

Calculations executed for the 3-bladed rotor of the VIRYA-4.1S windmill ($\lambda_d = 4.5$, stainless steel blades) driving the PM-generator of Magnetic Innovations type 260-75 LS for water pumping or grid connection or the type 260-75 HS for 48 V battery charging

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April 2026

KD 797

It is allowed to copy this report for private use. As manufacture of the blades requires an expensive blade press, making of the VIRYA-4.1S rotor is only advised for serial manufacture by a professional company. The generator characteristics as given in chapter 7 and 8 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

Already in 2006 I have designed a 3-bladed wind turbine with a rotor diameter of 4.1 m, a design tip speed ratio $\lambda_d = 5.25$ and 7.14 % cambered steel blades. This VIRYA-4.1 wind turbine has been built by AID Foundation in the Philippines and functioned well. The rotor calculations are given in report KD 303 (ref. 1). A blade is made out of a galvanised or stainless steel sheet size 3 * 200 * 1500 mm and fifteen blades for five rotors can be made out of a standard sheet size 1.5 * 3 m. The PM-generator is made from an asynchronous motor by changing the short-circuit armature by a permanent magnet armature. This procedure is described in chapter 4 of report KD 341 (ref. 2).

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 largest type: 260-75 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 4.1 m and a design tip speed ratio $\lambda_d = 4.5$. The design tip speed ratio is chosen lower than as chosen for the AID version to reduce noise. It is expected that the generator type 260-75 LS can be used for water pumping or grid connection and that the type 260-75 HS can be used for 48 V battery charging. The wind turbine is called the VIRYA-4.1S. An S from steel is added to distinguish it from the VIRYA-4.1 as used for AID Foundation. The generator is described in chapter 6.

As the VIRYA-4.1S has a lower design tip speed ratio than the VIRYA-4.1, the blades must have a larger chord c . A blade is made out of a stainless steel sheet size 3 * 250 * 1500 mm and twelve blades for four rotors can be made out of a standard sheet size 1.5 * 3 m. The VIRYA-4.1S blades can be cambered with a blade press which is derived from the blade press of the VIRYA-4.1 but it must be modified for a sheet width of 250 mm. The VIRYA-4.1S will use the same tower and head as used for the VIRYA-4.2. However, a special bracket has to be designed to connect the generator to the original generator bracket of the VIRYA-4.2 generator. The VIRYA-4.2 has a 2-bladed rotor with wooden blades. It might be difficult to get the needed quality of wood and machining of wood might be not common for an average workshop. Wooden blades can also be damaged easily during transport. Therefore it is investigated if an alternative rotor with stainless steel blades can be used. The VIRYA-4.1S has a somewhat smaller rotor diameter than the original VIRYA-4.2 but it is assumed that the head geometry of the VIRYA-4.2 can be maintained. The effect of the slightly smaller rotor diameter of the VIRYA-4.1S on the rotor thrust is compensated because rotors with cambered steel blades have a slightly larger thrust coefficient (about 0.75 instead of 0.7).

So the head and the tower are the same as the head and tower of the VIRYA-4.2. 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. 3). This safety system results in a rated wind speed of about 10 m/s.

The mass of the whole rotor is about 45 kg which seems reasonable for a steel rotor with a diameter of 4.1 m. The mass of the generator is 30 kg and so the total mass of rotor and generator is about 75 kg. A rather expensive blade press is needed for manufacture of the blades and the VIRYA-4.1S is therefore only suitable for serial manufacture by a professional company. The existing drawings of the head and the tower of the VIRYA-4.2 and the drawing of the blade press are available at certain conditions. May be I will also make detailed drawings of the rotor and the generator bracket if a serious company has interest in the VIRYA-4.1S.

2 Description of the rotor of the VIRYA-4.1S windmill

The 3-bladed rotor of the VIRYA-4.1S windmill has a diameter $D = 4.1$ m and a design tip speed ratio $\lambda_d = 4.5$. 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 $3 * 250 * 1500$ mm. The sheet is 7.14 % cambered. Information about cambered sheet airfoils is given in report KD 398 (ref. 4). The camber radius r_c can be derived from chapter 5.1 of KD 398 and it is found that $r_c = 440$ mm for $b = 250$ mm. The chord c is somewhat smaller than the width of the sheet and it is found that $c = 246.6$ mm = 0.2466 m. The whole blade length is cambered and no blade twist is used. This means that the blade has a constant chord and a constant blade angle.

The three blades are connected to each other by a spoke assembly. Every spoke is made out of a stainless steel strip size $8 * 120 * 850$ mm. Seven spokes can be made from a standard strip of 6 m. 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 435 mm. A blade is connected to a spoke by six bolts M10 * 40 and six self locking nuts M10. The spokes are twisted 8.8° 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.

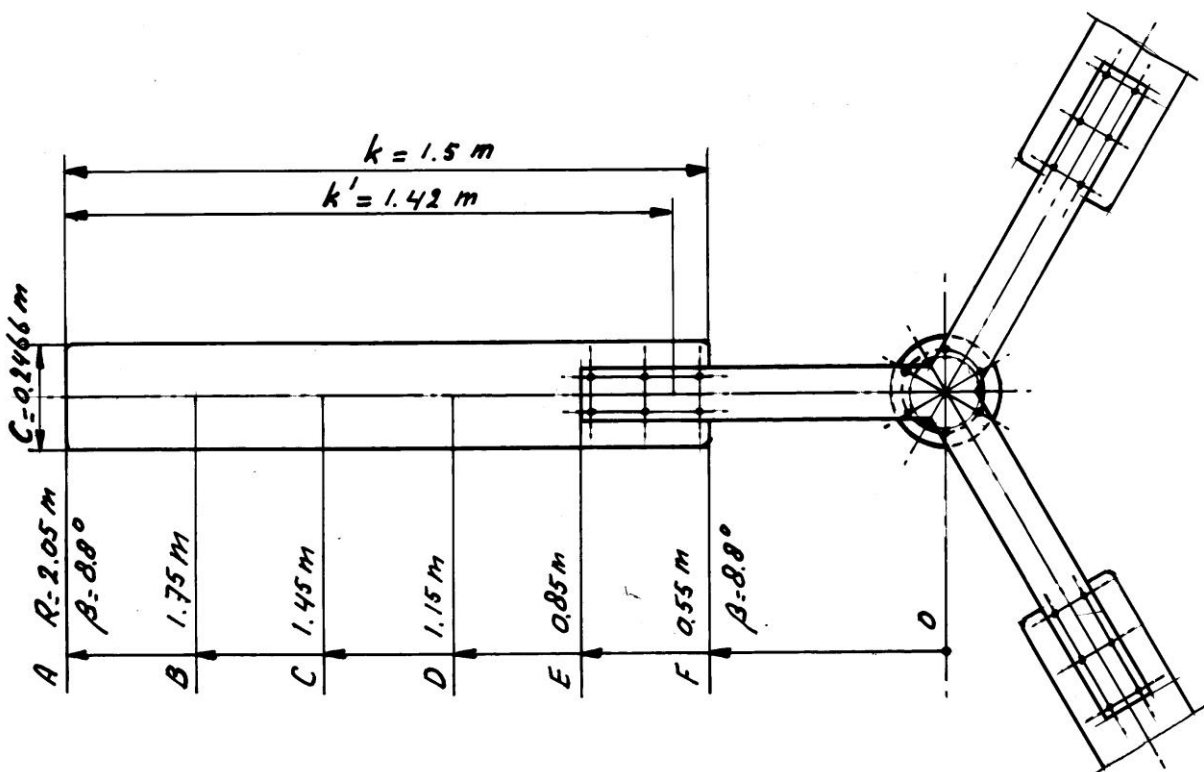


fig. 1 Front view of the VIRYA-4.1S rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 5). This report (KD 797) has its own formula numbering. Substitution of $\lambda_d = 4.5$ and $R = 2.05$ m in formula (5.1) of KD 35 gives:

$$\lambda_{rd} = 2.1951 * r \quad (-) \quad (1)$$

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

$$\beta = \phi - \alpha \quad (^\circ) \quad (2)$$

$$\phi = 2/3 \arctan 1 / \lambda_{rd} \quad (^\circ) \quad (3)$$

Substitution of $B = 3$ and $c = 0.2466$ m in formula (5.4) of KD 35 gives:

$$C_l = 33.972 * r (1 - \cos\phi) \quad (-) \quad (4)$$

Substitution of $V = 5$ m/s and $c = 0.2466$ m in formula (5.5) of KD 35 gives:

$$R_{er} = 0.822 * 10^5 * \sqrt{(\lambda_{rd}^2 + 4/9)} \quad (-) \quad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.3 m of one to another. 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. 4). 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.

