Use of the VIRYA-3.8 windmill for water pumping with a pump equipped with a permanent magnet DC motor

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1 Introduction

The VIRYA-3.8 windmill is designed especially for battery charging in very low wind regimes. It has a very low cut in wind speed of 2 m/s and the power at low wind speeds is very good. The rated wind speed is only 9.5 m/s which is realised by using a light foamed PVC vane blade. The generator is rectified in star for 26 V battery charging. This windmill is described together with the VIRYA-1.8D, the VIRYA-2.5 and the VIRYA-3.3D in a provisional folder of May 2005. Because of the rather large rotor diameter and the rather low rated wind speed it is expected that the VIRYA-3.8 can also be used for water pumping without the use of batteries and dump load. For this use the pump must be equipped with a 24 V permanent magnet (PM) direct current (DC) motor. The generator of the windmill must be rectified in delta. Some simple electronics are required for switching the pump motor in and out. A similar system has already been described for the VIRYA-3D windmill and a Solaflux solar pump in report KD 114 (ref. 1) and this system has been tested for about half a year by Teamwork Technology. However, the Solaflux pump is especially designed for heights in between 10 m and 100 m depending on the used camshaft height. In The Netherlands and other countries there is a possible market for low lift pumping for drainage or low lift irrigation. In this case a much bigger pump is required.

2 Characteristics of the VIRYA-3.8 windmill

The VIRYA-3.8 windmill is characterised by the P-n curves of the rotor. These curves depend on the C_p-λ curve of the rotor and the δ-V curve of the safety system. How the P-n curves are derived is described in general in chapter 8 of report KD 35 (ref. 2) and in detail in chapter 5 of the design report of the VIRYA-3.8 rotor, report KD 231 (ref. 3). The P-n curves of the rotor, given in figure 4 of KD 231, are copied as figure 1. The P-n curve of the generator for short-circuit in delta is also given in figure 1.

