Research to the usability of the Solaflux solar pump with a 2.6 mm cam in combination with the VIRYA-3B3 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.

In public report KD 490 (ref. 1), an overview is given of four options how water can be pumped by a windmill. The fourth option is to use an electricity generating windmill which is coupled to a pump which is driven by an electric motor. This idea has been tested for the VIRYA-3D windmill with the Solaflux solar pump in 2003. This idea is described in the (Dutch) report KD 114 (ref. 2). A photo of the VIRYA-3D prototype with 1 m long steel blades and a 6 m long, 4-legs lattice tower with a 2 m upper pipe section is given in figure 1.

fig. 1 First VIRYA-3D prototype at 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 predicted in KD 114.

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.

A licence of the VIRYA-3D is no longer available but it might be that the Solaflux pump can also be used in combination with the VIRYA-3B3 windmill which has a 3-bladed rotor with wooden blades and a much stiffer vane arm and tower pipe and a stronger head pin than the first VIRYA-3D. This will be investigated in this report KD 491.

The main differences in between the VIRYA-3D and the VIRYA-3B3 are: The VIRYA-3D has a 3-bladed rotor with steel blades and a design tip speed ratio of 5. The VIRYA-3B3 has a 3-bladed rotor with wooden blades and a design tip speed ratio of 6.5. The VIRYA-3D has a very light vane blade made of 8 mm foamed PVC. The rated wind speed with this vane blade is 8 m/s. The VIRYA-3B3 has a vane blade made of 9 mm water proof plywood. The rated wind speed with this vane blade is 9.5 m/s. The generator of the VIRYA-3D uses the original 230/400 V winding. The VIRYA-3B3 uses the same generator but now with a modified 115/200 V winding. The VIRYA-3B3 is designed to charge a 24 V battery and has a maximum power of 500 W. The VIRYA-3D was designed to be coupled to a Solaflux pump. It can also be used for 24 V battery charging but the maximum power is then only 200 W.

2 Description of the VIRYA-3B3 windmill

The VIRYA-3B3 rotor is an alternative 3-bladed rotor for the 2-bladed rotor of the VIRYA-3 windmill. All other components are the same. The VIRYA-3B3 is described in a folder dated April 2015 together with the VIRYA-3, the VIRYA-4.2 and the VIRYA-4.6B2 (this folder is no longer public). The design tip speed ratio of the VIRYA-3B3 rotor is 6.5. The design calculations of the VIRYA-3B3 rotor are given in public report KD 484 (ref. 3).

The VIRYA-3B3 has a PM-generator with a modified 115/200 V winding which is realised by connecting the first and the second layer in parallel in stead of in series. Modification of a standard 230/400 V winding into a 115/200 V winding is described in public report KD 341 (ref. 4). The generator is made from a 2.5 kW asynchronous motor with frame size 90 and a lengthened stator by replacing the original armature and shaft by a permanent magnet armature with neodymium magnets and a stainless steel shaft. The VIRYA-3B3 can be used for 24 V battery charging if the winding is rectified in star and for 12 V battery charging if the winding is rectified in delta. For coupling to the Solaflux pump the winding is rectified in star and no batteries are used. So the windmill can’t be used for pumping and battery charging at the same time!

An alternative PM-generator using a 2.2 kW motor frame size 100 is described in public report KD 503 (ref. 5). This generator will have about the same characteristics as the original generator with a 115/200 V winding if it has also a modified 115/200 V winding.

The maximum voltage at pumping will rise to a much higher value than for battery charging and as a high DC voltage is dangerous, care should be taken that no one can touch non isolated contacts of the wiring!

The VIRYA-3B3 is provided with the hinged side vane safety system which limits high rotational speeds and a high thrust at high wind speeds. The hinge side vane system for a rotor with blades with a normal Göttingen airfoil is described in public report KD 213 (ref. 6). The VIRYA-3B3 has a tower which consists of a 4-legged, 3.5 m long lower and a middle part made of angle iron and strip which are bolted together. It has a 3 m long upper part made of pipe. The overlap in between the tower pipe and the middle section is about 0.6 m, so the total tower height is about 8.4 m which is expected to be high enough for water pumping. On 1-1-2018, I stopped all my commercial activities so a licence of the VIRYA-3B3 is no longer available but with KD 484, KD 503 and KD 213 it must be possible to make its own design.

