**Calculations executed for the 2-bladed rotor of the VIRYA-10B2 windmill ($\lambda_d$ = 7, Gö 711 airfoil, wooden blades) using the hinged side vane safety system and a generator type TGET770-H-10KW-100R for grid connection**

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KD 787



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## 1 Introduction

The original VIRYA-10 with a 3-bladed wooden rotor with a design tip speed ratio $\lambda_d = 6$ is described in public report KD 715 (ref. 1). This wind turbine is equipped with the pendulum safety system with a torsion spring. The VIRYA-10R with a 2-bladed rotor made out of Roofmate, glass fibre and epoxy and a design tip speed ratio $\lambda_d = 7$ is described in report KD 774 (ref. 2). This wind turbine is provided with the hinged side vane safety system. Both wind turbines make use of a Chinese axial flux PM-generator of Hefei Top Grand type TGET770-H-10KW-100R. The whole generator housing is rotating for this generator type. The shaft has a diameter of 98 mm. However, it isn't sure if a rotor made out of Roofmate is strong enough. So the idea is to design a 2-bladed rotor with wooden blades with a design tip speed ratio $\lambda_d = 7$ which makes use of the same hinged side vane safety system as used for the VIRYA-10R. This wind turbine is called the VIRYA-10B2.

The VIRYA-10B2 will be grid connected. Selection of the right inverter is out of the scope of this report. The 18 m high tubular tower of the VIRYA-10 will also be used for the VIRYA-10B2.

## 2 Description of the rotor of the VIRYA-10B2 windmill

A blade is made out of a 4.6 m long wooden plank with a width of 480 mm and a thickness of 72 mm. The chosen constant chord is 0.48 m. The whole blade is provided with the Gö 711 airfoil. The geometry and the characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 3). A disadvantage of the Gö 711 airfoil is that the aerodynamic characteristics are only available for the rather high Reynolds number Re = 4 * $10^5$ but as the chord is rather large, the Reynolds values will be rather high. The lower side of the Gö 711 airfoil is flat over 97.5 % of the chord which simplifies manufacture. The airfoil has a maximum thickness of 14.85 % of the chord. So the maximum thickness is 0.1485 * 480 = 71.28 mm. The place of the maximum thickness is situated at 0.3 * c = 0.3 * 0.48 = 0.144 m = 144 mm from the airfoil nose. The connecting bolts are positioned at this point.

The two blades are connected to each other by a 2 m long steel strip with a width of 250 mm and a thickness of 20 mm. A blade is connected to the connecting strip by three blots M32 and six nuts M32. A cambered sheet is mounted in between the bolt heads and the blade to prevent that the wood is damaged when the nuts are tightened. The generator shaft has a diameter of 98 mm and a length of 250 mm. The head has a bracket in which the generator shaft is clamped.

The front side of the generator housing has a collar with a diameter of 300 mm. The collar is provided with eight threaded holes M16 at a pitch circle of 220 mm. The connecting strip is connected to the generator by eight bolts M16 * 55. Locking liquid has to be used at these bolts. A sketch of the rotor is given in figure 1.

