Measurements performed on a generator with housing 5RN90L04V and a 4-pole armature equipped with neodymium magnets

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March 2001
Reviewed March 2015

KD 78

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1 Introduction

General information about PM-generators developed by Kragten Design is given in the free public report KD 341 (ref. 1). The measured generator was developed for a small windmill with a rotor diameter of maximal 3 m. The windmill rotor is mounted directly to the generator shaft. The generator is made using the housing of a standard 4-pole asynchronous motor which is provided with a new stainless steel shaft and an armature with neodymium magnets.

The following motor was chosen: Manufacture: Rotor B.V. Eibergen, type: 5RN90L04V (with over-sized stator), provided with a standard 230/400V, 3-phase winding, nominal mechanical power 2.5 kW, mass 19.5 kg. The drawing number of the generator with the standard 230/400 V winding is 1101-02. This generator, with the winding rectified in delta for 24 V battery charging, is used for the VIRYA-2.68. The drawing number of the generator with the modified 115/200 winding is 0512-02. This generator, with the winding rectified in star for 24 V battery charging, is used for the VIRYA-3 and the VIRYA-3B3. The winding is modified by connecting the first and the second layer in parallel in stead of in series.

2 Measurements general

The generator was measured on a torque measuring device of the Laboratory of Electro-mechanics of the Eindhoven University of Technology in March 2001. Originally, the figures in the measuring report were hand written but in 2015 the figures have been made digital using Excel. The lay out of the report was changed and extra chapters were added.

The driving motor is supported pendulous in two air film bearings and therefore the torque can be measured very accurately. The rotational speed is measured by a counter which counts the number of sleeves of a disk mounted to the driving motor shaft. As the disk has 60 sleeves, the number of pulses per second is equal to the rotational speed in rpm. The torque measuring device was hired at a tariff of dfl 25,- / hour.

The measurements were performed for star and for delta rectification. A heavy 3-phase bridge rectifier was used made of three blocks with each 2 diodes. For battery charging, the generator was measured for the speed range in between 0 and 1000 rpm and for several constant voltages. The generator has been measured for constant voltages of 13 V, 26 V, 52 V and 76 V (it was planned to measure for 78 V but by mistake 76 V was chosen). For 13 V and 26 V low power, the battery charge controller of the VIRYA-2.2S windmill was used. For 26 V high power and for 52 V and 76 V a variable resistance was used as load. The combination of the resistance and the rotational speed was chosen such that the voltage had the correct constant value. Because this takes more time than with the battery charge controller, the generator becomes warmer at the end of a set of measurements and this will have influenced the result somewhat because the resistance of the windings increases by temperature. Rectification of the VIRYA generators is explained in report KD 340 (ref. 2).

The effective voltage of a 1-phase AC voltage $U_{AC\ eff}$ is given as a function of the peak value $U_{AC\ peak}$ by the formula:

$$U_{AC\ eff} = ½ \sqrt{2} * U_{AC\ peak} \quad \text{(V)} \qquad (1)$$

The open DC voltage U_{DC} for star rectification, neglecting the voltage drop over the diodes, is given by:

$$U_{DC} = 0.955 * \sqrt{2} * \sqrt{3} * U_{AC\ eff} = 2.3393 * U_{AC\ eff} \quad \text{(V)} \qquad (2)$$

The open DC voltage U_{DC} for delta rectification is given by:

$$U_{DC} = 0.955 * \sqrt{2} * U_{AC\ eff} = 1.3506 * U_{AC\ eff} \quad \text{(V)} \qquad (3)$$

If the windmill is coupled directly to a positive displacement pump, the pump torque and therefore the required current will be about constant. Therefore also measurements have been executed for star rectification for constant currents of 1 A up to 8 A.

For possible other applications than use in a windmill, the generator was also measured at 500, 750, 1000, 1250 and 1500 rpm for star rectification with a variable resistance as load.

The measured magnitudes are: torque Q (Nm), rotational speed n (rpm), rectified voltage U (V) and rectified current I (A). Calculated were: the resistance R (Ω), the required mechanical power P_{mech} (W), the generated electrical power after rectification P_{el} (W) and the efficiency η (%).