3 Description of the Solaflux pump

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 pistons are provided with a membrane and so it is prevented that the oil in which the cams are running, makes contact with the water. Both pistons have the pressing stroke at the same time and are therefore balancing each other. Only two valves are needed for this construction. An elastic element is used to flatten the flow. The pump can supply a large pressure and can be used up to water depths of 150 m if the smallest cam is chosen. Only the Solaflux pump with a 2.6 mm cam will be taken into account. The maximum height is 100 m and the minimum height is 25 m.

The pump motor is a DC, PM-motor working on voltages in between 24 V and 70 V and 80 V is allowed for a short time. 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 pump motor is normally connected to the generator at an unloaded voltage of about 57 V and disconnected at a loaded voltage of 20 V. For the VIRYA-3D prototype a relay was used but it might be better to develop an electronic circuit for which both voltages can be adjusted accurately to the optimum values for a certain height.

4 Determination of the Q-n curves of the rotor and the generator

To check the matching in between the rotor, the generator and the pump motor one needs the Q-n curves of the rotor for different wind speeds. The derivation of the P-n and Q-n curves of the rotor is given in chapter 6 of public report KD 35 (ref. 7). The P-n curves are given in report KD 484 but for water pumping use of the Q-n curves is easier. One needs the C_q-λ curve, the δ-V curve of the safety system and the formulas for the rotational speed n and the torque Q. The C_q-λ curve is given as figure 2 in report KD 484. The δ-V curve is given as figure 3 in report KD 484. The formula for the rotational speed n_δ for a yawing rotor is given as formula 7.1 of report KD 35. The formula for the torque Q_δ for a yawing rotor is given as formula 7.7 of report KD 35. Substitution of R = 1.5 m in formula 7.1 of KD 35 gives:

$$n_\delta = 6.366 * \lambda * \cos\delta * V \quad \text{(rpm)} \qquad (1)$$

Substitution of $\rho = 1.2\ kg/m^3$ and R = 1.5 m in formula 7.7 of KD 35 gives:

$$Q_\delta = 6.362 * C_q * \cos^2\delta * V^2 \quad \text{(Nm)} \qquad (2)$$

Next corresponding values of C_q and λ from the C_q-λ curve are substituted in formula 1 and 2 for a certain value of V and this gives the Q-n curve for that wind speed. This is repeated for other values of V. The result of the calculations is given in table 1 for wind speeds V = 3, 4, 5, 6, 7, 8 and 9.5 m/s and for tip speed ratios λ = 0, 1, 2, 3.5, 5, 6.5, 8, 9.5 and 10.4.

		V = 3 m/s $\delta = 0°$		V = 4 m/s $\delta = 0°$		V = 5 m/s $\delta = 0°$		V = 6 m/s $\delta = 0°$		V = 7 m/s $\delta = 5°$		V = 8 m/s $\delta = 15°$		V = 9.5 m/s $\delta = 30°$	
λ (-)	C_q (-)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n (rpm)	Q (Nm)	n_δ (rpm)	Q_δ (Nm)	n_δ (rpm)	Q_δ (Nm)	n_δ (rpm)	Q_δ (Nm)
0	0.0088	0	0.50	0	0.90	0	1.40	0	2.02	0	2.72	0	3.34	0	3.79
1	0.0105	19.1	0.60	25.5	1.07	31.8	1.67	38.2	2.40	44.4	3.25	49.2	3.99	52.4	4.52
2	0.016	38.2	0.92	50.9	1.63	63.7	2.54	76.4	3.66	88.8	4.95	98.4	6.08	104.7	6.89
3.5	0.0457	66.8	2.62	89.1	4.65	111.4	7.27	133.7	10.47	155.4	14.14	172.2	17.36	183.3	19.68
5	0.067	95.5	3.84	127.3	6.82	159.2	10.66	191.0	15.35	222.0	20.73	246.0	25.45	261.9	28.85
6.5	0.0615	124.1	3.52	165.5	6.26	206.9	9.78	248.3	14.09	288.6	19.03	319.8	23.36	340.4	26.48
8	0.0425	152.8	2.43	203.7	4.33	254.6	6.76	305.6	9.73	355.2	13.15	393.6	16.15	419.0	18.30
9.5	0.0174	181.4	1.00	241.9	1.77	302.4	2.77	362.9	3.99	421.7	5.38	467.3	6.61	497.6	7.49
10.4	0	198.6	0	264.8	0	331.0	0	397.3	0	461.7	0	511.6	0	544.7	0

table 1 Calculated values of n and Q as a function of λ and V for the VIRYA-3B3 rotor

The calculated Q-n curves for different wind speeds are given in figure 2. The optimum parabola is drawn through the points for the optimum tip speed ratio $\lambda = \lambda_{opt} = 6.5$. The C_p is maximal for this value of λ (the C_q is maximal for a lower value of λ).

