

**Calculations executed for the 3-bladed rotor of the VIRYA-2.7 windmill  
( $\lambda_d = 6$ , wooden blades) using the axial flux PM-generator of  
Hefei Top Grand model TGET260-0.5KW-350R**

ing. A. Kragten

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Engineering office Kragten Design  
Populierenlaan 51  
5492 SG Sint-Oedenrode  
The Netherlands  
telephone: +31 413 475770  
e-mail: [info@kdwindturbines.nl](mailto:info@kdwindturbines.nl)  
website: [www.kdwindturbines.nl](http://www.kdwindturbines.nl)

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## 1 Introduction

The VIRYA-2.7 windmill is developed for manufacture in western countries as well as in developing countries. The VIRYA-2.7 has a 3-bladed rotor with wooden blades. The construction of the rotor is about similar to the construction of the VIRYA-3B3 rotor.

The VIRYA-2.7 is meant for 24 V battery charging and makes use of a Chinese axial flux generator of Hefei Top Grand model TGET260-0.5KW-350R. All other VIRYA windmills also have PM-generators which are described in report KD 341 (ref. 1). Some of them have radial flux generators made from asynchronous motors which have a stator lamination made of iron sheets and therefore they have a certain sticking torque. The chosen PM-generator for the VIRYA-2.7 is of the type axial flux and has an armature which is rotating around the stator. The stator contains no iron and the sticking torque will therefore be rather low. This results in a low starting wind speed even if a rotor with a low starting torque coefficient is used. More information about the generator is given in chapter 6. Certain PM-generators of the older VIRYA windmills have been measured on an accurate test rig of the University of Technology Eindhoven. The most complete measuring report is report KD 78 (ref. 2) in which a PM-generator has been measured for different load conditions.

The windmill is provided with the so called hinged side vane safety system. The head is identical to the head of the VIRYA-2.68 with a 2-bladed stainless steel rotor with a 7.14 % cambered sheet airfoil. The somewhat larger rotor diameter of the VIRYA-2.7 is compensated because a rotor with a Gö 623 airfoil has a somewhat lower thrust coefficient than a rotor with a 7.14 % cambered sheet airfoil. Two special clamps are needed to connect the axial flux generator to the generator bracket. The vane blade is made of 2 mm aluminium sheet resulting in a rated wind speed of about 9 m/s. The hinged side vane safety system is described in general in chapter 3.2 of public report KD 485 (ref. 3). The 6 m high lattice tower is identical to the tower of the VIRYA-2.2S but the 2 m long tower pipe is made of stronger 1 ½" gas pipe in stead of 1 ¼" gas pipe which is used for the VIRYA-2.2S.

## 2 Description of the rotor of the VIRYA-2.7 windmill

The rotor of the VIRYA-2.7 windmill has a diameter  $D = 2.7$  m, a number of blades  $B = 3$  and a design tip speed ratio  $\lambda_d = 6$ . 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 hard wooden blades with a constant chord and is provided with a Gö 623 or a Gö 711-12% airfoil over the whole length of the blade. A blade is made out of a wooden plank with dimensions of 18 \* 150 \* 1210 mm. The chord  $c$  is chosen 150 mm = 0.15 m.

The three blades are connected to each other by a 4 mm thick galvanised steel hub plate with 300 mm long and 130 mm wide ears. If the corners are rounded with  $r = 15$  mm, ten hub plates can be laser cut from a sheet size 1 \* 2 m. The overlap in between a blade and the central strip is 160 mm, resulting in a free blade length of 1050 mm. The chosen dimensions give a rotor diameter of  $2 * (1050 + 300) = 2700$  mm = 2.7 m.

The central circular area with a diameter of 110 mm, where the central strip is connected to the generator, is flat. The three 160 mm long ends, where an ear is connected to the blades, are also flat. So a 85 mm long part outside the flat central part is twisted to give the blade the correct blade angle at the blade root. The hub plate is rather flexible and this neutralises the vibrations due to wind speed fluctuations. A blade is connected to the hub plate by three bolts M8 and six nuts M8. There is a cambered strip size 2 \* 40 \* 160 mm mounted under the bolt heads to prevent damage of the wood when the bolts are tightened.

The generator has an outside diameter of 260 mm and a 110 mm collar at the front side with eight threaded holes M8 at a pitch circle of 90 mm. The central strip is connected to the generator by eight bolts M8 \* 25 and some locking liquid. The rotor is balanced by adding balancing weights under the connecting bolts of the blades.

### 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 717) has its own formula numbering. Substitution of  $\lambda_d = 6$  and  $R = 1.35$  m in formula (5.1) of KD 35 gives:

$$\lambda_{rd} = 4.4444 * r \quad (-) \quad (1)$$

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  $c = 0.15$  m in formula (5.4) of KD 35 gives:

$$C_l = 55.851 r (1 - \cos\phi) \quad (-) \quad (4)$$

Substitution of  $V = 4.5$  m/s and  $c = 0.15$  m in formula (5.5) of KD 35 gives:

$$Re_r = 0.45 * 10^5 * \sqrt{(\lambda_{rd}^2 + 4/9)} \quad (-) \quad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.21 m of one to another. Station F corresponds to the end of the ear of the hub plate. 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  $C_l$ ,  $\alpha$  and  $\beta$  and next  $\beta$  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 Gö 623 airfoil are given in figure 5.8 and 5.9 of report KD 35 (ref. 4). As an alternative it seems possible to use the Gö 711-12% airfoil which is flat over 97.5 % of the chord and which is therefore easier to manufacture. This airfoil is given in report KD 333 (ref. 5). The Reynolds values for the stations are calculated for a wind speed of 4.5 m/s because this is a reasonable wind speed for a good wind regime. Those airfoil Reynolds numbers are used which are lying closest to the calculated values.

| station | r (m) | $\lambda_{rd}$ (-) | $\phi$ (°) | c (m) | $C_{lth}$ (-) | $C_{lin}$ (-) | $Re_r * 10^{-5}$<br>V = 4.5 m/s | $Re^* 10^{-5}$<br>Gö 623 | $\alpha_{th}$ (°) | $\alpha_{lin}$ (°) | $\beta_{th}$ (°) | $\beta_{lin}$ (°) | $C_d/C_{lin}$ (-) |
|---------|-------|--------------------|------------|-------|---------------|---------------|---------------------------------|--------------------------|-------------------|--------------------|------------------|-------------------|-------------------|
| A       | 1.35  | 6                  | 6.3        | 0.15  | 0.46          | 0.42          | 2.85                            | 2.3                      | -0.4              | -0.7               | 6.7              | 7.0               | 0.036             |
| B       | 1.14  | 5.067              | 7.4        | 0.15  | 0.54          | 0.54          | 2.30                            | 2.3                      | 0.4               | 0.4                | 7.0              | 7.0               | 0.031             |
| C       | 0.93  | 4.133              | 9.1        | 0.15  | 0.65          | 0.71          | 1.88                            | 2.3                      | 1.4               | 2.1                | 7.7              | 7.0               | 0.027             |
| D       | 0.72  | 3.2                | 11.6       | 0.15  | 0.82          | 0.86          | 1.47                            | 1.2                      | 3.9               | 4.6                | 7.7              | 7.0               | 0.034             |
| E       | 0.51  | 2.257              | 15.9       | 0.15  | 1.09          | 1.15          | 1.06                            | 1.2                      | 7.7               | 8.9                | 8.2              | 7.0               | 0.044             |
| F       | 0.3   | 1.333              | 24.6       | 0.15  | 1.52          | 0.85          | 0.67                            | 1.2                      | -                 | 17.6               | -                | 7.0               | 0.34              |

table 1 Calculation of the blade geometry of the VIRYA-2.7 rotor

No value for  $\alpha_{th}$  and therefore for  $\beta_{th}$  is found for station F because the required  $C_l$  value can't be generated. The theoretical blade angle  $\beta_{th}$  for stations A up to D varies in between  $6.7^\circ$  and  $7.7^\circ$ . If a constant blade angle of  $7^\circ$  is taken for the whole blade, the linearised blade angles are lying close to the theoretical values for the most important outer part of the blade. The ears of the hub plate are twisted  $7^\circ$  right hand to get the correct blade angle at the blade root.

