Calculations executed for the 3-bladed rotor of the VIRYA-7 windmill (λ_d = 7) for connection to the axial flux generator of Hefei Top Grand PMG-I-620-10kW-250R for grid connection, heating or water pumping using the hinged side vane safety system.

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KD 763

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1 Introduction

The VIRYA-7 windmill has a 3-bladed rotor with a design tip speed ratio λ_d = 7 and hollow stainless steel blades which are connected to each other by means of welded spoke assembly. Advantages of a 3-bladed rotor are that it has no pulsating gyroscopic moment in the rotor shaft and that a 3-bladed rotor looks nicer than a 2-bladed one. Advantage of using stainless steel blades for the VIRYA-7 is that manufacture of such blades is easy for a machine workshop if the required blade press is available and that such blades are not sensible to damage during transport. The blade press has still to be developed.

The generator is an axial flux PM-generator of Hefei Top Grand type PMG-I-620-10kW-250R. The same generator is also used in the VIRYA-6.5 windmill with wooden blades as described in chapter 7 of report KD 579 (ref. 1). It is expected that the same generator of Hefei Top Grand can also used in combination with the VIRYA-7. However, to prevent overloading of the generator at high wind speeds, the rated wind speed is chosen a little lower. This is realised by using a light hollow vane blade. It is expected that the rated wind speed V_{rated} is 10.5 m/s with this vane blade. The axial flux generators of Hefei Top Grand type PMG have an inner rotor, so the generator housing is fixed and the shaft is rotating. The generator has a 3-phase winding which is connected in star internally. So only the three phase wires are coming out of the hollow generator shaft. For use in combination with an inverter, the 3-phase current has to be rectified. Rectification of the winding is described in report KD 340 (ref. 2). Selection of the right rectifier and the right inverter is out of the scope of this report.

There might be a market in the outside area of The Netherlands for a grid connected windmill with a rotor diameter of 7 m as in the future, pumping of natural gas must be stopped. In this case most of the energy supplied by the windmill can be used to generate heat, using a heat pump. But this requires a windmill which is connected to the grid by an inverter. This option is described in chapter 2.4 of the Dutch report KD 709 (ref. 3). Another option is to connect the generator directly to a heating element. This option is described in chapter 2.3 of report KD 709. It might also be possible to use the VIRYA-7 for water pumping if the right pump with the right pump motor can be found.

The VIRYA-7 will have a 15 m or 18 m high free standing lattice or tubular tower. It might be possible to use the about 17 m high tubular tower of the VIRYA-6.5.

2 Description of the rotor of the VIRYA-7 windmill

The 3-bladed rotor of the VIRYA-7 windmill has a diameter D = 7 m and a design tip speed ratio λ_d = 7. The rotor has blades with a constant chord. A blade is made out of a stainless steel strip with dimensions of 3000 * 500 * 2 mm which is bent in the shape of a Gö 711 airfoil and welded at the tailing edge. So three blades can be made out of one standard sheet size 3 * 1.5 m. The blades have a constant chord and no twist and so the blade angle β is the same for the whole blade. The chord c is a little less than half the sheet width. It is assumed that c = 240 mm = 0.24 m.

The blades are connected to each other by a welded spoke assembly made out of three stainless steel strips size 750 * 120 * 15 mm which are welded to each other at an angle of 120°. The spoke assemble has a 72 mm central hole which fits around the thread M72 * 2 at the end of the generator shaft. The overlap in between spoke and blade is 250 mm. The strip is twisted 6.5° right hand in between the hub and the blade. The spoke is mounted against the inner flat side of the blade. An aluminium block is mounted in between the spoke and the inner cambered side of the blade. One side of this block is flat and the other side is cambered. A blade is connected to a spoke by three hexagon head bolts M16 * 80, three self locking nuts M16 and six or nine washers for M16. The stainless steel hub has an outer diameter of 160 mm. The spoke assembly is connected to the hub by three hexagon head bolts M16 and three self locking nuts M16 and a special slotted round nut M72 * 2 (no standard value).

A sketch of the VIRYA-7 rotor is given in figure 1.

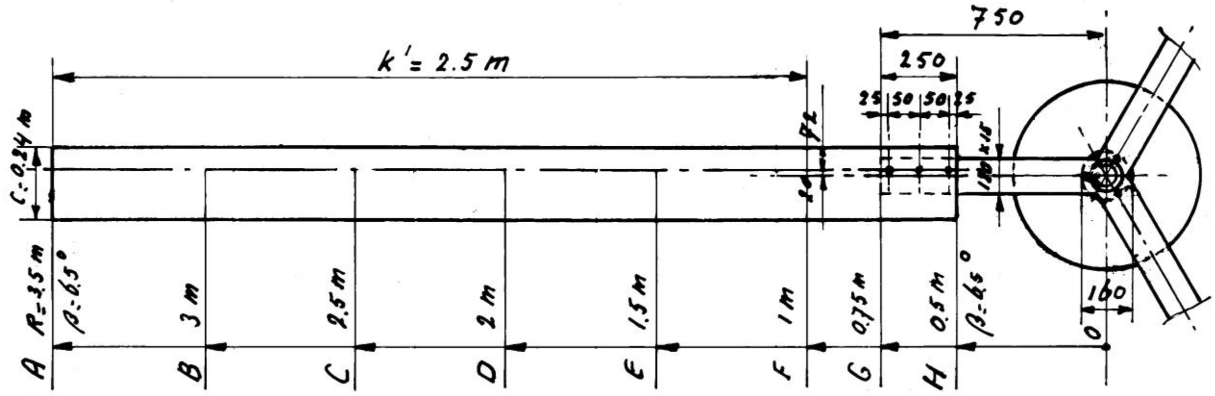

fig. 1 Sketch VIRYA-7 rotor

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 4). This report (KD 763) has its own formula numbering. Substitution of λ_d = 7 and R = 3.5 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 2 * r$ (-) (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 = 0.24 m in formula (5.4) of KD 35 gives:

$C_l = 34.907\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 6 m/s and c = 0.24 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 0.96 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for eight stations A till H which have a distance of 0.5 m of one to another except for the two inner sections for which the distance in between the stations is 0.25 m. Section G 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 blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root.

First the theoretical values are determined for C_l, α and β and next β is linearised such that the twist is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 5). This airfoil is flat over 97.5 % of the chord and is therefore rather easy to manufacture. The airfoil has only been measured for a Reynolds value of $4 * 10^5$. But this seems to be no problem for the rather large chord of the VIRYA-7 blades. The Reynolds values for the stations are calculated for a wind speed of 6 m/s because this is a reasonable wind speed for a windmill which is used in areas with moderate wind speeds.

station	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\ th}$ (-)	$C_{l\ lin}$ (-)	$R_{e\ r} * 10^{-5}$ V = 6 m/s	$R_e * 10^{-5}$ Gö 711	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\ lin}$ (-)
A	3.5	7	5.4	0.24	0.55	0.57	6.75	4	-1.4	-1.1	6.8	6.5	0.024
B	3	6	6.3	0.24	0.63	0.64	5.80	4	-0.4	-0.2	6.7	6.5	0.021
C	2.5	5	7.5	0.24	0.75	0.76	4.84	4	0.9	1.0	6.6	6.5	0.018
D	2	4	9.4	0.24	0.93	0.91	3.89	4	3.1	2.9	6.3	6.5	0.015
E	1.5	3	12.3	0.24	1.20	1.13	2.95	4	6.6	5.8	5.7	6.5	0.018
F	1	2	17.7	0.24	1.65	1.47	2.02	4	-	11.2	-	6.5	0.030
G	0.75	1.5	22.5	0.24	1.99	1.42	1.58	4	-	16.0	-	6.5	0.11
H	0.5	1	30.0	0.24	2.34	-	1.15	4	-	23.5	-	6.5	-

table 1 Calculation of the blade geometry of the VIRYA-7 rotor

No value for α_{th} and therefore for β_{th} is found for stations F, G and H because the required C_l values can't be generated. The variation of the theoretical blade angle β_{th} is only little for the stations A up to E and varies in between 6.8° and 5.7°. Therefore it is allowed to take a constant value of β_{lin} = 6.5° for the whole 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 0.02. Figure 4.7 of KD 35 (for B = 3) and λ_{opt} = 7 and C_d/C_l = 0.02 gives $C_{p\ th}$ = 0.47.

The blade is stalling in between station F and H and the airfoil is disturbed because of the connecting bolts and nuts. For the calculation of the maximum C_p therefore not the whole blade length k = 3 m is taken into account but only the part up to station F. This gives an effective blade length k' = 2.5 m.

Substitution of $C_{p\ th}$ = 0.47, R = 3.5 m and effective blade length k' = 2.5 m in formula 6.3 of KD 35 gives $C_{p\ max}$ = 0.43. $C_{q\ opt} = C_{p\ max} / \lambda_{opt}$ = 0.43 / 7 = 0.0614. Substitution of $\lambda_{opt} = \lambda_d$ = 7 in formula 6.4 of KD 35 gives λ_{unl} = 11.2. The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\ start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \quad (-) \qquad (6)$$

The blade angle is 6.5° for the whole blade. For a non rotating rotor, the angle of attack α is therefore 90° - 6.5° = 83.5°. The aerodynamic characteristics for the Gö 711 aren't given for large angles of α in KD 285. However, the estimated C_l-α curve for large values of α is given as figure 5.10 of KD 35 (ref. 4) for the Gö 623 airfoil and it is assumed that this curve can be used. For α = 83.5° it can be read that C_l = 0.23. The whole blade is stalling during starting and therefore now the whole blade length k = 3 m is taken.