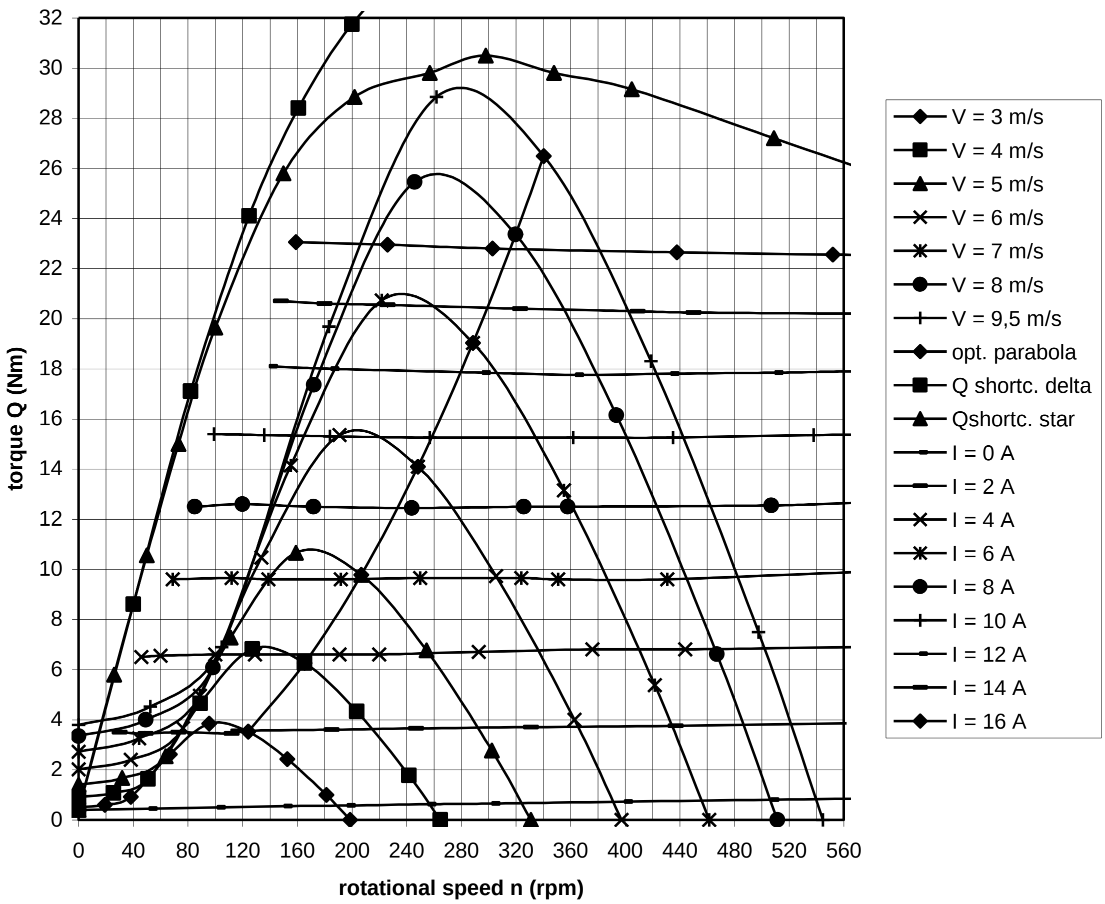

fig. 2 Q-n curves for different wind speeds, optimum parabola, short-circuit in delta and in star. Q-n curves for I = 0 A, 2 A, 4 A, 6 A, 8 A, 10 A, 12 A, 14 A and 16 A

The measured Q-n curves for short-circuit in delta and in star are also given in figure 2. It can be seen that the Q-n curve for short circuit in star is lying just a little higher than the Q-n curve of the rotor for V = 9.5 m/s (and higher) but the distance is little. So it is advised to make short-circuit in delta if the rotor must be stopped at high wind speeds. Short-circuit in delta is the same as short-circuit in star if the star point is short-circuited too. This requires an extra wire from the star point to the short-circuit switch and a short-circuit switch with three contacts.

