Water pumping with a windmill

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1 Introduction

During the period 1975 – 1990, I have worked as a designer of water pumping windmills in de Wind Energy Group of the University of Technology Eindhoven. This group was a member of CWD, Consultancy services Wind energy Developing countries, which was financed by the Ministry of Development Cooperation. CWD was discontinued in 1990 because the subsidy was stopped by the Ministry.

From 1989 up to present I am running the one man engineering office Kragten Design specialized in the development of small electricity generating windmills. Water pumping still has my interest and I have written several KD-reports about certain aspects of water pumping. An overview of my VIRYA windmills and public KD-reports is given on my website: www.kdwindturbines.nl .

In this report KD 490, I will give an overview of several options how water can be pumped by a windmill. It is assumed that the reader has general knowledge of energy. This knowledge is given in the free public report KD 378 (ref. 1). Four options will be explained.
Traditional water pumping windmills driving a piston pump.
CWD-like water pumping windmills driving a piston pump with a floating valve.
Windmills with a rotating vertical shaft in the tower driving a rope pump, a centrifugal pump or a rotating positive displacement pump.
Electricity generating windmills driving an electric pump.

2 Traditional water pumping windmills

Pumping water with a steel windmill is done for more than a century. Many different manufactures have existed but only a few like Southern Cross, Aermotor and Oasis still exist. The traditional water pumping windmills make use of a single acting piston pump which is positioned in the water of the well. The pump is driven by a very long pump rod which is moving in the rising main. A crank mechanism is used to transform the rotation of the rotor shaft into an oscillation of the pump rod. Most traditional windmills have a reducing gearing in between the rotor shaft and the crank shaft. This gearing is running in an oil bath which is formed by a cast iron reservoir positioned on the top of the tower.

The rotor has many blades with large blade angles to get a large starting torque at low wind speeds. This is required because a single acting piston pump has a fluctuating torque which is maximum during the upwards stroke when the crank is in the horizontal position. It can be proven that the peak torque is a factor π larger than the average torque. The rotor will only start at the wind speed where the peak torque can be supplied. Once the rotor is rotating only the average torque has to be supplied because the rotor is working as a flywheel. The description of the transmission, the main formulas and some examples are given in report KD 294 (ref. 2) for a traditional water pumping windmill.

The rotor is turned out of the wind by a safety system to limit the rotational speed and thrust at high wind speeds. An overview of safety systems for which the rotor is turned out of the wind is given in report KD 485 (ref. 3). Most traditional water pumping windmills make use of the ecliptic safety system or the inclined hinge main vane safety system. The tower is generally a four-leg construction with legs made of angel iron which is placed over the well.
Traditional water pumping windmills have some important disadvantages.

1) Because of the starting problems caused by the use of a single acting piston pump, a pump with only a low stroke volume can be used and this means that the windmill will have a low design wind speed. The design wind speed is the wind speed for which the rotor runs at the design tip speed ratio λ_d. For higher wind speeds, the rotor will run at a much higher tip speed ratio than the design tip speed ratio and the power coefficient C_p will therefore be rather low for moderate and high wind speeds.
2) The weight of a traditional water pumping windmill is very high because the rotor has many blades and because a cast iron gear box is heavy.

3) A large starting torque coefficient can only be gained if the rotor has a very low design tip speed ratio of about $\lambda_d = 1$. The tip speed ratio is the ratio in between the tip speed of a rotor blade and the undisturbed wind speed V far before the rotor. The very low design tip speed ratio means that a lot of energy is wasted in the rotation of the wake and therefore the maximum C_p will be rather low. Another reason for the low maximum C_p is that the blade length is normally chosen much shorter than the rotor radius R. These effects are explained in chapter 4 of report KD 35 (ref. 4).

Because of these disadvantages I advise to develop no new windmills of this type.

3 CWD-like water pumping windmills driving a piston pump with a floating valve

All three problems of traditional water pumping windmill can be solved if the peak on the pump torque can be eliminated at low rotational speeds. Several systems have been tried. The most promising system appeared to be a piston pump with a floating piston valve. This system is described in detail in report KD 364 (ref. 5). Only the latest CWD-windmill, the CWD 2000, (with a rotor diameter of 2 m) was tested with a floating valve. The CWD 2000 was the first water pumping windmill equipped with the hinged side vane safety system. The rotor had a large eccentricity of 0.3 m. A rocker arm was used in between the crank rod and the pump rod. The system worked really nice but problems with wear of the rocker arm bearings were not solved before CWD was discontinued. So the CWD 2000 was not tested in projects in developing countries.

