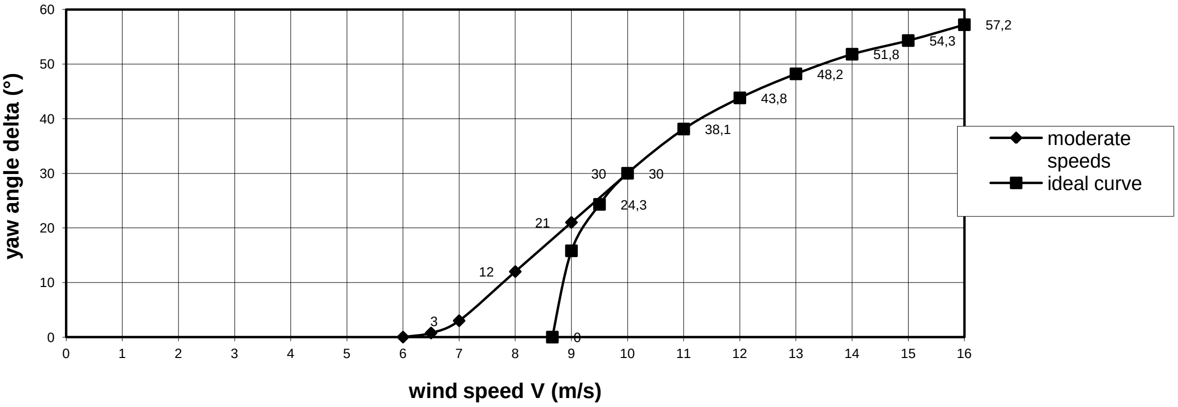


fig. 4 Estimated δ-V curve for a 9 mm meranti plywood vane blade

The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 10 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 = 1.8 m in formula 7.1 of KD 35 gives:

$$n_\delta = 5.3052 * \lambda * \cos\delta * V \qquad \text{(rpm)} \tag{8}$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 1.8 m in formula 7.10 of KD 35 gives:

$$P_\delta = 6.1073 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \tag{9}$$

The P-n curves are determined for C_p values belonging to λ is 1.75, 2.5, 3.25, 4, 4.75, 5.5, 6.25, 7 and 7.6 (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 8 and 9 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 4, 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 = 0°		V = 7 m/s δ = 3°		V = 8 m/s δ = 12°		V = 9 m/s δ = 21°		V = 10 m/s δ = 30°	
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)
1.75	0.065	27.9	10.7	37.1	25.4	46.4	49.6	55.7	86	64.9	136	72.6	190	78.0	235	80.4	258
2.5	0.17	39.8	28.0	53.1	66.4	66.3	129.8	79.6	224	92.7	355	103.8	497	111.4	616	114.9	674
3.25	0.3	51.7	49.5	69.0	117.3	86.2	229.0	103.5	396	120.5	626	134.9	878	144.9	1087	149.3	1190
4	0.37	63.7	61.0	84.9	144.6	106.1	282.5	127.3	488	148.3	772	166.1	1083	178.3	1340	183.8	1468
4.75	0.39	75.6	64.3	100.8	152.4	126.0	297.7	151.2	514	176.2	814	197.2	1141	211.7	1413	218.2	1547
5.5	0.37	87.5	61.0	116.7	144.6	145.9	282.5	175.1	488	204.0	772	228.3	1083	245.2	1340	252.7	1468
6.25	0.3	99.5	49.5	132.6	117.3	165.8	229.0	198.9	396	231.8	626	259.5	878	278.6	1087	287.2	1190
7	0.16	111.4	26.4	148.5	62.5	185.7	122.1	222.8	211	259.6	334	290.6	468	312.0	580	321.6	635
7.6	0	121.0	0	161.3	0	201.6	0	241.9	0	281.8	0	315.5	0	338.8	0	349.2	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-3.6 rotor

The calculated values for n and P are plotted in figure 5. The optimum cubic line which is going through the tops of the P-n curves is also given in figure 5.

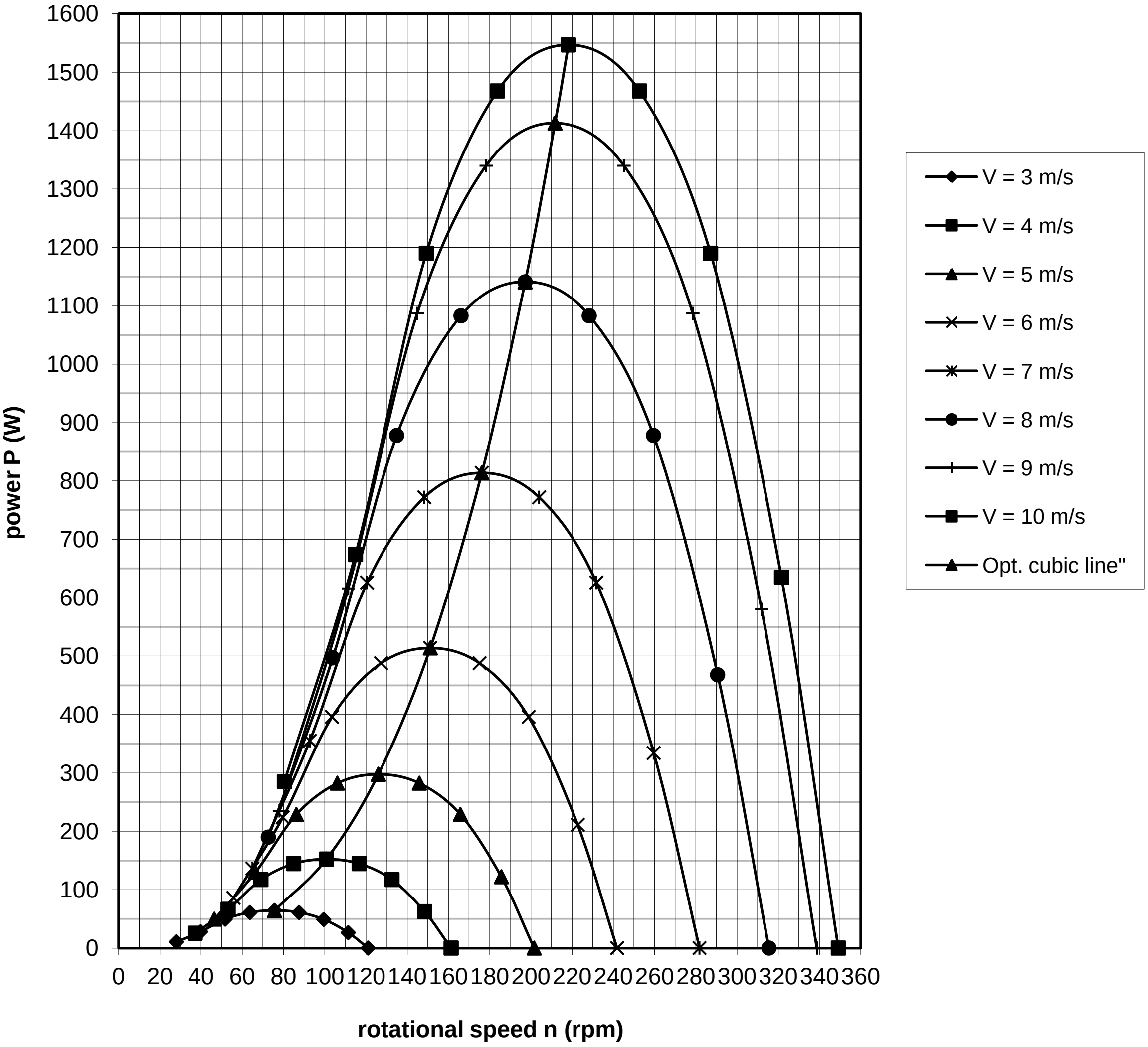


fig. 5 P-n curves of the VIRYA-3.6 rotor and the optimum cubic line

6 Checking of the head geometry

The VIRYA-3.5 head and tower pipe are given at drawing 1501-03. The VIRYA-3.5 is provided with a PM-generator of Hefei Top Grand type TGET320-1KW-350R. The whole generator housing is rotating and the fixed shaft has a diameter of 45 mm. Two generator clamps item 04 are used to connect the generator shaft to the square sheet item 01/06 of the vane arm assembly. This sheet has dimensions 6 * 120 * 120 mm and is positioned in parallel to the generator axis. The distance in between the shaft axis and the mounting plane of the sheet item 01/06 is 50 mm.