A sketch of the rotor and the PM-generator is given in figure 1.

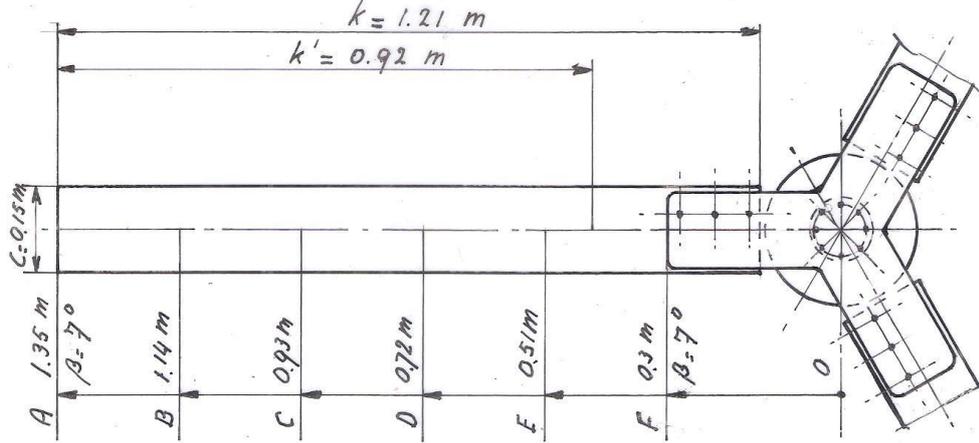


fig. 1 Sketch of the VIRYA-2.7 rotor and the PM-generator

#### 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 most important outer part of the blade is about 0.032. Figure 4.7 of KD 35 (for  $B = 3$ ) and  $\lambda_{opt} = 6$  and  $C_d/C_l = 0.032$  gives  $C_{p th} = 0.44$  (interpolation in between the lines for  $C_d/C_l = 0.03$  and  $C_d/C_l = 0.05$ ). The blade is stalling at station F so only the part of the blade until 0.13 m outside station F is taken for the calculation of  $C_p$ . This gives an effective blade length  $k' = 0.92$  m.

Substitution of  $C_{p th} = 0.44$ ,  $R = 1.3$  m and blade length  $k = k' = 0.92$  m in formula 6.3 of KD 35 gives  $C_{p max} = 0.4$ .  $C_{q opt} = C_{p max} / \lambda_{opt} = 0.4 / 6 = 0.0667$ .

Substitution of  $\lambda_{opt} = \lambda_d = 6$  in formula 6.4 of KD 35 gives  $\lambda_{unl} = 9.6$ .

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

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

The blade angle is  $7^\circ$  for the whole blade. For a non rotating rotor, the angle of attack  $\alpha$  is therefore  $90^\circ - 7^\circ = 83^\circ$ . The  $C_l$ - $\alpha$  curve for large values of  $\alpha$  is given as figure 5.10 of KD 35 for the Gö 623 airfoil. For  $\alpha = 83^\circ$  it can be read that  $C_l = 0.25$ . During starting, the whole blade is stalling. Therefore now the real blade length  $k = 1.21$  m is taken.

Substitution of  $B = 3$ ,  $R = 1.35$  m,  $k = 1.21$  m,  $C_l = 0.25$  and  $c = 0.15$  m in formula 6 gives that  $C_{q start} = 0.0098$ . For the ratio in between the starting torque and the optimum torque we find that it is  $0.0098 / 0.0667 = 0.147$ . This is acceptable for a rotor with a design tip speed ratio of 6. 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 sticking torque  $Q_s$  of the generator is very low because there is no iron in the coils. The manufacturer says that it is less than 0.1 Nm. However this counts if no seal is mounted at the rotor shaft. A seal is required if the rotor shaft is placed horizontally like this is the case for the VIRYA-2.7. For the smaller generator with model number TGET260-0.15KW-500R it has been measured that the sticking torque is 0.004 Nm without a seal but 0.13 Nm with a new seal (see KD 595 ref. 6). It was assumed that the sticking torque is 0.1 Nm when the seal is run in. The bigger generator of the VIRYA-2.7 has bigger bearings and a larger shaft (30 mm in stead of 25 mm) and so the sticking torque will be larger too.

Assume  $Q_s = 0.16 \text{ Nm}$  for a seal which has run in. Substitution of  $Q_s = 0.16 \text{ Nm}$ ,  $C_{q \text{ start}} = 0.0098$ ,  $\rho = 1.2 \text{ kg/m}^3$  and  $R = 1.35 \text{ m}$  in formula 7 gives that  $V_{\text{start}} = 1.9 \text{ m/s}$ . This is low for a 3-bladed rotor with a design tip speed ratio of 6 used at moderate wind speeds. The generator is rectified in star and the unloaded Q-n curve will rise only a little at increasing rotational speed. The Q-n curve of the rotor for  $V = 1.9 \text{ m/s}$  will rise faster and the real starting wind speed will therefore be about the same as the calculated value.

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 a 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  $\lambda$  can be determined (see report KD 97 ref. 7). With this method, it can be determined that the  $C_q$ - $\lambda$  curve is rising slowly for low values of  $\lambda$  if a Gö 623 airfoil is used. This effect has been taken into account and the estimated  $C_p$ - $\lambda$  and  $C_q$ - $\lambda$  curves for the VIRYA-2.7 rotor are given in figure 2 and 3.

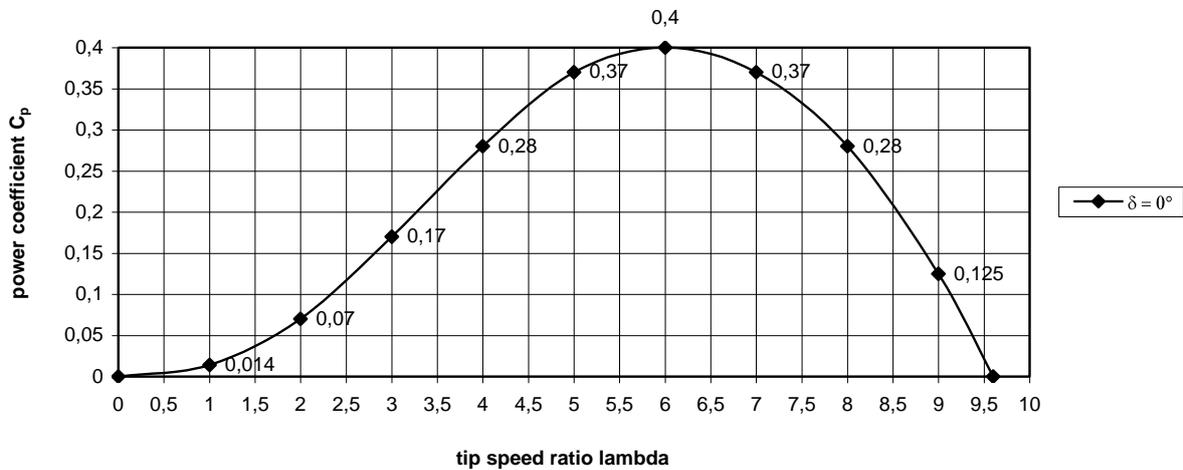


fig. 2 Estimated  $C_p$ - $\lambda$  curve for the VIRYA-2.7 rotor for the wind direction perpendicular to the rotor ( $\delta = 0^\circ$ )