For all measurements the generator was cooled with an external ventilator because the original motor ventilator was cancelled for the windmill generator. If the generator is used at higher rotational speeds, and therefore at higher powers, the original ventilator might be necessary and this will cause a small decrease in efficiency because of the power consumption of the ventilator.

After each set of measurements the generator was cooled for about half an hour so that all measurements start at room temperature. The generator was measured for the following configurations:

1 Unloaded, rectified in star and delta for 0 < n < 1500 rpm (see chapter 3).
2 Short-circuit before the rectifier in star and delta for 0 < n < 1000 rpm (see chapter 3).
3 Rectified in star for 26 V, 52 V and 76 V for 0 < n < 1000 rpm (see chapter 4).
4 Rectified in delta for 13 V, 26 V, 52 V and 76 V for 0 < n < 1000 rpm (see chapter 5).
5 Rectified in star for constant currents of 1 A, 2 A, 3 A, 4 A, 5 A, 6 A, 7 A and 8 A (see chapter 6).
6 Rectified in star for a variable resistance as load for n = 500 rpm, 750 rpm, 1000 rpm, 1250 rpm and 1500 rpm (see chapter 7)

The measurements for rectification in star and a variable resistance as load are not given as a function of the rotational speed n, like it is done for the other measurements, but as a function of the resistance R. However, in chapter 9 a method has been developed to give these measurements as a function of the rotational speed.