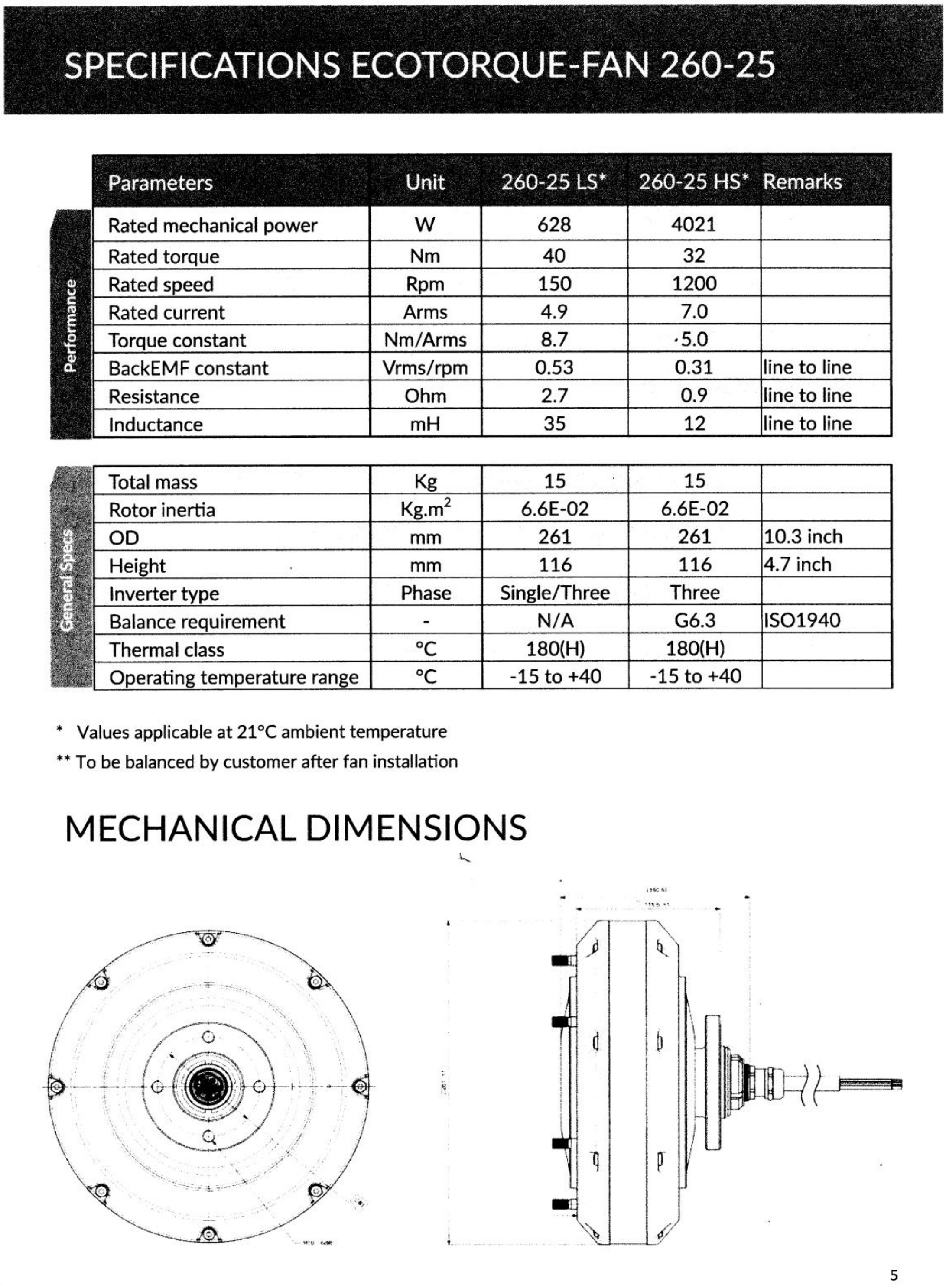
The VIRYA-3.6 generator is connected differently. It has a flange at the backside with a diameter of 108 mm and four threaded holes M10 at a pitch circle of 83 mm. It has a centring collar with a diameter of 58 mm. So the clamping blocks are cancelled and a special bracket is required with which the generator can be connected to the existing sheet item 01/06. This bracket can be made from for instance a 120 long part of square bar 100 * 100 mm. Another option is to cancel the existing item 01/06 and to make a new strip but now perpendicular to the generator shaft. The four holes for the bolts M10 are now directly made in this strip.

The eccentricity e is 0.3 m for the VIRYA-3.5. Assume that this eccentricity is maintained for the VIRYA-3.6. As the rotor diameter of the VIRYA-3.6 is larger, the rotor thrust will be about a factor $(3.6 / 3.5)^2 = 1.058$ larger if both rotors have the same thrust coefficient. However, a rotor with cambered steel blades has a somewhat higher thrust coefficient than a rotor wooden blades with a normal Göttingen airfoil (0.75 instead of 0.7) So the rotor moment increases by a factor 1.058 * 0.75 / 0.7 = 1.125. So I expect that the vane moment is too small. This can be solved by taking a somewhat larger vane blade. It is assumed that the vane blade width w is maintained at 0.8 m but that the vane blade height is increased from 0.8 up to 0.9 m.

The correct vane arm geometry can be checked for low wind speeds using formula 50 out of KD 213 (ref. 1). Substitution of R = 1.8 m, $C_t = 0.75$, e = 0.3 m, h = 0.9 m, w = 0.8 m, $R_v = 2.14$ m and $i_1 = 0.24$ m in formula 50 of KD 213 gives that $C_n = 1.34$. In figure 6 of KD 213 it can be seen that $\alpha = 30$ for $C_n = 1.34$. The angle in between the vane blade axis and the rotor axis is 30° which means that the rotor is just perpendicular to the wind for $\alpha = 30°$. So the head geometry is correct if the vane blade length is increased from 0.8 m up to 0.9 m.

7 Description of the generator

The generator is supplied by the Dutch company Magnetic Innovations website: www.magneticinnovations.com. The chosen generator is found following the path: website - products - EcoTorque-Fan Motor – Fan Motor 260 – 25. At the bottom of this file, one can click on Downloadable Content and at page 4 there is a photo of the armature and stator. It is assumed that the stator winding is connected in star. At page 7 of the download there is detailed information about the chosen motor. This information is copied as figure 6.



SPECIFICATIONS ECOTORQUE-FAN 260-25

	Parameters	Unit	260-25 LS*	260-25 HS*	Remarks
Performance	Rated mechanical power	W	628	4021	
	Rated torque	Nm	40	32	
	Rated speed	Rpm	150	1200	
	Rated current	Arms	4.9	7.0	
	Torque constant	Nm/Arms	8.7	5.0	
	BackEMF constant	Vrms/rpm	0.53	0.31	line to line
	Resistance	Ohm	2.7	0.9	line to line
	Inductance	mH	35	12	line to line
General Specs	Total mass	Kg	15	15	
	Rotor inertia	Kg.m^2	6.6E-02	6.6E-02	
	OD	mm	261	261	10.3 inch
	Height	mm	116	116	4.7 inch
	Inverter type	Phase	Single/Three	Three	
	Balance requirement	-	N/A	G6.3	ISO1940
	Thermal class	°C	180(H)	180(H)	
	Operating temperature range	°C	-15 to +40	-15 to +40	

* Values applicable at 21°C ambient temperature

** To be balanced by customer after fan installation

MECHANICAL DIMENSIONS

5

fig. 6 Detailed information about the Fan Motor 260 – 25

So the type 260-25 can be supplied in two versions; the version LS for low speeds and the version HS for high speeds. The version HS is chosen. I think that mechanically both versions are the same but that only the number of turns per coil is different. The version LS has a rated torque of 40 Nm at 150 rpm. The version HS has a rated torque of 32 Nm at 1200 rpm. I expect that the maximum torque which can be supplied by both motors is much higher than 40 Nm but that the maximum torque which is allowed for a long time is limited because of heat generation in the winding. As the version HS has a much higher rated power than the version LS (4021 W instead of 628 W), the generated heat is also much higher and would be too high at a torque of 40 Nm and n = 1200 rpm. But I see no reason why the version HS could not be used at 40 Nm if the rotational speed is low enough.

The first thing which has to be checked, is if the chosen generator is strong enough for the VIRYA-3.6 rotor. In table 2 it can be read that the maximum mechanical power which the rotor can produce at a wind speed V = 10 m/s is 1547 W at a rotational speed of 218.2 rpm. The relation in between the torque Q and the mechanical power P is given by:

$$Q = 30\ P / (\pi * n) \qquad \text{(Nm)} \qquad (10)$$

Substitution of P = 1547 W and n = 218.2 rpm in formula 10 gives that Q = 67.7 Nm. This is much higher than the nominal torque of 40 Nm for low rotational speeds. However, I expect that a much higher torque is allowed for generator use for a wind turbine than for motor use for a fan. Measurement as given in chapter 9 have shown that the Q-n curve for short-circuit is very steep and therefore it is expected that the peak torque is about 75 Nm. There are two reasons why it is allowed to use a higher torque level as generator than as motor.