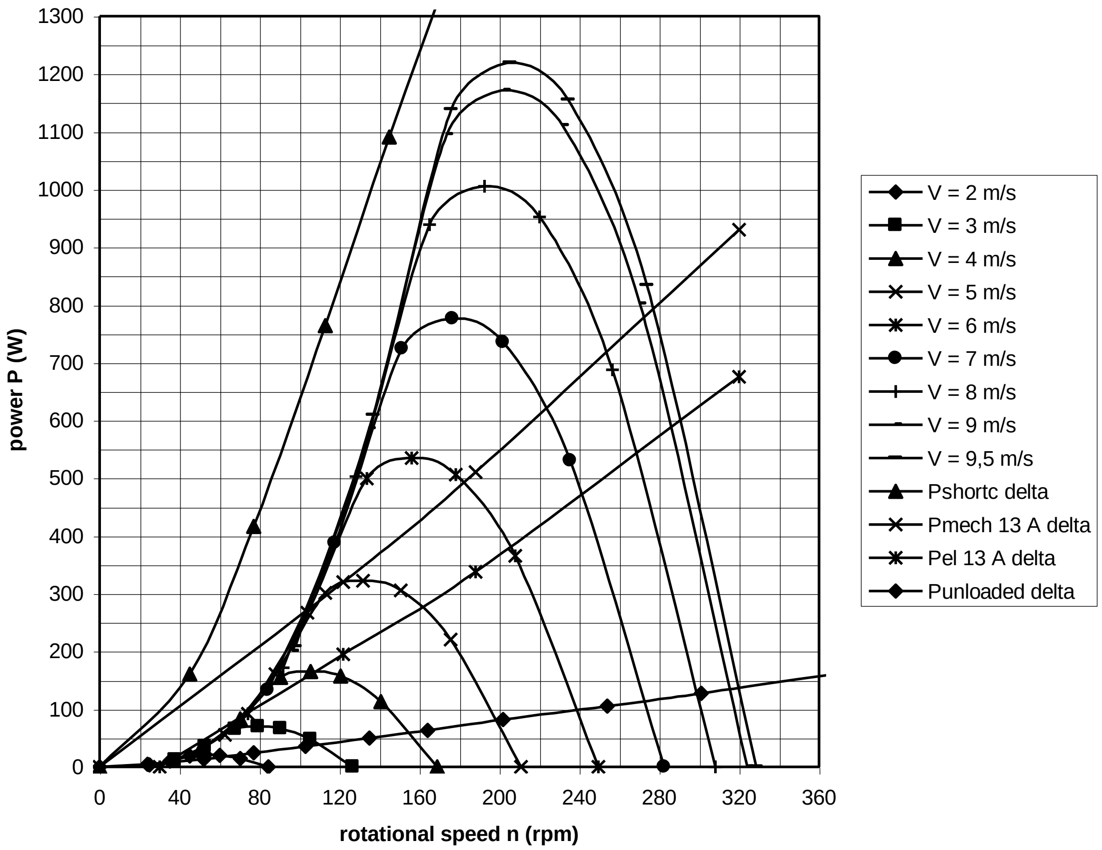

fig. 1 P-n curves of the VIRYA-3.8 rotor and of the generator for 13 A

The P-n curve of the generator for short-circuit in delta is laying left from the P-n curve of the rotor for V = 9.5 m/s and higher which means that the rotor can be stopped at any wind speed if short-circuit is made.

3 Characteristics of the pump

In the first instance a positive displacement pump is chosen but a centrifugal pump might also work. The pump is coupled directly to the PM DC motor. As no gearing is used, the pump speed n_{pump} and the pump motor speed n_{pm} are the same. The hydraulic power of a pump P_{hyd} is given by:

$$P_{hyd} = \rho_w * g * H * q \qquad (W) \qquad (1)$$

In this formula ρ_w is the density of water (1000 kg/m^3), g is the acceleration of gravity (9.81 m/s^2), H is the height (m) and q is the flow (m^3/s). The flow q is given by:

$$q = \eta_{vol} * \nabla * n_{pump} / 60 \qquad (m^3/s) \qquad (2)$$

In this formula η_{vol} is the volumetric efficiency (-), ∇ is the theoretical stroke volume for a piston pump or the theoretical water flow for one revolution of the rotor of a positive displacement pump (m^3) and n_{pump} is the rotational speed of the pump (rpm).

(1) + (2) gives:

$$P_{hyd} = \rho_w * g * H * \eta_{vol} * \nabla * n_{pump} / 60 \qquad (W) \qquad (3)$$

The required electrical power of the pump motor P_{elpm} is given by:

$$P_{elpm} = P_{hyd} / (\eta_{pm} * \eta_{pump}) \qquad (W) \qquad (4)$$

η_{pm} is the efficiency of the pump motor (-) and η_{pump} is the efficiency of the pump (-).

(3) + (4) gives:

$$P_{elpm} = \rho_w * g * H * \eta_{vol} * \nabla * n_{pump} / (60 * \eta_{pm} * \eta_{pump}) \qquad (W) \qquad (5)$$

It is supposed that η_{vol}, η_{pm} and η_{pump} are constant. Now in formula 5, n_{pump} is the only variable and this shows that P_{elpm} is proportional to n_{pump}.
The required mechanical power of the pump motor P_{mechpm} is given by:

$$P_{mechpm} = P_{hyd} / \eta_{pump} \qquad (W) \qquad (6)$$

(3) + (6) gives:

$$P_{mechpm} = \rho_w * g * H * \eta_{vol} * \nabla * n_{pump} / (60 * \eta_{pump}) \qquad (W) \qquad (7)$$

The torque of the pump Q_{pump} is given by:

$$Q_{pump} = 30\ P_{mechpm} / (\pi * n_{pump}) \qquad (Nm) \qquad (8)$$

(7) + (8) gives:

$$Q_{pump} = \rho_w * g * H * \eta_{vol} * \nabla / (2 * \pi * \eta_{pump}) \qquad (9)$$

It is supposed that η_{vol} and η_{pump} are constant. All other terms in formula 9 are also constant for a certain choice of H and ∇, so it is shown that the pump motor torque Q_{pump} is constant.