3 Unloaded and short-circuited measurements for star and delta

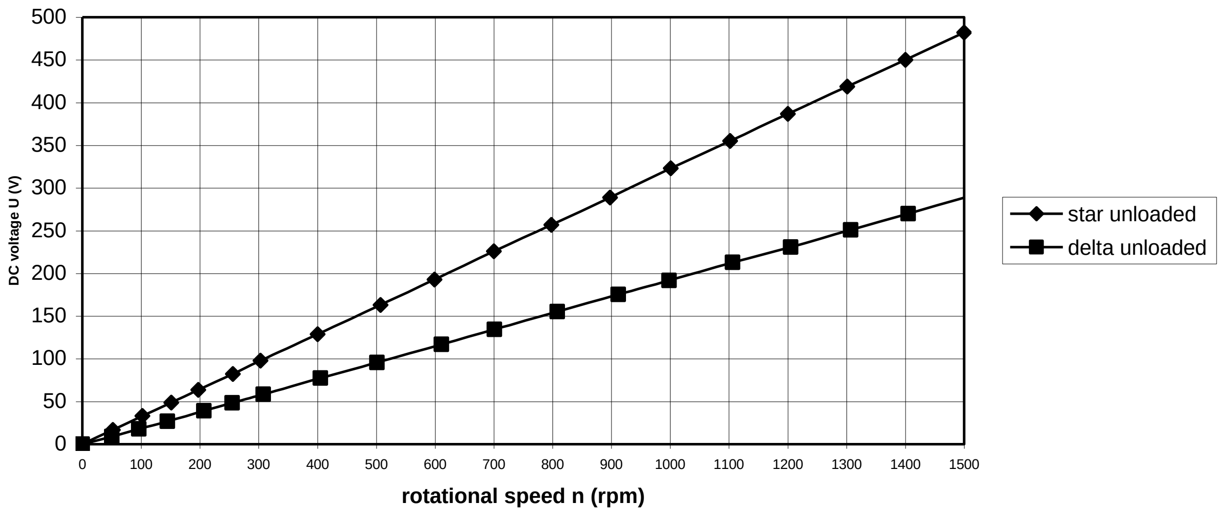

fig. 1 Unloaded DC voltage U as a function of n for star and delta

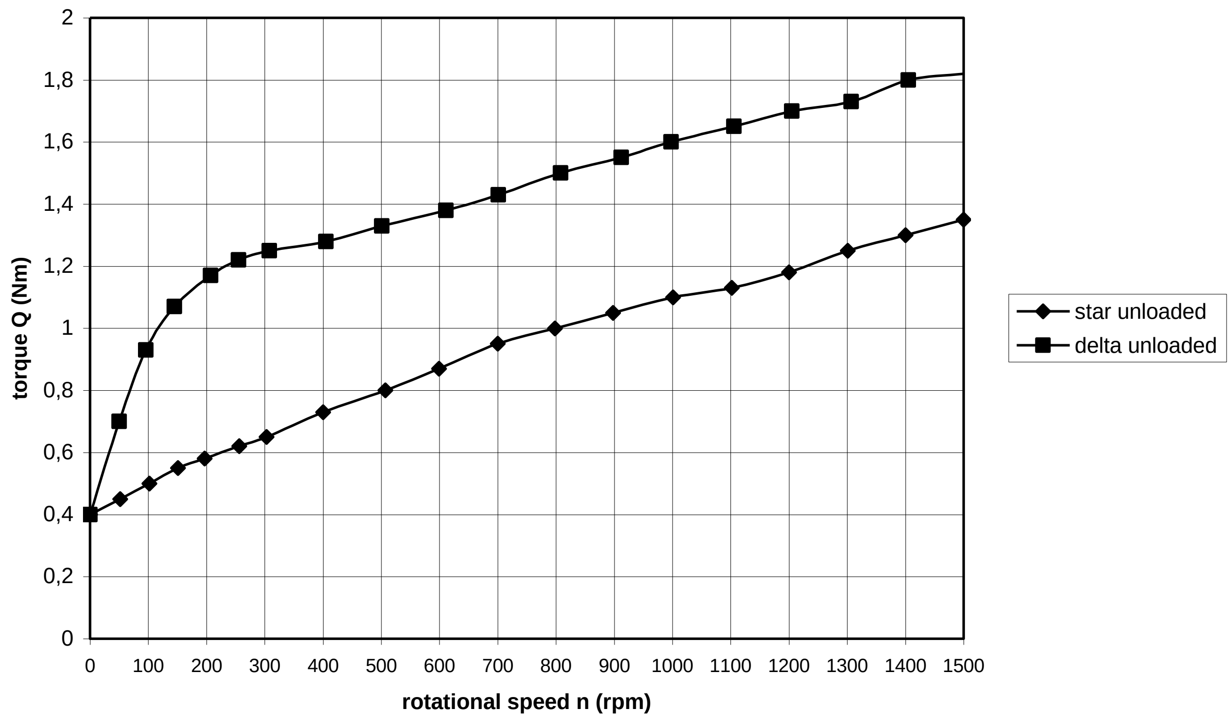