Assume we have a certain torque Q at a certain rotational speed n. This means a certain mechanical power P at that rotational speed. The required electrical power for motor use will be higher because of the efficiency η. Assume η = 0.8 at maximum power. So the required electrical power will be P / 0.8 = 1.25 P. The supplied electrical power for generator use will be lower because of the efficiency η. Assume η = 0.8 at maximum power. So the supplied electrical power will be P * 0.8 = 0.8 P. So the electrical power for generator use is a factor 0.8 / 1.25 = 0.64 lower for the same mechanical power. As the heat dissipation is proportional with the electrical power, the torque level for generator use can be a factor 1 / 0.64 = 1.563 higher for the same heat dissipation.

If the motor is used to drive a fan, it can be set at the maximum power for a permanent time. So the heat dissipation must be acceptable for endless time and this strongly limits the maximum electrical power. If the motor is used as generator for a wind turbine, the maximum electrical power is only supplied during strong wind gusts. The dissipated heat is therefore lower as only the heat dissipation for the average rotational speed has to be taken into account.

I have designed, built and measured several PM-generators. The most extensive measurements are given in report KD 78 (ref. 5) for a PM-generator made from an asynchronous motor. The 3-phase current coming out of the generator is rectified and the rectifier losses are incorporated in the generator efficiency. This generator has been measured for three different load types being several constant voltages, several constant currents and several constant resistances. A constant resistance load gives a high efficiency over a large rpm range because the current increases with the voltage. A constant voltage gives only a high efficiency at a small rpm range. This is because the electrical power increases only because of the increase of the current and this results in high copper losses at high powers.

The VIRYA-3.6 will be used to charge a 48 V lead acid battery. The charging current varies in between about 48 V at low currents and an almost empty battery and about 56 V at high currents and an almost full battery. So the average charging voltage is about 52 V. To check the matching in between rotor and generator and to determine the P_{el}-V curve, measured P_{mech}-n and P_{el}-n curves of the generator for a constant voltage of 52 V_{DC} are needed. But as these curves aren’t available, they have to be estimated.

At the specification as given in figure 6 it is mentioned for the 260-25 HS that the backEMF constant is 0.31 Vrms/rpm and that the voltage is measured line to line. This is the AC voltage measured in between two of the three phases if the motor is used as a generator. If the three phases are rectified, one gets a higher DC voltage. Rectification of a 3-phase current is explained in my report KD 340 (ref. 6). Formula 13 out of this report gives the effective DC voltage U_{DCeff} as a function of the effective AC phase voltage U_{eff} for connection of the winding in star and for neglecting the voltage drop over the rectifier diodes. U_{eff} is the effective AC voltage in between the star point and one of the phases. The AC voltage U_{line} in between two of the lines is a factor √3 higher than U_{eff}. So if instead of U_{eff}, U_{line} is used, formula 13 out of KD 340 changes into:

$$U_{DCeff} = 0.955 * \sqrt{2} * U_{line} \qquad (V_{DC}) \qquad (11)$$

So this means that the backEMF in DC voltage is a factor 0.955 * √2 higher and so the backEMF is 0.31 * 0.955 * √2 = 0.419 V_{DC}/ rpm for the 260-25 HS. The rotational speed for which the open DC voltage is 52 V is now found as n = 52 / 0.419 = 124 rpm.

It can now be calculated which wind speed is required to get an unloaded rotational speed of 124 pm. As this is a low wind speed, the rotor is still perpendicular to the wind and so for n, we now can use formula 4.8 out of KD 35. This formula can be written as:

$$V = \pi * R * n / (30 * \lambda) \qquad (m/s) \qquad (12)$$

In figure 2 it can be seen that the unloaded λ is 7.6. Substitution of R = 1.8 m, n = 124 rpm and $\lambda = \lambda_{unl} = 7.2$ in formula 12 gives that V = 3.08 m/s. This wind speed for which charging of the batteries starts is called the cut-in wind speed V_{cut-in}. The P_{mech}-n curve for 52 V rises strongly for rotational speeds higher than 124 rpm. The real shape of the P_{mech}-n curve depends on the shape of the Q-n curve for 52 V_{DC}.

In figure 8 of KD 78 the Q-n curves are given for 26 V, 52 V and 76 V star. All three curves have about the same shape but a curve is lying more to the right as the voltage is higher. In figure 8 of KD 78 the Q-n curves are given for short-circuit in star and delta. The maximum torque for short-circuit en delta is much higher than for short circuit in star because higher harmonic currents can circulate in the winding for short-circuit in delta. The Q-n curve for short-circuit in star has about the same shape as the Q-n curves for 26 V, 52 V and 76 V star. The first part of the curve is about a straight line up to about 2/3 of the peak value. For the VIRYA-3.6 generator it is assumed that the Q-n curve for a constant voltage is a straight line up to a torque of 50 Nm. The real shape of the Q-n curve for 52 V star can only be determined if a generator is tested on a test rig for a constant voltage of 52 V DC or even better for a real 48 V battery with enough capacity. But an estimation can be made because of the measurements as given in chapter 9.

8 Description of the generator winding

At the bottom of the manufacturers file Fan Motor 260 – 25, one can click on Downloadable Content and at page 4 there is a photo of the armature and stator. It can be seen that the stator has 30 coils with laminated iron cores and that the armature has 32 poles, so 16 north poles and 16 south poles. Nothing is said about the winding and so the question is how this winding can generate a 3-phase current. There are only two options being six coil bundles of each five coils or three coil bundles of each ten coils. The three phases are called U, V and W.

The first option, six coil bundles of five coils, is investigated first. The right hand coil sequence is: U1, U2, U3, U4, U5, W6, W7, W8, W9, W10, V1, V2, V3, V4, V5, U6, U7, U8, U9, U10, W1, W2, W3, W4, W5, V6, V7, V8, V9 and V10.

The armature pole angle is 360° / 32 = 11.25°. The stator pole angle is 360° / 30 = 12°. So the difference is 0.75°. Assume that the generator has a preference position if one armature pole is exactly opposed to a stator pole. This happens for only two of the thirty-two armature poles at the same time. The number of preference positions per revolution is then 360 / 0.75 = 480. The peak on the cogging torque will be very small for these many preference positions per revolution.

The north poles are called right hand N1 up to N8. The south poles are called right hand S1 up to S8. Assume that the armature north pole N1 is exactly opposed to coil U3. The armature south poles S8 and S1 will then be about opposed to coil U2 and coil U4. The difference is 0.75°. Assume that the armature north pole N1 is exactly opposed to coil U3. The armature north poles N8 and N2 will then be about opposed to coil U2 and coil U4. The difference is 1.5°.

Assume that all five coils U1 up to U5 are connected in series. Assume that the coils U1, U3 and U5 are wound right hand. The coils U2 and U4 then have to be wound left hand to make that the voltages strengthen each other. As there is an angle of 0.75° in between the armature pole angle and the stator pole angle, the generated voltages in the coils U1, U2, U4 and U5 will be out of phase with the voltage generated in coil U3.

The relation in between the phase angle α and the armature angle β is found in the following way. Assume that the magnet N1 is just opposite coil U3. Assume that the armature rotates right hand until the magnet N8 is just opposite coil U3. This takes a rotational angle $\beta = 2 * 11.25° = 22.5°$. So $\beta = 22.5°$ corresponds to $\alpha = 360°$. So $\beta = 1°$ corresponds to $\alpha = 16°$. So $\beta = 0.75°$ corresponds to $\alpha = 12°$ and $\beta = 1.5°$ corresponds to $\alpha = 24°$.

Assume that the voltage generated in one coil varies sinusoidal. The sum of sinusoidal voltages which are out of phase to each other is also a sinusoidal voltage. Assume that the voltage in one phase has a maximum U_{max}. The voltage U is then given by:

$$U = \sin \alpha * U_{max} \qquad (V_{AC}) \qquad (13)$$

The total voltage U_{tot} in all five coils is the given by:

$$U_{tot} = \{\sin (\alpha - 24°) + \sin (\alpha - 12°) + \sin \alpha + \sin (\alpha + 12°) + \sin (\alpha + 24°)\} * U_{max} \qquad (14)$$

The voltage in one phase has a maximum U_{max} for $\alpha = 90$. So $U_{tot\ max}$ is given by:

$$U_{tot\ max} = \{\sin (90° - 24°) + \sin (90° - 12°) + \sin 90° + \sin (90 + 12°) + \sin (90 + 24°)\}\ U_{max}$$

$$U_{tot\ max} = (\sin 66° + \sin 78° + \sin 90° + \sin 102° + \sin 114°) * U_{max} \quad \text{or}$$

$$U_{tot\ max} = (0.9135 + 0.9781 + 1 + 0.9781 + 0.9135) * U_{max} = 4.7832 * U_{max} \qquad (15)$$

If all five voltages would be exactly in phase to each other, $U_{tot\ max}$ would be $5 * U_{max}$. So the voltage is reduced by a factor 4.7832 / 5 = 0.9566 because the five voltages are not exactly in phase to each other. This is certainly acceptable and it gives only a small reduction of power.