The piston valve is made of polypropylene and because it is hollow, it is rather light and floating in water. So if the piston is moving slowly, the piston valve is open and no pressure is built up during the upwards stroke. So the rotor starts unloaded.

The water speed in the gap in between the valve and the valve seat increases at increasing rotational speed and the pressure in the gap decreases. At a certain piston speed, the pressure is that low that the piston valve closes suddenly. The piston speed is maximum half way the stroke when the crank is horizontal, so the first time the valve closes is at half the stroke and this means that the stroke volume is halve the theoretical stroke volume. At increasing rotational speeds, the valve will close more and more early and at high rotational speeds it will close only a little after the lowest dead centre. So now the stroke volume is only a little less than the theoretical stroke volume.

This means that the average torque at low rotational speeds is zero, that it is halve the theoretical torque when the valve closes for the first time and that it is almost equal to the theoretical torque at high rotational speeds. This results in a rather good matching for moderate wind speeds and therefore a much larger pump can be used than for a pump with no floating valve. The output at moderate wind speeds is at least a factor three higher than for a pump with no floating valve and the same starting wind speed.

A disadvantage of the floating valve is that the shock force in the pump rod is rather high because the water column has to be accelerated in a very short time when the valve closes. This means that an elastic element in the pump rod or in the water is needed. For the CWD 2000 it was chosen to use a closed air chamber in the suction line and an open air chamber in the pressure line.

The rotor needs no high starting torque coefficient and the design tip speed ratio can therefore be much higher than for tradition water pumping windmills. For most CWD windmills it was chosen that $\lambda_d = 2$. A rotor with $\lambda_d = 2$ has a much lesser total blade area and therefore also a much lower weight than a rotor with $\lambda_d = 1$. It also has a higher maximum C_p because the losses due to wake rotation are lesser. The CWD windmills had no reducing transmission so no cast iron oil bath was needed. This also resulted in reduction of the weight and made it possible to manufacture the windmill at places were no foundry was available.

Recently I have investigated if it is possible to design a rather big windmill using a pump with a floating valve. This idea is described in report KD 704: “Ideas about a piston pump with a floating valve for the VIRYA-3.6L2 windmill for irrigation of farmland from a river or a lake” (ref. 6). There are some basic differences with the CWD 2000. One is that the floating piston valve isn’t hollow but made of massive polypropylene. Another is that the construction of the rocker arm is different because the length of the rocker arm is twice the eccentricity e.

4 Windmills with a rotating vertical shaft in the tower

The rope pump is generally used as hand pump but it can also be used in combination with a windmill if the windmill has a transmission in between the horizontal rotor shaft and the horizontal pump shaft. As the windmill head can rotate 360°, this transmission must have a vertical shaft in the centre of the tower. If the hinged side vane safety system is chosen, the rotor shaft is eccentric from the tower axis. So the windmill must also have an upper transmission which bridges this eccentricity and which transforms the rotation of the horizontal rotor shaft to the vertical shaft. It must have a lower transmission which transforms the rotation of the vertical shaft into the horizontal pump shaft.

Several upper transmissions have been examined. The most promising option seems to be a round 12 mm Polycord string with only one auxiliary wheel. This option is described for the VIRYA-2.8B4 windmill in report KD 320 (ref. 7). The rotor calculations of the VIRYA-2.8B4 are given in report KD 319 (ref. 8). The rope pump is described in report KD 321 (ref. 9). For the lower transmission, more options than only the round string remain because the distance in between the vertical shaft and the pump shaft can be large.

The rope pump has a horizontal axis which is running into two bearings which are placed above the well. In between the bearings is a spoke wheel which is provided with a rim which is made of two halve car tires. These halve tires are connected to each other at the outer side of the tire and this creates a V-shaped groove. A nylon or polypropylene rope is running in the groove. A large number of pistons are connected to the rope at a distance of about 1 m. There is enough friction in between the rope and the V-shaped groove to allow a certain pulling force in the rope.

The rising part of the rope is running in a PVC rising main which has a T-shaped part at the top side and a cone at the bottom side. The down going part of the rope is hanging free in the well but is guided at the bottom side by a small piece of pipe which has a cone on the upper part. Then the rope is making a loop and is going upwards again.

The lowest side of the rising main is situated at least halve a metre below the water level in the well. As soon as the pump is driven, a column of water is sucked by each piston. Because the pistons have a distance with respect to each other of only 1 m, the pressure drop over each piston is only about 0.1 bar. Therefore a relatively large gap is allowed in between the piston and the inside diameter of the PVC pipe without resulting in a too large leaking flow. The raised water flows away through the horizontal part of the T-joint which is connected to the upper part of the rising main.