The generator has been measured with the original 230/400 V winding and the measurements are given in public report KD 78 (ref. 8). The generator has been measured for a range of constant currents from 1 up to 8 A and the characteristics are given in figure 16 up to 20 of KD 78. If the standard 230/400 V winding is modified into a 115/200 V winding, the current doubles and the voltage halves. So the measurements can be used for a 115/200 V winding if this effect is taken into account. The Q-n curves for constant currents from 2 A up to 16 A for the modified 115/200 V winding are also given in figure 2. The Q-n curve for open clamps, so for I = 0 A, is also given in figure 2.

Figure 17 out of report KD 78 is needed to make the Q-n curves for constant currents for a modified 115/200 V winding and a copy of figure 17 is given in appendix 1. This figure gives the torque Q as a function of the rotational speed n for a range of currents I, for the original 230/400 V winding.

5 Determination of the matching of generator and pump motor for a 2.6 mm cam

The point of intersection of the Q-n curve for a certain constant current and the right part of the Q-n curve of the rotor for a certain wind speed is the working point for that wind speed. The point of intersection with the left part of the Q-n curve is an instable point and therefore not relevant. The rotational speed can be read in figure 2 for the working points of each wind speed. The result is given in table 2.

The matching in between the generator and the pump motor can only be checked in a U-I graph. For each current and each rotational speed, the corresponding voltage U can be read in figure 16 of KD 78. However, for a current I = 2 A one has to use the line for I = 1 A out of figure 16 of KD 78. For a current of 4 A one has to use the line for I = 2 A and so on. The voltage read for the combination of current and rotational speed has to be divided by a factor two. The corrected voltage U found this way is also mentioned in table 2.

	I = 0 A		I = 2 A		I = 4 A		I = 6 A		I = 8 A		I = 10 A		I = 12 A		I = 14 A		I = 16 A	
V (m/s)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)	n (rpm)	U (V)
3	188	30	125	16														
4	258	41	215	30	155	18												
5	325	52	292	42	257	33.5	212	24										
6	392	62.5	365	53	335	45.5	305	38	274	30.5	220	20						
7	456	73	435	64	410	56.5	387	50.5	362	44	335	36.5	307	29	260	18.5		
8	506	81	487	72	465	65	448	59.5	422	53	400	46	380	39	355	31.5	328	23.5
9.5	540	86.5	520	77.5	502	70.5	482	65	463	59	443	52	422	45.5	402	38.5	380	30.5

table 2 Rotational speed n and voltage U as a function of wind speed V and current I

The voltage U as a function of I and V is drawn in figure 3.