fig. 2 Unloaded torque Q as a function of n for star and delta

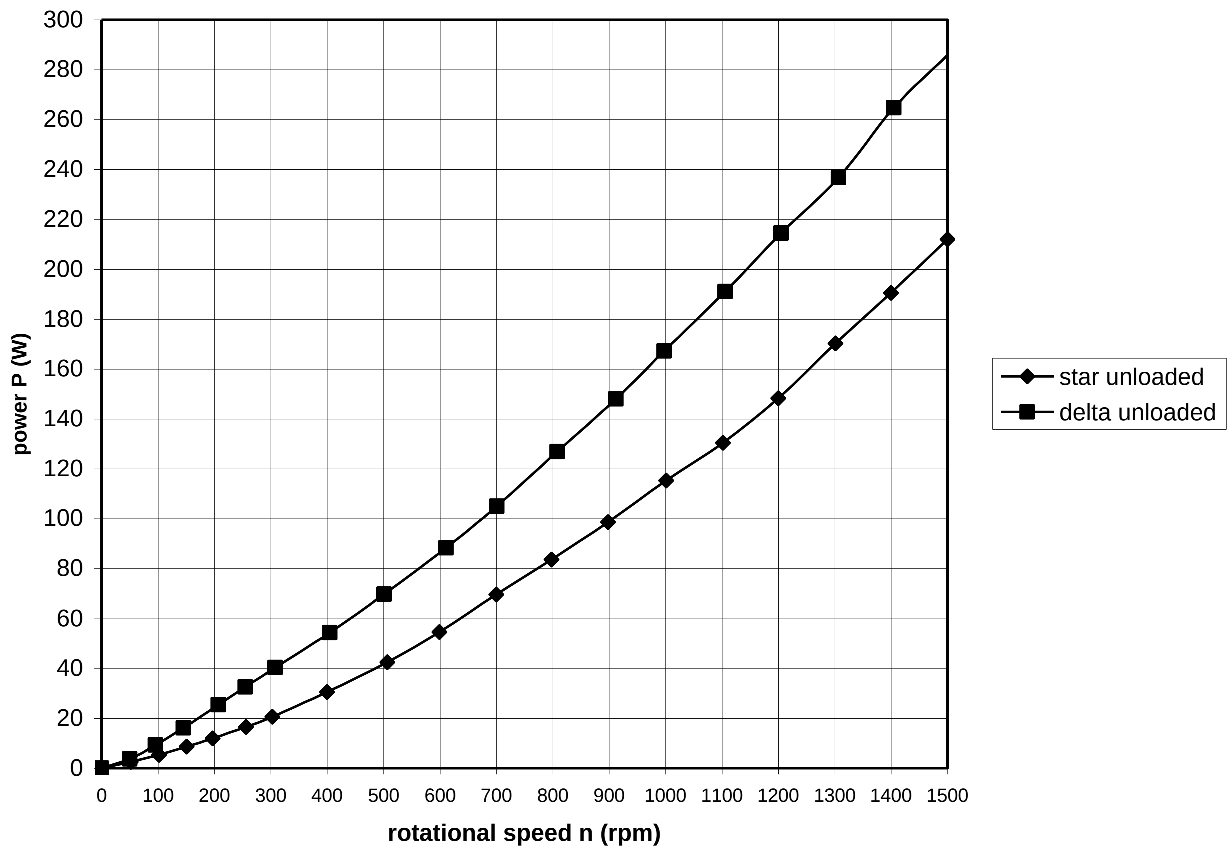

fig. 3 Unloaded power P as a function of n for star and delta

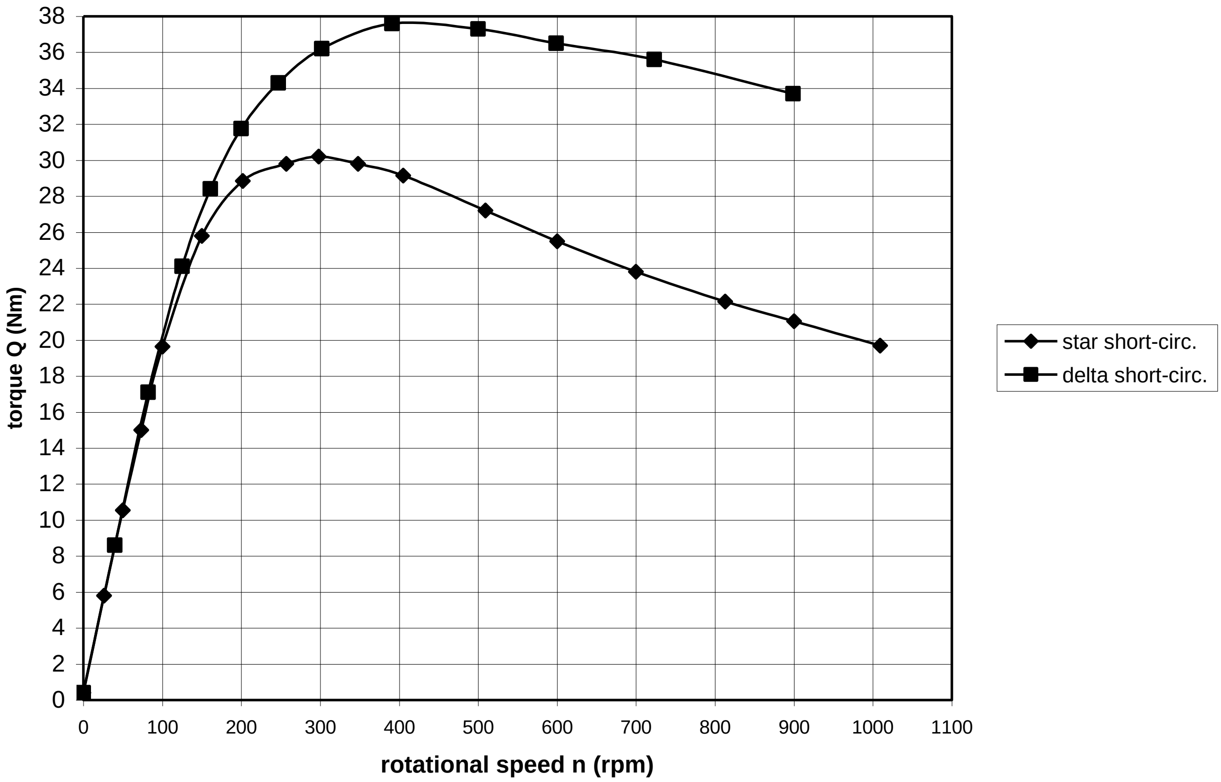