This pumping principle demands an almost constant pulling force in the rope and therefore an almost constant torque independent of the rotational speed. For a certain piston diameter and rubber wheel diameter, this torque is proportional to the height H in between the water level in the well and the outlet opening. The water can’t be pumped higher than the outlet and the pump is therefore not able to supply a large pressure height above ground level.

The fact that a rope pump has a constant torque eliminates the need of a windmill rotor with a very high starting torque coefficient. As there is a certain gap in between the pistons and the rising main, all the water will flow back into the well if the rotor is not turning for a certain time. This means that the rotor starts unloaded and that the pump torque increases proportional to the water level in the rising main. In report KD 321 it was calculated that the rotor can be accelerated up to a sufficient high tip speed ratio and so to a sufficient high torque, in a period where the water in the rising main has not yet reached the outlet opening.

Therefore it is expected that the rope pump can be used in combination with a rotor with a rather high design tip speed ratio λ_d = 2.5 and may be even somewhat higher, without getting starting problems. A rotor with this tip speed ratio can be designed such that it has only four blades and so the rotor will be simple and light. A composite drawing of the VIRYA-2.8B4 head has been made. However, detailed drawings were not made and so a prototype of the VIRYA-2.8B4 windmill coupled to a rope pump was not manufactured and tested.

An identical Polycord transmission but now with a 15 mm string is used for the 4-bladed VIRYA-3.5 windmill with λ_d = 4 which is driving a centrifugal pump. This option is described in report KD 693 (ref. 10). The same Polycord transmission as used for the VIRYA-3.5 is also used for the VIRYA-3.6L2 with λ_d = 2 which is driving a rotating positive displacement pump. This option is described in report KD 651 (ref. 11).

An idea to use a H-Darrieus rotor in combination with a direct drive centrifugal pump is described in report KD 601 (ref. 12). As a H-Darrieus rotor isn’t self starting a device was designed which varies the blade angle in between + 10° and – 10° without loosing the advantage that the rotor accepts wind from any direction.

5 Electricity generating windmills driving an electric pump

Several KD reports are written about ideas how to pump water with an electricity generating windmill and a pump which is driven by an electric motor. One idea has really been tested; the VIRYA-3D windmill with the Solaflux solar pump. This idea is described in the (Dutch) report KD 114 (ref. 13). A photo of the VIRYA-3D prototype is given in figure 1. The VIRYA-3D is no longer available but probably it is possible to use the idea for another VIRYA windmill like the 3-bladed VIRYA-3B3 with wooden blades. A new report based on KD 114 has been written. This new report has report number KD 491 (ref. 14).

fig. 1 First VIRYA-3D prototype at the test field
of Teamwork Technology in Zijdewind

The VIRYA-3D has been tested for about half a year by Teamwork Technology. The pump motor was coupled to the generator by means of a relay which was switched on at a certain voltage. So the windmill starts unloaded and the starting wind speed is therefore very low. The relay is switched off at a certain lower voltage and so the rotor doesn't stop if the wind speed is that low that the rotor can't supply the needed pump power. The water height was simulated by a pressure barrel. The system worked really nice and the output was certainly acceptable. At very low wind speeds the output was even higher than as predicted in KD 114.

The Solaflux pump is a positive displacement pump which has two pistons driven by a camshaft which can be supplied with different cam heights. The pump can supply a large pressure and can be used up to water depths of 150 m if the smallest cam is chosen. The pump motor is a DC, PM-motor working on voltages in between 20 V and 70 V. A picture of the pump is given on: http://greenbridge.com.au/solarPumps.htm The efficiency is rather high and the pump has output even at low rotational speeds. A centrifugal pump is much more sensible for the correct rpm.

The VIRYA-3D suffered mechanical problems of flutter of the vane blade at high wind speeds because the stiffness of the vane arm and the tower pipe was not high enough. This finally resulted in breaking of the head pin. The drawings were changed but a modified prototype was never built. The wind activities of Teamwork Technology were transferred to another company, WES, and this company was not interested in the VIRYA-3D.

Some research has also been done to the use of a windmill which is directly coupled to the 3-phase motor of a deep well centrifugal pump. In this case a direct drive PM-generator must have many poles to realise a frequency which is high enough or an accelerating gearing has to be used. The windmill must be rather large because standard deep well pumps have pump motors of at least some kW. It was researched by the Indian company Tinytech if the VIRYA-6.4 windmill can be coupled to the 3-phase asynchronous motor of a standard deep well pump. The VIRYA-6.4 has a direct drive 50-pole PM-generator using the housing of a big asynchronous motor. The design calculations of the VIRYA-6.4 are given in report KD 466 (ref. 15). The 50-pole generator is described in report KD 505 (ref. 16). A prototype of the armature of a 50-pole generator has been made but this armature appeared to be too heavy to handle.