If the north pole N1 is just opposite the coil U3, the north pole N9 will be just opposite to the coil U8. This means that the voltage generated in the coil bundle U6 up to U10 is in phase to the voltage generated in the coil bundle U1 up to U5. The coil bundle U6 up to U10 can be connected in series or can be connected in parallel with the coil bundle U1 up to U5. Connection in series gives the highest voltage. Connected in parallel makes that the voltage halves and the current doubles. It is assumed that all six coil bundles are wound in the same way. So coils 1, 3 and 5 are wound right hand and coils 2 and 4 are wound left hand. It then can be proven that there is a phase angle of 120° in between the voltage generated in the coils U3, V3 and W3 and so a 3-phase current is generated.

The second option, three coil bundles of ten coils is investigated next. The right hand coil sequence is: U1, U2, U3, U4, U5, U6, U7, U8, U9, U10, V1, V2, V3, V4, V5, V6, V7, V8, V9, V10, W1, W2, W3, W4, W5, W6, W7, W8, W9 and W10. Assume that all coils with odd coil numbers are wound right hand. All coils with even coil numbers must then be wound left hand. With ten coils, there is no central coil in a coil bundle. So for the calculation of the maximum total voltage $U_{tot\ max}$ it is assumed that magnet N1 is 0.375° to the left side of coil U5 and that magnet S1 is 0.375° to the right side of coil U6. It then can be proven that $U_{tot\ max}$ is given by:

$$U_{tot\ max} = (\sin 36° + \sin 48° + \sin 60° + \sin 72° + \sin 84° + \sin 96° + \sin 108° + \sin 120° + \sin 132° + \sin 144°)\ U_{max} \text{ or}$$

$$U_{tot\ max} = (0.5878 + 0.7431 + 0.8660 + 0.9659 + 0.9945 + 0.9945 + 0.8660 + 0.7431 + 0.5878)\ U_{max}$$

$$= 8.2850 * U_{max} \tag{16}$$

If all ten voltages would be exactly in phase to each other, $U_{tot\ max}$ would be 10 * U_{max}. So the voltage is reduced by a factor 8.2850 / 10 = 0.8285 because the ten voltages are not exactly in phase to each other. This is a much higher reduction of the voltage than for six coil bundles of five coils. The voltage is that much lower, mainly because the outer coils U1 and U10 contribute only a little to the total voltage. The generated power at a certain rotational speed depends on the generated voltage. So the power which is generated for three coil bundles of ten coils will be substantial lower than for six coil bundles of five coils.

To open the generator, the front bearing cover had to be removed by removing the eight torque screws M5. A bearing size 40 * 68 * 15 mm is left in the front bearing cover. I was afraid that the armature might touch the stator if the front bearing cover is removed but the armature still rotates smoothly. The back bearing cover probably contains two bearings. Contact with the manufacturer has shown that this is true and that these bearings are even bigger than the bearing in the front cover. A photo of the armature and stator is given in figure 7.

The winding was observed and it was found that at three points, two black wires are coming out of the stator. There is a connecting wire outside the coils which connects coils which are ten coils apart from each other. My first impression therefore was that one has chosen for three bundles of ten coils. However, after contact with Magnetic Innovations, it appeared that this wasn’t true. One has used six coil bundles of each five coils and the coil bundles of one phase are positioned opposed to each other. All ten coils of one phase are connected in series.

One of the black wires becomes brown. The three brown wires of the three phases are connected to each other and are forming the star point. So the star point isn’t guided to the outside of the generator. The other black wire has an eye at the end and is connected to an isolated threaded rod M4. From each isolated threaded rod, there is a black phase cable which is a part of the orange cable which is coming out of the central hole of the generator shaft. This orange cable has an outer diameter of 9.5 mm. There are also a red and a white cable coming from a thermometer. These cables are connected to two separate isolated threaded rods M4. From these points, a brown and a white cable are becoming part of the central orange cable. There is also a green-yellow earth cable becoming part of the central orange cable. So the central orange cable contains six wires. The central cable has a woven copper or iron cover and is clamped to the stator frame by an U-shaped bracket. On the outside of the orange cable it is mentioned that it is a hybrid cable with four wires of 1 mm^2 and two wires of 0.5 mm^2 (the brown and the white wire).

The 3-phase current has to be rectified by a 3-phase rectifier with six diodes for 48 V battery charging (see KD 340, ref. 6). Selection of the right rectifier is out of the scope of this report.

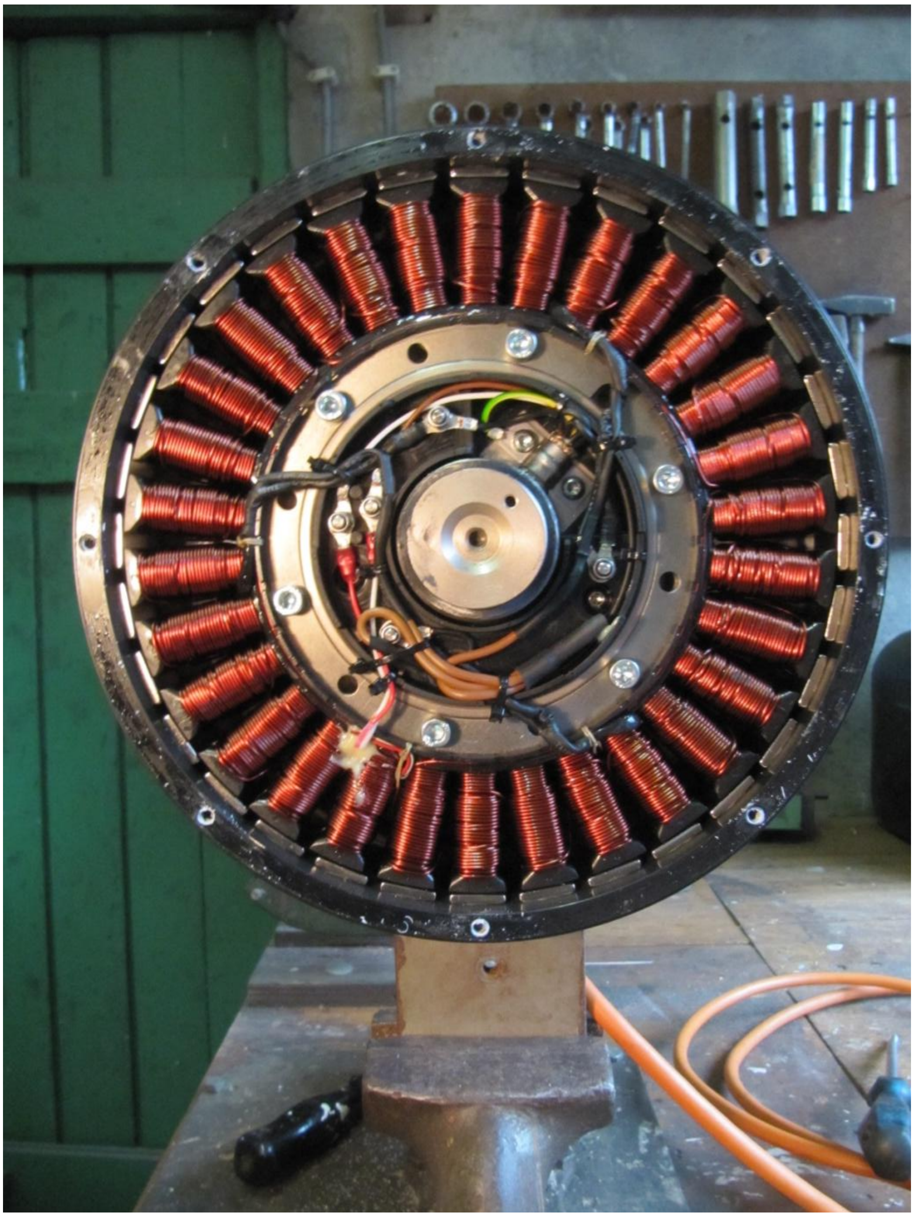


fig. 7 Photo of armature and stator

9 Measurements performed on the generator 260-25 LS

I have borrowed a generator type 260-25 LS for testing from Mr. H. Van Kaathoven from the company AGMAT B.V. from Beek en Donk. So this isn’t the type 260-25 HS which was selected for the VIRYA-3.6! The difference is probably only the winding. According to the manufacturers specification, the type 260-25 LS has a backEMF constant of 0.53 Vrms/rpm and the type 260-25 LS has a backEMF constant of 0.31 Vrms/rpm. But it is expected that the sticking torque at stand still position is the same.