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	2.05	4.5	8.4	0.2466	0.74	0.71	3.74	3.4	-0.2	-0.4	8.6	8.8	0.041
B	1.75	3.841	9.7	0.2466	0.85	0.86	3.20	3.4	0.7	0.9	9.0	8.8	0.035
C	1.45	3.183	11.6	0.2466	1.01	1.00	2.67	2.5	2.9	2.8	8.7	8.8	0.036
D	1.15	2.524	14.4	0.2466	1.23	1.27	2.15	2.5	5.2	5.6	9.2	8.8	0.051
E	0.85	1.866	18.8	0.2466	1.54	1.44	1.63	1.7	-	10.0	-	8.8	0.115
F	0.55	1.207	26.4	0.2466	1.95	1.27	1.13	1.2	-	17.6	-	8.8	0.29

table 1 Calculation of the blade geometry of the VIRYA-4.1S 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 8.6° and 9.2° for station A up to D. If a value $\beta_{lin} = 8.8^\circ$ 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 $\lambda_{opt} = 4.5$ 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 at station F and the airfoil is disturbed by the spoke, the bolt heads and the nuts. 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 0.08 m outside station F. This gives an effective blade length $k' = 1.42$ m.

Substitution of $C_{p\ th} = 0.43$, $R = 2.05$ m and effective blade length $k' = 1.42$ m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.39$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.39 / 4.5 = 0.0867$.

Substitution of $\lambda_{opt} = \lambda_d = 4.5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 7.2$.

The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

The blade angle is 8.8° for the whole blade. For a non rotating rotor, the angle of attack α is therefore $90^\circ - 8.8^\circ = 81.2^\circ$. 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 $C_l = 0.29$ for $\alpha = 81.2^\circ$. The whole blade is stalling during starting and therefore now the whole blade length $k = 1.5$ m is taken.

Substitution of $B = 3$, $R = 2.05$ m, $k = 1.5$ m, $C_l = 0.29$ and $c = 0.2466$ m in formula 6 gives that $C_{q\ start} = 0.0116$. For the ratio between the starting torque and the optimum torque we find that it is $0.0116 / 0.0867 = 0.134$. This is acceptable for a rotor with $\lambda_d = 4.5$. The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

The VIRYA-4.2 generator has a sticking torque of only 0.9 Nm but this generator has no torque fluctuation because the magnet grooves make the correct angle with the generator shaft. The sticking torque is then only caused by the friction of the bearings and the spring loaded oil seal on the shaft. The VIRYA-4.1S generator has 32 armature poles and 30 stator poles. This makes than only two armature poles are exactly opposite to a stator pole. If this situation causes a preference position, it can be calculated that the generator has 460 very small preference positions per revolution. It has been measured for a generator type 260-25 LS that the peak on the cogging torque is only 0.54 Nm. Most of this torque is caused by the friction of the bearings and the seal at the shaft which is the same for both generators. Assume that for the type 260-75 LS it has about the double value and so $Q_s = 1.1$ Nm. Substitution of $Q_s = 1.1$ Nm, $C_{q\ start} = 0.0116$, $\rho = 1.2$ kg/m³ and $R = 2.05$ m in formula 7 gives that $V_{start} = 2.4$ m/s. This is very low for a 3-bladed rotor with a design tip speed ratio of 4.5. The generator is used in star and the Q-n curve of the rotor for $V = 2.4$ 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. 6). 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-4.1S rotor are given in figure 2 and 3.

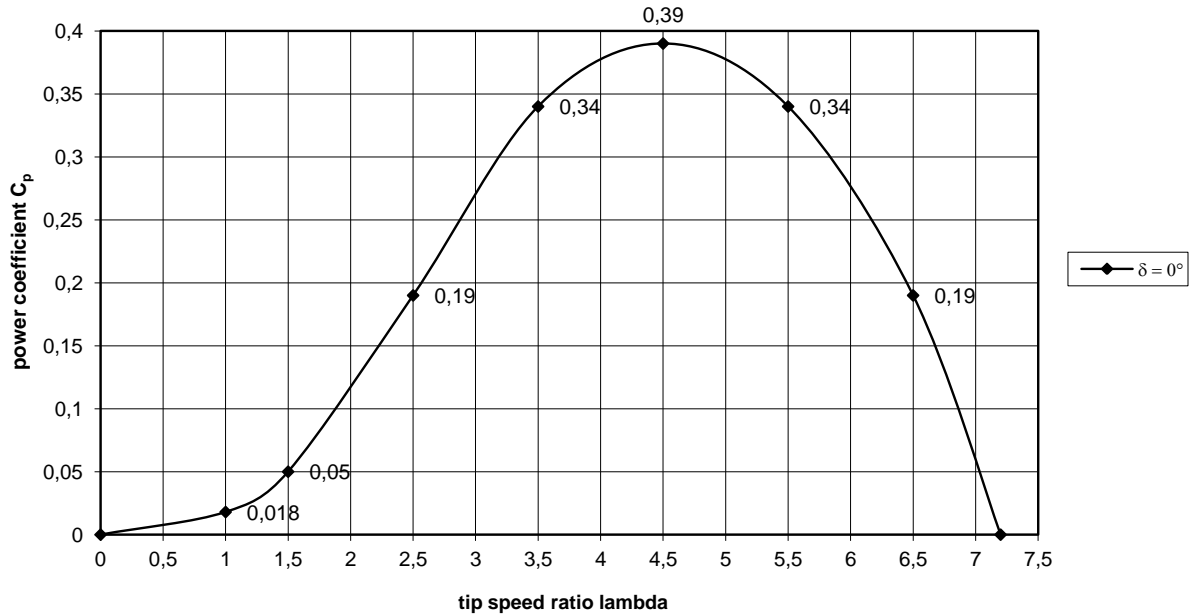


fig. 2 Estimated C_p - λ curve for the VIRYA-4.1S rotor for the wind direction perpendicular to the rotor ($\delta = 0$)

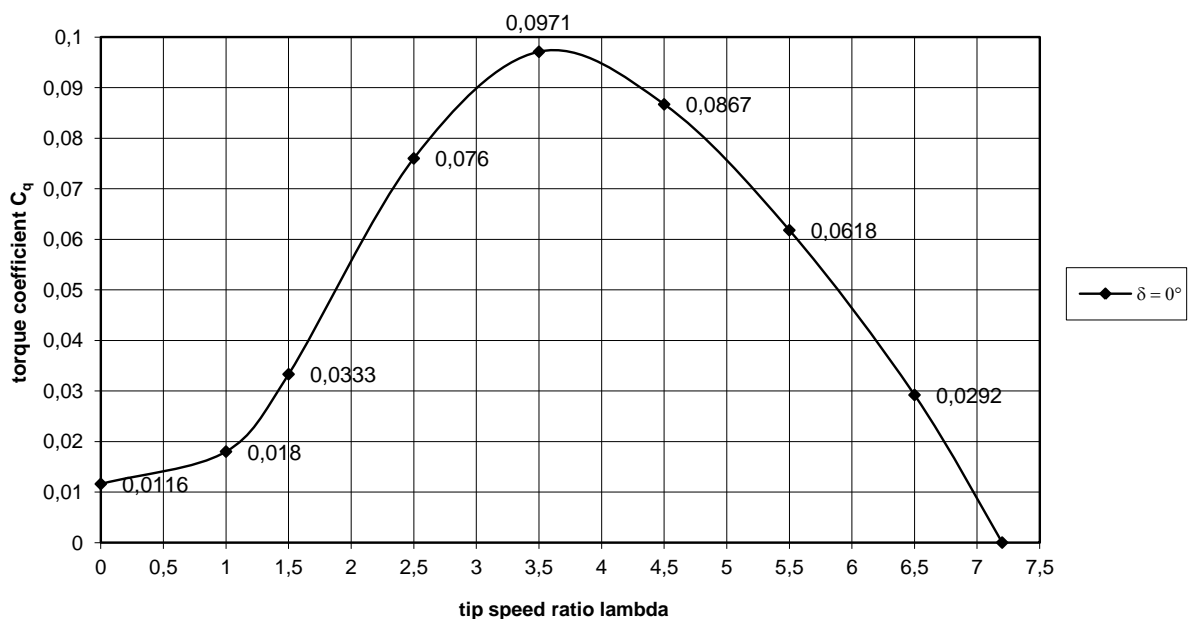


fig. 3 Estimated C_q - λ curve for the VIRYA-4.1S rotor for the wind direction perpendicular to the rotor ($\delta = 0^\circ$)

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 is made of 9 mm meranti waterproof plywood with a density of about $0.6 \cdot 10^3 \text{ kg/m}^3$. This vane blade gives a rated wind speed V_{rated} of 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.