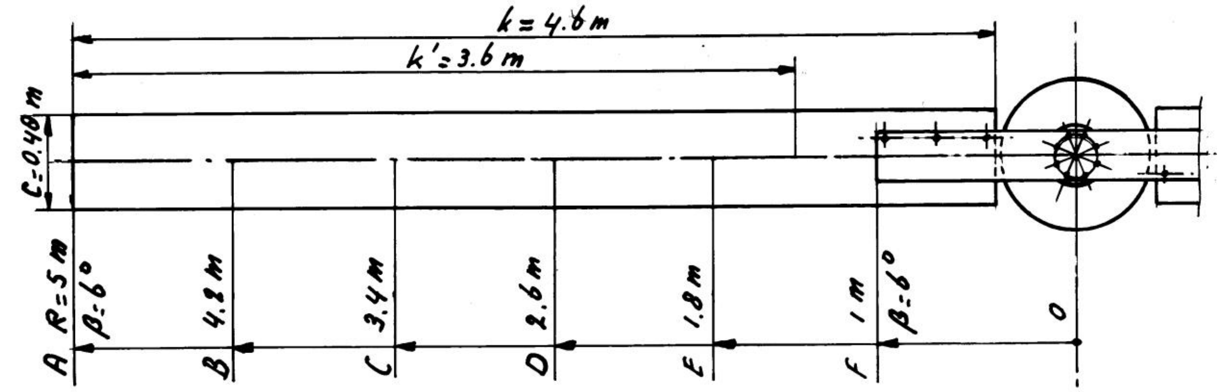


fig. 1 Sketch of the VIRYA-10B2 rotor

## 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 787) has its own formula numbering. Substitution of $\lambda_d$ = 7 and R = 5 m in formula (5.1) of KD 35 gives:

$\lambda_{r\,d} = 1.4 * r$ (-) (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 = 2 and c = 0.48 m in formula (5.4) of KD 35 gives:

$C_l = 26.180\ r\ (1 - \cos\phi)$ (-) (4)

Substitution of V = 5 m/s and c = 0.48 m in formula (5.5) of KD 35 gives:

$R_{e\,r} = 1.601 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)}$ (-) (5)

The blade is calculated for six stations A till F which have a distance of 0.8 m of one to another. Station F corresponds to the end of the connecting strip. First the theoretical values are determined for $C_l$, $\alpha$ and $\beta$. Next a constant value of $\beta$ is chosen linearised such that the linearised values correspond as good as possible with the theoretical values. The result of the calculations is given in table 1. The Reynolds values for the stations are calculated for a wind speed of 5 m/s because for most working hours, the windmill will be used at rather low wind speeds. The characteristics of the Gö 711 airfoil are given in report KD 285 (ref. 3).

| station | r (m) | $\lambda_{rd}$ (-) | $\phi$ (°) | c (m) | $C_{l\,th}$ (-) | $C_{l\,lin}$ (-) | $R_{e\,r} * 10^{-5}$ V = 5 m/s | $R_e * 10^{-5}$ Gö 711 | $\alpha_{th}$ (°) | $\alpha_{lin}$ (°) | $\beta_{th}$ (°) | $\beta_{lin}$ (°) | $C_d/C_{l\,lin}$ (-) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 5 | 7 | 5.4 | 0.48 | 0.59 | 0.61 | 11.26 | 4 | -0.9 | -0.6 | 6.3 | 6.0 | 0.026 |
| B | 4.2 | 5.88 | 6.4 | 0.48 | 0.69 | 0.7 | 9.47 | 4 | 0.3 | 0.4 | 6.1 | 6.0 | 0.020 |
| C | 3.4 | 4.76 | 7.9 | 0.48 | 0.85 | 0.82 | 7.70 | 4 | 2.1 | 1.9 | 5.8 | 6.0 | 0.017 |
| D | 2.6 | 3.64 | 10.2 | 0.48 | 1.08 | 1.01 | 5.92 | 4 | 5.1 | 4.2 | 5.1 | 6.0 | 0.015 |
| E | 1.8 | 2.52 | 14.4 | 0.48 | 1.49 | 1.33 | 4.17 | 4 | 11.5 | 8.4 | 2.9 | 6.0 | 0.021 |
| F | 1 | 1.4 | 23.7 | 0.48 | 2.21 | 1.35 | 2.65 | 4 | - | 17.7 | - | 6.0 | 0.155 |

table 1 Calculation of the blade geometry of the VIRYA-10B2 rotor

No value of $\alpha_{th}$ is found for station F because the required $C_l$ value can't be generated. The values $\beta_{th}$ for the most important stations A up to D vary only in between 6.3° and 5.1°. If a constant value $\beta_{lin}$ = 6° is chosen, the linearised angles are lying close to the theoretical angles for the most important outer side of the rotor. A sketch of the rotor is given in figure 1.