Substitution of B = 3, R = 3.5 m, k = 3 m, C_l = 0.23 and c = 0.24 m in formula 6 gives that $C_{q\ start}$ = 0.0055. For the ratio between the starting torque and the optimum torque we find that it is 0.0055 / 0.0614 = 0.09. This is acceptable for a rotor with λ_d = 7.

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

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * ½\rho * \pi R^3} \right)} \quad (m/s) \qquad (7)$$

At point 11 of the specification of the generator it is mentioned that the starting torque is smaller than 0.5 Nm. This is very low and I doubt if this is correct if the generator has a seal on the shaft. The generator can be used without a seal for a vertical axis wind turbine but for a horizontal axis wind turbine, a seal is certainly necessary to prevent that water enters the bearings. Assume that the sticking torque with a seal is 4 Nm.

Substitution of Q_s = 4 Nm, $C_{q\ start}$ = 0.0055, ρ = 1.2 kg/m^3 and R = 3.5 m in formula 7 gives that V_{start} = 3 m/s. This is low for a 3-bladed rotor with a design tip speed ratio λ_d = 7.

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 λ = 0. Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 6). With this method, it can be determined that the C_q-λ curve is about straight and horizontal for low values of λ if a Gö 711 airfoil is used. A scale model of a 3-bladed rotor with constant chord and blade angle and with a design tip speed ratio λ_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-7 rotor are given in figure 2 and 3

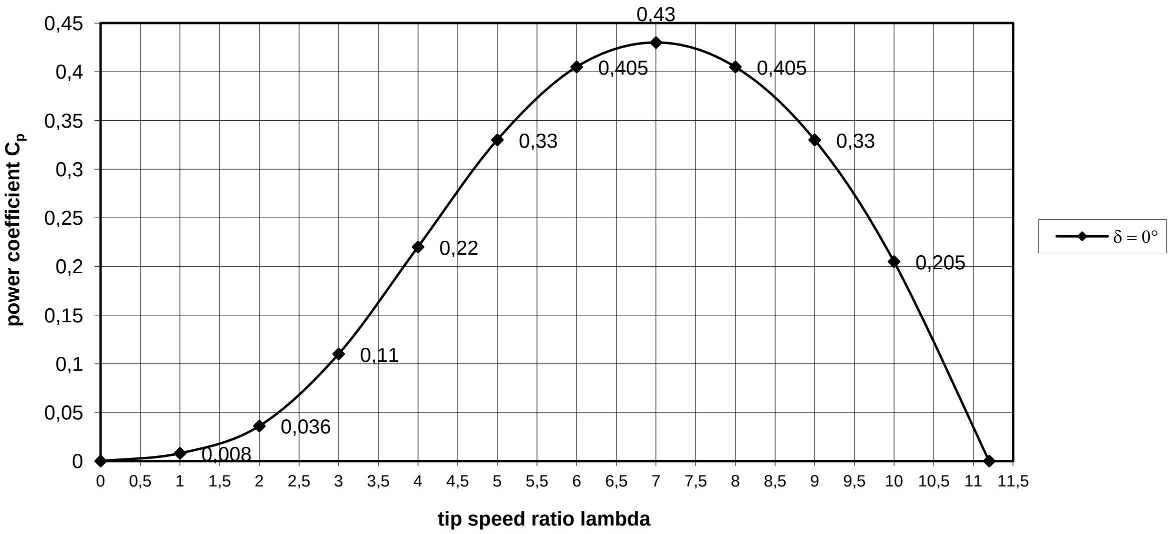

fig. 2 Estimated C_p-λ curve for the VIRYA-7 rotor for the wind direction perpendicular to the rotor (δ = 0°)

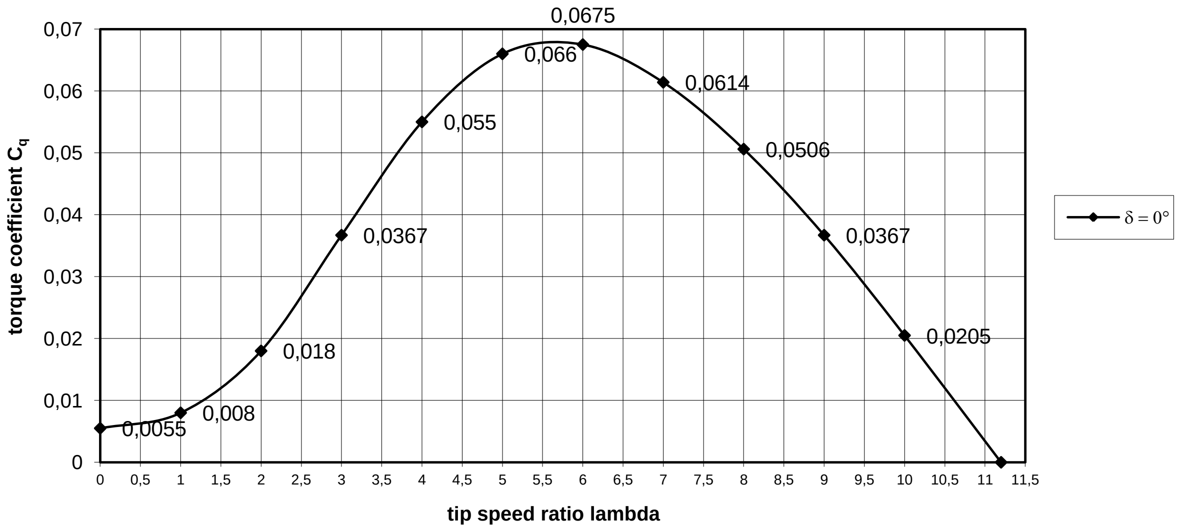

fig. 3 Estimated C_q-λ curve for the VIRYA-7 rotor for the wind direction perpendicular to the rotor (δ = 0°)

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 the characteristics of the safety system together with the formulas for the power P and the rotational speed n. The estimated δ-V curve of the VIRYA-4.2 windmill is given in figure 5 of report KD 213 (ref. 7). The VIRYA-4.2 has a vane blade made out of 9 mm meranti plywood with a density of about $0.6 * 10^3$ kg/m^3. The rated wind speed for this vane blade is about 9.5 m/s. The VIRYA-7 will get a hollow vane blade made out of two sheets of 6 mm oucume plywood with a density of about $0.45 * 10^3$ kg/m^3. The rated wind speed for this vane blade will be about 10.5 m/s. The rotor starts turning out of the wind at a wind speed of about 7 m/s The estimated δ-V curve for the VIRYA-7 is given in figure 4.

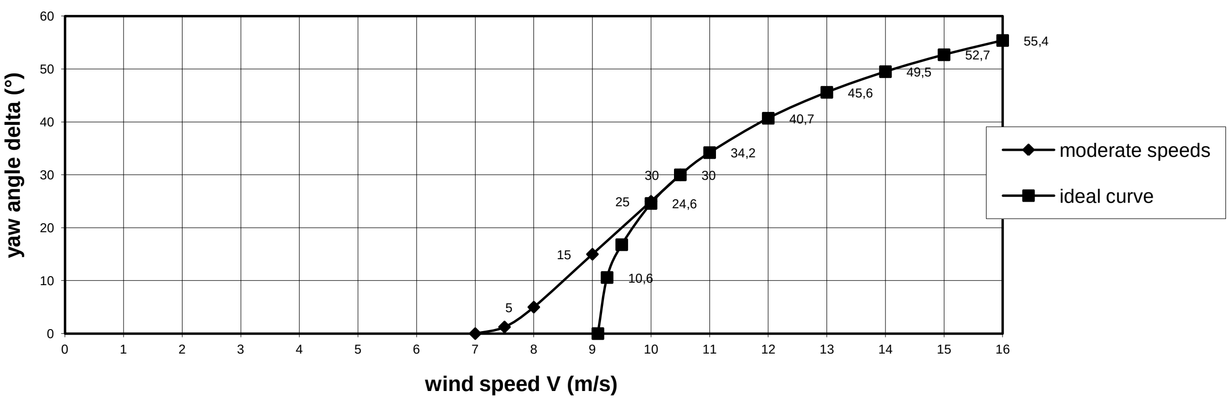

fig. 4 Estimated δ-V curve for a hollow oucume plywood vane blade

Because the P-n curve for low values of λ appears to lie very close to each other, the P-n curves are not determined for very low values of λ. The P-n curves are determined for C_p values belonging to λ is 3, 4, 5, 6, 7, 8, 9, 10 and 11.2 (see figure 1). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 10.5 m/s. The yaw angles δ for wind speeds above 7 m/s are read from figure 4.

Substitution of R = 3.5 m in formula 7.1 of KD 35 gives:

$$n = 2.7284 * \lambda * \cos\delta * V \qquad \text{(rpm)} \tag{8}$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 3.5 m in formula 7.10 of KD 35 gives:

$$P = 23.091 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \tag{9}$$

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.