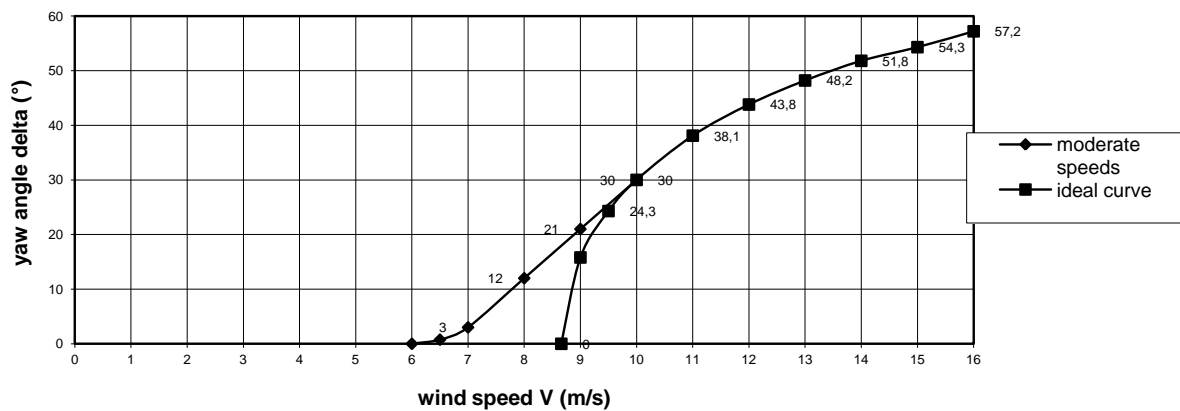


fig. 4 Estimated δ -V curve for a 9 mm plywood vane blade

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 $R = 2.05 \text{ m}$ in formula 7.1 of KD 35 gives:

$$n_{\delta} = 4.6582 * \lambda * \cos \delta * V \quad (\text{rpm}) \quad (8)$$

Substitution of $\rho = 1.2 \text{ kg / m}^3$ and $R = 2.05 \text{ m}$ in formula 7.10 of KD 35 gives:

$$P_{\delta} = 7.9215 * C_p * \cos^3 \delta * V^3 \quad (\text{W}) \quad (9)$$

The P-n curves are determined for C_p values belonging to λ is 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, and 7.2 (see figure 2). For a certain wind speed, for instance $V = 3 \text{ m/s}$, 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.

λ (-)	C_p (-)	V = 3 m/s $\delta = 0^\circ$		V = 4 m/s $\delta = 0^\circ$		V = 5 m/s $\delta = 0^\circ$		V = 6 m/s $\delta = 0^\circ$		V = 7 m/s $\delta = 3^\circ$		V = 8 m/s $\delta = 12^\circ$		V = 9 m/s $\delta = 21^\circ$		V = 10 m/s $\delta = 30^\circ$	
		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)
1.5	0.05	21.0	10.7	27.9	25.3	34.9	49.5	41.9	85.6	48.8	135	54.7	190	58.7	235	60.5	257
2.5	0.19	34.9	40.6	46.6	96.3	58.2	188.1	69.9	325.1	81.4	514	91.1	721	97.8	893	100.9	978
3.5	0.34	48.9	72.7	65.2	172.4	81.5	336.7	97.8	581.8	114.0	920	127.6	1291	137.0	1598	141.2	1749
4.5	0.39	62.9	83.4	83.8	197.7	104.8	386.2	125.8	667.3	146.5	1055	164.0	1480	176.1	1833	181.5	2007
5.5	0.34	76.9	72.7	102.5	172.4	128.1	336.7	153.7	581.8	179.1	920	200.5	1291	215.3	1598	221.9	1749
6.5	0.19	90.8	40.6	121.1	96.3	151.4	188.1	181.7	325.1	211.7	514	236.9	721	254.4	893	262.2	978
7.2	0	100.6	0	134.2	0	167.7	0	210.2	0	234.5	0	262.4	0	281.8	0	290.5	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-4.1S 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.

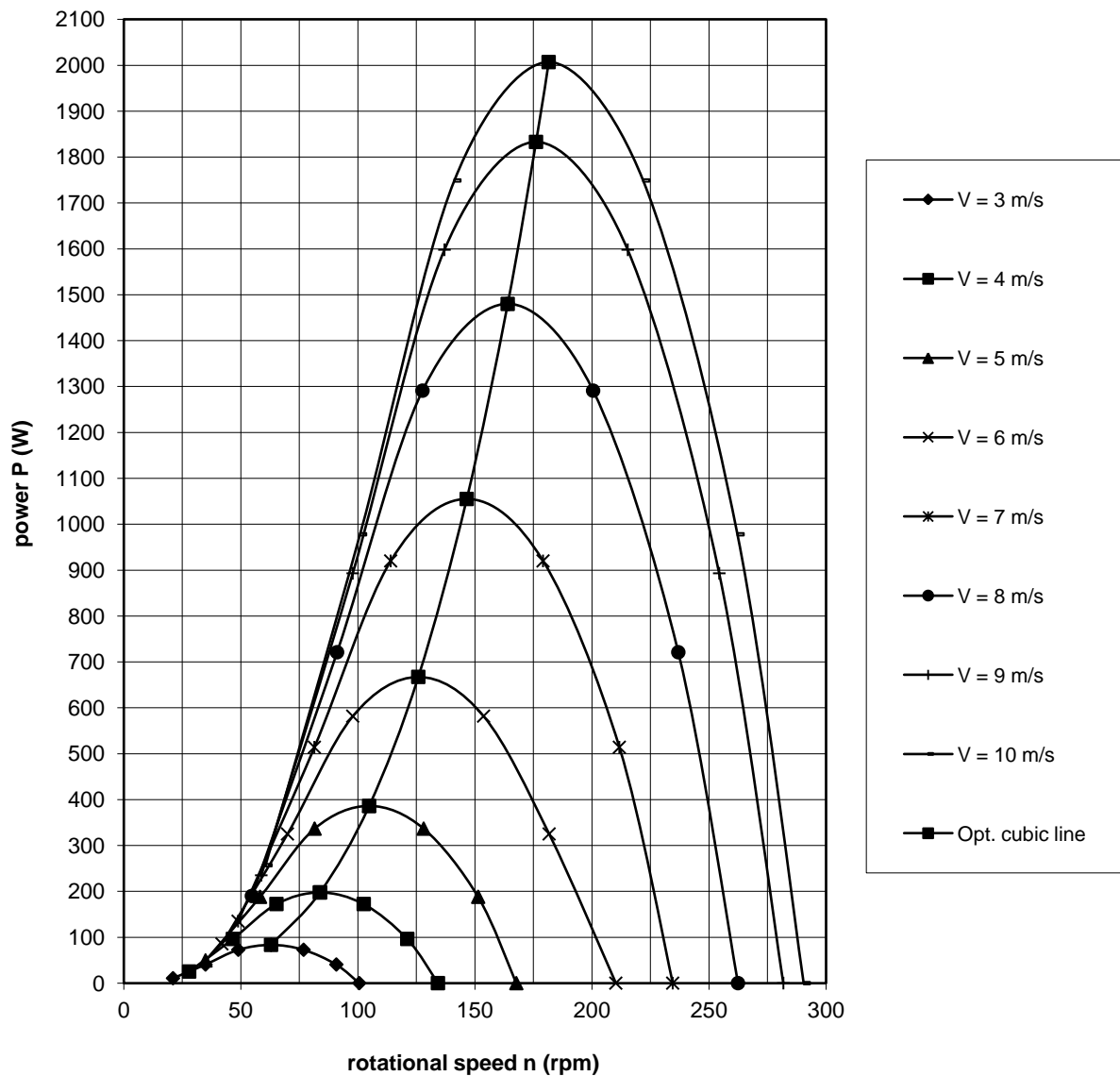


fig. 5 P-n curves of the VIRYA-4.1S rotor and the optimum cubic line

6 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 – 75. 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.