## 4 Determination of the $C_p$-$\lambda$ and the $C_q$-$\lambda$ curves

The determination of the $C_p$-$\lambda$ and $C_q$-$\lambda$ curves is given in chapter 6 of KD 35. The average $C_d/C_l$ ratio for the outer stations of the blade is about 0.02. Figure 4.6 of KD 35 (for B = 2) and $\lambda_{opt}$ = 7 and $C_d/C_l$ = 0.02 gives $C_{p\,th}$ = 0.465. The blade is stalling at station F. Therefore for the calculation of $C_p$, only the effective blade length k' half way in between station E and F is taken into account. This gives an effective blade length k' = 3.6 m.

Substitution of $C_{p\ th}$ = 0.465, R = 5 m and effective blade length k = k' = 3.6 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 $\lambda_{unl}$ = 11.2. The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

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

Formula 6 is only valid for a blade with a constant chord and a constant blade angle which is the case for this rotor. The chord c = 0.48 m and the blade angle $\beta$ = 6° for the whole blade. If the rotor is not rotating, the angle of attack $\alpha$ = 90° - $\beta$. So the angle of attack is 90° - 6° = 84°.

The $C_l$-$\alpha$ curves for the Gö 711 airfoil are not given for large angles $\alpha$. However, the airfoil is completely stalling during starting and it is expected that the $C_l$-$\alpha$ curve for large angles $\alpha$ will be about the same as the $C_l$-$\alpha$ curve for the Gö 623 airfoil. The $C_l$-$\alpha$ curve for the Gö 623 airfoil for large angles $\alpha$ is given in figure 5.10 of report KD 35 (ref. 5). For $\alpha$ = 84° it can be read in this figure that $C_l$ = 0.21. During starting, the whole blade is stalling. So for calculation of the starting torque coefficient, the real blade length k = 4.6 m is taken into account.

Substitution of B = 2, R = 5 m, k = 4.6 m, $C_l$ = 0.21 and c = 0.48 m in formula 6 gives that $C_{q\ start}$ = 0.0048. For the ratio between the starting torque and the optimum torque we find that it is 0.0048 / 0.0614 = 0.078. This is acceptable for a rotor with a design tip speed ratio of 7 and a constant chord. The starting wind speed $V_{start}$ of the rotor is calculated with formula 8.6 of KD 35 which is given by:

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

For the sticking torque $Q_s$ of the generator it is specified that it is less than 0.5 Nm. However this is the case if no oil seal is used at the generator shaft. But for horizontal positioning of the shaft, a seal is certainly necessary. Assume that the sticking torque with an oil seal is 4 Nm. Substitution of $Q_s$ = 4 Nm, $C_{q\ start}$ = 0.0048, $\rho$ = 1.2 kg/m$^3$ and R = 5 m in formula 7 gives that $V_{start}$ = 1.9 m/s. This is very low for a rotor with a design tip speed ratio of 7. It is the same as for the 2-bladed VIRYA-10R rotor.

In chapter 6.4 of KD 35 it is explained how rather accurate $C_p$-$\lambda$ and $C_q$-$\lambda$ curves can be determined if only two points of the $C_p$-$\lambda$ curve and one point of the $C_q$-$\lambda$ curve are known. The first part of the $C_q$-$\lambda$ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for $\lambda$ = 0. Kragten Design has developed a method with which the value of $C_q$ for low values of $\lambda$ can be determined (see report KD 97 ref. 5). With this method, it can be determined that the $C_q$-$\lambda$ curve is about straight and horizontal for low values of $\lambda$ if a Gö 711 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 open wind tunnel of the University of Technology Delft already on 20-11-1980. It has been found that the maximum $C_p$ was more than 0.4 and that the $C_q$-$\lambda$ curve for low values of $\lambda$ was not horizontal but somewhat rising. This effect has been taken into account and the estimated $C_p$-$\lambda$ and $C_q$-$\lambda$ curves for the VIRYA-10B2 rotor are given in figure 2 and 3. The low $C_q$ and $C_p$ values at low values of $\lambda$ are caused by stalling of the airfoil.