		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 = 0°		V = 8 m/s δ = 5°		V = 9 m/s δ = 15°		V = 10.5 m/s δ = 30°	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	P_δ (W)	n_δ (rpm)
3	0.11	24.6	69	32.7	163	40.9	318	49.1	549	57.3	871	65.2	1286	71.2	1669	74.4	1910
4	0.22	32.7	137	43.7	325	54.6	635	65.5	1097	76.4	1742	87.0	2571	94.9	3338	99.2	3820
5	0.33	40.9	206	54.6	488	68.2	953	81.9	1646	95.5	2614	108.7	3857	118.6	5006	124.1	5729
6	0.405	49.1	253	65.5	599	81.9	1169	98.2	2020	114.6	3208	130.5	4734	142.3	6144	148.9	7032
7	0.43	57.3	268	76.4	635	95.5	1241	114.6	2145	133.7	3406	152.2	5026	166.0	6523	173.7	7466
8	0.405	65.5	253	87.3	599	109.1	1169	131.0	2020	152.8	3208	174.0	4734	189.8	6144	198.5	7032
9	0.33	73.7	206	98.2	488	122.8	953	147.3	1646	171.9	2614	195.7	3857	213.5	5006	223.3	5729
10	0.205	81.9	128	109.1	303	136.4	592	163.7	1022	191.0	1624	217.4	2396	237.2	3110	248.1	3559
11.2	0	91.7	0	122.2	0	152.8	0	183.3	0	213.9	0	243.5	0	265.7	0	277.9	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-7 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_{mech}-n curves is also given in figure 5.

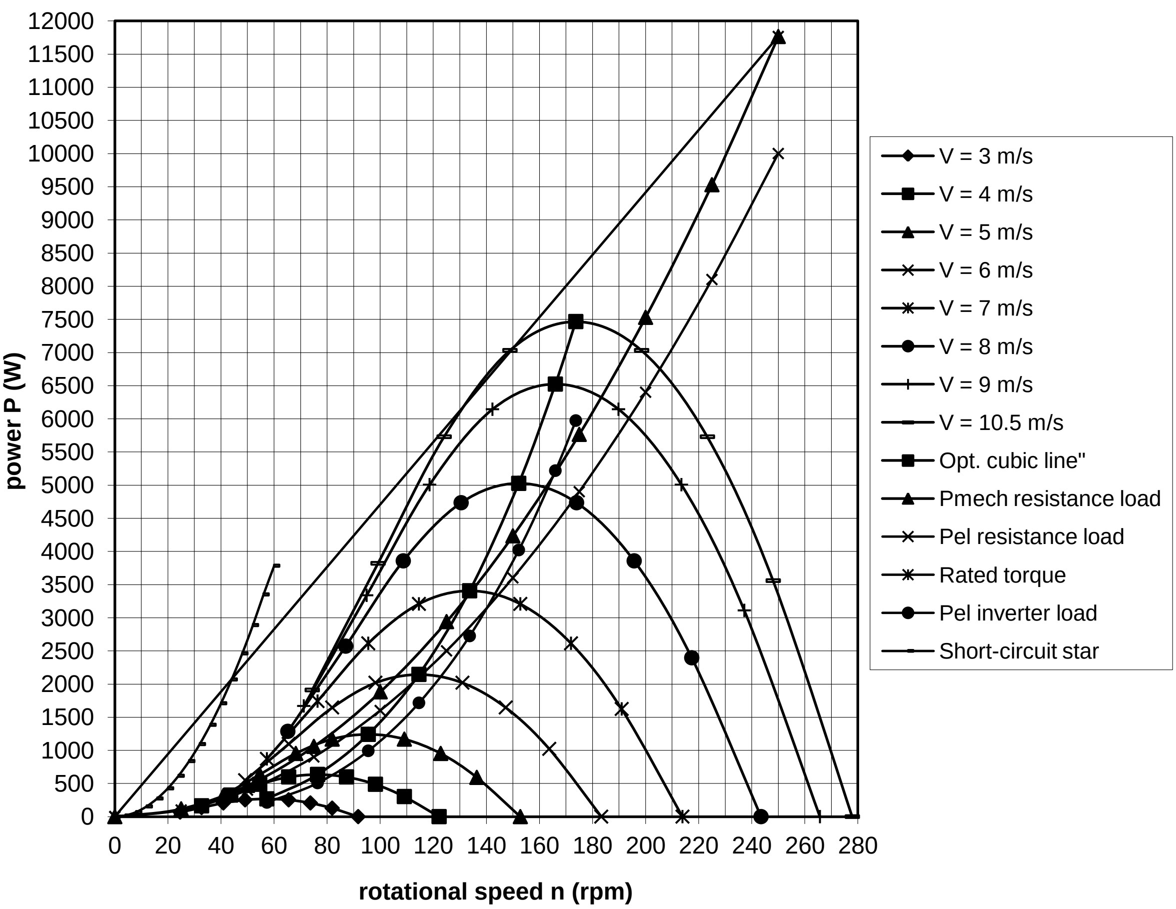

fig. 5 P-n curves of the VIRYA-7 rotor, optimum cubic line, P_{mech}-n and P_{el}-n curves for the generator with a resistance load such that P_{el} = 10000 W at n = 250 rpm, P-n curve for the rated torque, P_{el}-n curve for an inverter load, P-n curve for short-circuit in star

6 Determination of the generator characteristics and the P_{el}-V curve

An axial flux generator of Chinese manufacture has been chosen. Axial flux means that the magnetic flux which is flowing through the coils is in parallel to the generator axis. There is no iron in the coils and so the sticking torque is only determined by the friction of the bearings and the seal on the shaft. As there is no iron in the coils, there are no magnetic losses and the peak efficiency is rather high. Such generators are supplied by different Chinese suppliers like Hefei Top Grand, Xinda Green Energy, Hiestmotor and Qiangsheng Magnets. I have chosen Hefei Top Grand, website: www.china-topgrand.com because they gave the clearest answers on my questions. I have bought and tested a smaller generator type TGET165-0.15kW-500R at this company and they keep their promises. Measurements for this generator and experiments with a small wind turbine are given in report KD 595 (ref. 8).

For the VIRYA-7, I have chosen the generator with type PMG-I-620-10kW-250R (620 refers to about the housing diameter, the real diameter is 625 mm, 10kW refers to the rated power in kW and 250R refers to the rated rotational speed in rpm). A data sheet about this generator can be found on the website of the supplier following the path: www.china-topgrand.com – product – Permanent Magnet Generator Inner Rotor – page 4 – PMG-I-620-10kW-250R. The data sheet gives: Shape Drawing at point 4, Performance Parameter at point 5 and Curve Graph at point 6. At point 3, Range of Application, it is mentioned: “1 – 10 kW vertical axis wind turbine”. I think that this is mentioned because the generator has probably no oil seal on the rotor shaft. So no water will enter the bearings if the shaft is mounted vertical. The same was the case with the generator model TGET165-0.15kW-500R which I have tested. However, the housing of this generator was provided with a chamber in which an oil seal can be mounted. I expect that this is also the case for the PMG-I-620-10kW-250R housing if it has no standard seal. The generator has a mass of 140 kg which seems acceptable for the VIRYA-7.

The generator is of the type “inner Rotor” which means that the housing is fixed and that the shaft is rotating. The rated loaded voltage at n = 250 rpm is specified as 450 VAC. So no DC voltage is specified but the loaded DC voltage can be calculated. This generator has a 3-phase winding with an internal star point and three phase wires are coming out of the generator housing. The given voltage is the voltage in between two of the three phases and not the phase voltage U_f, which is the voltage in between the star point and one of the phases. U_f is a factor $\sqrt{3}$ lower, so 259.8 VAC. A large 3-phase rectifier (not included) must be used to get a DC current which is needed for the inverter. Rectification of a 3-phase current is explained in report KD 340 (ref. 2). However, it might be that the rectifier is included in the inverter and in this case the three phase wires are directly connected to the inverter. To stop the rotor, a 3-phase switch has to be mounted at the tower foot. The switch must be mounted as close as possible to the generator to prevent a voltage drop over the lines in between the generator and the switch.

The nominal line current I is specified as I = 12.83 A at n = 250 rpm. So the nominal power generated by one phase is U_f * I = 259.8 * 12.83 = 3333 W. So the nominal power generated by three phase is 3 * 3333 = 9999 W. This matches with the given power of 10 kW. The small difference must be caused by rounding off the current.

The sticking torque of the generator is very low without an oil seal and is only caused by the friction of the bearings. It is specified that this torque is less than 0.5 Nm. An oil seal is needed if the axis is horizontal. The sticking torque will be much higher if an oil seal is mounted but it is expected that it is low enough for the VIRYA-7 rotor (see calculation of the starting wind speed in chapter 4).

The generator has a shaft with a diameter of 80 mm and this shaft will be strong enough for a horizontal axis wind turbine with a rotor diameter of 7 m. The length of the cylindrical part of the shaft is 210 mm which is rather long. The generator shaft has a 22 mm wide key groove. The front side of the shaft is provided with thread M 72 * 2 over a length of 40 mm.

The generator housing has a collar with a diameter of 200 mm at the front and at the back side. In the photo of the generator it can be seen that eight threaded holes are made in each collar but the diameter and the pitch circle aren't specified. As these holes are used to connect the generator to the generator bracket of the head frame, the measures should have been given. A composite drawing of the hub and the generator bracket have still to be made.

The generator characteristics are derived in chapter 7 of report KD 579 (ref. 1). These characteristics are copied in figure 5. The curves for a resistance load are measured by the manufacturer. The load resistance R can be calculated if it is assumed that three identical resistors are connected in star to the three phase wires. The voltage over one resistor is equal to the phase voltage U_f = 259.8 V. The line current I = 12.83 A at n = 250 rpm. So according to the law of Ohm, the resistance R is given by R = U / I or R = 259.8 / 12.83 = 20.2 Ω.