SPECIFICATION SECOTORQUE-FAN 260-75

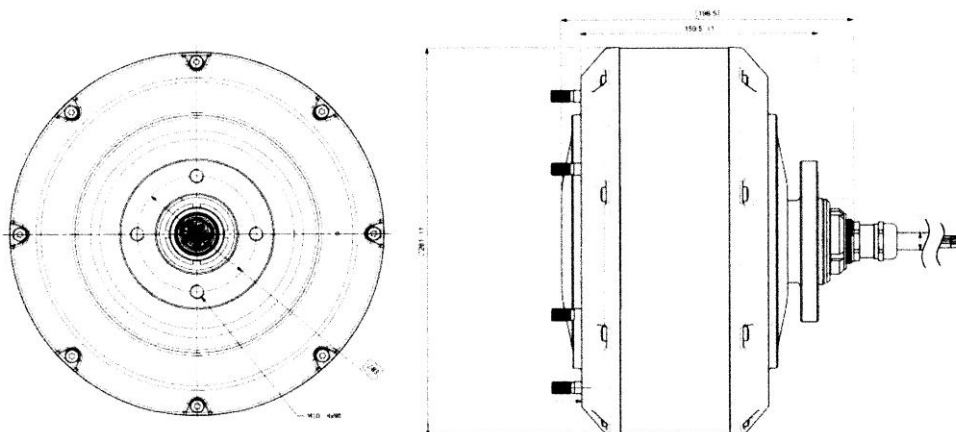
	Parameters	Unit	260-75 LS*	260-75 HS*	Remarks
Performance	Rated mechanical power	W	1037	5890	
	Rated torque	Nm	90	75	
	Rated speed	Rpm	110	750	
	Rated current	Arms	4.4	13.5	
	Torque constant	Nm/Arms	21.6	6.1	
	BackEMF constant	Vrms/rpm	1.33	0.38	line to line
	Resistance	Ohm	3.9	0.3	line to line
	Inductance	mH	56	4.5	line to line

	Parameters	Unit	260-75 LS*	260-75 HS*	Remarks
General Specs	Total mass	Kg	30	30	
	Rotor inertia	Kg.m ²	1.2E-01	1.2E-01	
	OD	mm	261	261	10.3 inch
	Height	mm	160	160	6.3 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



7

fig. 6 Detailed information about the Fan Motor 260 – 75

So the type 260-75 can be supplied in two versions; the version LS for low speeds and the version HS for high speeds. The version LS is chosen for water pumping and for grid connection. The version HS is chosen for 48 V battery charging. 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 90 Nm at 110 rpm. The version HS has a rated torque of 75 Nm at 750 rpm. I expect that the maximum torque which can be supplied by both motors is much higher than 90 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 (5890 W instead of 1037 W), the generated heat is also much higher and would be too high at a torque of 90 Nm and $n = 750$ rpm. But I see no reason why the version HS could not be used at 90 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-4.1S 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 1910 W at a rotational speed of 206.7 rpm. The relation in between the torque Q and the mechanical power P is given by:

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

Substitution of $P = 2007$ W and $n = 181.5$ rpm in formula 10 gives that $Q = 106.6$ Nm. This is higher than the nominal torque of 90 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. The short-circuit torque of the type 260-25 LS has been measured and the measurements are given in chapter 9 of report KD 794 (ref. 7). The measurements show that the Q - n curve for short-circuit is very steep and therefore it was expected that the peak torque is about 75 Nm for the type 260-25. The nominal torque is 40 Nm at low rpm. The type 260-75 has the triple width of the armature and the stator and the nominal torque is 90 Nm at low rpm. Therefore it is assumed that the peak torque is at least a factor $90 / 40 = 2.25$ larger for the 260-75. This results in a peak torque of at least $2.25 * 75 = 168.8$ Nm.

The nominal torque of the 260-75 isn't triple the nominal torque of the 260-25. This must have to do with heat dissipation. If the thickness of the stator is tripled, only the outside cylindrical area is tripled. The left and the right side area of the stator stay the same. So the total area isn't tripled if the thickness is tripled. This explains why the nominal torque isn't tripled if the thickness is tripled. 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 $\eta = 0.8$ 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 $\eta = 0.8$ 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. 8) 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.

7 Use of the VIRYA-4.1S for water pumping and grid connection

It seems possible to use the VIRYA-4.1S for water pumping and in The Netherlands the most obvious use is drainage of low flat lands. If the windmill is used in open terrain, a 12 m high tower isn't necessary. So one can use the about 8.6 m high tubular tower as described in report KD 582 (ref. 10).

The most elegant option for water pumping is to directly use the 3-phase current coming from the generator for a centrifugal pump with a 3-phase asynchronous motor. But this is only possible if the generator has the correct frequency and voltage range. As the generator has 30 armature poles, a frequency of 50 Hz is already reached at a rotational speed of 200 rpm. In figure 5 it can be seen that a rotational speed of 200 rpm isn't reached at a wind speed of 10 m/s if the optimum cubic line is followed. So this means that it isn't possible to use a standard centrifugal pump equipped with a standard asynchronous 3-phase motor at the standard frequency of 50 Hz. However, a centrifugal pump can be used at a rotational speed which belongs to a lower frequency if the static head H is reduced.

At the specification as given in figure 6 it is specified that the Back EMF constant for the 260-75 LS is 1.33 V_{rms}/rpm. This is the open AC voltage measured in between two of the three phases. So the open AC voltage at $n = 200$ rpm is $200 * 1.33 = 266$ V_{AC}. The loaded voltage will be lower. Assume that it is 230 V_{AC} at $n = 200$ rpm.

The 3-phase motor of a centrifugal pump connected in star requires a frequency of 50 Hz and a loaded voltage in between the phases of about 400 V_{AC}. This is much higher than the loaded voltage of about 230 V_{AC} which is supplied by the generator. But it is assumed that the pump motor can also be connected in delta. The required phase voltage then is a factor $\sqrt{3}$ lower and so 230 V_{AC}. This matches well with the loaded generator voltage at $n = 200$ rpm.

So the frequency f is 50 Hz at a rotational speed n of 200 rpm. As the frequency is proportional to the rotational speed, n can easily be calculated for other frequencies. This is done for frequencies of 25, 30, 35, 40, 45, 50, 55 and 60 Hz. The corresponding rotational speeds are respectively 100, 120, 140, 160, 180, 200, 220 and 240 rpm. Figure 5 is now copied as figure 7. The lines for frequencies of 25 Hz up to 60 Hz are also given in figure 7.

The static head H for which a centrifugal pump is designed, depends on the rotational speed n . Water starts only flowing out of the pump above a certain critical rotational speed n_{crit} . Below n_{crit} , the water is only rising in the pressure pipe up to a certain height which is smaller than H . The allowed static head H increases quadratic with n . So a pump designed for a certain head H at a certain rotational speed n can be used at a rotational speed $\frac{1}{2} n$ for a static height of $\frac{1}{4} H$.

Assume that a centrifugal pump is used with a 3-phase asynchronous motor. Assume that the pump motor is used at a nominal frequency of 35 Hz. This means that the pump rotates only at a factor $35 / 50 = 0.7$ of its nominal rotational speed. Therefore it can be used at a factor $0.7^2 = 0.49$, so about half of its nominal head H . Assume that the critical rotational speed n_{crit} is then reached for a frequency $f = 25$ Hz belonging to $n = 100$ rpm.