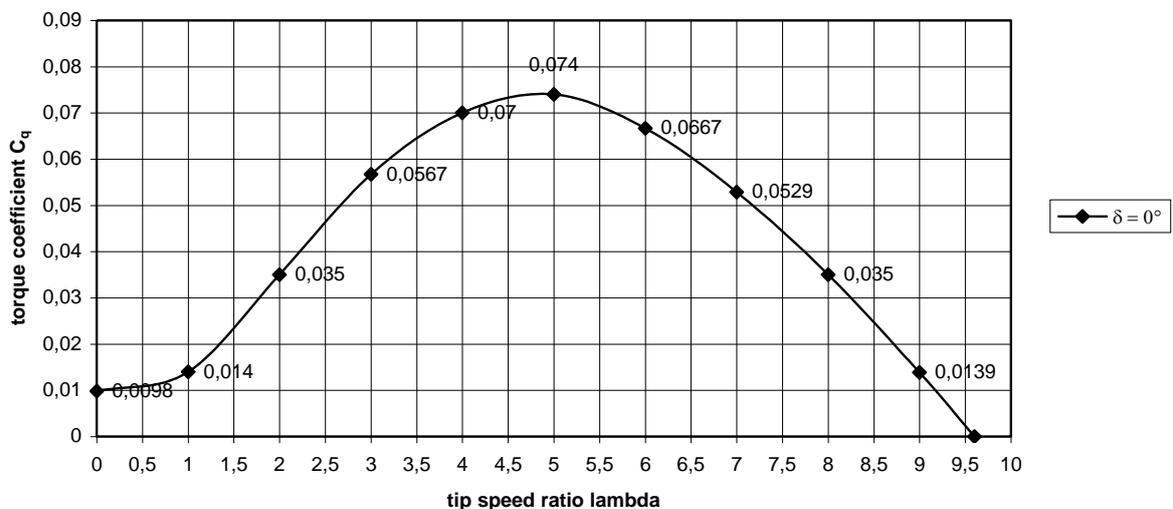


fig. 3 Estimated  $C_q$ - $\lambda$  curve for the VIRYA-2.7 rotor for the wind direction perpendicular to the rotor ( $\delta = 0^\circ$ )

## 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  $C_p$ - $\lambda$  curve of the rotor and a  $\delta$ -V curve of the safety system together with the formulas for the power P and the rotational speed n. The  $C_p$ - $\lambda$  curve is given in figure 2. The  $\delta$ -V curve of the safety system depends on the vane blade mass per area. The vane blade is made of 2 mm aluminium sheet. The rated wind speed for this vane blade is about 9 m/s. The estimated  $\delta$ -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 9 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 9 m/s will therefore also be valid for wind speeds higher than 9 m/s.

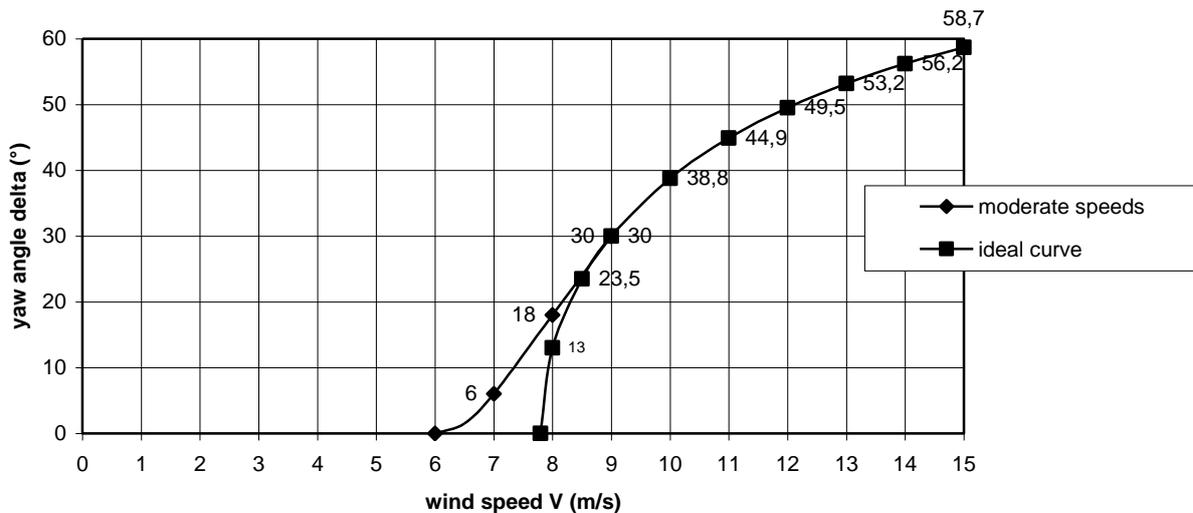


fig. 4 Estimated  $\delta$ -V curve VIRYA-2.7 for a 2 mm aluminium vane blade

The P-n curves are used to check the matching with the  $P_{\text{mech}}$ -n curve of the generator for a certain gear ratio  $i$  (the VIRYA-2.7 has no gearing so  $i = 1$ ). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves for low values of  $\lambda$  appear to lie very close to each other, the P-n curves are not determined for low values of  $\lambda$ . The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8 and 9 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle  $\delta$  and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of  $R = 1.35$  m in formula 7.1 of KD 35 gives:

$$n_{\delta} = 7.074 * \lambda * \cos\delta * V \quad (\text{rpm}) \quad (8)$$

Substitution of  $\rho = 1.2$  kg / m<sup>3</sup> and  $R = 1.35$  m in formula 7.10 of KD 35 gives:

$$P_{\delta} = 3.435 * C_p * \cos^3\delta * V^3 \quad (\text{W}) \quad (9)$$

The P-n curves are determined for  $C_p$  values belonging to  $\lambda = 3, 4, 5, 6, 7, 8$  and  $9.6$ . (see figure 2). 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 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.