The original idea of using a multi pole direct drive generator is described in report KD 560 (ref. 17) for the 34-pole generator frame size 112 of the VIRYA-3.3S windmill which can be coupled to a 0.55 kW, 3-phase asynchronous motor of a centrifugal pump. Drawings of the VIRYA-3.3S are ready. Information about this windmill is given in a separate KD-folder.

The same idea of a bigger 34-pole PM-generator is described for the 2-bladed rotor with wooden blades of the VIRYA-5 windmill in report KD 614 (ref. 18) and for the 3-bladed stainless steel rotor of the VIRYA-4.4 in report KD 699 (ref. 19). This 34-pole generator makes use of a bigger motor housing frame size 132 and the windmill can be coupled to a bigger 1.1 kW, 3-phase asynchronous motor of a centrifugal pump.

The same idea of a multi pole PM-generator with 46 poles is described for the bigger rotor of the VIRYA-6.5 windmill in report KD 624 (ref. 20). The 46-pole generator makes use of a bigger motor housing frame size 180 and the windmill can be coupled to a bigger 2.2 kW, 3-phase asynchronous motor of a centrifugal pump. A 24-pole PM-generator with no iron in the coils meant for use with a 1.1 kW pump motor is described in report KD 668 (ref. 21).

Report KD 672 (ref. 22) describes the use of the VIRYA-1, the VIRYA-1.02 or the VIRYA-1.04 for pumping of drinking water using a 12 V battery and a pump with a 12 V, DC motor. Although these windmill are rather small, even the VIRYA-1 is big enough for a flow q of about 200 litres per day at a height H of 17 m.

It is important that the pump efficiency is as high as possible if electricity generated by a windmill is used to drive a pump through and electrical shaft because there is energy loss in the generator, the cables and the pump motor. I have written several KD-reports about positive displacement pumps which have a constant flow and a high efficiency and which are much less sensible to the correct rotational speed than centrifugal pumps.

Report KD 539 (ref. 23) describes a fast running vane pump driven by an asynchronous motor. Report KD 542 (ref. 24) describes a diaphragm pump with three in line diaphragms to get an almost constant torque and flow. Report KD 544 (ref. 25) describes a double piston pump with a constant upwards piston speed to get a constant torque and flow. Report KD 661 (ref. 26) describes a fast running vane pump for irrigation driven by a 24 V DC, PM-motor. In chapter 7 of report KD 758 (ref. 27), the use of the VIRYA-5T is described in combination with a standard centrifugal pump with a 4 kW or 5.5 kW asynchronous 3-phase motor.

6 References

1 Kragten A. Basic knowledge about electrical, chemical, mechanical, potential and kinetic energy to understand literature about the generation of energy by small windmills, May 2008, free public report KD 378, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Coupling of a windmill to a single acting piston pump by means of a crank mechanism, September 2006, free public report KD 294, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Safety systems for small wind turbines which turn the rotor out of the wind at high wind speeds, February 2012, reviewed April 2016, free public report KD 485, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Rotor design and matching for horizontal axis wind turbines, January 1999, latest review November 2015, free public report KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Derivation of the formulas for torque and volumetric efficiency for a single acting piston pump with a floating valve, November 2007, modified May 2008, free public report KD 364, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Ideas about a piston pump with a floating valve for the VIRYA-3.6L2 windmill for irrigation of farmland from a river or a lake, August 2020, free public report KD 704, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Kragten A. Development of the VIRYA-2.8B4, a windmill with a Polycord transmission in between the rotor shaft and a vertical shaft to drive a rope pump or an Archimedian screw pump, February 2007, free public report KD 320, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Calculations executed for the 4-bladed rotor of the VIRY-2.8B4 windmill (λ_d = 2.5, galvanised steel blades), February 2007, reviewed December 2015, free public report KD 319, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

9 Kragten A. Combination of the VIRY-2.8B4 windmill with a rope pump, February 2007, free public report KD 321, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands

10 Kragten A. Calculations executed for the 4-bladed rotor of the VIRYA-3.5 windmill (λ_d = 4, stainless steel blades) meant to drive a centrifugal pump through a Polycord transmission with an accelerating gear ratio 2.5 : 1 and a vertical shaft in the tower, January 2020, free public report KD 693, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