In figure 7 it can be seen that the line for $f = 35$ Hz or $n = 140$ rpm intersects with the optimum cubic line at a power of about 920 W. This power can be supplied at a wind speed of about 6.7 m/s which seems a reasonable wind speed for the VIRYA-4.1S if it is used for water pumping. So the point $P = 920$ W and $n = 140$ rpm is taken as the design point and a wind speed of 6.7 m/s is the design wind speed V_d .

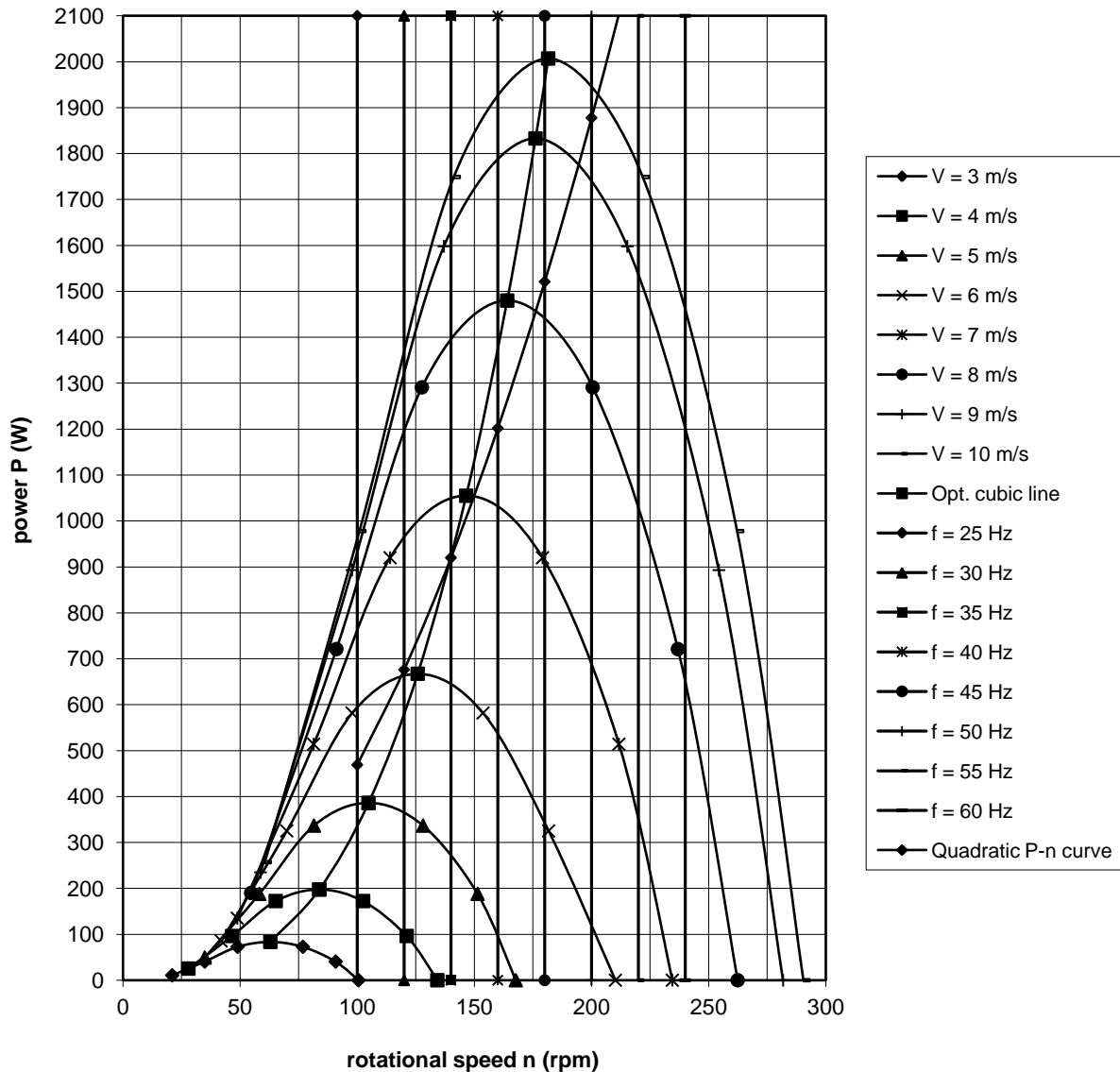


fig. 7 P-n curves and optimum cubic line of the VIRYA-4.1S rotor, lines for frequencies of 25 Hz up to 60 Hz for a 30-pole generator

The electrical power P_{el} for $V_d = 6.7$ m/s depends on the generator efficiency η_{gen} . Assume $\eta_{gen} = 0.85$. This gives that $P_{el} = 0.85 * 920 = 782$ W for $V_d = 6.7$ m/s. To find the working points for other rotational speeds, a P-n curve for a pump load has to be estimated.

A positive displacement pump requires about a constant torque for any rotational speed. This means that the P-n curve is a straight line through the origin. A centrifugal pump with only a dynamic head formed by the resistance of the pump fan and the tubing, needs a pressure which is increasing quadratic with the flow and so with the rotational speed. The torque then increases quadratic with n and this means that the P-n curve then will be a cubic line. For a centrifugal pump which is used for a static head H , a part of the required pressure is used to overcome the pressure drop of the static head but another part of the pressure drop is used to overcome the dynamic head which is caused by the friction of the water when it passes the pump fan and the tubing. These friction losses makes that a centrifugal pump normally has a much lower efficiency than a positive displacement pump. Assume that the pump has a quadratic P-n curve as the result of both pressure drops.

A quadratic curve through the origin has a formula:

$$P = C * n^2 \quad \text{which can be written as}$$

$$C = P / n^2 \quad (11)$$

Substitution of $P = 920 \text{ W}$ and $n = 140 \text{ rpm}$ in formula 11 gives that $C = 0.04694$. So the formula for the expected P-n curve is:

$$P = 0.04694 * n^2 \quad (\text{W}) \quad (12)$$

P is now calculated for the rotational speeds belonging to the eight chosen frequencies. The result of the calculation is given in table 3.

f (Hz)	n (rpm)	P (W)
25	100	469
30	120	676
35	140	920
40	160	1202
45	180	1521
50	200	1878
55	220	2272
60	240	2704

table 3 Calculated values of the quadratic P-n curve

The P-n curve found this way is also given in figure 5. In figure 5 it can be seen that the P-n curve of the rotor for $V = 10 \text{ m/s}$ is intersecting with the P-n curve for a quadratic pump load at a frequency of about 51 Hz. This frequency is certainly no problem for the pump and the pump motor.

It was assumed that $n_{\text{crit}} = 100 \text{ rpm}$ belonging to a frequency of 25 Hz. So for lower rotational speeds, no water will be pumped. The water will rise in the pressure pipe but only up to a level lower than the static head H. So it is useless to connect the generator to the pump motor for frequencies lower than 25 Hz. Assume that the connection is broken if the frequency becomes 25 Hz. So then the rotor turns unloaded. In figure 5 it can be seen that an unloaded rotor has a rotational speed of about 120 rpm belonging to a frequency of 30 Hz for a wind speed of about 3.6 m/s. Assume that the connection is made again at this frequency. The required power at this frequency is the point of intersection of the line $f = 30 \text{ Hz}$ with the quadratic P-n curve for a pump load. This power is 676 W but this power can't be supplied at a wind speed of 3.6 m/s. So the rotor slows down until the frequency has been reduced to 25 Hz and then the connection is broken again. But this means that some water is pumped at a wind speed of 3.6 m/s or higher.

In figure 5 and table 4 it can be seen that the required power at $n = 120 \text{ rpm}$ is 676 W. A wind speed of about 6 m/s is required so supply this power at a constant rotational speed. So the procedure of connecting and disconnecting is stopped for wind speeds higher than about 6 m/s.

Next it is supposed that the VIRYA-4.1S is used for drainage in The Netherlands and that the static head $H = 1 \text{ m}$. This means that one has to chose a pump which is designed for a static head $H = 2 \text{ m}$. Assume the pump dimensions are such that the working point is lying at $P = 920 \text{ W}$ at $n = 140 \text{ rpm}$ belonging to $V_d = 6.7 \text{ m/s}$. Earlier it was calculated that the supplied electrical power $P_{\text{el}} = 782 \text{ W}$ for $V_d = 6.7 \text{ m/s}$ if the generator efficiency is 0.85.