| $\lambda$<br>(-) | $C_p$<br>(-) | V = 3 m/s<br>$\delta = 0^\circ$ |          | V = 4 m/s<br>$\delta = 0^\circ$ |          | V = 5 m/s<br>$\delta = 0^\circ$ |          | V = 6 m/s<br>$\delta = 0^\circ$ |          | V = 7 m/s<br>$\delta = 6^\circ$ |                   | V = 8 m/s<br>$\delta = 18^\circ$ |                   | V = 9 m/s<br>$\delta = 30^\circ$ |                   |
|------------------|--------------|---------------------------------|----------|---------------------------------|----------|---------------------------------|----------|---------------------------------|----------|---------------------------------|-------------------|----------------------------------|-------------------|----------------------------------|-------------------|
|                  |              | n<br>(rpm)                      | P<br>(W) | n<br>(rpm)                      | P<br>(W) | n<br>(rpm)                      | P<br>(W) | n<br>(rpm)                      | P<br>(W) | $n_\delta$<br>(rpm)             | $P_\delta$<br>(W) | $n_\delta$<br>(rpm)              | $P_\delta$<br>(W) | $n_\delta$<br>(rpm)              | $P_\delta$<br>(W) |
| 3                | 0.17         | 63.7                            | 15.8     | 84.9                            | 37.4     | 106.1                           | 73.0     | 127.3                           | 126.1    | 147.7                           | 197.0             | 161.5                            | 257.2             | 165.4                            | 276.5             |
| 4                | 0.28         | 84.9                            | 26.0     | 113.2                           | 61.6     | 141.5                           | 120.2    | 169.8                           | 207.7    | 197.0                           | 324.5             | 215.3                            | 423.6             | 220.5                            | 455.4             |
| 5                | 0.37         | 106.1                           | 34.3     | 141.5                           | 81.3     | 176.9                           | 158.9    | 212.2                           | 274.5    | 246.2                           | 428.8             | 269.1                            | 559.8             | 275.7                            | 601.8             |
| 6                | 0.4          | 127.3                           | 37.1     | 169.8                           | 87.9     | 212.2                           | 171.8    | 254.7                           | 296.8    | 295.5                           | 463.6             | 322.9                            | 605.2             | 330.8                            | 650.6             |
| 7                | 0.37         | 148.6                           | 34.3     | 198.1                           | 81.3     | 247.6                           | 158.9    | 297.1                           | 274.5    | 344.7                           | 428.8             | 376.8                            | 559.8             | 386.0                            | 601.8             |
| 8                | 0.28         | 169.8                           | 26.0     | 226.4                           | 61.6     | 282.0                           | 120.2    | 339.6                           | 207.7    | 394.0                           | 324.5             | 430.6                            | 423.6             | 441.1                            | 455.4             |
| 9.6              | 0            | 203.7                           | 0        | 271.6                           | 0        | 339.6                           | 0        | 407.5                           | 0        | 472.8                           | 0                 | 516.7                            | 0                 | 529.3                            | 0                 |

table 2 Calculated values of n and P as a function of  $\lambda$  and V for the VIRYA-2.7 rotor

The calculated values for n and P are plotted in figure 5. The optimum cubic line which can be drawn through the maximum of all P-n curves is also given in figure 5.

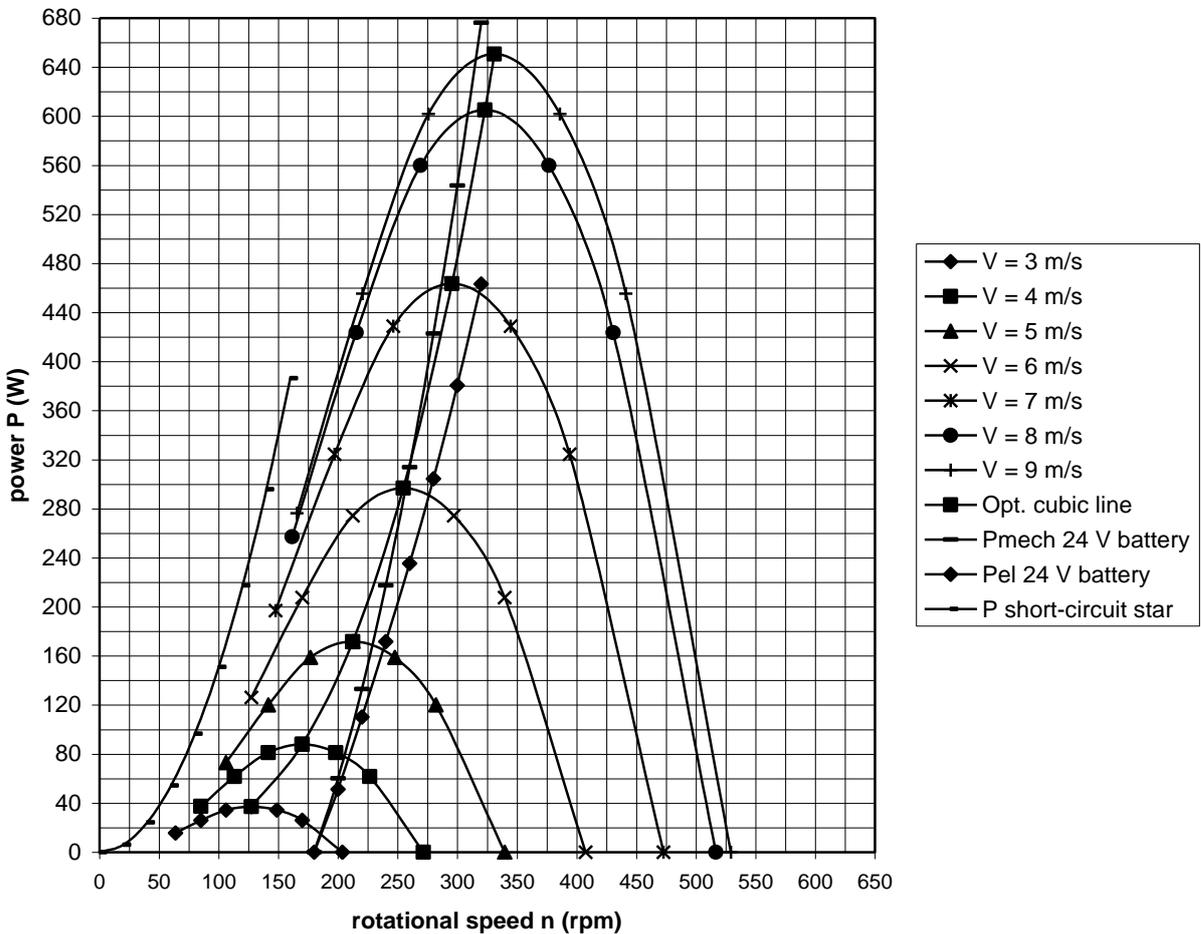


fig. 5 P-n curves of the VIRYA-2.7 rotor and optimum cubic line, estimated  $P_{mech-n}$  and  $P_{el-n}$  curves for 24 V battery charging, P-n curve for short-circuit in star

## 6 Estimation of the generator characteristics and the $P_{el}$ -V curve

A data sheet of the chosen PM-generator can be found on the website of the company: Hefei Top Grand: [www.china-topgrand.com](http://www.china-topgrand.com) following the path: Product – Outer rotor – page 2 – TGET260-0.5KW-350R. A copy of this data sheet is given in Appendix 1.

I have bought and tested a smaller generator of this company with model TGET165-0.15KW-500R and the measurements are given in report KD 595 (ref. 6). The electrical output at 500 rpm was smaller than the manufactures specification but technically the generator performed well and it has been tested in the field for about three years without problems. So I expect the same quality for the bigger type as used for the VIRYA-2.7.

In chapter 5 of the data sheet it is mentioned that the voltage is 28/56VDC. This doesn't mean that one generator can supply two different voltages. It means that the generator can be supplied with a 28 V winding or with a 56 V winding. The generator will be used for 24 V battery charging so one has to order the version with the 28 V winding! Two different voltage curves are presented in chapter 6 of the data sheet and one has to use the right picture.

The rated power is specified as 500 W at a rated rotational speed of 350 rpm. However, in the right voltage curve it can be seen that the loaded voltage is about 33 V for  $n = 350$  rpm. So the rated voltage is 33 V and not 28 V as may be expected from chapter 5 of the data sheet! The voltage can't be read very accurately because the y-axis has a very strange diversion of the numbers in 0, 6, 12, 18, 25, 31 and 37 V.