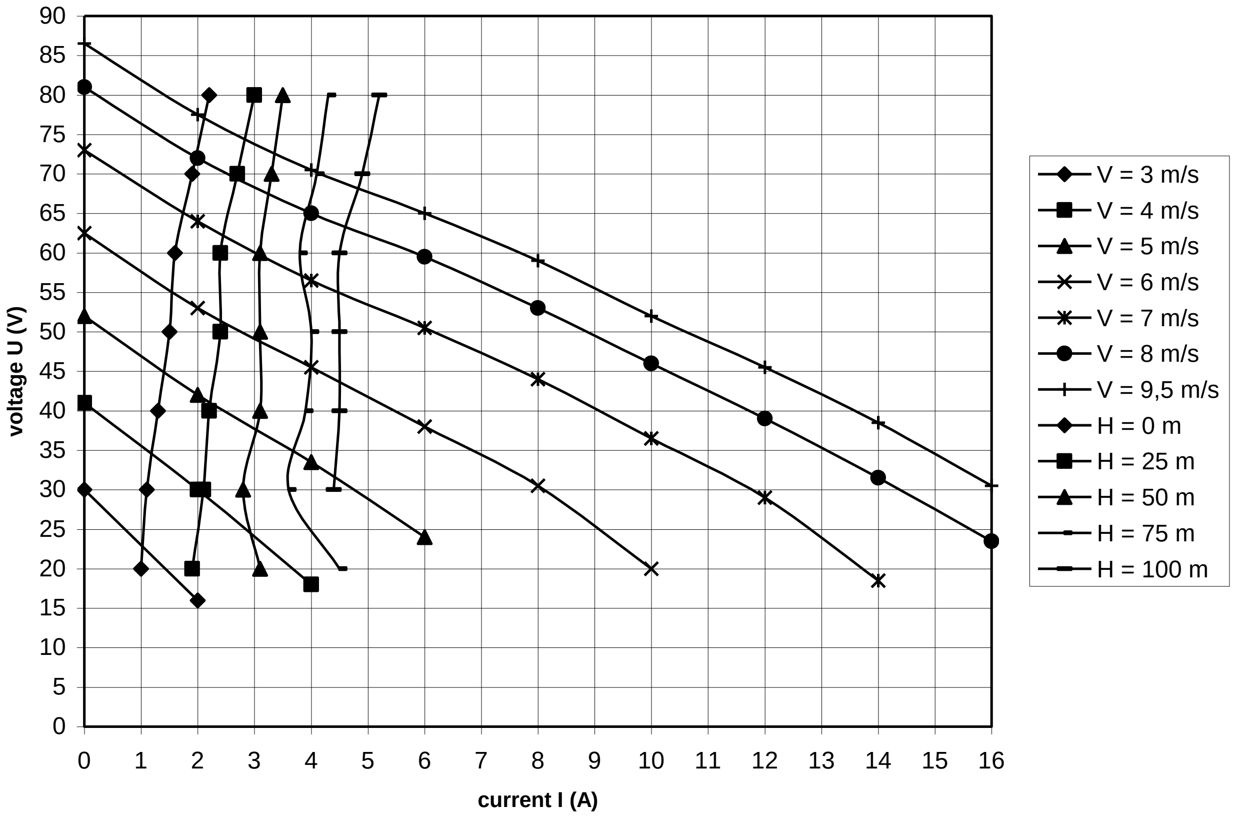

fig. 3 Variation of the generator voltage U as a function of I and V. U-I curves of the pump motor for H = 0, 25, 50, 75 and 100 m for a 2.6 mm cam

The Solaflux pump used for the first prototype of the VIRYA-3D built in 2003 in Zijdewind was supplied by Mr. T. E. Manning from Wieringerwerf. From him I also received a data sheet for the Solaflux pump with a 2.6 mm cam. The pump motor has a nominal voltage of 48 V but it can be used on much lower and higher voltages. The maximum allowable voltage for short times is 80 V. The nominal motor power is 200 W, so much less than the maximum power of 500 W which can be supplied by the VIRYA-3B3 windmill. The data sheet of the pump is copied in table 3.

	U = 20 V			U = 30 V			U = 40 V			U = 50 V			U = 60 V			U = 70 V		
H (m)	I (A)	q (l/h)	η (%)	I (A)	q (l/h)	η (%)	I (A)	q (l/h)	η (%)	I (A)	q (l/h)	η (%)	I (A)	q (l/h)	η (%)	I (A)	q (l/h)	η (%)
0	1.0	440	0	1.1	510	0	1.3	600	0	1.5	740	0	1.6	855	0	1.9	920	0
25	1.9	250	45	2.1	375	42	2.2	500	39	2.4	620	35	2.4	720	35	2.7	820	30
50	3.1	190	42	2.8	330	55	3.1	450	50	3.1	550	49	3.1	660	49	3.3	750	44
75	4.5	150	34	3.6	290	55	3.9	400	53	4.0	500	51	3.8	570	51	4.1	680	49
100	-	-	-	4.4	260	54	4.5	360	55	4.5	450	55	4.5	530	54	4.9	640	51

table 3 Current I, flow q and efficiency η as a function of height H and voltage U

The flow q is given in litres per hour. I assume that the efficiency η is the total efficiency, so the supplied hydraulic power divided by the needed electrical power. This means that the efficiency of the pump motor is incorporated in the total pump efficiency. The efficiency of the pump motor will be about 80 % for a DC permanent magnet motor. So the efficiency of only the pump can be found by dividing the total efficiency by a factor 0.8. The average pump efficiency for voltages in between 30 V and 60 V found this way is about 62 % which is rather high for a small pump.

From table 3, U-I curves can be derived for each height H. These curves are also drawn in figure 3. The values for a voltage U = 80 V are not given in table 3 but are estimated by interpolation. The point of intersection of a generator curve for a certain wind speed V and the pump curve for a certain height H is the working point for that wind speed and that height.