Assume that the efficiency of the pump motor at a frequency $f = 35$ Hz is 0.75. This means that the mechanical power supplied by the pump motor is $0.75 * 782 = 587$ W. The nominal motor power at a frequency of 50 Hz must be a factor 2 higher because of the higher head and a factor $\sqrt{2}$ higher because of the higher flow. So it must be about a factor 2.83 higher and so about 1660 W = 1.66 kW. This isn't a standard value. I think that a nominal motor power of 1.5 kW or 2.2 kW at 50 Hz is a good choice. The pump must be designed for a static head of 2 m if it is used for a static head of 1 m at $f = 35$ Hz.

The next question is how much water can be pumped for the design wind speed $V_d = 6.7$ m/s. Earlier it was calculated that $P_{el} = 782$ W for $V_d = 6.7$ m/s. The hydraulic power P_{hyd} is given by:

$$P_{hyd} = \rho_w * g * H * q \quad (W) \quad (13)$$

In this formula P_{hyd} is the hydraulic power in W, ρ_w is the density of water in kg/m^3 and $\rho_w = 1000$ kg/m^3 , g is the acceleration of gravity and $g = 9.81$ m/s^2 . H is the static head in m and q is the flow in m^3/s . The required electrical power of the pump motor P_{el} depends of the pump efficiency η_p and on the motor efficiency η_m . The efficiencies aren't given as a percentage but as a factor of 1. This results in:

$$P_{el} = \rho_w * g * H * q / (\eta_p * \eta_m) \quad (W) \quad (14)$$

Formula 14 can be written as:

$$q = \eta_p * \eta_m * P_{el} / (\rho_w * g * H) \quad (m^3/s) \quad (15)$$

Assume $\eta_p = 0.6$, $\eta_m = 0.75$, $P_{el} = 782$ W, $\rho_w = 1000$ kg/m^3 , $g = 9.81$ m/s^2 and $H = 1$ m. Substitution of these values in formula 15 gives that $q = 0.0359$ $m^3/s = 129.1$ $m^3/hour$. This is a substantial flow. So this is the flow which belongs to the design point at a frequency of 35 Hz and a design wind speed of 6.7 m/s. At higher wind speeds and so at higher rotational speeds and higher frequencies, the flow will be a lot higher. I think that the VIRYA-4.1S can very well be used for drainage using the generator type 260-75 LS if the correct pump with the correct pump motor can be found. But it can also be used for other heights H if a pump is used which is designed for two times the height H . A big advantage of the VIRYA-4.1S is that it isn't necessary to place the wind turbine close to the pump. As a rather high voltage is used, the wind turbine can be placed at a large distance from the pump without getting too much copper losses in the cables in between the generator and the pump motor.

The rotor can be stopped by making short-circuit in the winding. The short-circuit switch must be placed as close as possible to the generator. It is advised to place the short-circuit switch in a box at the tower foot. The cable must enter the box from below such that there is a loop in the cable. Now it is easy to see if the cable has twisted too much if the head has made many rotations in the same direction. It is advised to order the generator with a 13 m long cable with three flexible wires of 2.5 mm^2 for the 12 m high tower. One should also use a 3-phase cable with wires of 2.5 mm^2 in between the box and the pump motor.

It might be possible to use the VIRYA-4.1S for grid connection if the right inverter can be found. If the 3-phase rectifier is incorporated in the inverter, one should use the same 3-phase cable as for connection to the pump motor. If the 3-phase rectifier isn't incorporated in the inverter, the 3-phase rectifier should be mounted in the box at the tower foot after the short-circuit switch. Then a 2-phase cable with wires of 2.5 mm^2 can be used in between the box and the inverter. It is assumed that the inverter can be adjusted such that the optimum cubic line is followed. If the combined efficiency of the generator and the inverter is 0.8, a maximum electrical power of about 1600 W can be supplied at a wind speed of 10 m/s. The cut-in wind speed depends on the minimum voltage which is accepted by the inverter.

Assume that the inverter starts at the voltage which belongs to a wind speed of 3 m/s. The P_{el} - V curve is given in figure 8 if the optimum cubic line is followed and if the combined efficiency of generator and inverter is 0.8.