For a PM DC pump motor, the required current I is about proportional to the torque Q_{pump} and the rotational speed n_{pump} is about proportional to the voltage U. So this means that if the pump torque Q is constant the current will be constant too and that the rotational speed n_{pump} will increase proportional to the voltage U. Formula 5 shows that P_{elpm} is proportional to n_{pump} and because n_{pump} is proportional to U, P_{elpm} will be proportional to U.

The generator of the windmill is a three phase PM generator which is provided with a three phase rectifier and therefore it produces DC current and DC voltage. For battery use the voltage is almost constant and it rises only a little depending on the current. For direct coupling of the windmill generator with a PM DC pump motor, the current will be constant and the voltage will rise proportional to n_{pump}. Therefore the P_{mech}-n and P_{el}-n curves of the generator, if coupled to a pump motor, will differ a lot from the curves for battery charging.

The generator of the VIRYA-3.8 has not been measured for different constant currents. However, this has been done for a smaller generator with housing 5RN90L04V and the measurements are given in report KD 78 (ref. 4). In figure 8 of KD 78 it can be seen that the torque Q is almost constant for a constant current I. This means that all P_{mech}-n curves will be about straight lines through the origin.

In figure 9 of KD 78 it can be seen that the P_{el}-n curves are also about straight lines but that they don’t go through the origin. Each P_{el}-n line intersects with the n-axis and the point of intersection is at a higher rotational speed as the current is higher.

In figure 9 of KD 78 it can be seen that the generator efficiency η_{gen} for a certain current I is rising with rising rotational speed. In the beginning the rise is very fast but at higher rotational speeds the η-n curves have a tendency to become about horizontal and reach a value of more than 80 %.

The position of the P_{mech}-n and P_{el}-n lines in the P-n diagram depends on choice of ∇ and H and on the kind of pump motor. In the first instance a PM DC motor of the Dutch manufacture Creusen from Roermond has been chosen. This company supplies PM DC motors with frame size 56, 71 and 90.

In the first instance it is chosen for motor type 71M-2GP with nominal voltage U = 24 V, nominal mechanical power P_{mech} = 250 W, nominal rotational speed n = 1500 rpm and nominal current I = 13 A. The required nominal electrical power is calculated with $P_{el} = U * I = 24 * 13 = 312$ W. The nominal pump motor efficiency (dimensionless) is calculated with $\eta_{pm} = P_{el} / P_{mech} = 250 / 312 = 0.8$. I have contacted the manufacturer and it is allowed to use this motor up to a voltage of 48 V if the current is not higher than the nominal current of 13 A. In this case the heat losses in the armature windings stay the same. The iron losses in the rotor and the ventilator losses will increase but the efficiency at 48 V will certainly be higher than at 24 V. But for ease of calculation, the efficiency is supposed to be constant and 0.8 for all voltages.

Next it is assumed that the combination of the stroke volume ∇ and the height H is chosen such that the required mechanical pump motor power P_{mechpm} = 250 W at n_{pump} = 1500 rpm and so that P_{elpm} = 312 W for I = 13 A and U = 24 V. It is also assumed that the current I is constant and 13 A for all rotational speeds of the pump and so for all voltages.

For this condition the P_{mech}-n and P_{el}-n curves of the generator will be determined. The generator of the VIRYA-3.8 has not been measured for constant currents but it has been measured for three constant voltages being 15 V, 26 V and 52 V delta. The P_{mech}-n and P_{el}-n lines for a current I = 13 A will be derived from these measurements. This goes as follows.

The I-n curves for these three voltages are given in figure 15 of report KD 200 (ref. 5). Now a horizontal line is drawn in this figure for I = 13 A. The points of intersection of this line with the three I-n curves are determined. The rotational speeds of the points of intersection found this way, are given in table 1. The electrical power is calculated by $P_{el} = U * I$. The mechanical power for the three different voltages is given in figure 12 of KD 200. The efficiency is calculated by $\eta_{gen} = P_{el} / P_{mech}$. For each rotational speed P_{mech}, P_{el} and η_{gen} are determined and are also given in table 1.