The generator has a 3-phase winding which is connected in star. The star point is lying somewhere inside the generator so only the three phase wires are coming out of the hollow generator shaft. The specified voltage is the DC-voltage which means that one has used a 3-phase rectifier for the measurements. The rectifier isn't included in the generator so one has to select a 3-phase rectifier which can guide the maximum generator current. Information about rectification of a 3-phase current is given in report KD 340 (ref. 8).

The  $P_{el}$ - $n$  curve for a fixed resistor load is about a parabola (see report KD 78, ref. 2) and the given  $P_{el}$ - $n$  curve is about a parabola, so the load must have been a fixed resistor. The characteristics for a battery load are completely different than those for a resistor load but it might be possible to derive the characteristics for a 24 V battery load from the characteristics for a resistor load. The procedure how to do this requires calculation of the torque  $Q$ .

In the right voltage curve it can be seen that the loaded voltage is about 28 V for  $n = 300$  rpm. In the power curve it can be seen that  $P_{el} = 380$  W for  $n = 300$  rpm. It is specified in the data sheet that the efficiency is at least 85 % or 0.85 but this is much too optimistic for a heavy load. For my measurements with the smaller generator it was found that the peak efficiency is about 0.72 and that the efficiency at the rated rotational speed is about 0.61 if the power loss in the rectifier is included in the generator efficiency (see KD 595 figure 7). The efficiency normally increases with the generator size and the power loss in the rectifier is relatively smaller for a 24 V battery load than for a 12 V battery load. Assume the efficiency is 0.7 for a rotational speed of 300 rpm. This gives a mechanical power  $P_{mech} = 380 / 0.7 = 543$  W at  $n = 300$  rpm. The relation in between the torque  $Q$  (Nm), the mechanical power  $P_{mech}$  (W) and the rotational speed  $n$  (rpm) is given by:

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

Substitution of  $P_{mech} = 543$  W and  $n = 300$  rpm gives that  $Q = 17.3$  Nm at  $n = 300$  rpm.

The maximum allowable charging voltage of a 24 V battery is about 28 V if the battery is full. So one needs a voltage controller + dump load to prevent that a full battery is over charged. A 27.6 V, 200 W battery charge controller is described in a manual which can be found on my website at the bottom of the menu KD-reports (ref. 9). The power can be increased by connecting several modules of the dump load in parallel.

Charging of a battery starts when the open DC-voltage of the generator is equal to the open battery voltage. The open battery voltage depends on the charging state of the battery but it is about 25.2 V for an almost full 24 V battery. The open voltage curve isn't given but based on the measurements for the smaller generator, it is assumed that the open voltage at a certain rotational speed is a factor 1.5 higher than the loaded voltage for a resistor load. This means that the open DC voltage is about 42 V for  $n = 300$  rpm. As the open voltage increases linear to the rotational speed it means that the open voltage is about 25.2 V for  $n = 300 * 25.2 / 42 = 180$  rpm. It is assumed that the torque  $Q$  is zero for the open voltage at  $n = 180$  rpm.

In KD 78 it is found that the  $Q$ - $n$  curve for a constant or an almost constant voltage is about a straight line. So the  $Q$ - $n$  curve for a 24 V battery load is about a straight line through the point  $n = 180$  rpm and  $Q = 0$  Nm and the point  $n = 300$  rpm and  $Q = 17.3$  Nm. The torque can now easily be determined for other rotational speeds in between 180 rpm and 300 rpm and also for  $n = 320$  rpm. The result is given in table 3. Formula 10 can be written as:

$$P_{\text{mech}} = Q * n * \pi/30 \quad (\text{W}) \quad (11)$$

$P_{\text{mech}}$  is calculated using formula 11 and is also given in table 3. The efficiency is about constant for a resistor load but not for a battery load. It is assumed that the efficiency is 0.85 for  $n = 200$  rpm and 0.7 for  $n = 300$  rpm.

| n (rpm) | Q (Nm) | $P_{\text{mech}}$ (W) | $\eta$ (-) | $P_{\text{el}}$ (W) |
|---------|--------|-----------------------|------------|---------------------|
| 180     | 0      | 0                     | 0          | 0                   |
| 200     | 2.88   | 60.3                  | 0.85       | 51.3                |
| 220     | 5.77   | 132.9                 | 0.83       | 110.3               |
| 240     | 8.65   | 217.4                 | 0.79       | 171.7               |
| 260     | 11.53  | 313.9                 | 0.75       | 235.4               |
| 280     | 14.42  | 422.8                 | 0.72       | 304.4               |
| 300     | 17.3   | 543.5                 | 0.7        | 380.5               |
| 320     | 20.18  | 676.2                 | 0.685      | 463.2               |

Table 3 Estimated values for  $Q$ ,  $P_{\text{mech}}$ ,  $\eta$  and  $P_{\text{el}}$  for a 24 V battery load

The values for  $P_{\text{mech}}$  and  $P_{\text{el}}$  as given in table 3 are now copied in figure 5. In figure 5 it can be seen that the  $P_{\text{mech}}$ - $n$  curve for a 24 V battery load is intersecting with the optimum cubic line at a wind speed of about 6 m/s. So the matching is perfect for this wind speed. For lower wind speeds, the rotor runs at a higher tip speed ratio than 6. For higher wind speeds, the rotor runs at a lower wind speed than 6. This reduces the sound production of the rotor at high wind speeds.

The matching is good for wind speeds in between 3.5 m/s and 9 m/s as the  $P_{\text{mech}}$ - $n$  curve of the generator is lying close to the optimum cubic line of the rotor for this wind speed interval. However, this is only true if the real  $P_{\text{mech}}$ - $n$  and  $P_{\text{el}}$ - $n$  curves for a 24 V battery load are about identical to the estimated curves. If this generator is used in a windmill project, it is advised to buy one and to measure it on an accurate test rig for a real 24 V battery load or for a constant voltage of about 26.5 V. To see if the generator can also be used as a brake by making short-circuit (before the rectifier), it should also been measured for short-circuit

The point of intersection of the  $P_{\text{mech}}$ - $n$  curve of the generator with the  $P$ - $n$  curve of the rotor for a certain wind speed gives the working point for that wind speed. The electrical power generated for that working point is found by going down vertically until the  $P_{\text{el}}$ - $n$  curve is intersected. The electrical powers for a certain wind speed found this way are put in the  $P_{\text{el}}$ - $V$  curve which is given in figure 6.