The first thing which was done is measuring of the sticking torque at stand still position. To measure the sticking torque, the generator must be mounted such that the housing can rotate freely. A heavy steel strip was made with two 10.5 mm holes in it and the top part of this strip was mounted against the generator flange with two bolts M10 * 20. The bottom part was clamped in a vice. An aluminium strip was mounted against two of the six threaded holes M8 at the front side of the generator. This strip is symmetrical and so it gives no imbalance. A thin rope is connected to one end and weights are added at the end of the rope until the generator housing just starts rotating. The length of the arm is 0.24 m. The mass was 230 gram = 0.23 kg. This gives a weight of 9.81 * 0.23 = 2.256 N.

This gives a moment of 2.256 * 0.24 = 0.54 Nm. In chapter 4 it was calculated that the starting wind speed is only 2.2 m/s. So the starting behaviour of this generator in combination with the VIRYA-3.6 rotor will be very good.

The second thing which was done is measuring of the open AC voltage U_{AC} and the open DC voltage U_{DC} as a function of the rotational speed n. Therefore it is necessary to drive the generator. Some years ago I have built a small test rig to test a small axial flux generator of Hefei Top Grand. This test rig is described in report KD 595 (ref. 7). This test rig is certainly too small to test the generator type 250-25 LS for a battery load but it can be used to measure the unloaded voltage. The test rig contains a permanent magnet DC motor and a second shaft for which a small asynchronous motor is used. This motor isn't powered and only the shaft is used. Both shafts are connected to each other by a reducing chain transmission with a gear ratio of 47 / 13 = 2.615. A problem with this transmission is that both chain wheels have some non concentricity and this gives strong vibrations when the motor is running. The motor can be driven with a variable DC voltage. The second shaft has a hub with six 8.5 mm holes at a pitch circle of 65 mm. The generator has six threaded rods M8 at a pitch circle of 196 mm. To connect the generator to the flange of the second shaft, a hexagonal sheet was made from 2 mm galvanised steel sheet. First six long nuts M8 * 30 were screwed onto the six threaded rods. The hexagonal sheet was connected to the flange by six bolts M8 * 20 and six nuts M8.

The hexagonal sheet was connected to the generator by six bolts M8 * 12. It must be prevented that the generator flange is rotating when the generator housing is driven. So a 400 mm long aluminium strip is connected to the flange by two bolts M10 * 20. This strip is also made symmetrical to prevent imbalance. To measure the torque Q, an accurate Berkel balance is used which can measure a maximum of 5 kgf with five rotations of the pointer. This balance is placed on the ground. One end of the strip is connected to the balance by a rope. Some weights are put on the balance until the pointer shows 4550 gr. So if the generator rotates, the measured weight is reduced. The rotational speed is measured by a laser meter. The hub is made black with one white dot on it and the laser meter measures the number of dots which passes per minute. The length of the arm is 0.195 m. The test rig is shown in the photo of figure 8.

fig. 8 Photo of the test rig

The rotational speed of the driving motor is varied by a Variac and a strong rectifier. The whole construction is vibrating a lot if it is running and the rotational speed and the voltage are therefore varying too but it is tried to read the average values. First the open AC line voltage was measured. Next the open DC voltage was measured. The pulling force F in the rope was measured for both measurements. The measuring results are given in table 3 and table 4.

n (rpm)	U_{AC} (V)	F (gr)	U_{AC} / n	ΔF (gr)	ΔF (N)	Q (Nm)
113.4	58.9	4190	0.519	360	3.53	0.69
135.2	70.5	4165	0.521	385	3.78	0.74
174.5	90.1	4130	0.516	420	4.13	0.80
203.1	16.4	4100	0.524	450	4.4	0.86

table 3 Measured open AC voltage U_{AC} and pulling force F as a function of n

The measured value U_{AC} / n is about 0.52. This is a little lower than the specified value 0.53 for the motor type 260-26 LS.

n (rpm)	U_{AC} (V)	F (gr)	U_{DC} / n	ΔF (gr)	ΔF (N)	Q (Nm)
134.1	92.3	4175	0.688	375	3.68	0.72
173.3	121	4130	0.698	420	4.12	0.80
236.3	163	4080	0.693	470	4.61	0.90

table 4 Measured open DC voltage U_{DC} and pulling force F as a function of n

The measured value U_{DC} / n is about 0.693. According to formula 11, it should be $0.995 * \sqrt{2} * 0.52 = 0.73$. So the measured value of U_{DC} is a little lower than expected. Formula 11 is only valid if the AC voltage varies sinusoidal and this might not be the case. The voltage drop over the rectifier diodes is also not taken into account. However, this voltage drop is only small for the small current during measuring of the voltage and it has only a very small relative influence for the high AC voltage of 163 V at n = 236.3 rpm. The U-n curves derived from table 3 and 4 are given in figure 9.

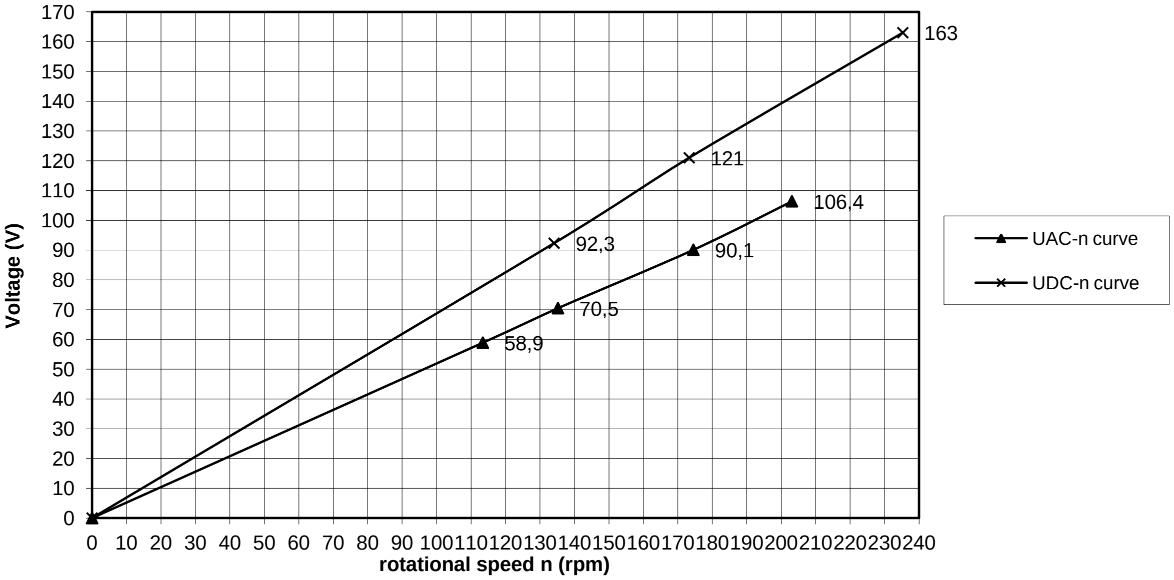


fig. 9 Measured open U_{AC}-n and U_{DC}-n curves for generator 260-25 LS

The open Q-n curve is given in figure 10. The measuring point for n = 0 rpm is also given.

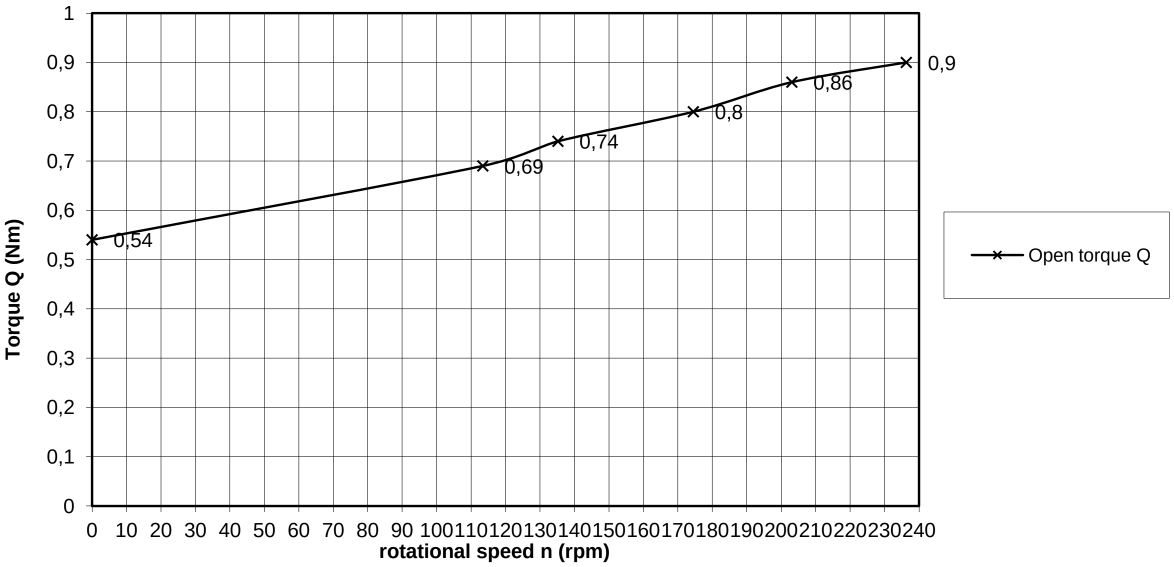


fig. 10 Measured open Q-n curve

In figure 10, the points for Q = 0.69 Nm, Q = 0.74 Nm, Q = 0.8 Nm and Q = 0.86 Nm are copied from table 3. The point for Q = 0.9 Nm is copied from table 4. It can be seen that all points are about lying on a straight line which is an indication that the winding is internally connected in star (see KD 78 figure 2). The torque of 0.54 Nm at stand still position is mainly caused by the friction of the bearings and the seal on the generator shaft. The increase of the torque for higher rotational speeds is caused by the magnetic losses in the stator iron.