If three resistors are used as load, the winding of one phase is used for all the time to generate power. This power varies according to a $\sin^2\alpha$ function. The power fluctuation is given in figure 2 of report KD 340 (ref. 2). If a 3-phase winding is rectified in star, only two of the three phases are generating power at the same time. This means that in one phase, power is only generated for $30° < \alpha < 150°$ and for $210 < \alpha < 330°$. This means that no power is generated for $0° < \alpha < 30°$, for $150° < \alpha < 210°$ and for $330° < \alpha < 360°$. The loss of generated power because of this effect is about 7 % of the power generated for a resistance load. But this effect is neglected and so it is assumed that the generator is able to generate a DC power of 10 kW at n = 250 rpm.

The electrical power for a resistance load is 10000 W at n = 250 rpm. It is assumed that the generator efficiency is 0.85 and so the mechanical power is 10000 / 0.85 = 11765 W at n = 250 rpm. It is assumed that the torque Q which belongs to this power and rotational speed can also be supplied for lower rotational speeds. This means that the power decreases proportional to the rotational speed. This straight line "P for rated torque" is also given in figure 5. It can be seen that the peak power for V = 10.5 m/s (so if the optimum cubic line is followed) is lying just below this straight line. So the generator is strong enough.

If the generator is grid connected by an inverter it is assumed that the inverter can be programmed such that the optimum, cubic line of the rotor is followed. Modern inverters have a very high efficiency. It is assumed that the overall efficiency of the generator and the inverter is 0.8. The P_{el}-n curve for an inverter load with an overall efficiency of 0.8 is also given in figure 5. This curve is used to determine the P_{el}-V curve for an inverter load as given in figure 6.

It is expected that the inverter needs a minimum input voltage to function. So the rotor must have a certain minimal rotational speed. This speed isn't known but at the moment it is supposed that the voltage is too low for wind speeds below 3 m/s. This means that the little energy available in wind speeds below 3 m/s can't be captured. So this is the reason why the P_{el}-V curve starts suddenly with P_{el} = 214 W at V = 3 m/s. The critical voltage may lie lower and if this is the case, the P_{el}-V curve starts at a lower wind speed.

The P_{el}-V curve is valid for constant wind speeds and not for average wind speeds. The output for a certain average wind speed is larger than for a certain constant wind speed. This can be demonstrated as follows. Assume we have a constant wind speed of 5 m/s. In the P_{el}-V curve it can be read that P_{el} = 993 W. Assume we have a wind speed of 7 m/s for one hour and of 3 m/s for one hour. So the average wind speed is 5 m/s. The power for V = 3 m/s is 214 W. The power for V = 7 m/s is 2725 W. So the average power is (214 + 2725) / 2 = 1470 W. This is 477 W more or a factor 1470 / 993 = 1.48 higher than for a constant wind speed of 5 m/s.

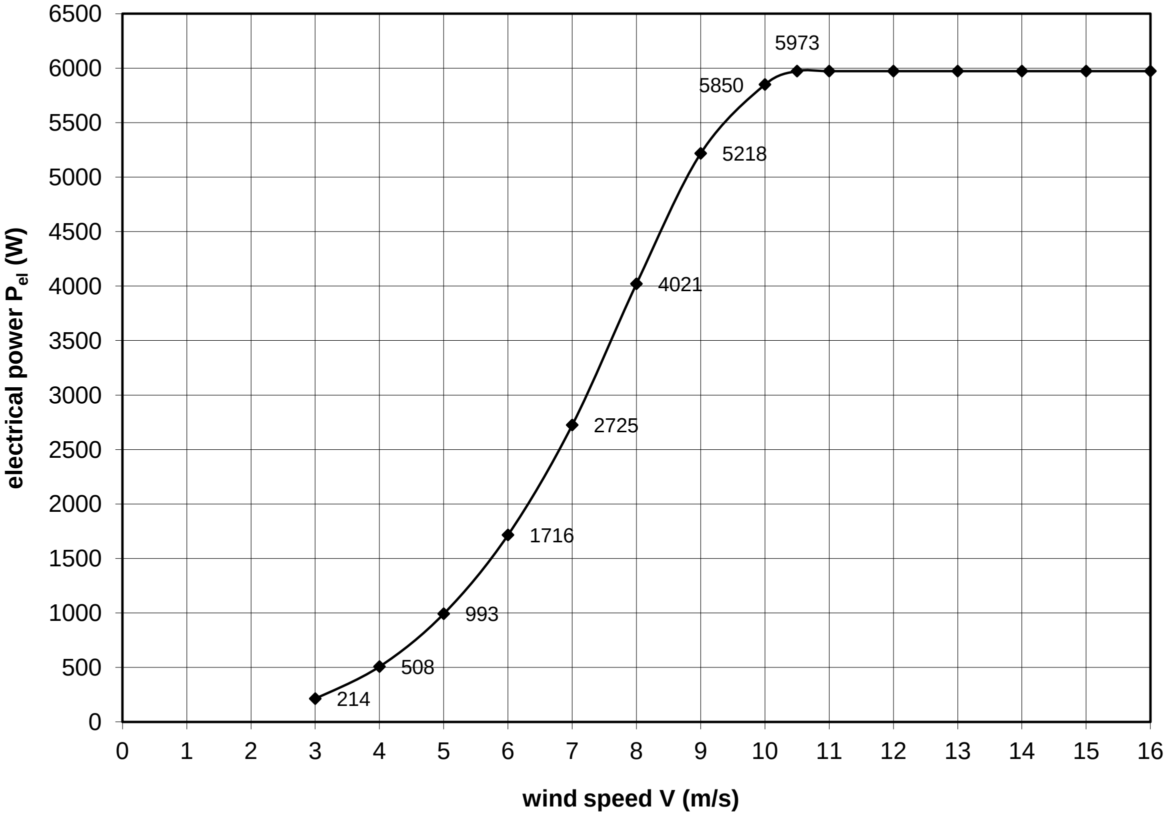

fig. 6 P_{el}-V curve for an inverter load such that the optimum cubic line is followed

In figure 6 it can be seen that the maximum electrical power is about 6 kW. This is very good for a wind turbine with a rotor diameter of 7 m and a rated wind speed of 10.5 m/s.

The P_{mech}-n, the P_{el}-n curves as given in figure 5 and the P_{el}-V as given in figure 6 are estimated and not measured. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the chosen generator of Hefei Top Grand, it is necessary to buy one and to test it at a large test rig with which it is possible to also measure the torque Q. One should also select and buy an inverter and measure the real electrical output for grid connection.

The P-n curve for short-circuit in star can is also given in figure 5. It can be seen that there is a large distance in between the P-n curve for short-circuit in star and the P-n curve of the rotor for V = 10.5 m/s. The P-n curve for short-circuit in star couldn't be determined for higher rotational speeds than 60 rpm but by interpolation it can be concluded that the generator can be used as a brake to stop the rotor at any wind speed.

7 Calculation of the strength of the spokes

The three blades are connected to each other by the spoke assembly. The spoke assembly is made of three spokes which are welded together under an angle of 120°. It has a 72 mm central hole which fits around the 40 mm long part with thread M72 * 2 at the end of the generator shaft. The hub has an outside diameter of 160 mm and an inside diameter of 80 mm. It is provided with a key groove.

The spoke assembly is bolted to the hub by three bolts M16 and three self locking nuts M16 at a pitch circle of 130 mm. A special round nut with thread M72 * 2 is used for axial fixation of the hub. A spoke has a length to the centre of 750 mm. The width b = 120 mm and the height h = 15 mm. The stainless steel blades have a large bending strength and the bending stiffness because of the Gö 711 airfoil, is rather large. It is therefore assumed that the spoke is the weakest component.

A spoke is loaded by a bending moment with axial direction which is caused by the rotor thrust and by the gyroscopic moment. A spoke is also loaded by a centrifugal force and by a bending moment with tangential direction caused by the torque and by the weight of the blade but the stresses which are caused by these loads can be neglected.

Because a spoke is rather long it makes the blade connection elastic and therefore the blade will bend backwards already at a low load. As a result of this bending, a moment with direction forwards is created by a component of the centrifugal force in the blade. The bending is substantially decreased by this moment and this has a favourable influence on the bending stress.

It is started with the determination of the bending stress which is caused by the rotor thrust. There are two critical situations:

1^e The load which appears for a rotating rotor at V_{rated} = 10.5 m/s. For this situation the bending stress is decreased by the centrifugal moment. The yaw angle is 30° for V_{rated} = 10.5 m/s.

2^e The load which appears for a stopped rotor. The spoke strength is calculated if the rotor is stopped by a brake.

7.1 Bending stress in the spoke for a rotating rotor and V = 10.5 m/s

The rotor thrust is given by formula 7.4 of KD 35 (ref. 4). The rotor thrust is the axial load of all blades together and exerts in the heart of the rotor. The thrust per blade $F_{t\,\delta\,bl}$ is the rotor thrust $F_{t\,\delta}$ divided by the number of blades B. This gives:

$$F_{t\,\delta\,bl} = C_t * \cos^2\delta * \tfrac{1}{2}\rho V^2 * \pi R^2 / B \qquad \text{(N)} \qquad (10)$$

For the rotor theory it is assumed that every small area dA which is swept by the rotor, supplies the same amount of energy and that the generated energy is maximised. For this situation the wind speed in the rotor plane has to be slowed down till 2/3 of the undisturbed wind speed V. This results in a pressure drop over the rotor plane which is the same for every value of r. It can be proven that this results in a triangular axial load which forms the thrust and in a constant radial load which supplies the torque.