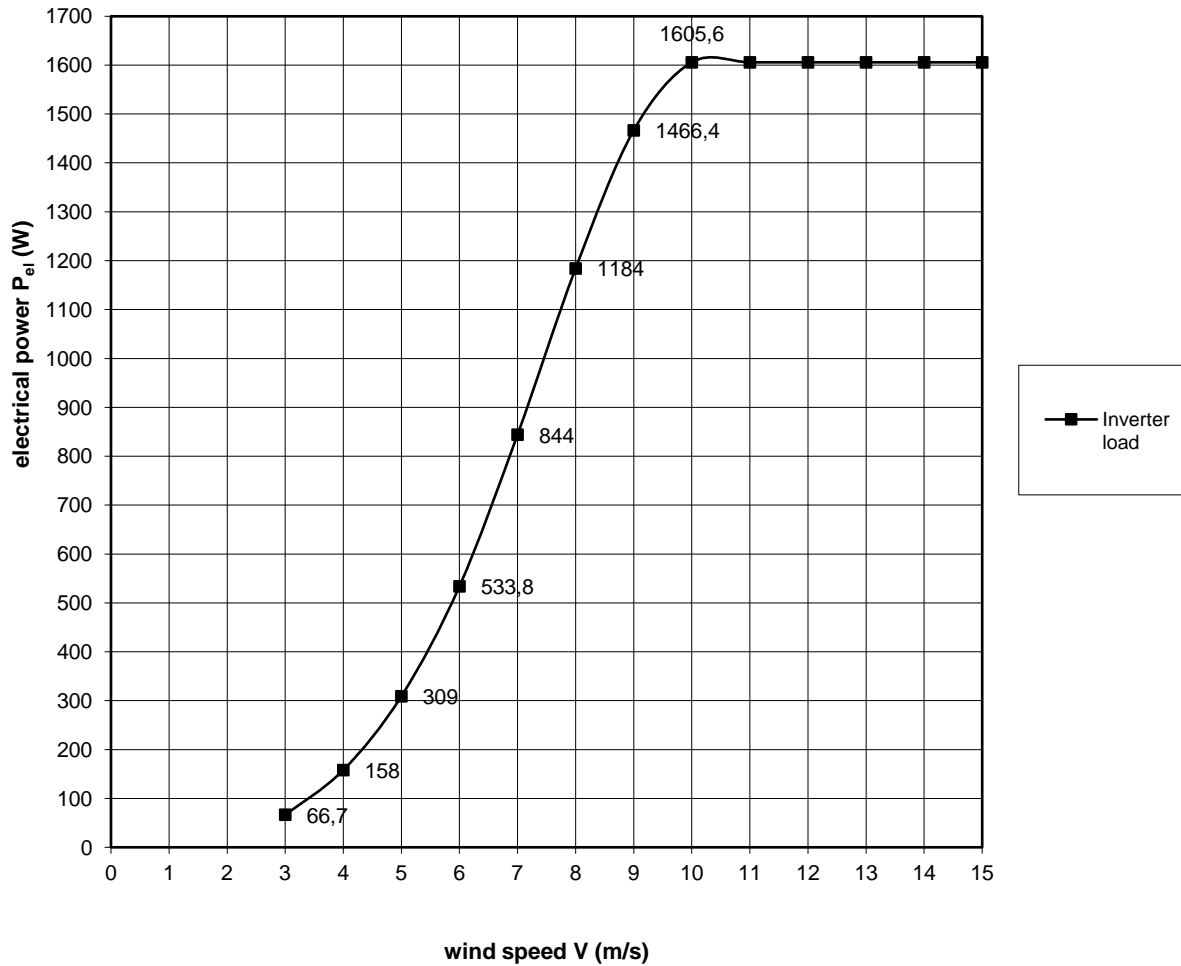


fig. 8 P_{el} - V curve for an inverter load

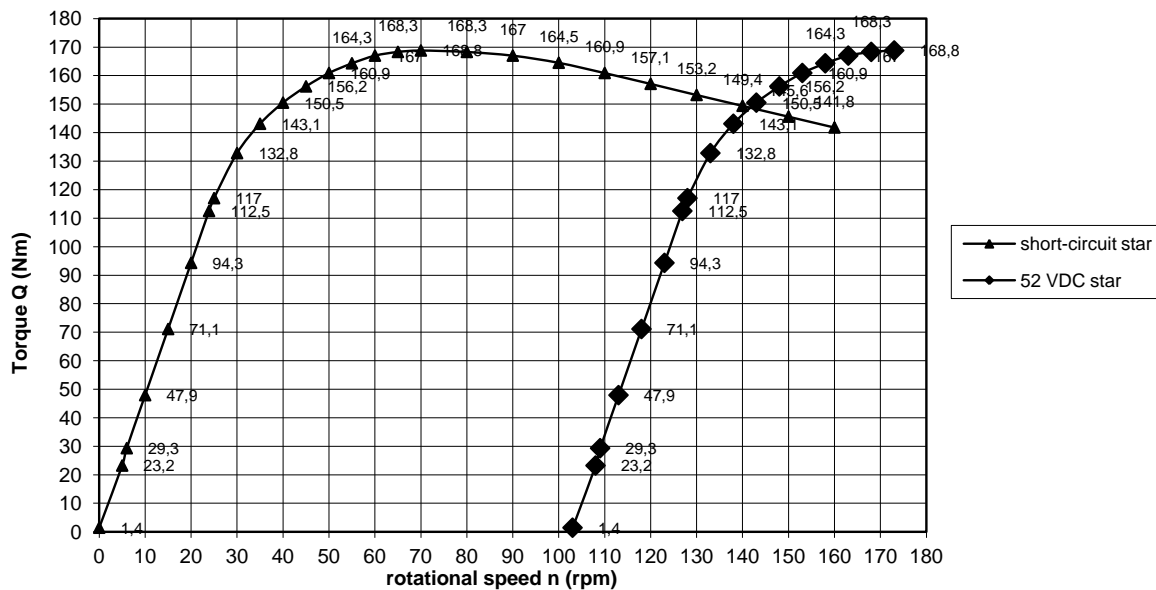
8 Use of the VIRYA-4.1S for 48 V battery charging

The VIRYA-4.1S with the generator type 260-75 LS can only be used for battery charging if a very high nominal battery voltage of 168 V_{DC} is chosen. This is a dangerous high DC voltage and so this isn't advised. For 48 V battery charging, one needs the generator type 260-75 HS as this type has a much lower backEMF than the type 260-75 LS. The backEMF of the type 260-75 HS is 0.38 V_{rms}/rpm. At the measurements for the 250-25 LS as given in KD 792 (ref. 7), it was found that the DC voltage after rectification with a 3-phase rectifier is about a factor 1.33 higher and so it is $1.33 * 0.38 = 0.505$ V_{DC}/rpm.

The average charging voltage for a 48 V lead acid battery is about 52 V, So this voltage is obtained at a rotational speed of $52 / 0.505 = 103$ rpm. In figure 7 it can be seen that the rotational speed is reached for an unloaded rotor at a wind speed just above $V = 3$ m/s. This means that the cut-in wind speed will be about 3.1 m/s which is acceptable.

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 distance of 103 rpm with respect to the Q-n curve for short-circuit. The nominal torque of the 260-75 LS is 90 Nm and the nominal torque of the 260-25 LS is 40 Nm. To simplify the calculations it is assumed that the Q-n curve for short-circuit is a factor $90 / 40 = 2.25$ higher than the curve which was estimated in KD 794 for the generator type 260-25. This means that the straight part of the curve starts at $Q = 1.4$ Nm and that it ends at a torque of 112.5 Nm at a rotational speed of 23.9 rpm. The curved part of the curve has a peak of 168.8 Nm at a rotational speed of 70 rpm. The Q-n curves derived this way are given in figure 9.

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 9 and in table 4.



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	1.4	0	103	1.4	15.1	0	0
5	23.2	12.1	108	23.2	262.4	0.79	207.3
6	29.3	18.4	109	29.3	334.4	0.81	270.9
10	47.9	50.2	113	47.9	566.8	0.85	481.8
15	71.1	111.7	118	71.1	878.6	0.83	729.2
20	94.3	197.5	123	94.3	1214.6	0.8	971.7
23.9	112.5	281.6	126.9	112.5	1495	0.785	1173.6
25	117	306.3	128	117	1568.3	0.78	1223.3
30	132.8	417.2	133	132.8	1849.6	0.76	1405.7
35	143.1	524.5	138	143.1	2068	0.74	1530.3
40	150.5	630.4	143	150.5	2250.7	0.72	1620.5
45	156.2	736.1	148	156.2	2420.9	0.703	1701.9
50	160.9	842.5	153	160.9	2578	0.692	1783.9
55	164.3	946.3	158	164.3	2718.5	0.68	1848.6
60	167	1049.3	163	167	2850.6	0.67	1909.9
65	168.3	1145.6	168	168.3	2960.9	0.66	1954.2
70	168.8	1237.4	173	168.8	3058.1	0.65	1987.7
80	168.3	1409.9					
90	167	1573.9					
100	164.5	1722.6					
110	160.9	1853.4					
120	157.1	1974.2					
130	153.2	2085.6					
140	149.4	2190.3					
150	145.6	2287.1					
160	141.8	2375.9					

table 4 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:

$$P = Q * n * \pi / 30 \quad (W) \quad (16)$$

Formula 16 is used to calculate P and P_{mech}. The result is also given in table 4. Figure 5 is now copied as figure 10. The P-n curve for short-circuit in star is derived from table 4 and is given in figure 10. The P-n curve for short-circuit in star is lying left from the P-n curve of the rotor for V = 10 m/s and higher. This means that the rotor can be slowed down at any wind speed if short-circuit is made. At short-circuit, the rotor will rotate only very slowly. During short-circuit, all power is dissipated in the winding but slowing down to almost stand still takes only a short time and so the winding will not be over heated. The short-circuit switch must be mounted as close as possible to the generator to prevent a large voltage drop over the cables. The most practical position is at a box which is mounted at the tower foot.