	I = 13 A			
U (V)	n (rpm)	P_{mech} (W)	P_{el} (W)	η_{gen} (-)
15	122	320	195	0.609
26	188	510	338	0.663
52	320	930	676	0.727

table 1 Values for n, P_{mech}, P_{el} and η_{gen} for a current I = 13 A and delta rectification

The P_{mech}-n and P_{el}-n lines which can be drawn through the values for the three rotational speeds of table 1 are also plotted in figure 1. As the P_{mech}-n line is about a straight line through the origin it is extended to the origin. For the P_{el}-n line it is assumed that it is intersecting with the n-axis for n = 30 rpm. The unloaded P-n curve for rectification in delta is also plotted in figure 1.

The pump motor characteristics are given for a voltage of 24 V. At a rotational speed n = 188 rpm, the voltage U = 26 V for I = 13 A. At a rotational speed n = 30 rpm, the voltage U = 0 V for I = 13 A. It is estimated that the voltage rises linear in between these points. This results in about a voltage U = 24 V at n = 176 rpm. In figure 1 it can be read that P_{mech} = 475 W and that P_{el} = 312 W for n = 176 rpm. This gives a generator efficiency of 0.657. In table 1 it can be seen that the efficiency is rising at increasing rotational speed. The average generator efficiency in the rpm range of the windmill will be about 0.65. For a pump motor efficiency of 0.8 this gives an average efficiency of the electrical shaft of 0.65 * 0.8 = 0.52. A windmill with a mechanical transmission to the pump may have a transmission efficiency of about 0.9 which is a factor 1.73 higher than for an electrical shaft. But a mechanical transmission has a lot of disadvantages, especially for an eccentric rotor.

In figure 1 it can be seen that the P_{mech}-n line of the pump touches the imaginary P-n line of the rotor for V = 4.9 m/s at a rotational speed of about 115 rpm. This means that a running rotor will be slowed down as soon as the wind speed becomes lower than 4.9 m/s. The voltage at this speed will be about 14 V. So the pump motor has to be disconnected at a certain low cut off voltage which can even be somewhat lower than 14 V. Suppose we take a cut off voltage U_{cutoff} = 8 V. This loaded voltage will be reached at a rotational speed of about 79 rpm. In figure 1 it can be seen that the rotor can produce its maximum power for a wind speed of 3 m/s at n = 79 rpm. Suppose the pump motor is coupled at a voltage which belongs to the unloaded rotational speed belonging to a wind speed of 3 m/s. In figure 1 it can be seen that the unloaded rotational speed in delta for V = 3 m/s is about 110 rpm.

The generator measurements of the VIRYA-3.8 generator are given in report KD 200 (ref. 5). In figure 3 of KD 200 it can be read that the open voltage for delta rectification and n = 110 rpm is about 22 V. So the pump motor can be coupled to the windmill generator as soon as the open generator voltage is 22 V. This gives U_{cutin} = 22 V. The loaded voltage at n = 110 rpm is about 13 V which is higher than U_{cutoff} = 8 V. However, if the starting current causes an extra voltage drop of more than 5 V, U_{cutin} has to be taken higher.

So for wind speeds higher than 4.9 m/s pump motor and generator will be coupled permanently and the working point can be found by the points of intersection of the P_{mech}-n line of the generator for 13 A delta with the P-n lines of the rotor. For wind speed of 9.5 m/s and higher, the point of intersection lays at a rotational speed of about 278 rpm.

The generator voltage will be about 44.5 V. This is lower than the 48 V which the pump motor can certainly have so the choice of windmill and pump motor seems to be OK.

For wind speeds in between 3 and 4.9 m/s, the pump is working discontinue because as soon as the cut in voltage of 22 V is reached the pump is working but as soon as the voltage is decreased up to 8 V, the pump motor is disconnected. But then the rotor is accelerating again and the whole process is repeated. So for wind speeds in between 3 and 4.9 m/s there is still a certain output.