The third thing which was done is that the three wires coming out of the generator are connected to each other which means that short-circuit in star was made. However, the torque increases very strongly for short-circuit and the driving motor wasn’t strong enough to realise even a very low rotational speed. So this demonstrates that the test rig is much too light to measure this generator for short-circuit. However, verification of the Q-n curve for short-circuit in star is important as it gives also insight in the Q-n curve for 52 V_{DC}.

The fourth thing which was done is that one point on the Q-n curve for short-circuit in star was measured in a totally different way. So the three wires coming out of the generator are connected to each other. The steel strip which was used to measure the sticking torque for stand still position was mounted again. Next the generator was mounted above the entrance door of my shed. A thin rope was wound around the generator housing and a heavy weight was mounted at the end of the rope. Only one of the six nuts M8 was mounted at the front side of the generator. A pointer was mounted close to radius of this nut. The weight was formed by a 10 litre jerry can which was filled with that much water that the total weight was 10194 grf = 10.194 kgf. This gives a pulling force in the rope of 9.81 * 10.194 = 100 N. The generator housing has a diameter of 260 mm at the stator stamping and so the radius at which the rope is pulling is 0.13 m. So the torque Q = 100 * 0.13 = 13 Nm.

Next the rope is wound around the housing and the weight is lifted that far that the pointer is just at the nut M8. Next the weight is let loose and it is measured how long it takes for one revolution of the generator housing. This takes about 10 s. So this means that the rotational speed is 6 rpm for a torque of 13 Nm. A photo of the test rig is given in figure 11.

fig. 11 Photo of the test rig for measuring of short-circuit in star

10 Estimation of the Q-n curves for short-circuit and for 52 V star

Next a certain slope of the Q-n curve for short-circuit and for 52 V_{DC} star has to be estimated. Hereby it is assumed that both curves are identical but that the Q-n curve for 52 V_{DC} star is shifted to the right over a certain distance with respect to the Q-n curve for short-circuit. The distance is derived from the measurements. It was found that the ratio U_{DC} / U_{AC} = 0.693 / 0.52 = 1.333. This is a little smaller than the factor 0.995 * √2 as given by formula 11. The reason might be that the voltage drop over the rectifier diodes isn't taken into account. So the back EMF constant for a DC voltage is 1.333 * 0.31 = 0.413 V_{DC} / rpm. This means that the rotational speed for an open voltage of 52 V_{DC} = 52 / 0.413 = 126 rpm.

In figure 10 it can be seen that the unloaded torque increases from 0.54 Nm at n = 0 rpm up to about 0.71 Nm at n = 126 rpm. For simplification of the Q-n curves, it is assumed that both curves start at a torque of 0.6 Nm.

It was measured for short-circuit that the torque is 13 Nm for a rotational speed of about 6 rpm. Next it is assumed that the Q-n curve for short-circuit is a straight line from Q = 0.6 Nm at n = 0 rpm up to Q = 50 Nm and that this line intersects with the point Q = 13 Nm and n = 6 rpm. It can be calculated that Q = 50 Nm corresponds to n = 23.9 rpm.

For higher rotational speeds than 28.7 rpm, the Q-n curve is no longer a straight line. It is assumed that the Q-n curve for short-circuit has a maximum of Q = 75 Nm for n = 70 rpm. The Q-n curves for short-circuit in star and delta are given in figure 4 of KD 78 (ref. 5) for the PM-generator which is used for the VIRYA-3 windmill. The Q-n curve for short-circuit in star for the VIRYA-3.6 generator is estimated such that the shape is about the same as for the measured Q-n curve for short-circuit in star of the VIRYA-3 generator. The estimated curve is given in figure 12. The Q-n curve for 52 V_{DC} star is found by shifting the short-circuit curve over 126 rpm to the right. This curve is also given in figure 12.

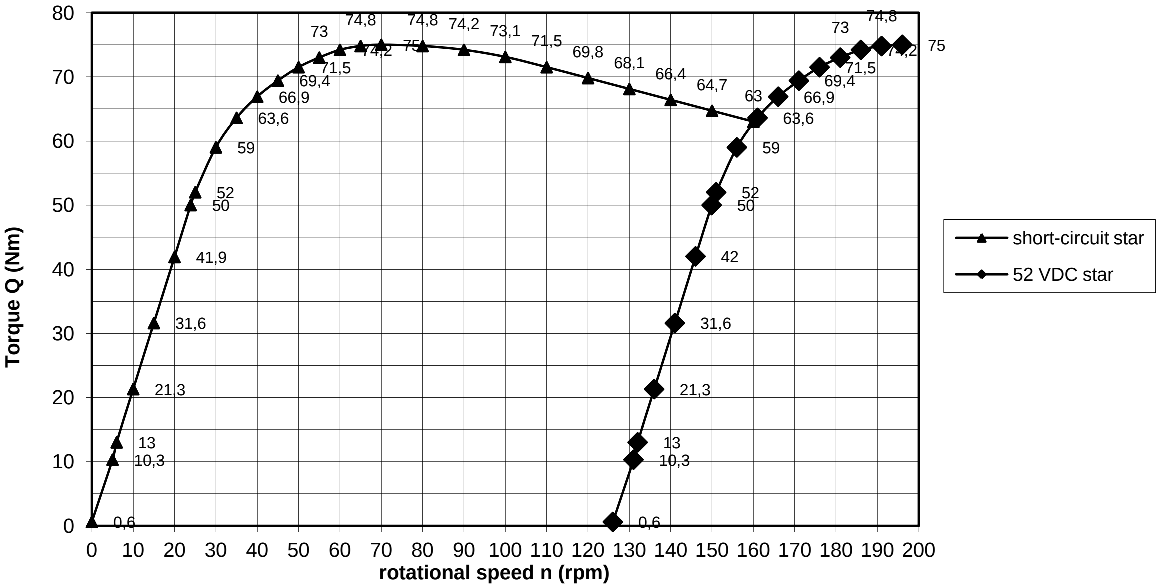


fig. 12 Estimated Q-n curve for short-circuit in star and for 52 V_{DC} star

To derive the P-n curves, some extra points on the Q-n curve have to be chosen. It is chosen for points every 5 rpm. The estimated Q-n curve for short-circuit in star is extended up to n = 160 rpm. This is done in steps of 10 rpm. These points are also given in figure 12 and in table 5.

Short-circuit in star			52 V_{DC} star				
n (rpm)	Q (Nm)	P (W)	n (rpm)	Q (Nm)	P_{mech} (W)	η (-)	P_{el} (W)
0	0.6	0	126	0.6	7.9	0	0
5	10.3	5.4	131	10.3	141.3	0.79	111.6
6	13	8.2	132	13	179.7	0.81	145.6
10	21.3	22.3	136	21.3	303.4	0.85	257.9
15	31.6	49.6	141	31.6	466.6	0.83	387.3
20	41.9	87.8	146	41.9	640.6	0.8	512.5
23.9	50	125.1	149.9	50	784.9	0.785	616.1
25	52	136.1	151	52	822.3	0.78	641.4
30	59	185.4	156	59	963.8	0.76	732.5
35	63.6	233.1	161	63.6	1072.3	0.74	793.5
40	66.9	280.2	166	66.9	1163.0	0.72	837.4
45	69.4	327.0	171	69.4	1242.8	0.703	873.7
50	71.5	374.4	176	71.5	1317.8	0.692	911.9
55	73	420.4	181	73	1383.7	0.68	940.9
60	74.2	466.2	186	74.2	1445.3	0.67	968.4
65	74.8	509.1	191	74.8	1496.1	0.66	987.4
70	75	549.8	196	75	1539.4	0.65	1000.6
80	74.8	626.6					
90	74.2	699.3					
100	73.1	765.5					
110	71.5	823.6					
120	69.8	877.1					
130	68.1	927.1					
140	66.4	973.5					
150	64.7	1016.3					
160	63	1055.6					

table 5 Estimated torque Q for short-circuit in star for 52 V_{DC} in star, estimated η, calculated P for short-circuit, P_{mech} and P_{el} for 52 V_{DC} star

Formula 10 can be written as:

$$P = Q * n * \pi / 30 \quad \text{(W)} \qquad (17)$$

Formula 17 is used to calculate P and P_{mech}. The result is also given in table 5. Figure 5 is now copied as figure 13.