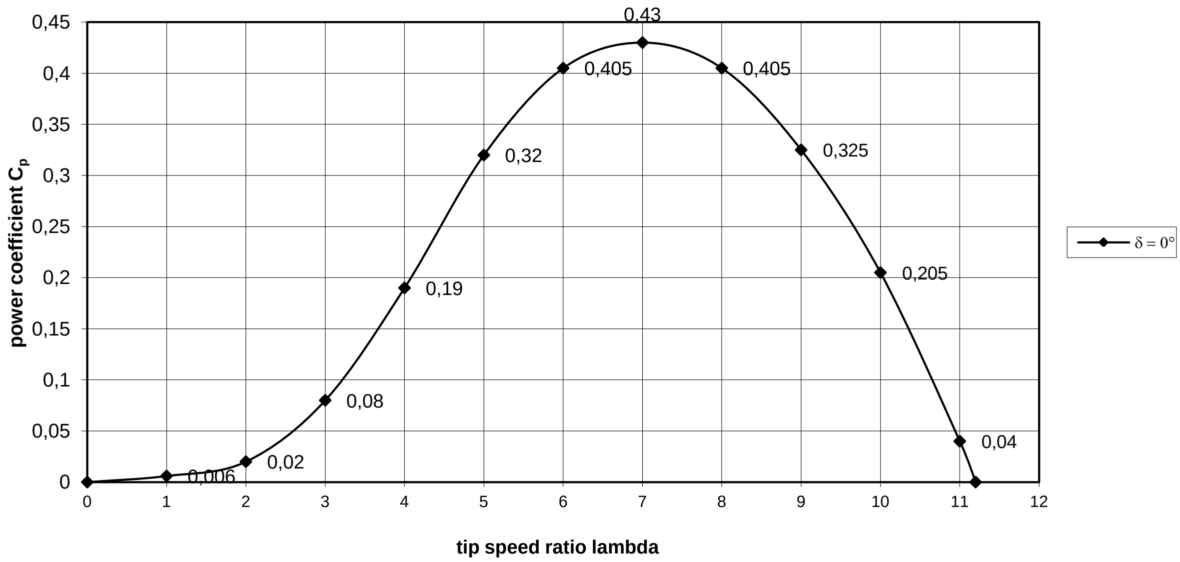


fig. 2 Estimated $C_p$-$\lambda$ curve for the VIRYA-10B2 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