In figure 3 it can be seen that the maximum voltage for H = 0 m is about 77.5 V for V = 9.5 m/s. But a height H = 0 m is certainly not advised for this pump. The maximum voltage for H = 25 m is about 74 V for V = 9.5 m /s (and higher). This seems to be acceptable as very high wind speeds will probably not occur for very long times. But if the maximum voltage is too high, the rated wind speed of the windmill must be reduced by taking a lighter vane blade.

In figure 3 it can be seen that the current I is increasing somewhat at increasing voltage. The Q-n lines for a constant current are about horizontal (see figure 1). So the Q-n lines for an increasing current will slightly incline at increasing n. The maximum electrical power is needed for the working point of the curves for V = 9.5 m/s and H = 100 m. This gives U = 68 V and I = 4.8 A, so P_{el} = 68 * 4.8 = 326 W. This is far below the maximum power of 500 W of the VIRYA-3B3 windmill, so at high wind speeds, the rotor will run at a rather high tip speed ratio.

The q-U curves for different heights H can also be derived from table 3. These curves are given in figure 4. The values for a voltage U = 80 V are not given in table 3 but are estimated by interpolation. Next the voltages U for the working points found in figure 3 for certain combinations of H and V are put in table 4. Using figure 4, the flow q can be read for each voltage U and height H. These values are also mentioned in table 4.

	V = 3 m/s		V = 4 m/s		V = 5 m/s		V = 6 m/s		V = 7 m/s		V = 8 m/s		V = 9.5 m/s	
H (m)	U (V)	q (l/h)	U (V)	q (l/h)	U (V)	q (l/h)	U (V)	q (l/h)	U (V)	q (l/h)	U (V)	q (l/h)	U (V)	q (l/h)
0	22.5	455	34.5	540	44.5	660	55	800	65	890	72	930	77.5	950
25			29	370	41	510	51.5	630	62	740	69.5	815	74	860
50			24.5	250	37.5	425	49	540	59.5	650	67.5	725	72.5	770
75					35	350	46	460	57	545	65.5	625	70	680
100					31.5	270	43.5	395	55	485	63.5	565	68	615