The theoretical thrust coefficient C_t for the whole rotor is 8/9 = 0.889 for the optimal tip speed ratio. In practice C_t is lower because of the tip losses and because the blade is not effective up to the rotor centre. The effective blade length k’ of the VIRYA-7 rotor is only 2.5 m but the rotor radius R = 3.5 m. Therefore there is a disk in the centre with an area of about 0.082 of the rotor area on which almost no thrust is working. This results in a theoretical thrust coefficient C_t = 8/9 * 0.918 = 0.816.

Because of the tip losses the real C_t value is substantially lower. Assume this results in a real practical value of $C_t = 0.7$. It is assumed that the thrust coefficient is constant for values of λ in between 0.75 λ_d and $\lambda_{unloaded}$.
Substitution of $C_t = 0.7$, $\delta = 30°$, $\rho = 1.2$ kg/m^3, V = 10.5 m/s, R = 3.5 m and B = 3 in formula 10 gives $F_{t\,\delta\,bl} = 446$ N.

For a pure triangular load, the same moment is exerted in the heart of the rotor as for a point load which exerts in the centre of gravity of the triangle. The centre of gravity is lying at 2/3 R = 2.333 m. Because the effective blade length is only k', there is no triangular load working on the blade but a load with the shape of a trapezium as the triangular load over the part R – k' falls off. The centre of gravity of the trapezium has been determined graphically and is lying at about $r_1 = 2.45$ m.

The maximum bending stress is not caused at the heart of the rotor but at the edge of the hub because the strip bends backwards from this edge. This edge is lying at $r_2 = 0.08$ m. At this edge we find a bending moment $M_{b\,t}$ caused by the thrust which is given by:

$$M_{b\,t} = F_{t\,\delta\,bl} * (r_1 - r_2) \qquad \text{(Nm)} \qquad (11)$$

Substitution of $F_{t\,\delta\,bl} = 446$ N, $r_1 = 2.45$ m and $r_2 = 0.08$ m in formula 11 gives $M_{b\,t} = 1057$ Nm = 1057000 Nmm.

For the stress we use the unit N/mm^2 so the bending moment has to be given in Nmm. The bending stress σ_b is given by:

$$\sigma_b = M / W \qquad \text{(N/mm}^2\text{)} \qquad (12)$$

The moment of resistance W of a strip is given by:

$$W = 1/6\ bh^2 \qquad \text{(mm}^3\text{)} \qquad (13)$$

(12) + (13) gives:

$$\sigma_b = 6\ M / bh^2 \qquad \text{(N/mm}^2\text{)} \qquad \text{(M in Nmm)} \qquad (14)$$

Substitution of M = 1057000 Nmm, b = 120 mm and h = 15 mm in formula 14 gives $\sigma_b = 235$ N/mm^2. For this stress the effect of the stress reduction by bending forwards of the blade caused by the centrifugal force in the blade has not yet been taken into account. The gyroscopic moment has also not yet been taken into account.

Next it is investigated how far the blade bends backwards as a result of the thrust load and what influence this bending has on the centrifugal moment. Hereby it is assumed that the strip is only bending over part from the root of the blade to the hub. The root of the blade lies at $r_3 = 0.5$ m = 500 mm.

So the length of the strip l which is loaded by bending is given by:

$$l = r_3 - r_2 \qquad \text{(mm)} \qquad (15)$$

The load from the blade on the strip at r_3 can be replaced by a moment M and a point load F. F is equal to $F_{t\,\delta\,bl}$. M is given by:

$$M = F * (r_1 - r_3) \qquad \text{(Nmm)} \qquad (16)$$

The bending angle ϕ (in radians) at r_3 for a strip with a length l is given by (combination of the standard formulas for a moment plus a point load):

$\phi = l * (M + ½ Fl) / EI$ (rad) (17)

The bending moment of inertia I of a strip is given by:

$I = 1/12\ bh^3$ (mm^4) (18)

(15) + (16) + (17) + (18) gives:

$\phi = 12 * F * (r_3 - r_2) * \{(r_1 - r_3) + ½ (r_3 - r_2)\} / (E * bh^3)$ (rad) (19)

Substitution of F = 446 N, r_3 = 500 mm, r_2 = 80 mm, r_1 = 245 0 mm, E = 2.1 * 10^5 N/mm^2, b = 120 mm and h = 15 mm in formula 19 gives: ϕ = 0.05709 rad = 3.27°. This is an angle which can't be neglected. In report KD 684 (ref. 9) a formula is derived for the angle ε with which the blade moves backwards if it is connected to the hub by a hinge. This formula is valid if both the axial load and the centrifugal load are triangular. For the VIRYA-7 this is not exactly the case but the formula gives a good approximation. The formula is given by:

$$\varepsilon = \arcsin \left(\frac{C_t * \rho * R^2 * \pi}{B * A_{pr} * \rho_{pr} * \lambda^2} \right) \quad (°) \qquad (20)$$

In this formula A_{pr} is the cross sectional area of the airfoil (in m^2) and ρ_{pr} is the density of the used airfoil material (in kg/m^3). The Gö 711 airfoil is made from a sheet size 500 * 2 mm. So the cross sectional area of the sheet is 500 * 2 = 1000 mm^2 = 0.001 m^2. The blade is made of stainless steel with a density ρ_{pr} of about ρ_{pr} = 7.8 * 10^3 kg/m^3. It is assumed that he rotor is loaded such that it runs with de design tip speed ratio λ = 7. Substitution of C_t = 0.7, ρ = 1.2 kg/m^3, R = 3.5 m, B = 3, A_{pr} = 0.001 m^2, ρ_{pr} = 7.8 * 10^3 kg/m^3 and λ = 7 in formula 20 gives: ε = 1.62°. This angle is smaller than the calculated angle of 3.27° with which the blade would bend backwards if the compensating effect of the centrifugal moment is not taken into account. This means that the real bending angle will be less than 1.62°.

The real bending angle ε is determined a follows. A thrust moment M_t = 1057 Nm is working backwards and M_t is independent of ε for small values of ε. A bending moment M_b is working forwards and M_b is proportional with ε. M_b = 1057 Nm for ε = 3.27°. A centrifugal moment M_c is working forwards and M_c is also proportional with ε. M_c = 1057 Nm for ε = 1.62°. The path of these three moments is given in figure 7. The sum total of $M_b + M_c$ is determined and the line $M_b + M_c$ is also given in figure 7.

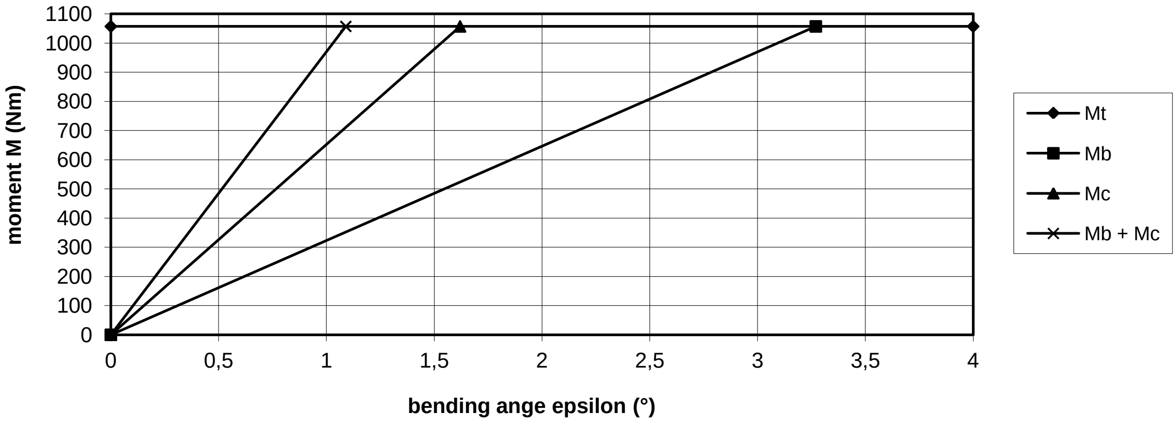

fig. 7 Path of M_t, M_b, M_c, and $M_b + M_c$ as a function of ε

The point of intersection of the line of M_t with the line of $M_b + M_c$ gives the final angle ε. In figure 7 it can be seen that ε = 1.09°. This is a factor 0.333 of the calculated angle of 3.27°. Because the bending stress is proportional to the bending angle it will also be a factor 0.333 of the calculated stress of 235 N/mm^2 resulting in a stress of about 78 N/mm^2. This is a rather low stress but up to now the gyroscopic moment, which can be rather large, has not yet been taken into account.

The gyroscopic moment is caused by simultaneously rotation of rotor and head. One can distinguish the gyroscopic moment in a blade and the gyroscopic moment which is exerted by the whole rotor on the rotor shaft and so on the head. On a rotating mass element dm at a radius r, a gyroscopic force dF is working which is maximum if the blade is vertical and zero if the blade is horizontal and which varies with sinα with respect to a rotating axis frame. α is the angle with the blade axis and the horizon. So it is valid that $dF = dF_{max} * \sin\alpha$. The direction of dF depends on the direction of rotation of both axis and dF is working forwards or backwards. The moment dF * r which is exerted by this force with respect to the blade is therefore varying sinusoidal too.

However, if the moment is determined with respect to a fixed axis frame it can be proven that it varies with $dF_{max} * r \sin^2\alpha$ with respect to the horizontal x-axis and with $dF_{max} * \sin\alpha * \cos\alpha$ with respect to the vertical y-axis. For two and more bladed rotors it can be proven that the resulting moment of all mass elements around the y-axis is zero.