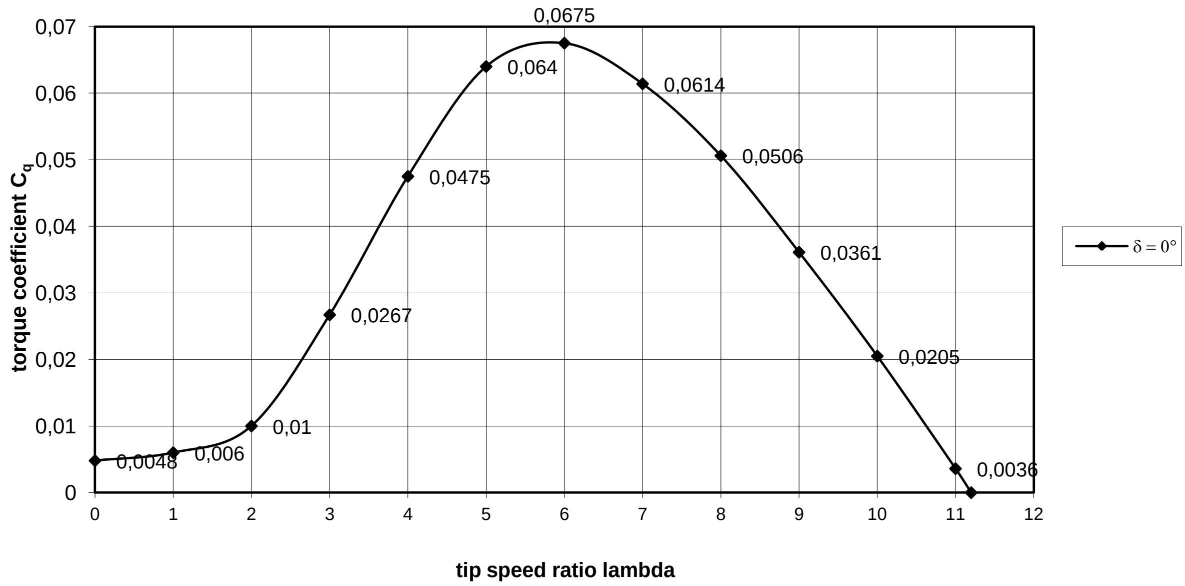


fig. 3 Estimated $C_q$-$\lambda$ curve for the VIRYA-10B2 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

## 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 (ref. 5). One needs a $C_p$-$\lambda$ curve of the rotor and the $\delta$-V curve of the safety system together with the formulas for the power P and the rotational speed n. The VIRYA-10B2 will be executed with the hinged side vane safety system which is described in report KD 213 (ref. 7) for the VIRYA-4.2 windmill. The VIRYA-10B2 head is derived from the head of the VIRYA-5 by scaling the outside dimensions with a factor 2. The VIRYA-5 head is described in chapter 10 of report KD 614 (ref. 7). However, the vane blade is hollow and made out of two sheets of 5.5 mm thick okoume plywood resulting in a rated wind speed of about 10 m/s. The estimated $\delta$-V curve is given in figure 3. The rotor starts turning out of the wind at a wind speed of about 6 m/s. The rotor is turned out of the wind 30° at a wind speed of 10 m/s. It is assumed that the ideal curve is followed for wind speeds above 10 m/s.

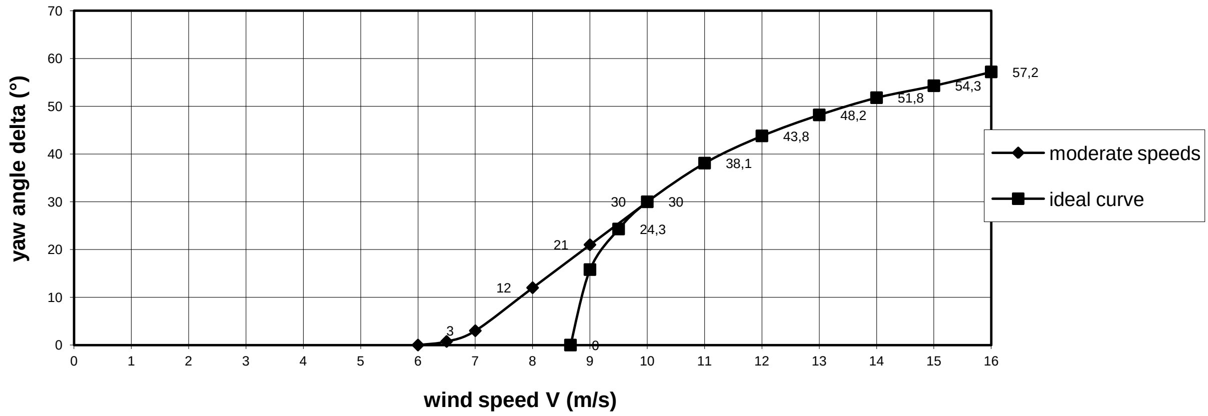


fig. 3  Estimated $\delta$-V curve for a hollow plywood vane blade

The P-n curves are used to check the matching with the $P_{mech}$-n curve of the generator and to determine the $P_{el}$-V curve. Because the P-n curve for low values of $\lambda$ appears to lie very close to each other, the P-n curves are not determined for very low values of $\lambda$. The P-n curves are determined for $C_p$ values belonging to $\lambda$ is 4, 5, 6, 7, 8, 9, 10 and 11.2 (see figure 2). The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9 and 10 m/s.