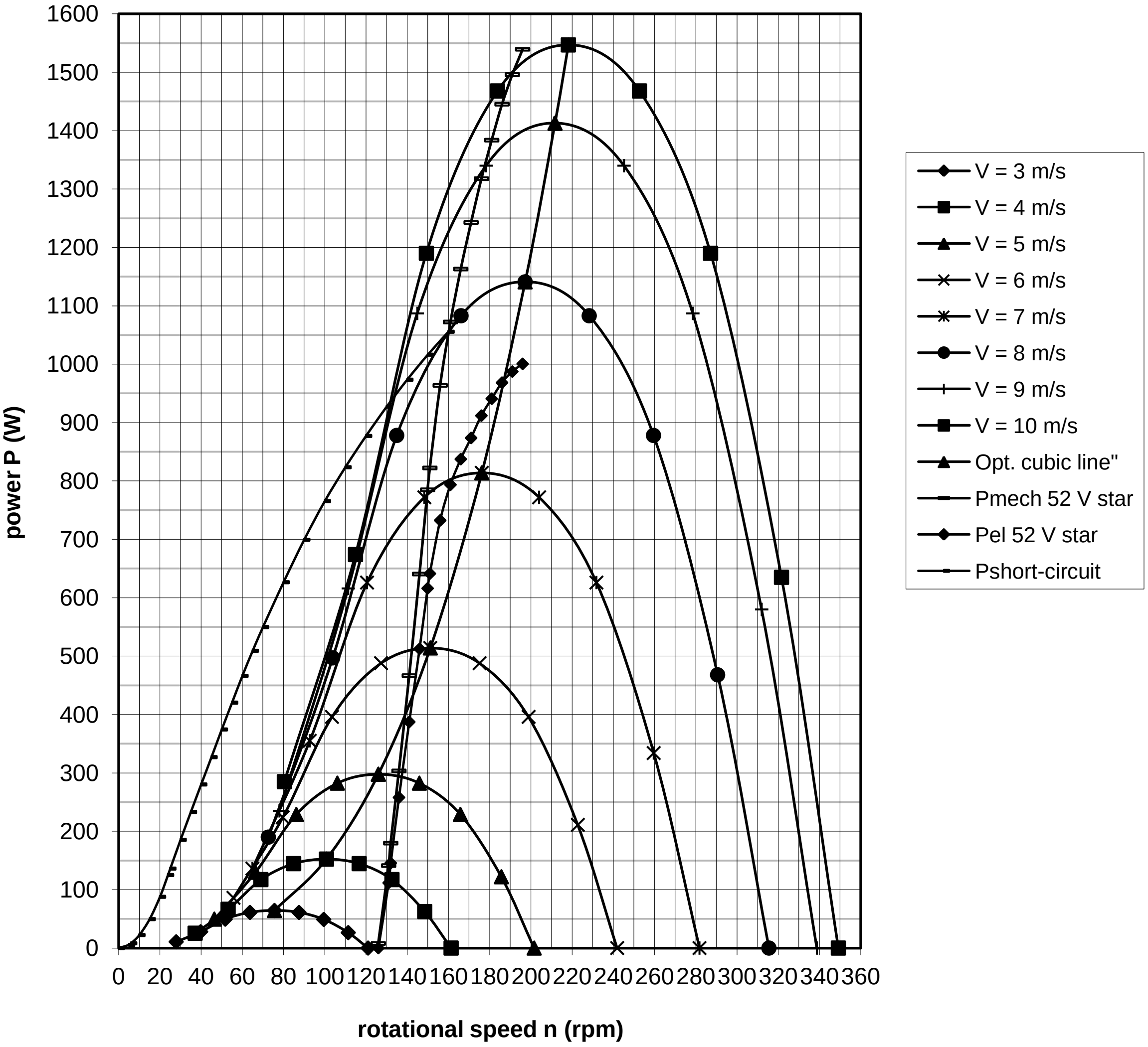


fig. 13 P-n curves of the VIRYA-3.6 rotor and the optimum cubic line, estimated P-n curve for short-circuit in star, estimated P_{mech}-n and P_{el}-n curves for 52 V_{DC} star

The P-n curve for short-circuit in star is derived from table 5 and is given in figure 13. The P-n curve for short-circuit in star is touching the P-n curve of the rotor for V = 8 m/s. So the rotor can only be slowed down by making short-circuit if the wind speed is lower than 8 m/s. It is expected that the rotor won't start at wind speeds above 10 m/s, once it has slowed down. At short-circuit, the rotor will rotate only very slowly. During short-circuit, all power is dissipated in the winding and so one should not make short-circuit if there is no immediate slowing down up to almost stand still! The short-circuit switch must be mounted at the tower foot in the 3-phase cables to prevent a large voltage drop over the cables to the batteries.

The P_{mech}-n curve for $52V_{DC}$ star is also given in figure 13. It can be seen that the P_{mech}-n curve of the generator is intersecting with the optimum cubic line at a wind speed of about 5.5 m/s. The matching is good for wind speeds above 4 m/s because the P_{mech}-n curve of the generator is lying close to the optimum cubic line but for wind speeds above 7 m/s, the tip speed ratio is about 4. The advantage of a low tip speed ratio at high wind speeds is that the noise production will be very low.

At high powers, the real charging voltage will be higher than 52 V and this makes that the P_{mech}-n curve shifts somewhat to the right resulting in a higher rotational speed and so also in a higher tip speed ratio and a higher C_p. So I think that the matching is good at high wind speeds when a real 48 V battery is used. But to be sure, the chosen generator has to be tested for a real 48 V battery and for short-circuit in star.

For the P_{el}-n curve, it is necessary to estimate a η-n curve. The efficiency η is taken as a factor of 1, so not as a percentage. The estimated efficiencies are also given in table 3. It is estimated that η = 0.85 for n = 136 rpm and that η = 0.65 for n = 196 rpm and that the right part of the curve is hollow. The estimated η-n curve is given in figure 14. The P_{el}-n curve derived from table 5 is also given in figure 13. At high powers, the charging voltage will be higher than 52 V which results in a somewhat higher C_p and a somewhat higher generator efficiency. This gives a somewhat higher electrical power than for 52 V. The P_{el}-V curve is corrected for this effect at high wind speeds.

The working point for a certain wind speed is the point of intersection of the P_{mech}-n curve of the generator with the P-n curve of the rotor for that wind speed. The electrical power for a certain wind speed is found if a vertical line is drawn downwards from the working point until the P_{el}-n curve is crossed. The P_{el}-V curve found this way is given in figure 15.