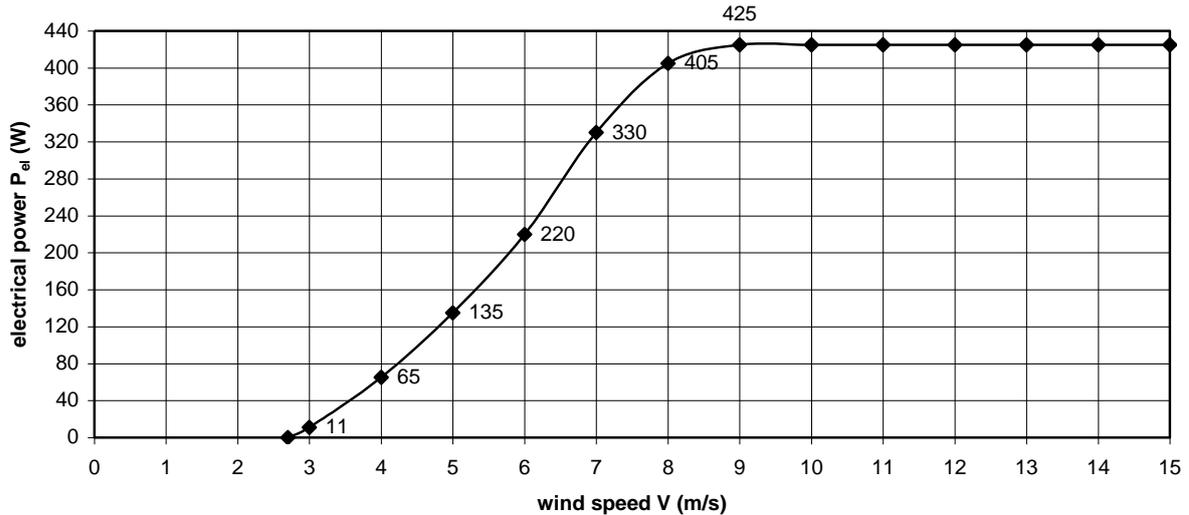


fig. 6 Estimated  $P_{el}$ - $V$  curve VIRYA-2.7 for 24 V battery charging

In figure 6 it can be seen that the cut-in wind speed is about 2.7 m/s. In chapter 4 it was calculated that the starting wind speed is 1.9 m/s, so there is no hysteresis in the  $P_{el}$ - $V$  curve. The maximum power is about 425 W for a wind speed of 9 m/s or higher. This is very good for a wind turbine with a rotor diameter of 2.7 m and a rated wind speed of 9 m/s.

As the maximum power is about 425 W and as always some power will be absorbed by the batteries, one needs two 200 W dump loads connected in parallel using an aluminium sheet of 500 \* 500 mm. This dump load is steered by one voltage controller (see manual). The maximum DC current is about  $425 / 27.6 = 15.4$  A if the maximum charging voltage is limited up to 27.6 V. So one has to select a 3-phase rectifier with heat sink and a short-circuit switch which can conduct at least this current. It is advised to place the short-circuit switch and the 3-phase rectifier in a box at the tower foot. So a cable with only two wires of each minimal 2.5 mm<sup>2</sup> connects the rectifier to the dump load and the batteries. The dump load and the batteries are placed inside the house on a place where the dump load can't be touched by sunlight.

## 7 Checking if the generator can be used as a brake

In KD 78 it was found that the first part of the Q-n curves for different voltages are straight lines which are all in parallel to each other. Short-circuit means a constant voltage of 0 V. So the Q-n curve for short-circuit in star can be found by shifting the Q-n curve for 28 V that much to the left until it intersects with the origin of the Q-n graph. The result of this shifting is given in table 4.  $P_{mech}$  was calculated using formula 11.

| n (rpm) | Q (Nm) | $P_{mech}$ (W) |
|---------|--------|----------------|
| 0       | 0      | 0              |
| 20      | 2.88   | 6.0            |
| 40      | 5.77   | 24.2           |
| 60      | 8.65   | 54.3           |
| 80      | 11.53  | 96.6           |
| 100     | 14.42  | 151.0          |
| 120     | 17.3   | 217.4          |
| 140     | 20.18  | 295.9          |
| 160     | 23.07  | 386.5          |

Table 4 Estimated values for Q and  $P_{mech}$  for short-circuit in star

The P-n curve for short-circuit in star can be derived from table 4 and is also given in figure 5. This curve is only given up to a rotational speed of 160 rpm. The Q-n curve for higher rotational speeds is no longer a straight line and bends to the right. So the P-n curve will also bend to the right and this part of the curve can only be determined by measuring of the generator. But by interpolation it seems that the P-n curve for short-circuit in star is lying left from the P-n curve of the rotor for  $V = 9$  m/s and higher and so the generator can be used as a brake to stop the rotor at any wind speed.

### 8 Use of the VIRYA-2.7 for 12 V battery charging

For sites with very low wind speeds it may be wanted to use the VIRYA-2.7 for 12 V battery charging in stead of 24 V battery charging. The generator can also be used for a lower voltage but this makes that the Q-n curve, the  $P_{\text{mech}}$ -n curve and the  $P_{\text{el}}$ -n curve will shift to the left. The matching will therefore be good for very low wind speeds but rather bad for high wind speeds. It is assumed that charging starts at a voltage of 12.6 V for a 12 V battery. So the Q-n curve for a 12 V battery starts at a rotational speed which is a factor 2 lower than for a 24 V battery and so the Q-n curve starts at 90 rpm. Table 3 is now copied as table 5 and the values of Q are now shifted to the left such that the Q-n curve starts at  $n = 90$  rpm. The efficiency for a 12 V battery will be lower than for a 24 V battery and so all efficiencies are reduced by 0.05.  $P_{\text{mech}}$  is calculated using formula 11.

| n (rpm) | Q (Nm) | $P_{\text{mech}}$ (W) | $\eta$ (-) | $P_{\text{el}}$ (W) |
|---------|--------|-----------------------|------------|---------------------|
| 90      | 0      | 0                     | 0          | 0                   |
| 110     | 2.88   | 33.2                  | 0.8        | 26.6                |
| 130     | 5.77   | 78.6                  | 0.78       | 61.3                |
| 150     | 8.65   | 135.9                 | 0.74       | 100.6               |
| 170     | 11.53  | 205.3                 | 0.7        | 143.7               |
| 190     | 14.42  | 286.9                 | 0.67       | 192.2               |
| 210     | 17.3   | 380.4                 | 0.65       | 247.3               |
| 230     | 20.18  | 486.0                 | 0.635      | 308.6               |

Table 5 Estimated values for Q,  $P_{\text{mech}}$ ,  $\eta$  and  $P_{\text{el}}$  for a 12 V battery load

Figure 5 is now copied as figure 7 and the  $P_{\text{mech}}$ -n and  $P_{\text{el}}$ -n curves for a 24 V battery are replaced by the  $P_{\text{mech}}$ -n and  $P_{\text{el}}$ -n curves for a 12 V battery. The  $P_{\text{el}}$ -V curve for 12 V battery charging is derived in the same way as it was done for 24 V battery charging and is given in figure 8.