For a single blade and for two bladed rotors, the resulting moment of all mass elements with respect to the x-axis is varying with $\sin^2\alpha$, so just the same as for a single mass element. However, for three and more bladed rotors, the resulting moment of all mass elements with respect to the x-axis is constant. The resulting moment with respect to the x-axis for a three (or more) bladed rotor is given by the formula:

$$M_{gyr\ x\text{-}as} = I_{rot} * \Omega_{rot} * \Omega_{head} \qquad \text{(Nm)} \qquad (21)$$

In this formula I_{rot} is the mass moment of inertia of the whole rotor around the axis of rotation, Ω_{rot} is the angular velocity of the rotor and Ω_{head} is the angular velocity of the head.

The resulting moment is constant for a three bladed rotor because adding three $\sin^2\alpha$ functions which make an angle of 120° which each other, appear to result in a constant value. The three functions are given in figure 8. It can be proven for a three bladed rotor that the sum value of the three blades is equal to 3/2 of the peak value of one blade.

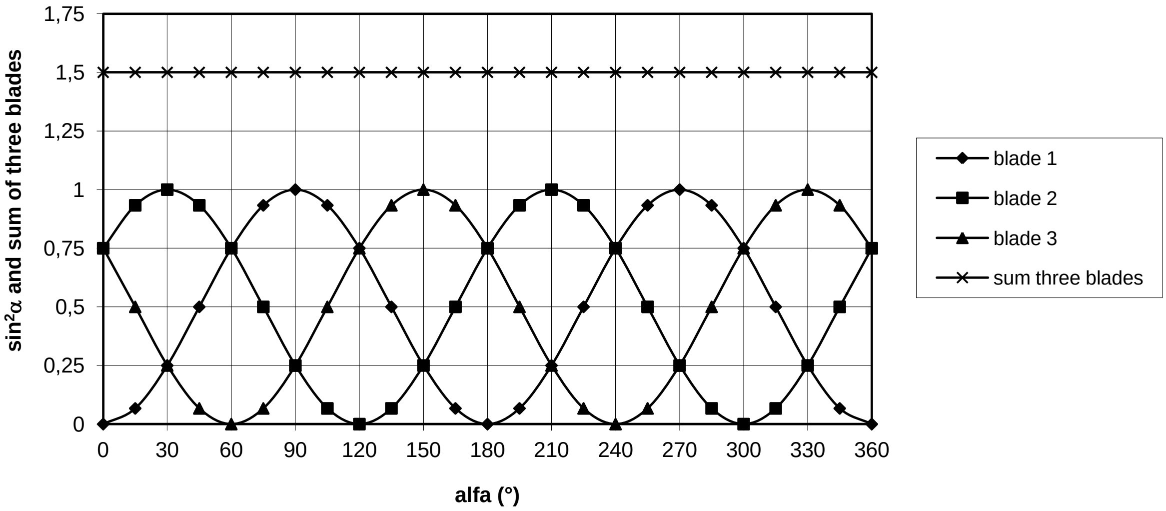

fig. 8 Path of $\sin^2\alpha$ and the sum of three blades

For the calculation of the blade strength we are not interested in the variation of the gyroscopic moment with respect to a fixed axis frame but in variation of the moment in the blade itself so with respect to a rotation axis frame for which it was explained earlier that the moment is varying sinusoidal. If the blade is vertical both axis frames coincide and the moment for both axis frames is the same. The maximum moment in one blade is then 2/3 of the sum moment as given by formula 21. The variation of the moment in the blade with respect to a rotating axis frame is therefore given by:

$$M_{gyr\ bl} = 2/3 \sin\alpha * I_{rot} * \Omega_{rot} * \Omega_{head} \quad \text{(Nm)} \qquad (22)$$

For a three bladed rotor, the moment of inertia of the whole rotor I_{rot} is three times the moment of inertia of one blade I_{bl}. Therefore it is valid that:

$$M_{gyr\ bl} = 2 \sin\alpha * I_{bl} * \Omega_{rot} * \Omega_{head} \quad \text{(Nm)} \qquad (23)$$

Up to now it is assumed that the blades have an infinitive stiffness. However, in reality the blades are flexible and will bend by the fluctuations of the gyroscopic moment. Therefore the blade will not follow the curve for which formula 22 and 23 are valid. I am not able to describe this effect physically but the practical result of it is that the strong fluctuation on the $\sin^2\alpha$ function is rather flattened. However, the average moment is assumed to stay the same as given by formula 23. I estimate that the flattened peak value is given by:

$$M_{gyr\ bl\ max} = 1.2 * I_{bl} * \Omega_{rot} * \Omega_{head} \quad \text{(Nm)} \qquad (24)$$

For the chosen blade geometry it is calculated that I_{bl} = 111 kgm^2. The maximum loaded rotational speed of the rotor can be read in figure 4 of and it is found that n_{max} = 174 rpm. This gives $\Omega_{rot\ max}$ = 18.2 rad/s (because $\Omega = \pi * n / 30$).

It is not easy to determine the maximum yawing speed. The VIRYA-7 is provided with the hinged side vane safety system which has a light van blade and a large moment of inertia of the whole head around the tower axis. This is because the vane arm is a part of the head. For sudden variations in wind speed and wind direction the vane blade will therefore react very fast but the head will follow only slowly. It is assumed that the maximum angular velocity of the head can be 0.14 rad/s at very high wind speeds.
Substitution of I_{bl} = 111 kgm^2, $\Omega_{rot\ max}$ = 18.2 rad/s and $\Omega_{head\ max}$ = 0.14 rad/s in formula 24 gives: $M_{gyr\ bl\ max}$ = 339 Nm = 339000 Nmm.
Substitution of M = 339000 Nmm, b = 120 mm and h = 15 mm in formula 14 gives $\sigma_{b\ max}$ = 75 N/mm^2. This value has to be added to the bending stress of 78 N/mm^2 which was the result of the thrust because there is always a position were both moments are strengthening each other. This gives $\sigma_{b\ tot\ max}$ = 153 N/mm^2. The minimum stress is 78 - 75 = 3 N/mm^2. So the stress is not becoming negative and therefore it is not necessary to take the load as a fatigue load.

The strip is made out of stainless steel with quality 1.4404 (AISI 316L). The 0.2 % deformation limit lays at a stress of 200 N/mm^2. However, this is for a pulling stress. The allowable bending stress is a lot higher and I expect about 270 N/mm^2. The calculated stress is much lower than the 0.2 % deformation stress for bending, so the strip is strong enough. In reality the blade will also bend somewhat. This reduces the bending of the strip and therefore the stress in the strip will be somewhat lower than the calculated value. It might even be better to use bare drawn mild steel as this has a much higher 0.2 % deformation limit of 300 N/mm^2.

7.2 Bending stress in the spoke for a stopped rotor

I is assumed that the rotor is stopped by a brake. For a stopped rotor there is no compensating effect of the centrifugal moment on the moment of the thrust. However, there is also no gyroscopic moment. The safety system is also working if the rotor is stopped but a much larger wind speed will be required to generate the same thrust as for a rotating rotor.

In chapter 7.1 it has been calculated that the maximum thrust on one blade for a rotating rotor is 446 N for V = V_{rated} = 10.5 m/s and δ = 30°. The head turns out of the wind such at higher wind speeds, that the thrust stays almost constant above V_{rated}. A stopped rotor will therefore also turn out of the wind by 30° if the force on one blade is 446 N. Also for a slowed down rotor the force is staying constant for higher yaw angles. However, for a stopped rotor, the resulting force of the blade load is exerting in the middle of the blade at r_4 = 2 m because the relative wind speed is constant along the whole blade. The bending moment around the edge of the hub is therefore somewhat smaller. Formula 11 changes into:

$$M_{b\ t} = F_{t\ \delta\ bl} * (r_4 - r_2) \qquad \text{(Nm)} \qquad (25)$$

Substitution of $F_{t\ \delta\ bl}$ = 446 N, r_4 = 2 m and r_2 = 0.08 m in formula 16 gives $M_{b\ t}$ = 856 Nm = 856000Nmm. Substitution of M = 856000 Nmm, b = 120 mm and h = 15 mm in formula 25 gives σ_b = 190 N/mm^2. This is higher than the calculated stress for a rotating rotor. The load is not fluctuating and therefore it is surly not necessary to use the allowable fatigue stress. But the spoke is strong enough for a stopped rotor.

Because the spoke and the blade are rather flexible it has to be checked if a stopped rotor can't hit the tower. In chapter 7.1 it has been calculated, for no compensation of the gyroscopic moment, that the bending angle is 3.27° for a stress of 235 N/mm^2. So for a stress of 190 N/mm^2 the bending angle will be 3.27 * 190 / 235 = 2.64°. For a rotor radius of R = 3.5 m this results in a movement at the tip of about 0.16 m. Because the blade itself will bend too, the movement will be larger and it is expected that it will be about 0.2 m. The minimum distance in between the blade tip and the tower pipe is much larger if the blade is not bending. So there is no chance that the blade hits the tower for a stopped rotor.

8 Checking of the head geometry and the tower

The head of the VIRYA-6.5 is taken as a starting point. The VIRYA-6.5 head is derived from the VIRYA-4.2 head as the VIRYA-4.2 has been tested for two years and it has functioned well. The scaling procedure is explained in chapter 5 of report KD 579 (ref. 1). The head geometry of the VIRYA-6.5 is given in figure 4 of KD 579. The VIRYA-6.5 has a massive vane blade of 15 mm ocoume plywood. This results in a rated wind speed of about 11 m/s. The VIRYA-7 has a hollow vane blade made out of two 6 mm plates with a distance in between the plates of about 10 mm. This results in a rated wind speed of about 10.5 m/s. The height and width of both vanes are the same. A vane is made out of a standard sheet size 1530 * 3100 mm by cutting it in half. This is the largest standard sheet size available.