4 Determination of flow and stroke volume as a function of wind speed and height

For each wind speed of 5 m/s and higher, the working point can be determined. The working point is the point of intersection of the P_{mech}-n line of the generator for 13 A delta with the P-n line of the rotor for a certain wind speed. For each working point the generated electrical power P_{el}, can be determined by going vertically from the working point till the P_{el}-n line for 13 A delta is intersected. The values for P_{el} found this way are given in the P_{el}-V curve of figure 2. For wind speeds in between 3 and 5 m/s this method doesn't work because the pump motor is working intermittent. The estimated part of the P_{el}-V curve for wind speeds in between 3 and 5 m/s is also given in figure 2.

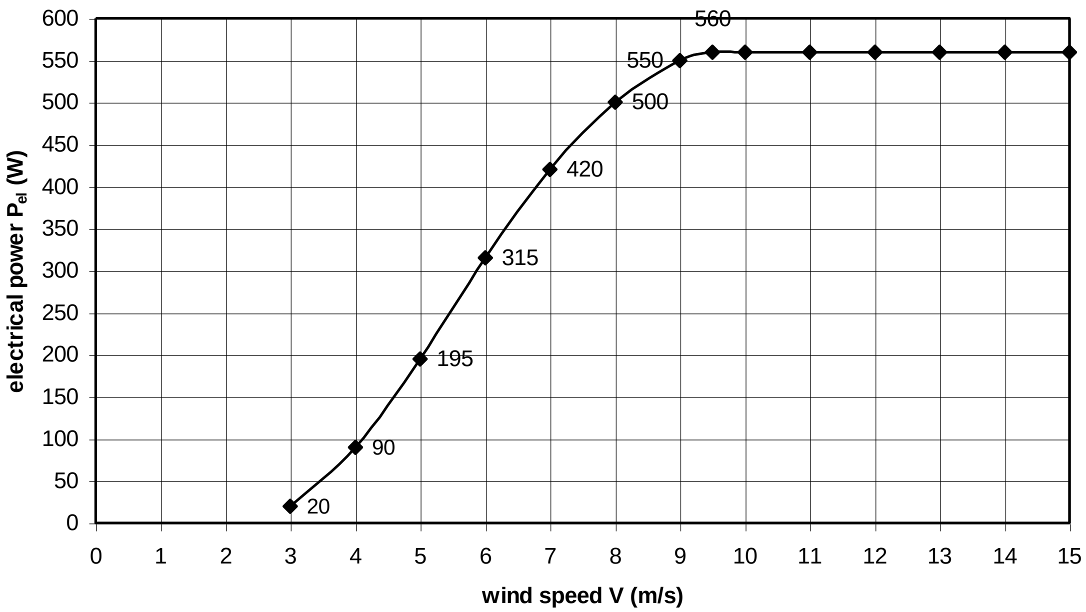

fig. 2 P_{el}-V curve of the VIRYA-3.8 windmill for coupling to the pump motor of a positive displacement pump with a choice of ∇ and H such that I = 13 A.

For the determination of the q-V curves for certain heights H the following procedure is used:

(1) + (4) gives:

$$P_{elpm} = \rho_w * g * H * q / (\eta_{pm} * \eta_{pump}) \quad \text{(W)} \qquad (10)$$

Formula 10 can be written as:

$$q = P_{elpm} * \eta_{pm} * \eta_{pump} / (\rho_w * g * H) \quad (m^3/s) \qquad (11)$$

Assume $\eta_{pm} = 0.8$, a positive displacement pump will have a rather high efficiency so assume $\eta_{pump} = 0.7$, $\rho_w = 1000$ kg/m^3, g = 9.81 m/s^2. Substitution of these values in formula 11 gives:

$q = 5.71 * 10^{-5} * P_{elpm} / H$ (m^3/s) (12)

If q is wanted in m^3/hour formula 12 changes into:

$q = 0.2056 * P_{elpm} / H$ (m^3/hour) (13)

So the q-V curves will have a similar shape as the P_{el}-V curve of figure 2 but the height of the curve depends on the chosen value for H. Next the q-V curves are determined for seven values of H being H = 0.5 m, H = 1 m, H = 2 m, H = 4 m, H = 8 m, H = 16 m and H = 32 m. It appears to be easy, first to make a table in which all the calculated values are given. The calculated values from table 2 are plotted in figure 3.