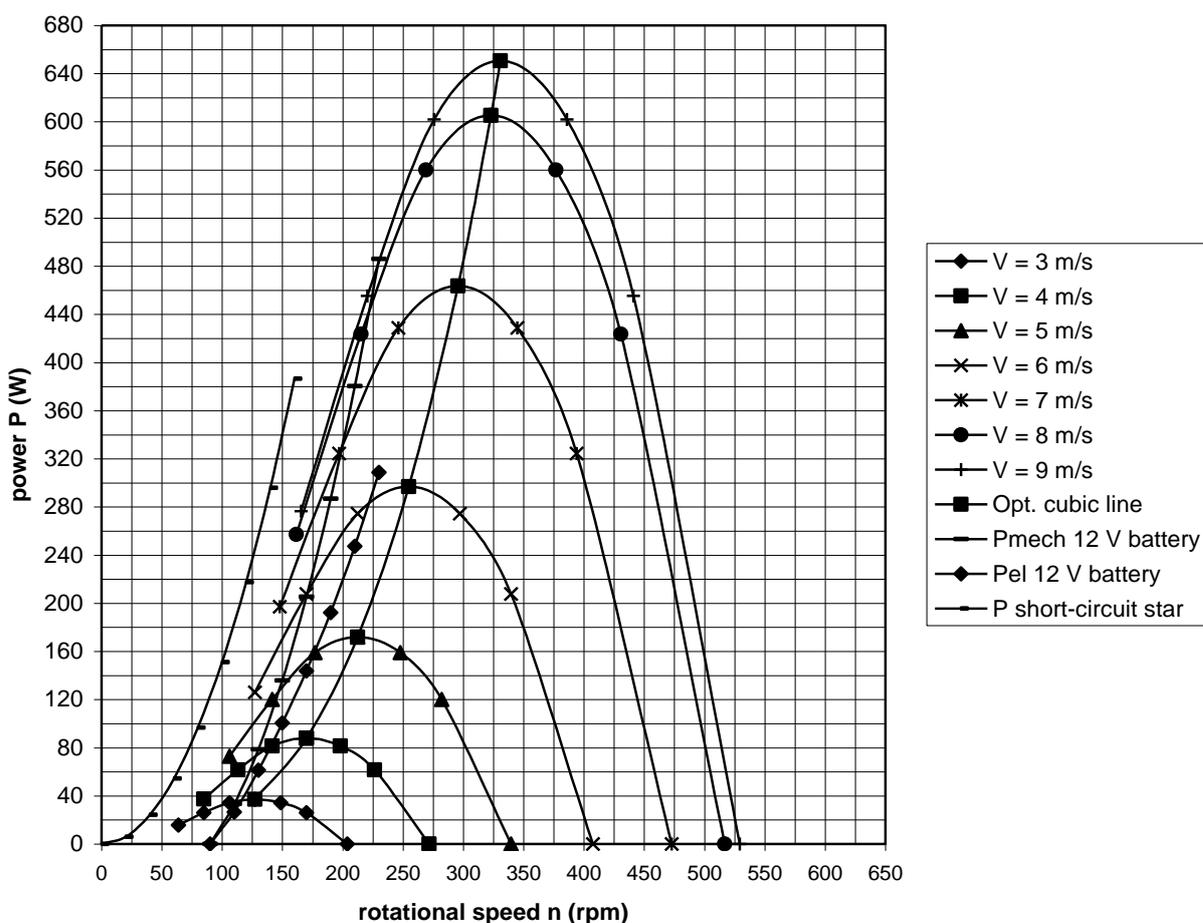


fig. 7 P-n curves of the VIRYA-2.7 rotor and optimum cubic line, estimated  $P_{\text{mech}}-n$  and  $P_{\text{el}}-n$  curves for 12 V battery charging, P-n curve for short-circuit in star

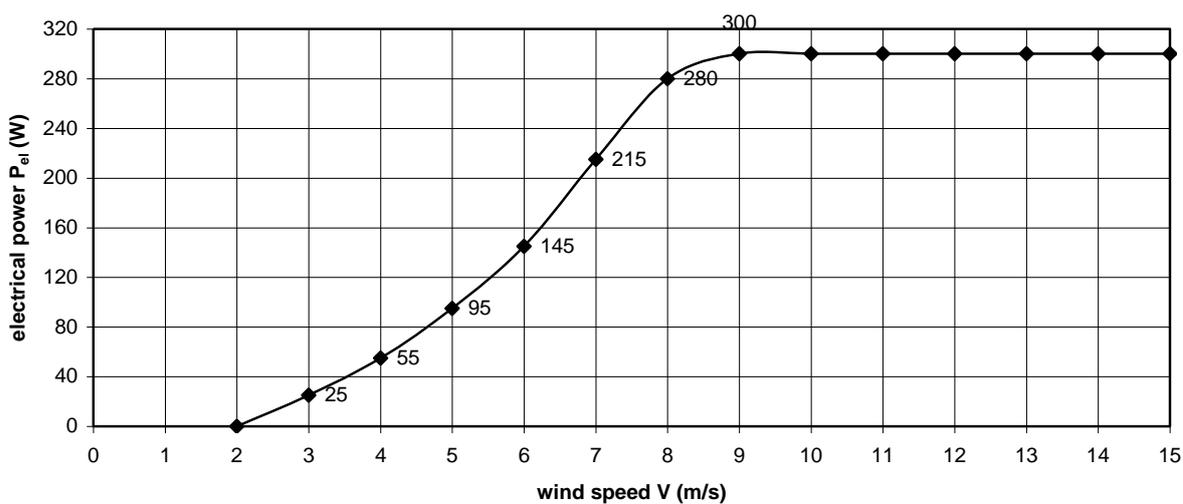


fig. 8 Estimated  $P_{\text{el}}-V$  curve VIRYA-2.7 for 12 V battery charging

In figure 8 it can be seen that now the cut-in wind speed is only 2 m/s. However the maximum power is only 300 W. If figure 8 is compared with figure 6 it can be seen that the  $P_{\text{el}}-V$  curve for 12 V battery charging is better for wind speeds in between 2 m/s and about 3.5 m/s but that the  $P_{\text{el}}-V$  curve for 24 V battery charging is much better for wind speeds above 3.5 m/s.

## 8 References

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**Appendix 1** Folder PM-generator Hefei Top Grand TGET260-0.5KW-350R**PRODUCT DETAIL**

**1. Model:** TGET260-0.5KW-350R

**2. Character**

Our disc coreless PMG have advantage in low Rated speed, Low starting wind speed, Small volume, Energy Small, Light weight, Compact structure, High efficiency etc.

- 1) Coreless, anhysteresis, slotless, have low starting torque.
- 2) No iron loss, have high efficiency
- 3) Adopt unique coreless precision winding technology design precision coil
- 4) Adopt the rare earth permanent magnet, which is multipole, mean gap, high power density and high output power.
- 5) Low speed direct driving, no torque fluctuations
- 6) Compact structure, high ratio of power to volume
- 7) No iron loss, low calorific value, small temperature rise
- 8) Simple structure, easy to install
- 9) The brushless structure, free maintenance