Substitution of R = 5 m in formula 7.1 of KD 35 gives:

$$n = 1.9099 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho$ = 1.2 kg / $m^3$ and R = 5 m in formula 7.10 of KD 35 gives:

$$P = 47.124 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

For a certain wind speed, for instance V = 3 m/s, related values of $C_p$ and $\lambda$ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed. For wind speeds higher than 6 m/s, the yaw angle $\delta$ is taken into account. The result of the calculations is given in table 2.

| | | V = 3 m/s δ = 0° | | V = 4 m/s δ = 0° | | V = 5 m/s δ = 0° | | V = 6 m/s δ = 0° | | V = 7 m/s δ = 3° | | V = 8 m/s δ = 12° | | V = 9 m/s δ = 21° | | V = 10 m/s δ = 30° | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| λ | $C_p$ | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) |
| 4 | 0.19 | 22.9 | 242 | 30.6 | 573 | 38.2 | 1119 | 45.8 | 1934 | 53.4 | 3058 | 59.8 | 4290 | 64.2 | 5311 | 66.2 | 5816 |
| 5 | 0.32 | 28.6 | 407 | 38.2 | 965 | 47.7 | 1885 | 57.3 | 3257 | 66.8 | 5151 | 74.7 | 7226 | 80.2 | 8945 | 82.7 | 9795 |
| 6 | 0.405 | 34.4 | 515 | 45.8 | 1221 | 57.3 | 2386 | 68.8 | 4122 | 80.1 | 6519 | 89.7 | 9145 | 96.3 | 11321 | 99.2 | 12396 |
| 7 | 0.43 | 40.1 | 547 | 53.5 | 1297 | 66.8 | 2533 | 80.2 | 4377 | 93.5 | 6922 | 104.6 | 9709 | 112.3 | 12020 | 115.8 | 13161 |
| 8 | 0.405 | 45.8 | 515 | 61.1 | 1221 | 76.4 | 2386 | 91.7 | 4122 | 106.8 | 6519 | 119.6 | 9145 | 128.4 | 11321 | 132.3 | 12396 |
| 9 | 0.325 | 51.6 | 414 | 68.8 | 980 | 85.9 | 1914 | 103.1 | 3308 | 120.2 | 5232 | 134.5 | 7339 | 144.4 | 9085 | 148.9 | 9948 |
| 10 | 0.205 | 57.3 | 261 | 76.4 | 618 | 95.5 | 1208 | 114.6 | 2087 | 133.5 | 3300 | 149.5 | 4629 | 160.5 | 5730 | 165.4 | 6275 |
| 11.2 | 0 | 64.2 | 0 | 85.6 | 0 | 107.0 | 0 | 128.3 | 0 | 149.5 | 0 | 167.4 | 0 | 179.7 | 0 | 185.3 | 0 |

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-10B2 rotor

The calculated values for n and P are plotted in figure 4. The optimum cubic line which is going through the tops of the $P_{mech}$-n curves is also given in figure 4.