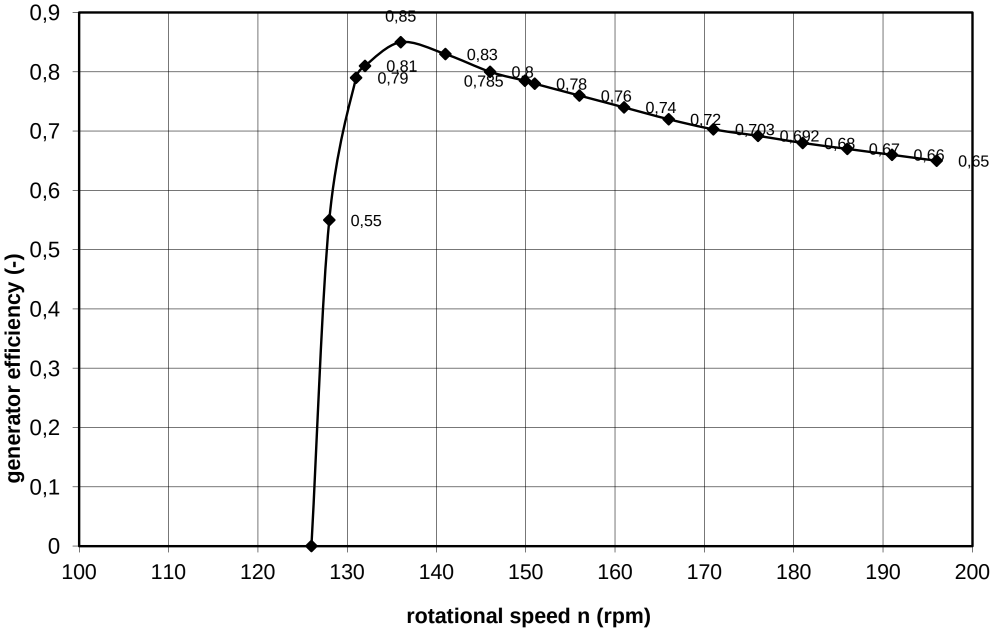


fig. 14 Estimated η-n curve

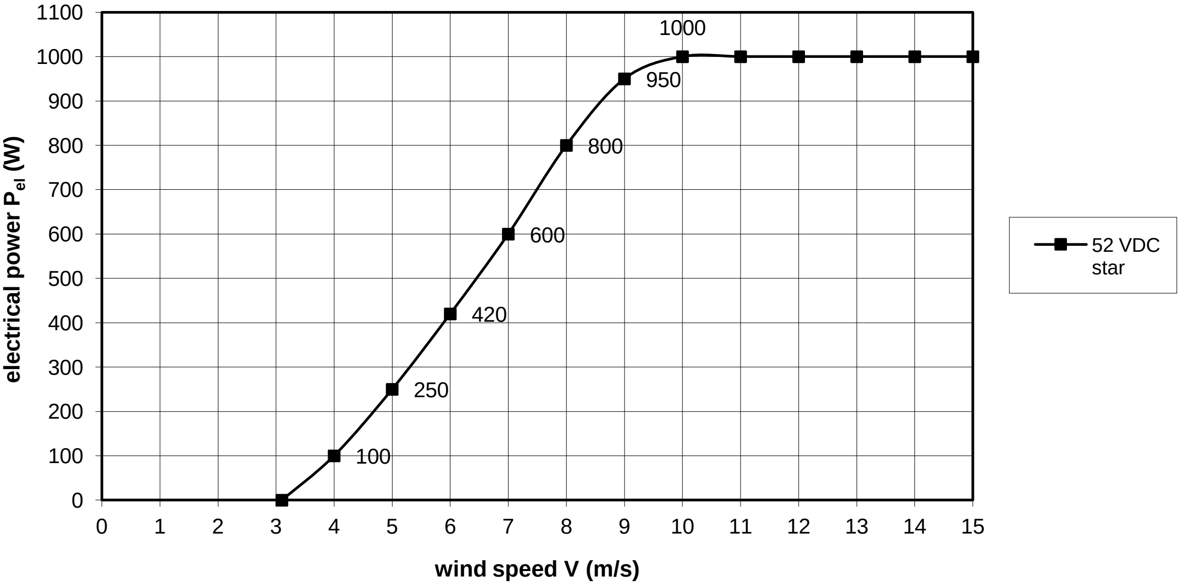


fig. 15 Estimated P_{el}-V curve for 52 V_{DC} star

In figure 15 it can be seen that the maximum power is about 1000 W at a wind speed of 10 m/s and higher. This is good for a wind turbine with a rotor diameter of 3.6 m and a rated wind speed of 10 m/s. If the charging voltage at a maximum power is 55.2 V_{DC}, it means that the current I is 1000 / 55.2 = 18.1 A. This is too high for the three 1 mm^2 black wires in the central orange cable. So it is advised to change the central orange cable by a 3-phase mains cable with three flexible wires of 2.5 mm^2 and a length of 10 m. Such a cable has an outside diameter of about 10 mm and I expect that the central hole in the shaft is large enough for such a cable.

The cut-in wind speed is about 3.1 m/s which means that the VIRYA-3.6 can be used in regions with low wind speeds. In chapter 4 it was calculated that the starting wind speed is only 2.2 m/s which means that there is no hysteresis in the P_{el}-V curve.

The mechanical power at V = 10 m/s is about 1520 W. The generated electrical power is about 1000 W and so the dissipated heat is about 520 W. For motor use, the nominal power is 4021 W at n = 1200 rpm. If the efficiency is 0.85, the required electrical power is 4731 W. So the dissipated heat is 710 W which is more than the dissipated heat as generator use.

The generator shaft has a diameter of about 56 mm in between the connecting flange and the housing. This flange is provided with four threaded holes M10 at a pitch circle of 83 mm. It has a collar at the back side with a diameter of 58 mm. So there must be a 58 mm hole in the generator bracket. I don’t know what shaft diameter is used at the bearings at the flange side but it might be 50 mm. Magnetic Innovations has confirmed that two bearings are used at the flange side. But I don’t know the size of the bearings and the seal at the generator shaft. So it can be expected that the chosen generator is mechanically strong enough for the VIRYA-3.6 even if the shaft is hollow. The shaft is hollow because the cable is guided through the central hole.

The short-circuit switch must be placed as close as possible to the generator. The best place is at a box which is positioned at the tower foot. This box also contains the 3-phase rectifier. Short-circuit is made in between the three phase cables. So a 2-phase cable connects the rectifier to the batteries. This 2-phase cable must have two wires of at least 2.5 mm^2.

The head pin has a central hole with a diameter of 17 mm which is large enough for a much heavier cable. The height of the VIRYA-3.5 tower is about 8.5 m. The generator should therefore be ordered with cable with a length of 10 m for this tower height. The cable should enter the box at the bottom which creates a loop. Because of this loop, it is easy to see if the cable has twisted too much in case the head has rotated many times in the same direction. If this has happened, the cable has to be disconnected from the box and twisted back.

11 Use of the VIRYA-3.6 for water pumping

It might be possible to use the VIRYA-3.6 for water pumping and in The Netherlands the most obvious use is drainage of low flat lands. As the generator has 30 armature poles, a frequency of 50 Hz is already reached at a rotational speed of 200 rpm. However, the backEMF for the original winding is 0.31 VAC/rpm. This means that the open AC voltage in between two of the phases is 0.31 * 200 = 62 V_{AC} at f = 50 Hz. So the loaded AC voltage will even be lower. The 3-phase motor of a centrifugal pump connected in star requires a loaded voltage in between the phases of about 400 V. This means that the generated voltage is much too low to connect the generator directly to the 3-phase asynchronous motor of a centrifugal pump. The only way this might work is if the pump motor is provided with a special low voltage winding. Another problem of this option is that in figure 7 it can be seen that a rotational speed of 200 rpm requires a wind speed of about 8 m/s if the optimum cubic line is followed. So at lower wind speeds, the frequency is lower than 50 Hz and this strongly reduces the static head H which can be used for pumping if the pump motor and the pump are meant for 50 Hz.

Another option is to use a pump with a permanent magnet DC motor. In this case one can chose for a system with or without a battery. With a battery, a nominal battery voltage of 48 V is most convenient as this is the battery voltage for the standard winding. I don’t know if permanent magnet DC motors with the right voltage range are on the market. It might be required to use a voltage controller with dump load to limit the maximum voltage at high wind speeds. I prefer the option for which the pump motor is connected direct drive to the centrifugal pump.

Drainage of flat low lands is often done with a Bosman windmill in The Netherlands. This windmill has a 4-bladed rotor with a diameter of 3 m and an accelerating gear box in top of the tower with a gear ratio of about 4. The centrifugal pump is driven direct drive by the vertical shaft in the tower. This windmill has a double vane steered by the water level and the windmill turns out of the wind if the water level is low enough. But this system isn’t working as safety system and the rotor must therefore be very strong. The spars of the blades are mounted at the back side of the blades which results in stalling and the maximum C_p of the rotor is therefore rather low. The centrifugal pump is very simple and is made of four curved strips turning in a concrete housing. The pump efficiency is therefore rather low too.

The VIRYA-3.6 has a swept rotor area which is a factor 1.44 larger than that of the Bosman windmill. The maximum C_p of the rotor is much higher because freely supported blades are used. The used centrifugal pump will have a correct fan and will therefore have a higher efficiency. The total efficiency of the generator and the pump motor will be lower than the efficiency of the rectangular gear box of the Bosman windmill. However, all effects together will make that the output of the VIRYA-3.6 will be substantial higher than that of the Bosman windmill.

The VIRYA-3.6 can be stopped by making short circuit in the winding of the generator. So if the short-circuit switch is steered by a float, the VIRYA-3.6 can also be stopped if the water level is low enough. But the short-circuit switch can also be used to stop the windmill rotor for other reasons than a low water level.

Up to now, only drainage has been taken into account. But the VIRYA-3.6 can be coupled to any pump if this pump is provided with a permanent magnet DC motor of the right voltage range. So the VIRYA-3.6 can also be used for irrigation or for pumping drinking water if the head is much higher than a head of about 1 m which is common for drainage.

If a 48 V battery is used, the VIRYA-3.6 can be used for water pumping but simultaneously it can also be used for other equipment which is working on 48 V_{DC}. One can even use an inverter and transform the battery voltage into AC current with 230 V_{AC} and a frequency f = 50 Hz. In this case one can also use a standard pump with an asynchronous motor. So the use of the VIRYA-3.6 is very versatile. The Bosman windmill can only be used for drainage.

At this moment I can’t say how high the production cost of the VIRYA-3.6 will be if it is serial manufactured. This can only be calculated if all detailed drawings are ready. But before serial production is started, first one prototype has to be built and tested thoroughly at a site with high wind speeds.

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