**3. Range Of Application**

0.05-0.3 kw wind turbine; gasoline generators; hydroelectric generator

#### 4. Shape Drawing

## PRODUCT DETAIL

1. **Model:** TGET260-0.5KW-350R

#### 2. Character

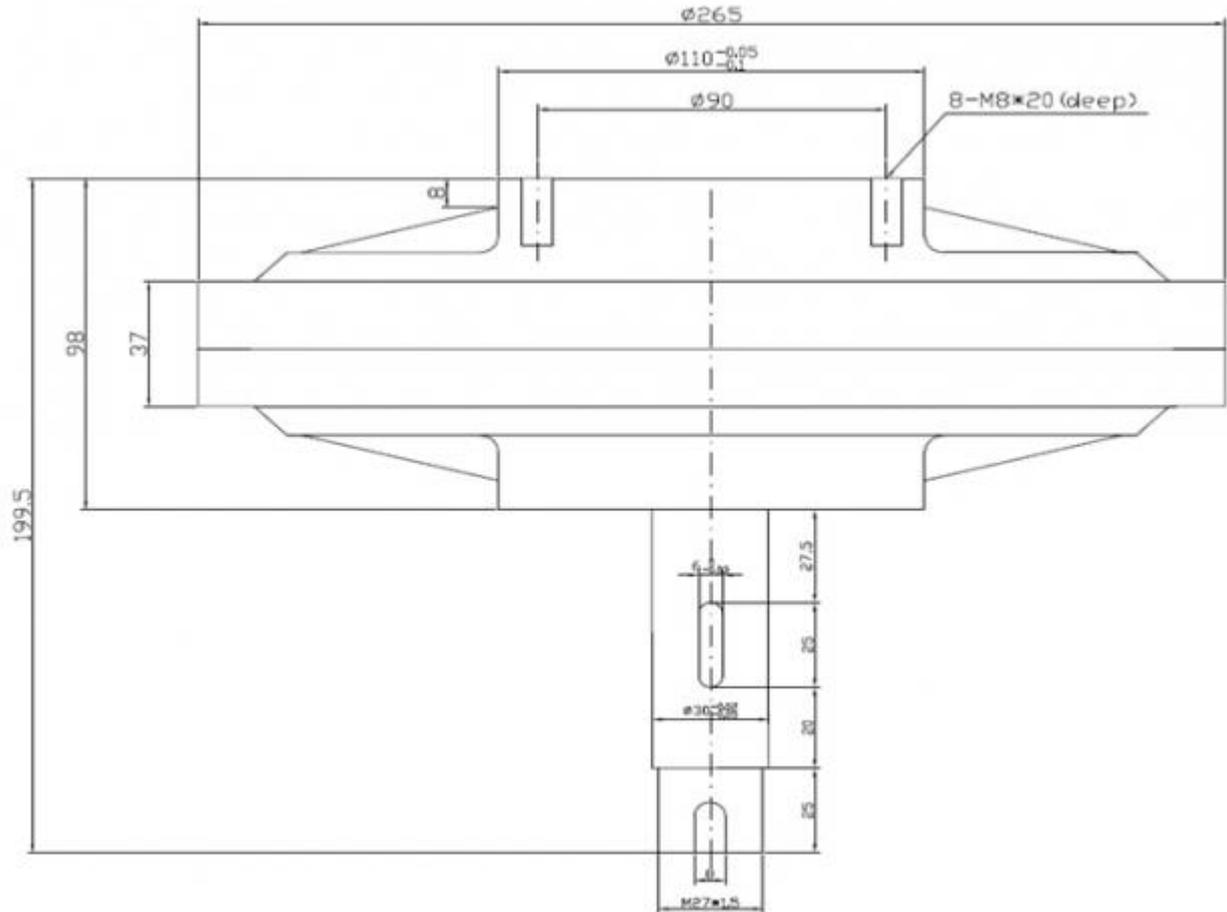
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0.05-0.3 kw wind turbine; gasoline generators; hydroelectric generator

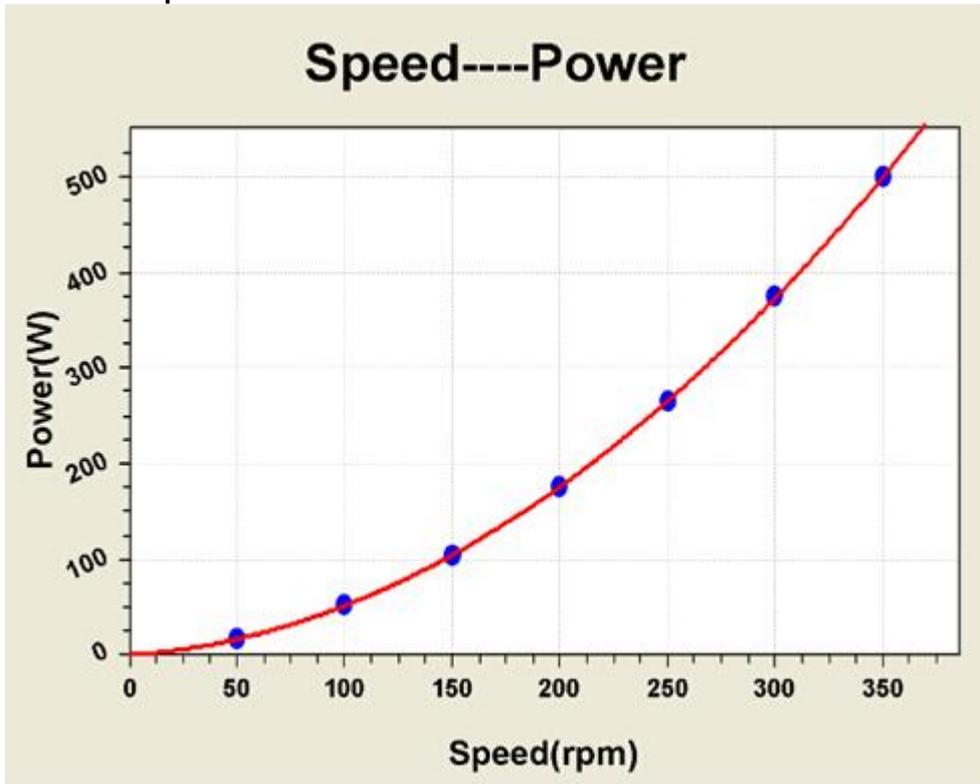
#### 4. Shape Drawing



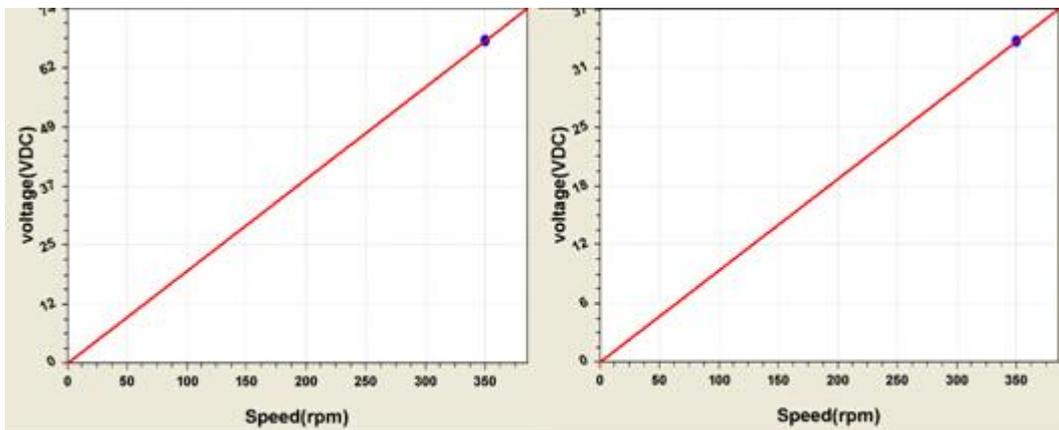
## 5. Performance Parameter

| NO. | PARAMETER              | UNITS | DATA                                   |
|-----|------------------------|-------|--|
| 1   | Rated power            | KW    | 0.5                                    |
| 2   | Rated speed            | RPM   | 350                                    |
| 3   | Rated voltage          | V     | 56/28VDC                               |
| 4   | Rated Line Current     |       | 6.44/12.88                             |
| 6   | Efficiency             |       | >85%                                   |
| 7   | Resistance (Line-Line) |       | -                                      |
| 8   | Winding type           |       | Y                                      |
| 9   | Insulation Resistance  |       | 100Mohm Min(500V DC)                   |
| 10  | Leakage level          |       | <5 ma                                  |
| 11  | Start torque           | N/M   | <0.1                                   |
| 12  | Phase                  |       | Three phase                            |
| 13  | Structure              |       | outer rotor                            |
| 14  | Stator                 |       | coreless                               |
| 15  | Rotor                  |       | Permanent magnet type<br>(outer rotor) |
| 16  | Gen. Diameter          | mm    | 265                                    |
| 17  | Gen. Length            | mm    | 199.5                                  |
| 18  | Gen. Weight            | kg    | 11                                     |
| 19  | Shaft. Diameter        | mm    | 30                                     |
| 20  | Housing Material       |       | Aluminum ( Alloy )                     |
| 21  | Shaft Material         |       | Steel                                  |
| 22  | Gross Weight           | KG    | 15                                     |

## 6. Curve Graph



ON-LOAD Power Curve



ON-LOAD Voltage Curve