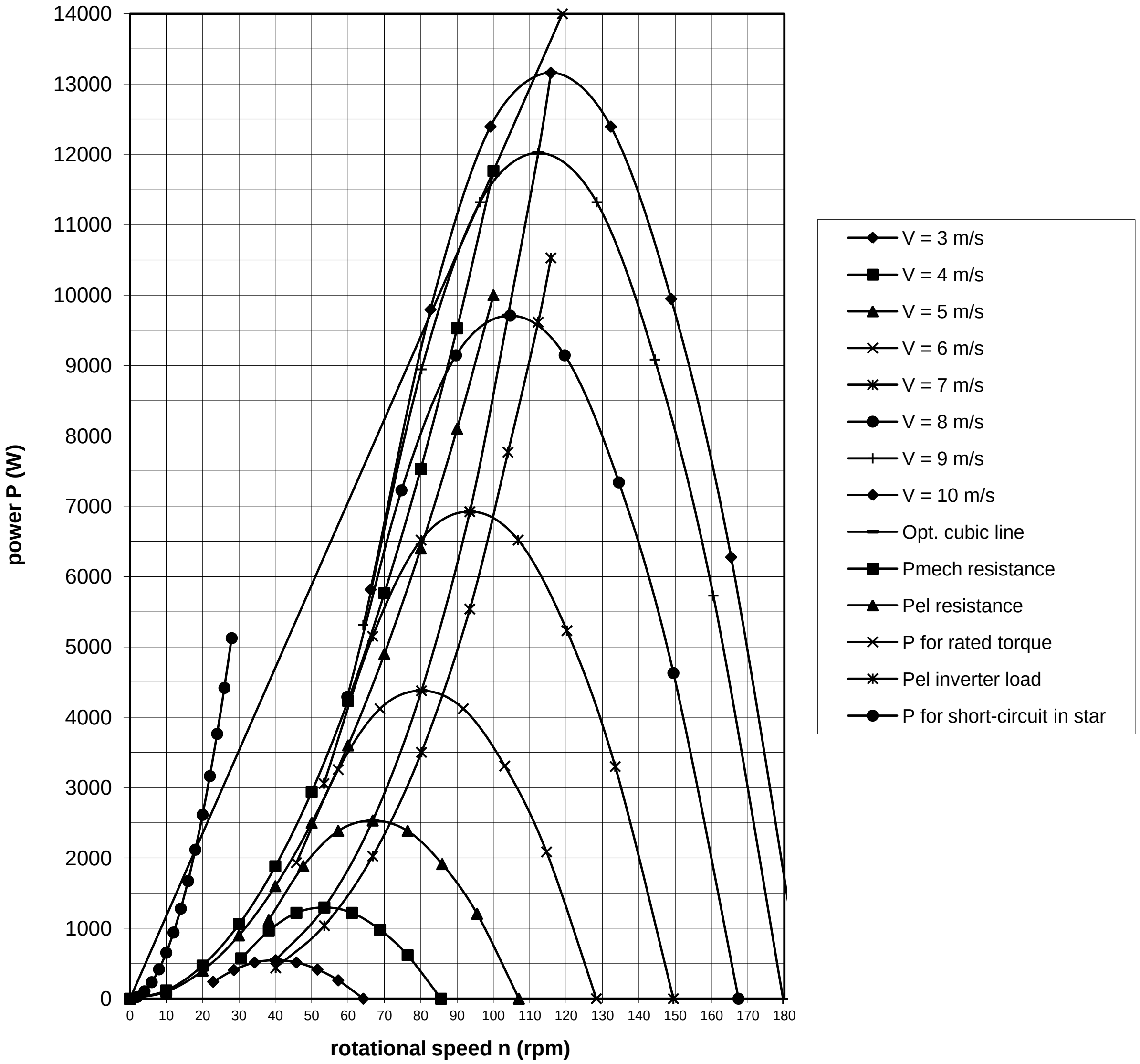


fig. 4 P-n curves of the VIRYA-10B2 rotor, optimum cubic line, $P_{mech}$-n and $P_{el}$-n curves for the TGET770-H-10KW-100R generator with a resistance load such that $P_{el}$ = 10000 W at n = 100 rpm, P-n curve for the rated torque Q = 1123.5 Nm, $P_{el}$-n curve for an inverter load, P-n curve for short-circuit in star

**6 Use of the VIRYA-10B2 rotor with the axial flux generator** PMG770-I-H-10KW-100R

The characteristics of the generator of Hefei Top Grand type TGET770-H-10KW-100R are derived in chapter 6 of KD 715 for a resistance load with a value of the resistance such that the electrical power is 10 KW at a rotational speed of 100 rpm. The $P_{mech}$-n and $P_{el}$-n curve for a resistance load are copied in figure 4. It can be seen that the whole $P_{mech}$-n curve for a resistance load is lying far left from the optimum cubic line.

The rated torque is 1123.5 Nm for n = 100 rpm. The P-n curve for the rated torque is also given in figure 4. This is a straight line through the origin. This line is extended up to a power of 14000 W. The optimum cubic line of the rotor for V = 10 m/s is lying to the right side of the P-n curve for the rated torque and so the generator is certainly strong enough for the VIRYA-10B2.