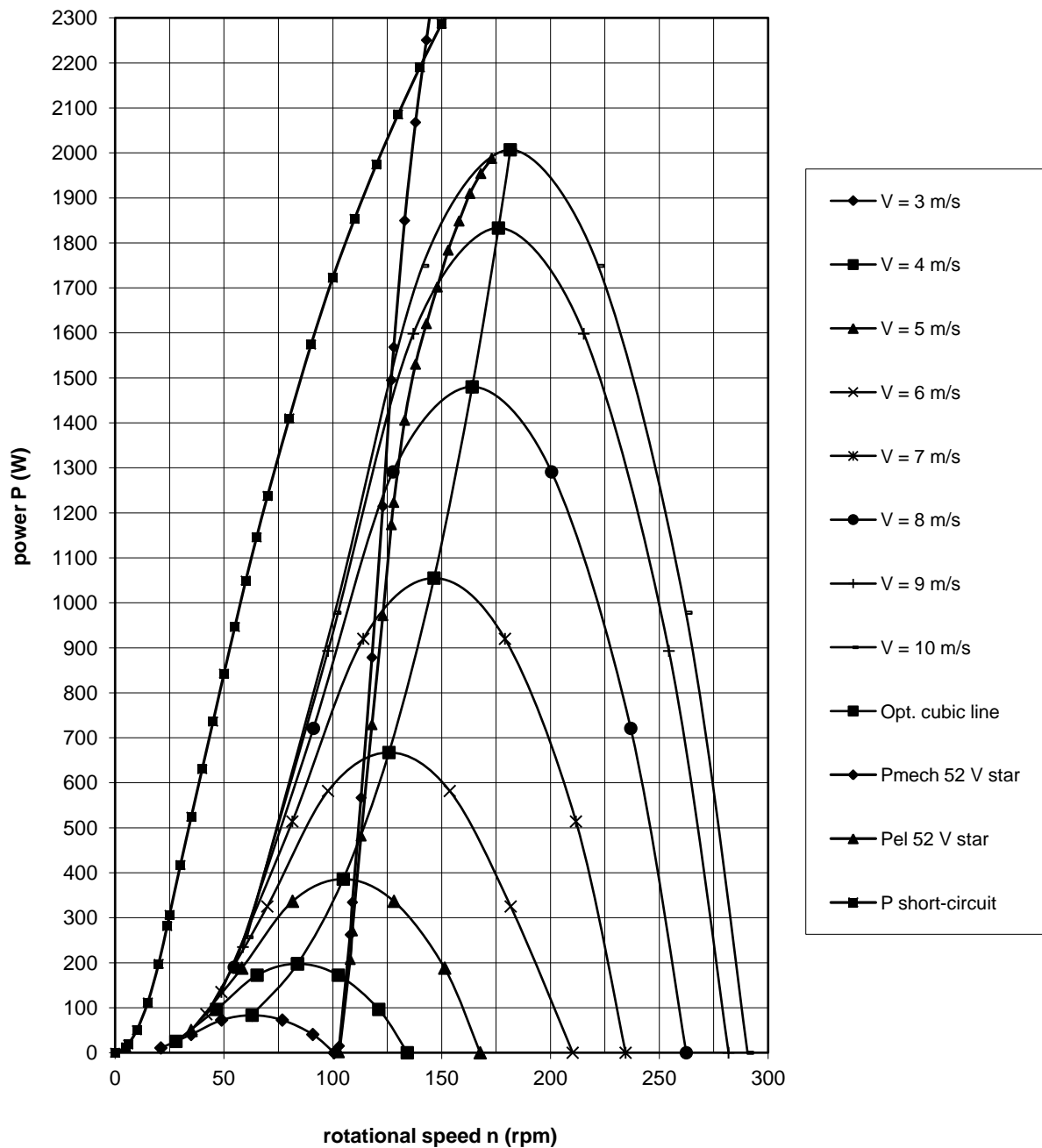


fig. 10 P-n curves of the VIRYA-4.1S rotor and the optimum cubic line, estimated P-n curve for short-circuit in star, estimated P_{mech} -n and P_{el} -n curves for 52 V_{DC} star

The P_{mech} -n curve for 52V_{DC} star is also given in figure 10. 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 5.3 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 3.5. 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 4. It is estimated that $\eta = 0.85$ for $n = 113$ rpm and that $\eta = 0.65$ for $n = 173$ rpm and that the right part of the curve is hollow. The estimated η - n curve is given in figure 11. The P_{el} - n curve derived from table 4 is also given in figure 10. 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 12.

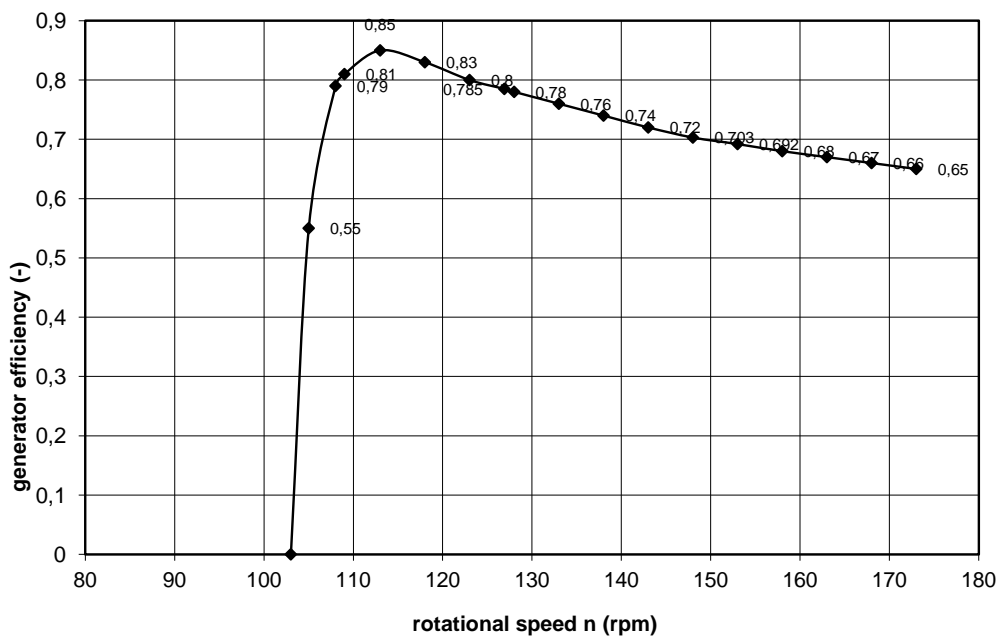


fig. 11 Estimated η - n curve

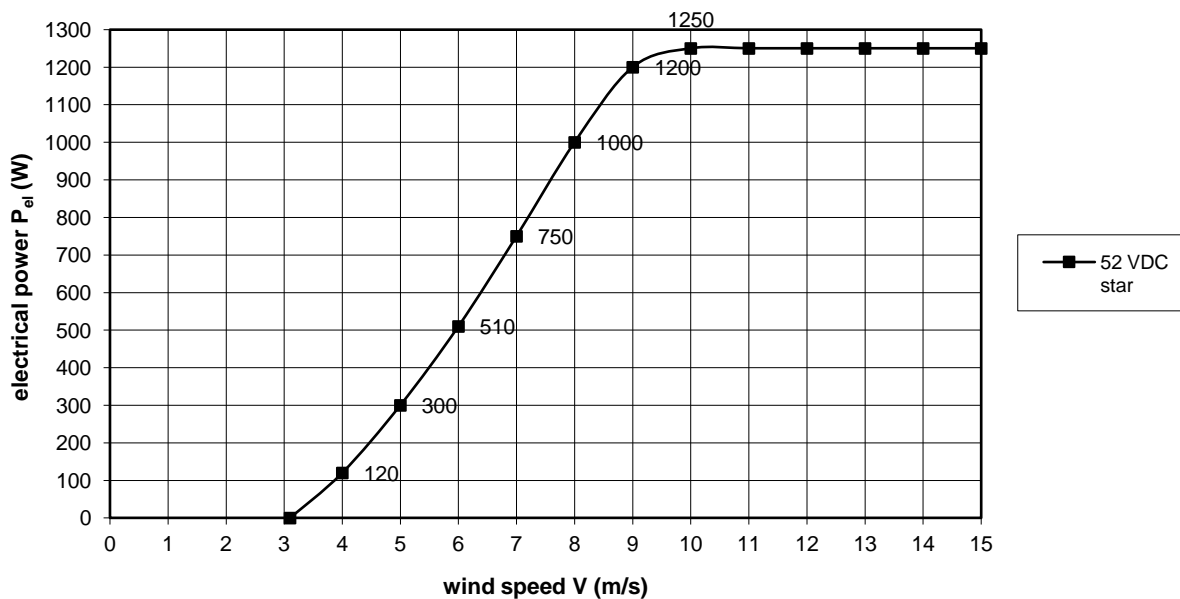


fig. 12 Estimated P_{el} -V curve for 52 V_{DC} star

In figure 12 it can be seen that the maximum power is about 1250 W at a wind speed of 10 m/s and higher. This is good for a wind turbine with a rotor diameter of 4.1 m and a rated wind speed of 10 m/s. But it is lower than the 1600 W which can be expected for grid connection. This is caused because the matching at high wind speeds is better for grid connection and the generator efficiency is also higher because of the higher voltage.

If the charging voltage at a maximum power is 55.2 V_{DC}, it means that the current I is $1250 / 55.2 = 22.6$ A. This is too high for the three 1 mm² 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 mm² and a length of 13 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-4.1S can be used in regions with low wind speeds. In chapter 4 it was calculated that the starting wind speed is only 2.4 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 1600 W. The generated electrical power is about 1250 W and so the dissipated heat is about 350 W. For motor use, the nominal power is 5890 W at n = 750 rpm. If the efficiency is 0.85, the required electrical power is 7363 W. So the dissipated heat is 1473 W which is much 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-4.1S 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 mm² for a short distance and at least two wires of 4 mm² for a large distance. One can also use to use a ground cable with four massive wires of 2.5 mm² and to use two wires in parallel for one phase. This was done for the prototype of the VIRYA-4.2.

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-4.2 tower is about 12 m. The generator should therefore be ordered with cable with a length of 13 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.

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