11 Kragten A. Calculations executed for the 4-bladed rotor of the VIRYA-3.6L2 windmill (λ_d = 2, galvanised steel blades) with a Polycord transmission in between the rotor shaft and the vertical shaft to drive a rotating positive displacement pump, March 2018, reviewed September 2018, free public report KD 651, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

12 Kragten A. Ideas about a self starting, 3-bladed H-Darrieus rotor for water pumping, December 2015, free public report KD 601, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

13 Kragten A. Onderzoek naar de bruikbaarheid van de Solaflux zonnepomp met nokhoogtes van 2,6 en 3 mm in combinatie met de VIRYA-3D windmolen (research to the usability of the Solaflux solar pump with cam heights of 2.6 and 3 mm in combination with the VIRYA-3D windmill), October 2002, report KD 114, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

14 Kragten A. Research to the usability of the Solaflux solar pump with a 2.6 mm cam in combination with the VIRYA-3B3 windmill, March 2012, reviewed October 2018, free public report KD 491, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

15 Kragten A. Calculations executed for the 2-bladed rotor of the VIRYA-6.4 windmill (λ_d = 6.5, 7.14 % cambered, stainless steel blades), meant for grid connection by means of an asynchronous generator, September 2011, modified December 2011, report KD 466, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

16 Kragten A. Ideas about a direct drive 50-pole permanent magnet generator for the VIRYA-6.4 windmill using the stator stamping of an Indian 4-pole, 3-phase, 3 kW asynchronous motor frame size 180 and 150 neodymium magnets size 40 * 10 * 5 mm, October 2012, report KD 505, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

17 Kragten A. Ideas about a direct drive 34-pole permanent magnet generator for the VIRYA-3.3S windmill using the stator stamping of an Indian 6-pole, 3-phase, 2.2 kW asynchronous motor frame size 112 and 51 neodymium magnets size 40 * 10 * 5 mm, May 2014, reviewed December 2014, free public report KD 560, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

18 Kragten A. Calculations executed for the 2-bladed rotor of the VIRYA-5 windmill (λ_d = 7, Gö 711 airfoil) meant for connection to a 34-pole PM-generator for driving the 1.1 kW asynchronous motor of a centrifugal pump. Description of the 34-pole generator. August 2016, free public report KD 614, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

19 Calculations executed for the 3-bladed rotor of the VIRYA-4.4 windmill (λ_d = 5.25, stainless steel blades) using a 34-pole PM-generator for coupling to a centrifugal pump with a 1.1 kW asynchronous motor, February 2020, free public report KD 699, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

20 Kragten A. Ideas about a direct drive 46-pole PM-generator for the VIRYA-6.5 windmill meant for driving the 2.2 kW asynchronous motor of a centrifugal pump, January 2017, free public report KD 624, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

21 Kragten A. Ideas about a 24-pole permanent magnet generator with a stator with no iron in the coils for the alternative VIRYA-4.2 rotor for battery charging or for combination to the 1.1 kW, 3-phase asynchronous motor of a centrifugal pump, December 2018, free public report KD 668, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

22 Kragten A. Use of the VIRYA-1, the VIRYA-1.02 or the VIRYA-1.04 for pumping of drinking water using a 12 V battery and a pump with a 12 V, DC motor, May 2019, reviewed August 2019, free public report KD 672, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

23 Kragten A. Ideas about a fast running vane pump directly driven by a 0.37 kW, 4-pole asynchronous motor frame size 71, December 2013, reviewed September 2018, free public report KD 539, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

24 Kragten A. Ideas about a diaphragm pump with three in line diaphragms driven by a 0.37 kW asynchronous 4-pole motor or a permanent magnet DC motor frame size 71 and a reducing gear box frame size 32 of manufacture Rossi, January 2014, free public report KD 542, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

25 Kragten A. Ideas about a double piston pump with a constant upwards piston speed driven by a 0.37 kW asynchronous 4-pole motor or a permanent magnet DC motor frame size 71 and a reducing 2-step gear box frame size 32 of manufacture Rossi, January 2014, reviewed May 2016, free public report KD 544, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

26 Kragten A. Ideas about a vane pump for low height irrigation directly driven by a 24 V, 0.35 kW, permanent magnet DC motor frame size 71, October 2018, free public report KD 661, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

27 Kragten A. Calculations executed for the 2-bladed rotor of the VIRYA-5T windmill (λ_d = 6, galvanised steel tapered blades) meant for connection to the axial flux generator of Hefei Top Grand type TGET450-5KW-300R for grid connection or water pumping, December 2023, reviewed April 2024.