It is assumed that the inverter can be adjusted such that the optimum cubic line is followed and that the total efficiency of generator, rectifier and inverter is 0.8. The $P_{el}$-n curve for an inverter load is also given in figure 4. So if the optimum cubic line is followed, the load is much lighter than a resistance load. The maximum mechanical power at a wind speed of 10 m/s is 13161 W at a rotational speed of 115.8 rpm. This point is lying below the straight line for the rated torque.

The working point for an inverter load is the point of intersecting of the optimum cubic line with the P-n curve of the rotor for a certain wind speed. The electrical power for a certain wind speed V is found by going down vertically from the working point until the $P_{el}$-n curve for an inverter load is crossed. The $P_{el}$-V curve found this way is given figure 5.

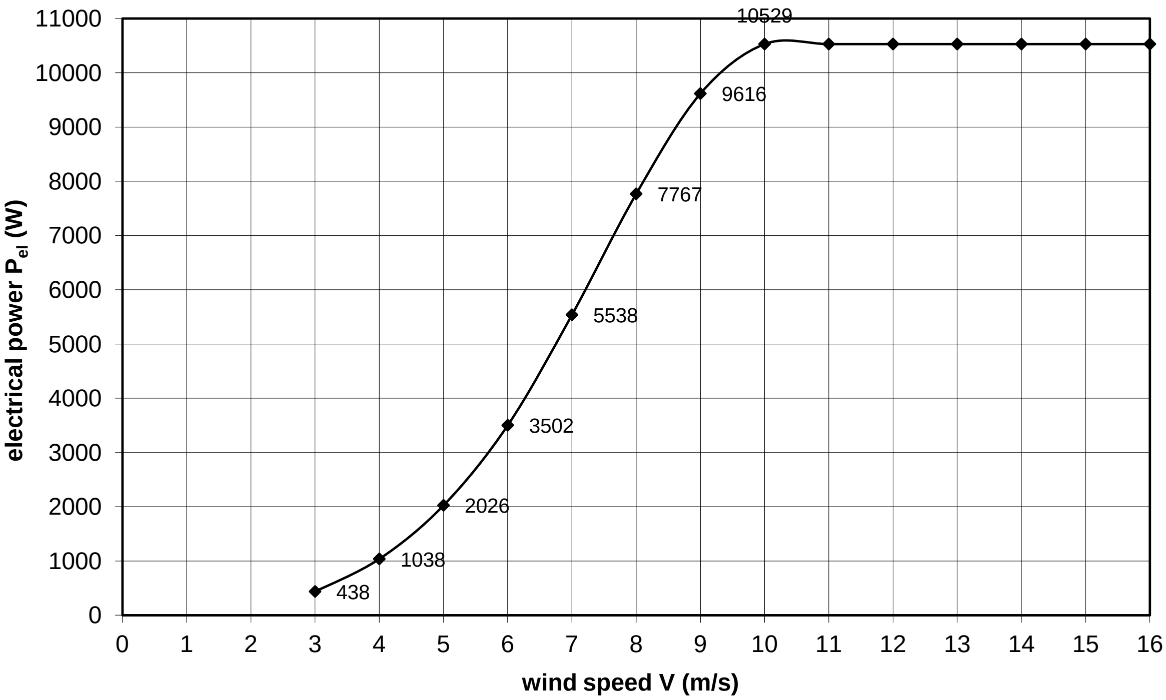


fig. 5 $P_{el}$-V curve VIRYA-10B2 for a load such that the optimum cubic line is followed.

The inverter needs a minimum voltage to start functioning. It is assumed that this voltage is generated at V = 3 m/s. This is the reason why the $P_{el}$-V curve starts suddenly with $P_{el}$ = 438 W at V = 3 m/s. In chapter 4 it was calculated that the starting wind speed is 1.9 m/s and so there is no hysteresis in the $P_{el}$-V curve. The maximum power is about 10.5 kW at a wind speed of 10 m/s or higher which is very good for a wind turbine with a rotor diameter of 10 m and a rated wind speed of 10 m/s.

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