table 4 Voltage U and flow q as a function of the height H and the wind speed V

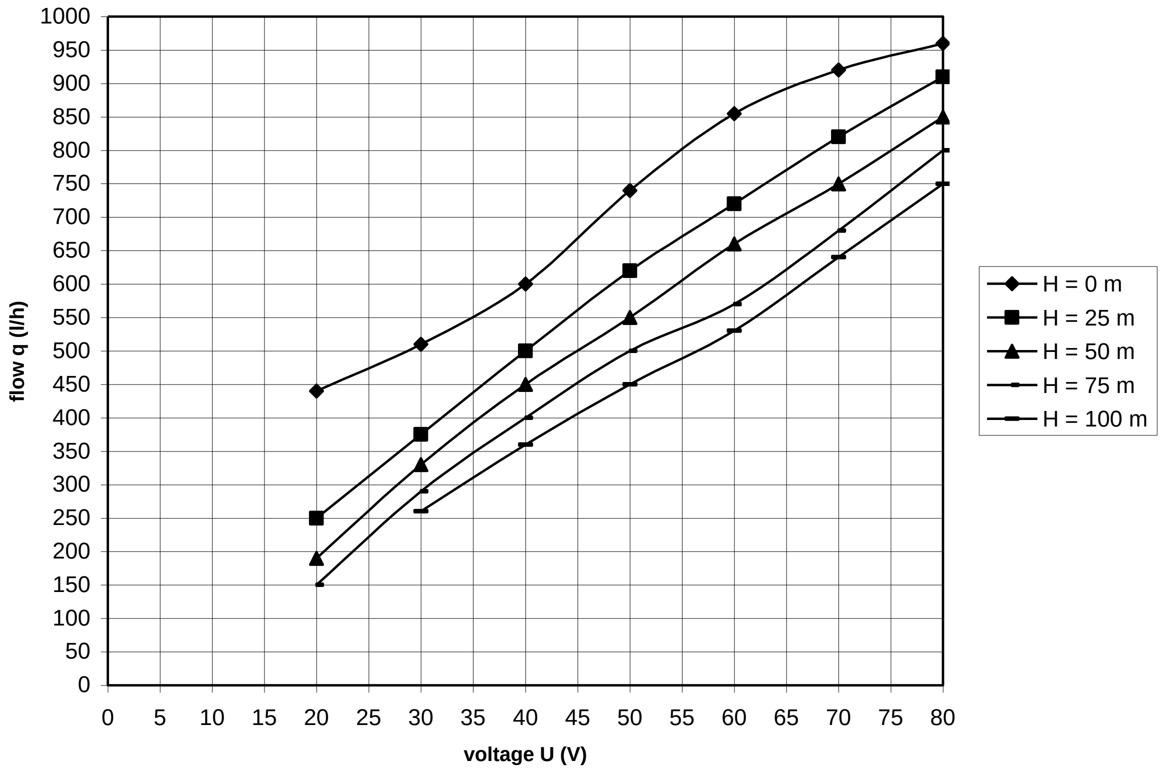

fig. 4 Flow q as a function of voltage U and height H for 2.6 mm cam

Finally from table 4, a graph can be derived which gives the flow q as a function of the height H and the wind speed V. This curve is given in figure 5.

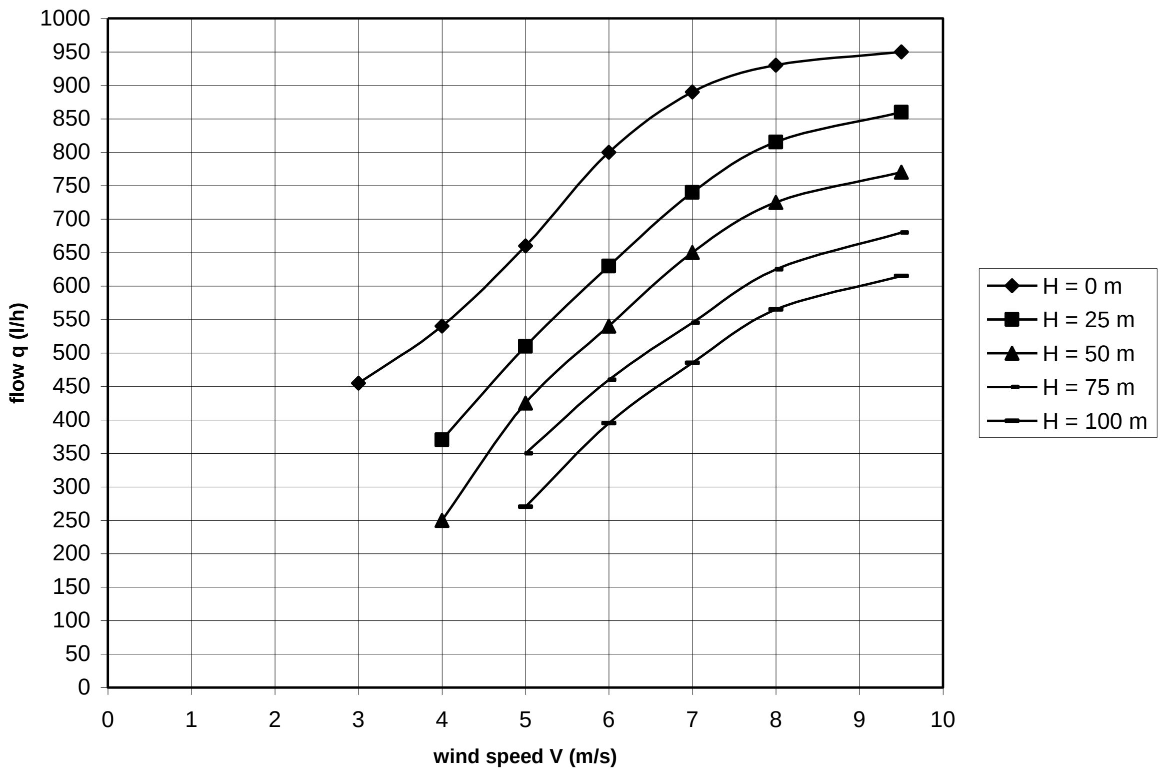

fig. 5 Flow q as a function of the wind speed V and the height H for use of the VIRYA-3B3 windmill in combination with the Solaflux pump with a 2.6 mm cam

From figure 5 it seems that there is no flow left from the starting point of the curves but this is not true. For low wind speeds, the rotor accelerates up to the switch-on voltage is reached. If the required pump power is more than the rotor can generate, the rotor decelerates up to the switch-off voltage but during this period some water is pumped. If the switch-off voltage is reached, the pump motor is disconnected from the generator and the rotor will run unloaded. It will accelerate till the switch-on voltage is reached again. So even at low wind speeds some water will be pumped especially for low heights. This is important if the water is used as drinking water.