		H = 0.5 m	H = 1 m	H = 2 m	H = 4 m	H = 8 m	H = 16 m	H = 32 m
V (m/s)	P_{el} (W)	q (m^3/hour)	q (m^3/hour)	q (m^3/hour)	q (m^3/hour)	q (m^3/hour)	q (m^3/hour)	q (m^3/hour)
3	20	8.22	4.11	2.06	1.03	0.51	0.26	0.13
4	90	37.01	18.50	9.25	4.63	2.31	1.16	0.58
5	195	80.18	40.09	20.05	10.02	5.01	2.51	1.25
6	315	129.53	64.76	32.38	16.19	8.10	4.05	2.02
7	420	172.70	86.35	43.18	21.59	10.79	5.40	2.70
8	500	205.60	102.80	51.40	25.70	12.85	6.43	3.21
9	550	226.16	113.08	56.54	28.27	14.14	7.07	3.53
9.5	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
10	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
11	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
12	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
13	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
14	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60
15	560	230.27	115.14	57.57	28.78	14.39	7.20	3.60

table 2 Calculated values for q depending on V and H

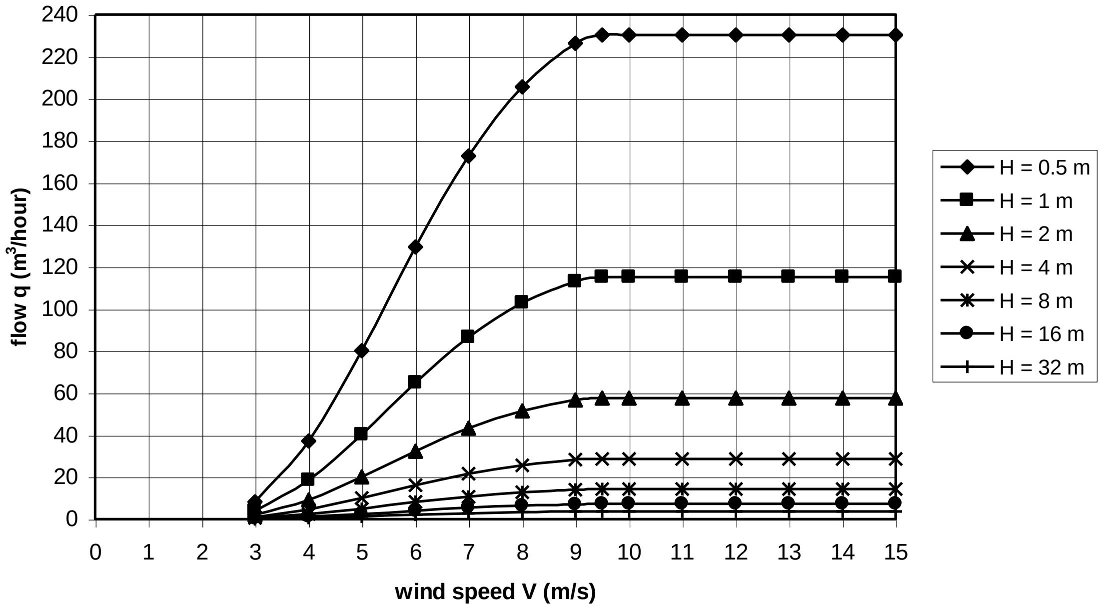

fig. 3 Calculated q-V curves for seven different values of H

Especially for low heights, the supplied flow q is very high even for low wind speeds. It must be clear that for every height H a different pump with a different stroke volume ∇ will be required. Formula 2 can be written as:

$$\nabla = 60 * q / (\eta_{vol} * n_{pump}) \qquad (m^3) \qquad (14)$$

(12) + (14) gives:

$$\nabla = 3.426 * 10^{-3} * P_{elpm} / (\eta_{vol} * n_{pump} * H) \qquad (m^3) \qquad (15)$$

The required stroke volume must be determined for a DC voltage of 24 V belonging to a rotational speed of the rotor n = 176 rpm. The electrical power P_{elpm} = 312 W and the rotational speed of the pump n_{pump} = 1500 rpm. It is estimated that η_{vol} = 0.95.
Substitution of these values in formula 15 gives:

$$\nabla = 7.5 * 10^{-4} / H \qquad (m^3) \qquad (16)$$

Using formula 16, ∇ is determined for the seven chosen values of H. The result is given in table 2.