The thrust at a certain wind speed and yaw angle is larger for the VIRYA-7 than for the VIRYA-6.5. The factor is equal to the factor in between the swept area of the rotors which is $(7 / 6.5)^2 = 1.16$. So if the head geometry would be kept the same, the moment executed by the thrust would also be a factor 1.16 larger. This isn't allowed because this would mean that the rotor isn't perpendicular to the wind at low wind speeds. A larger vane blade isn't possible because sheet size 1530 * 3100 mm is already the largest standard size. So balance in between the rotor moment and the vane moment at low wind speeds can only be realised by reduction of the eccentricity e or by increase of the length vane arm R_v.

Assume that e is a factor 0.08 * D. So e = 0.08 * 7 = 0.56 m. This is only 0.02 m smaller than the value e = 0.58 m which was chosen for the VIRYA-6.5. The rotor moment is reduced by a factor 0.56 / 0.58 = 0.966 because of the reduced eccentricity. So this isn't enough to compensate the increase of the rotor thrust. The other option is to increase R_v. In figure 4 of KD 579 it can be seen that the vane arm is built up from 2 m, 5" pipe and 1.5 m, 3" pipe. A part of the 5" pipe is lying at the front side of the tower centre. The length of this part depends on de generator dimensions. The VIRYA-7 makes use of an axial flux generator of Hefei Top Grand and the housing of this generator is bolted to a generator bracket which is in parallel to the rotor plane. Assume that the length of the part of the 5" pipe before the tower centre is kept the same. Assume that the length of the 3" pipe is chosen 2 m instead of 1.5 m. One has to take the increase in the direction of the vane hinge axis. This results in an increase of R_v of about 0.48 m. So R_v becomes 3.88 + 0.48 = 4.36 m. The vane moment is determined by $R_v + i_1$. So $R_v + i_1 = 4.36 + 0.566 = 4.926$ m. For the VIRYA-6.5 it is found that $R_v + i_1 = 3.88 + 0.566 = 4.446$ m. So the vane moment increases by a factor 4.926 / 4.446 = 1.108.

The combined effect of the reduced eccentricity and the increased value of $R_v + i_1$ results in a factor 1.108 / 0.966 = 1.147. This is almost the same as the factor 1.16 for the increase of the rotor thrust and therefore I think that this new geometry of the head is okay. But a detailed composite drawing of the head has to be made and the balance of moments at low wind speeds has to be checked for the final geometry.

Another point is that lengthening of the 3" pipe with 0.5 m makes that the relative stiffness of the whole vane arm becomes lower. It must be checked on a prototype if the stiffness of the van arm is still high enough to prevent flutter of the vane at high wind speeds.

In chapter 1 it was suggested to use the tubular tower of the VIRYA-6.5. The rotor thrust at high wind speeds is increased by a factor $(7 / 6.5)^2 = 1.16$ because of the larger rotor diameter. However it is reduced by a factor $(10.5 / 11)^2 = 0.911$ because of the lower rated wind speed. Finally this results in increase of the maximum thrust by a factor 1.16 * 0.911 = 1.057. This is only a small increase and so I think that the VIRYA-6.5 tower is strong enough. Calculations of the VIRYA-6.5 tower are given in chapter 6.2 of report KD 579 (ref. 1).

Building of a prototype of the VIRYA-7 with the chosen PM-generator of Hefei Top Grand is only possible if detailed drawings are available but I won't make them. So only companies with enough engineering capacity should start with the VIRYA-7. The VIRYA-7 is certainly not a windmill which can be built by an amateur.

9 Using a rotor with round spokes

The rotor as given in figure 1 has spokes made out of strip 150 * 15 mm. Each strip has to be twisted 6.5° to get the correct blade angle. A very large twisting moment is required and therefore a special twisting tool is needed. A different construction for the VIRYA-7 rotor with round spokes is described in chapter 2 of report KD 773 (ref. 10). The wind turbine described in this report is equipped with the pendulum safety system with a torsion spring but the same rotor can also be used with the hinged side vane safety system. The round spokes are made out of stainless steel bar with a diameter of 40 mm. This bar is flattened to a thickness of 31 mm for the part where is overlaps the blade. A blade is connected to a spoke by four bolts M12 * 70. The inner side of the bare is provided with a half taper angle of 3°. The hub is made out of stainless steel bar with a diameter of 210 mm. It has three 80 mm wide ears under 120°. Each ear is provided with a tapered hole. A spoke is pulled in this hole by a bolt M22 * 50. The advantage of this construction is that the blade can be adjusted to any blade angle. The distance in between the spoke axis and the generator axis is 70 mm. Figure 1 out of KD 773 is copied as figure 9.

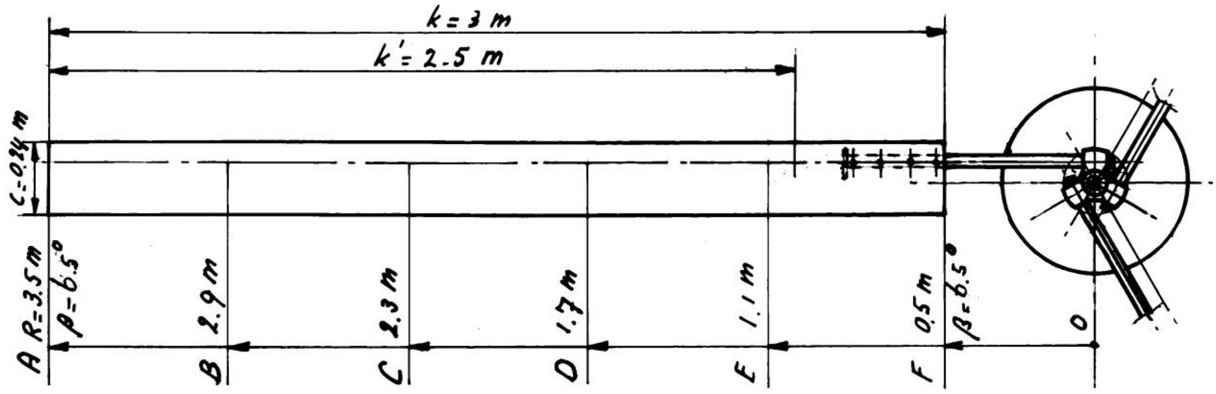

fig. 9 VIRYA-7 rotor with round spokes

10 Using of a resistance as load for heating

Instead of using an inverter, it is also possible to use a resistance as load. The generated power in the resistance can be used for heating of a room. Assume that the same resistance is used as used for the measurements of the manufacturer. So this means that the P_{mech}-n and P_{el}-n curves for a resistance load as given in figure 4 are followed. The matching is good for wind speeds in between 5 m/s and 10.5 m/s because the working point is lying close to the optimum cubic line. However, the P_{mech}-n curve is about touching the P-n curve of the rotor for V = 4 m/s. This means that the load is too strong at low wind speeds and the rotor will slow down to almost stand still for a wind speed below 4 m/s. The rotor will certainly not start with the load connected. This problem can be solved by connecting the load at about 120 rpm (reached unloaded at about V = 4 m/s) and disconnecting the load at about 80 rpm. However, this has as disadvantage that no power is generated for wind speeds below 4 m/s. This problem can be solved by using a star-delta switch and a higher value for the load resistance. The generator winding is now connected in star for low rotational speeds and connected in delta for high rotational speeds.

At chapter 7 of KD 579 (ref. 1) it has been calculated that the resistance used by the manufacturer is 20.25 Ω if the load resistors are connected in star. The load resistance must be a factor three higher, so 60.75 Ω, to generate the same power if the resistors are connected in delta. This follows directly from the law of Ohm as the power is given by $P = U^2 / R$ (W). The AC voltage over one resistor is a factor √3 higher in delta than in star. The voltage in between two phases U = 450 V for n = 250 rpm. So the power in one phase is $450^2 / 60.75 = 3333$ W.

So the power of three resistors is 3 * 3333 = 9999 W. This is the same as for three resistors of 20.25 Ω connected in star. So this will also result in the same P_{mech}-n and P_{el}-n curves.

However, if three 60.75 Ω resistors are connected in star, the load resistance is a factor three higher than for three 20.25 Ω resistors connected in star and the required mechanical power will therefore be a factor three lower. This will give an acceptable matching for low wind speeds. The matching at low rotational speeds can better be checked in the Q-n curve than in the P-n curve because the P-n curves for low rotational speeds all go to zero for n = 0 rpm. The Q-n curves are made in the same way as the P-n curves but the C_q-λ curve and the formula for the torque Q have to be used. The C_q-λ curve is given in figure 3. The Q-n curves are made for wind speeds up to 8 m/s. The rotor is perpendicular to the wind up to V = 7 m/s. The formula for Q_δ is given as formula 7.7 of report KD 35. Substitution of $\rho = 1.2$ kg/m^3 and R = 3.5 m in this formula gives formula 14.

$$Q_\delta = 80.817 * C_q * \cos^2\delta * V^2 \qquad \text{(Nm)} \qquad (26)$$

Formula 8 is still valid. The result of the calculations is given in table 3.