In figure 5 it can be seen that the flow q is considerably large, even for large heights H. Assume V = 5 m/s and H = 75 m. This gives a flow q = 350 l/h. This is 8.4 m^3/day which is enough for drinking water of a whole village and the surplus water might even be enough for irrigation of small gardens. So I think that the VIRYA-3B3 windmill, combined with the Solaflux pump with 2.6 mm cam, can compete with mechanically water pumping windmills, especially for low levels of the ground water. Mounting of the Solaflux pump in a tube well is very simple as the whole pump is hanging on the electricity cable and the flexible plastic rising main.

Extra advantages of the VIRYA-3B3 windmill above mechanical water pumping windmills are that the windmill can be positioned at a certain distance from the well where there might be no trees or buildings and that the generated power can be used for other purposes than water pumping like battery charging. The pump will not work if the windmill is used for battery charging because the switch on voltage will not be reached if a 24 V battery is connected. So the windmill can be used for battery charging and pumping but in this case one needs a switch which selects in between the battery or the pump motor.

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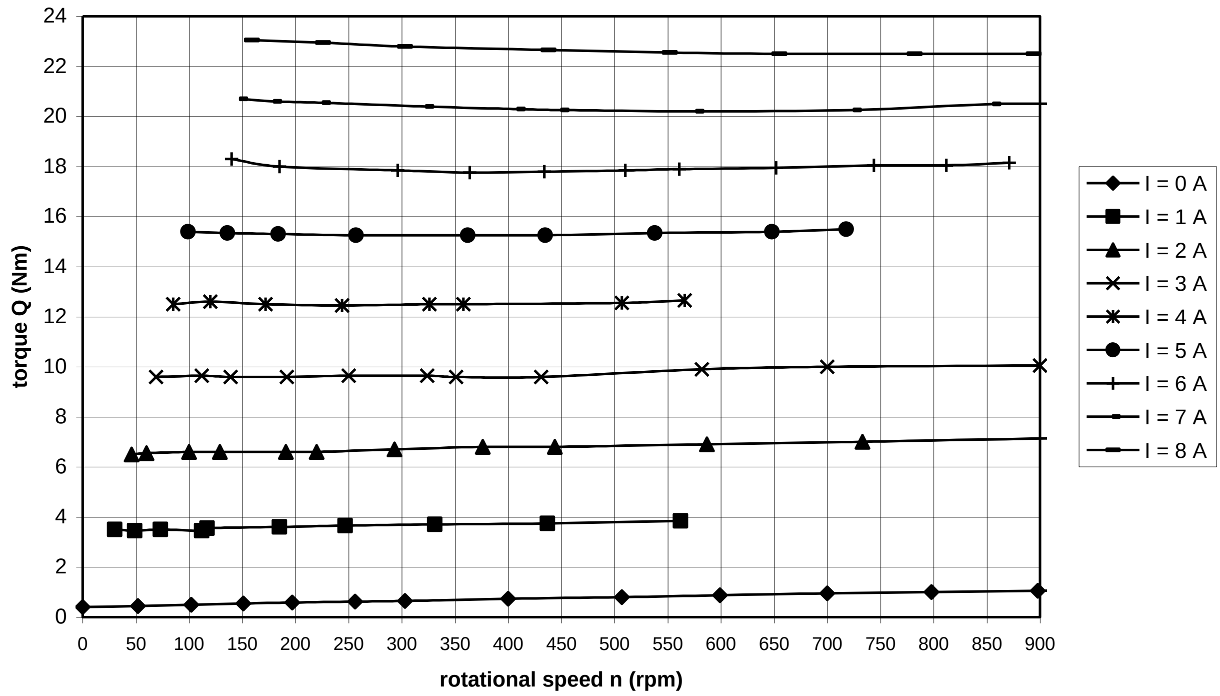
Appendix 1 Figure 17 out of KD 78



Torque Q and voltage U as a function of rotational speed n for a range of currents I for the original 230/400 V winding