H (m)	∇ (m^3)
0.5	$15 * 10^{-4}$
1	$7.5 * 10^{-4}$
2	$3.75 * 10^{-4}$
4	$1.88 * 10^{-4}$
8	$0.94 * 10^{-4}$
16	$0.47 * 10^{-4}$
32	$0.23 * 10^{-4}$

table 2 Required stroke volume ∇ of the pump as a function of the height H.

If the pump is not coupled directly to the pump motor but if a decelerating gear ratio i is used, the required stroke volume increases proportional to i (if the transmission losses are neglected). This may be a good option if a large slow running pump, like a rope pump, is used for larger heights. For i = 10, table 2 can be used but 10^{-4} has to be replaced by 10^{-3}.

The determination of the kind of positive displacement pump and of the pump geometry for different stroke volumes ∇ is without the scope of this report. Many different pump types are on the market and some of them may be suitable for manufacture in developing countries. The pump selection, the development of the electronics for coupling of generator and pump motor and the testing of the pump might be a good subject for a technical school.

5 Use of the VIRYA-3.8 for drainage or very low lift irrigation

For drainage with heights in between 0.5 and 1.5 m very often centrifugal pumps driven by a three phase motor, are used. These pumps have as advantages that there is no mechanical contact in between the pump fan and the pump housing, that they can run rather fast, that they are rather cheap and that they can pump water which may be polluted by water plants. Disadvantages are that the pump fan must be placed under the lowest water level, that the water can flow back through the pump, that below a certain rotational speed the flow is zero and that the efficiency is rather low. Because the water can flow back through the pump, the pump outlet must be above the highest level of the upper channel.

This results in a higher height than the difference of the water levels in between the lower and the upper channel. Especially when this difference is very low, say 0.5 m, the real height may be 1 m which doubles the required power.

A positive displacement pump can be placed in between the upper and lower channel and will have only the real difference in water level as height. A prerequisite is that the pump has no or only a little leakage. It must also be prevented that the pump can run backwards because of the pressure difference over the pump if the motor is not powered. This can be gained by a one direction clutch on the motor shaft.

A windmill with a mechanical transmission driving a centrifugal pump, has to be placed on the dam in between the upper and lower channel. Therefore this dam has to be made of concrete and must be very heavy. The foundation of VIRYA-3.8 can be placed besides the dam and the dam can be lighter or can even be made of ground.

The VIRYA-3.8 has a direct drive generator and therefore it has no oil filled gearbox. So there is no chance of oil leakage and the VIRYA-3.8 can therefore be used in nature areas.

The generator of the VIRYA-3.8 can be used as a brake by making short-circuit in the winding. So if pumping of water is not necessary, the windmill can be stopped very easily. This can be done manually or automatically steered by a switch activated by a float in the lower channel.

The VIRYA-3.8 has a rather high tower with a height of 9.5 m and therefore it can be used in regions with low bushes or high crops like maize. The tower has hinges in the tower foot which makes erection easy. The tower can be lowered in case of tornado's.

6 References

1 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 (in Dutch), October 2002, report KD 114, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 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.

3 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-3.8 windmill (λ_d = 5.25, galvanised steel blades) for use in countries with very low wind speeds, April 2005, report KD 231, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Measurements performed on a generator with housing 5RN90L04V and a 4-pole armature equipped with neodymium magnets, March 2001, reviewed March 2015, free public report KD 78, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. Measurements performed on a generator with housing 5RN112M04V and a 4-pole armature equipped with neodymium magnets, June 2004, free public report KD 200, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.