		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 = 0°		V = 8 m/s δ = 5°	
λ	C_q	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n_δ (rpm)	Q_δ (Nm)
0	0.0055	0	4.0	0	7.1	0	11.1	0	16.0	0	21.8	0	28.2
1	0.008	8.2	5.8	10.9	10.3	13.6	16.2	16.4	23.3	19.1	31.7	21.7	41.1
2	0.018	16.4	13.1	21.8	23.3	27.3	36.4	32.7	52.4	38.2	71.3	43.5	92.4
3	0.0367	24.6	26.7	32.7	47.5	40.9	74.1	49.1	106.8	57.3	145.3	65.2	188.4
4	0.055	32.7	40.0	43.7	71.1	54.6	111.1	65.5	160.0	76.4	217.8	87.0	282.3
5	0.066	40.9	47.9	54.6	85.3	68.2	133.3	81.9	192.0	95.5	261.4	108.7	338.8
6	0.0675	49.1	49.0	65.5	87.3	81.9	136.4	98.2	196.4	114.6	267.3	130.5	346.5
7	0.0614	57.3	44.6	76.4	79.4	95.5	124.1	114.6	178.6	133.7	243.1	152.2	315.2
8	0.0506	65.5	36.8	87.3	65.4	109.1	102.2	131.0	147.2	152.8	200.4	174.0	259.7
9	0.0367	73.7	26.7	98.2	47.5	122.8	74.1	147.3	106.8	171.9	145.3	195.7	188.4
10	0.0205	81.9	14.9	109.1	26.5	136.4	41.4	163.7	59.6	191.0	81.2	217.4	105.2
11.2	0	91.7	0	122.2	0	152.8	0	183.3	0	213.9	0	243.5	0

table 3 Calculated values of n_δ and Q_δ as a function of λ and V for the VIRYA-7 rotor

The Q-n curves of the rotor derived from table 3 are given in figure 10. The optimum parabola which can be drawn through the points for λ = 6 is also given in figure 10. The torque for a resistance load is a straight line through the origin and is given in figure 10 for three 20.25 Ω resistors connected in star. The same line is found for three 60.75 Ω resistors connected in delta. The line for three 60.75 Ω resistors connected in star is also given in figure 10. The line for three 60.75 Ω resistors connected in star is laying a factor 3 lower than the line for three 60.75 Ω resistors connected in delta.

In figure 10 it can be seen that the line for 3 * 60.75 Ω for connection in delta is intersecting with Q-n curve of the rotor for V = 5 m/s at rotational speeds of about 8, 40 and 77 rpm. So for rotational speeds in between about 8 rpm and 40 rpm it is lying higher than the Q-n curve of the rotor for V = 5 m/s. This means that if the rotor starts from stand still position, it will reach only a rotational speed of about 8 rpm at V = 5 m/s and so it will not accelerate to rotational speeds for which a stable working point is reached. Only the Q-n curve of the rotor for V = 8 m/s is laying completely left from the line for 3 * 60.75 Ω for connection in delta. This means that a wind speed of 8 m/s is needed if this load is connected permanently!

In figure 10 it can be seen that the line for 3 * 60.75 Ω for connection in star is lying even lower than the Q-n curve of the rotor for V = 3 m/s. So the rotor will certainly start at a wind speed of 3 m/s if the 3 * 60.75 Ω load for connection in star is connected to the generator at stand still position. It will reach a stable working point at V = 3 m/s for a rotational speed of about 64 rpm. This stable working point is lying at the right side of the optimum parabola.

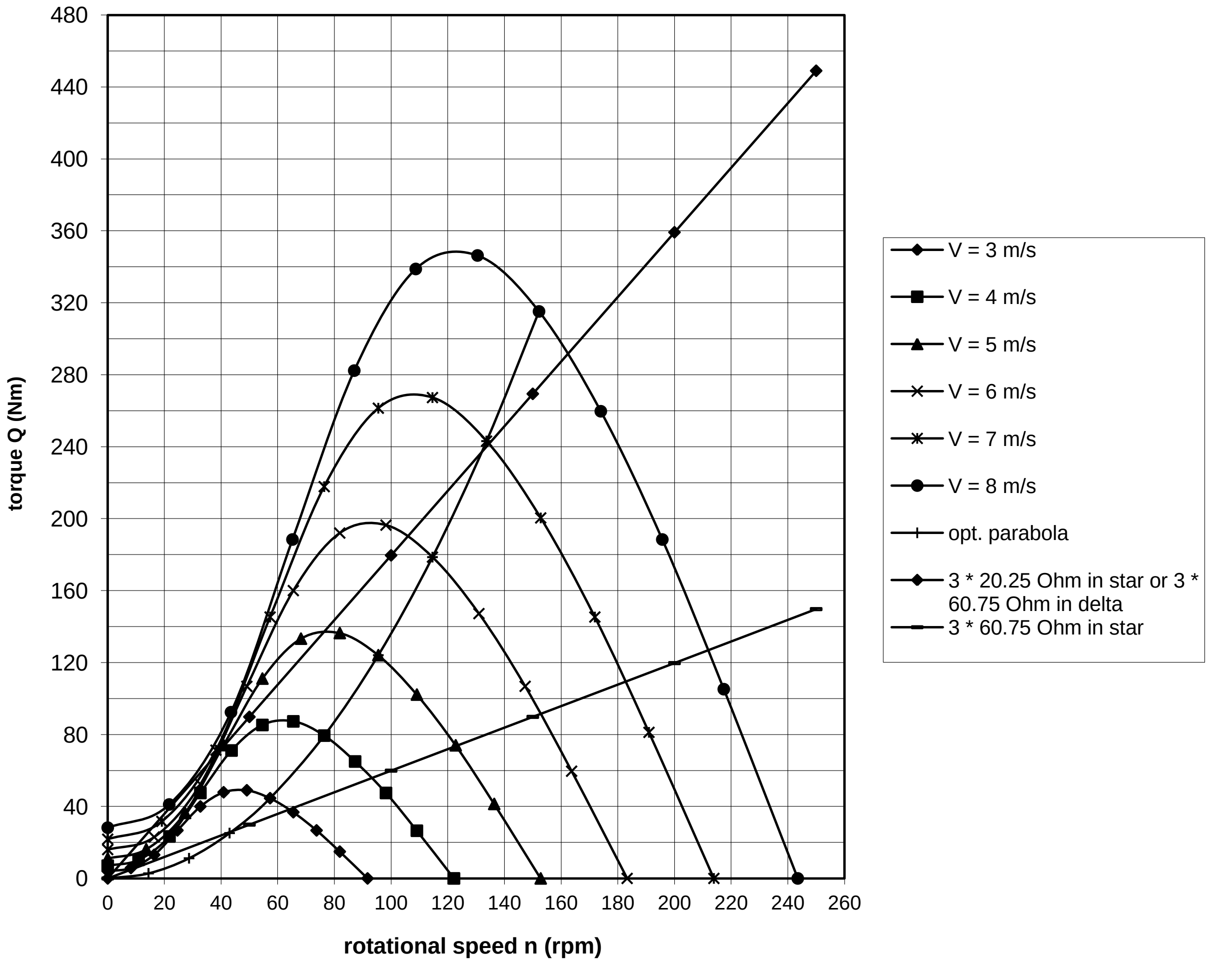

fig. 10 Q-n curves of the VIRYA-7 rotor, optimum parabola

Next it is assumed that it is switched from star to delta if a rotational speed of 124 rpm is reached. This rotational speed belongs to a wind speed of about 5 m/s. So at this point, the torque increases from about 57 Nm up to about 220 Nm. This torque can't be supplied at a wind speed of 5 m/s and so the rotational speed will slow down. It slows down to a rotational speed of 77 rpm belonging to a torque of about 138 Nm. Next it is assumed that it is switched back from delta to star at a rotational speed of 60 rpm. So for low wind speeds, the connection is switched in between star and delta. For higher wind speeds delta connection is maintained.

This results in a positive power for wind speeds higher than 3 m/s and so a star delta switch is an option to prevent loss of power at low wind speeds. However, this option has as disadvantages that the torque suddenly increases strongly if the system switches from star to delta and that the working point for wind speeds in between 3 m/s and 5 m/s is lying far to the right side of the optimum cubic line if the winding is connected in star. The C_p of the rotor is therefore a lot lower than the optimum C_p.

It might be possible to rectify the 3-phase current and to develop an electronic circuit with resistors and transistors with which it is possible to exactly follow the optimum parabola. A simpler option is to rectify the 3-phase current and to use a resistor with a value such that the line for 3 * 60.75 Ω in star is followed up to a rotational speed of about 75 rpm. At this rotational speed, the system will have a certain critical DC-voltage U_{crit}. Next in parallel to the resistor, a voltage controller plus dump load is placed similar to the system to limit the maximum charging voltage for a battery. The dump load contains resistors and transistors. So this system keeps the voltage constant at U_{crit} for higher rotational speeds. This results in a strong increase of the torque and the optimum parabola will about be followed at higher rotational speeds than 75 rpm. This idea needs more research to be developed.

Building of a prototype of the VIRYA-7 with the chosen PM-generator of Hefei Top Grand is only possible if a composite drawing is made and if detailed drawings are available. This includes detailed drawings of the rotor, the head with the vanes and torsion springs and the tower plus foundation but I won’t make them.

If the wind turbine is used for grid connection, the right inverter has to be found. If the wind turbine is used for direct generation of heat, one has to design a controller and a heat capacitor with a water or sand reservoir in which the load resistors are imbedded. The advantage of using water is that water out of the heat capacitor can be guided to radiators in different rooms. Storage of heat in sand is only possible for a heat capacitor in the living room.

The main disadvantage of a resistance load is that the generated power can only be used for heating. Further development of such a system is a lot of work. So only companies with enough engineering and manufacturing capacity should start with the VIRYA-7. The VIRYA-7 is certainly not a windmill which can be built by an amateur.

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