fig. 4 Torque Q for short circuit in star and delta as a function of n

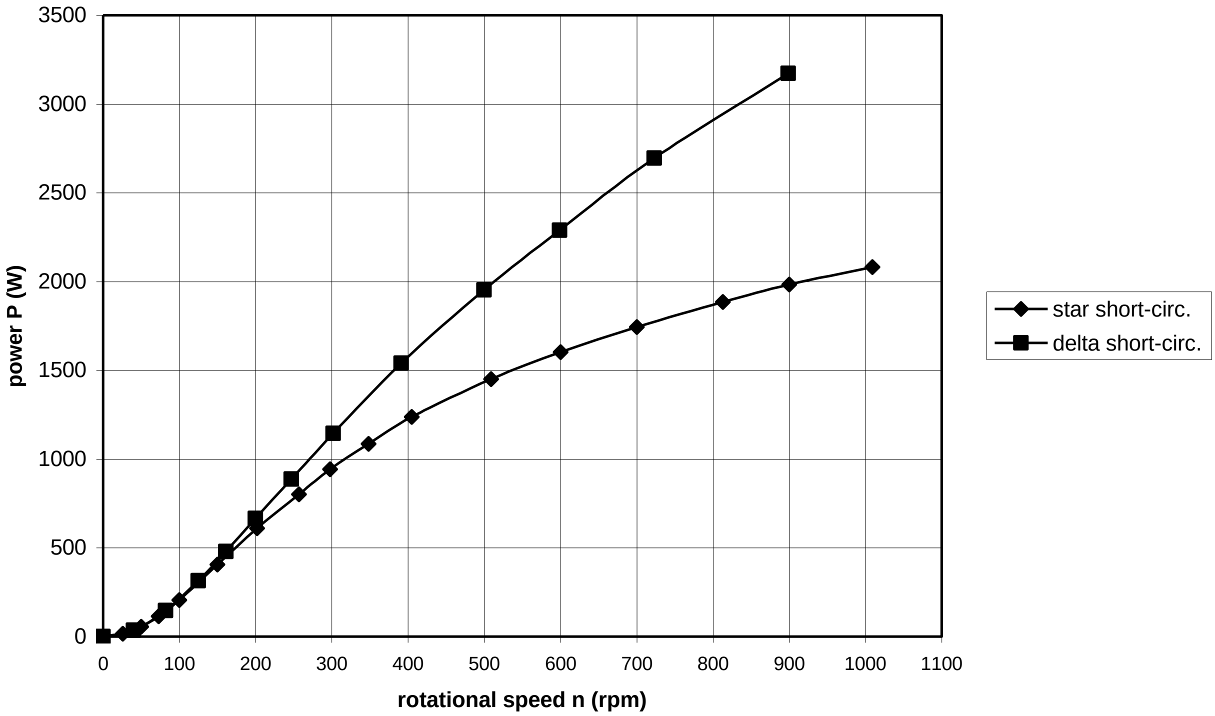

fig. 5 Power P for short circuit in star and delta as a function of n

4 Measurements for different constant voltages in star

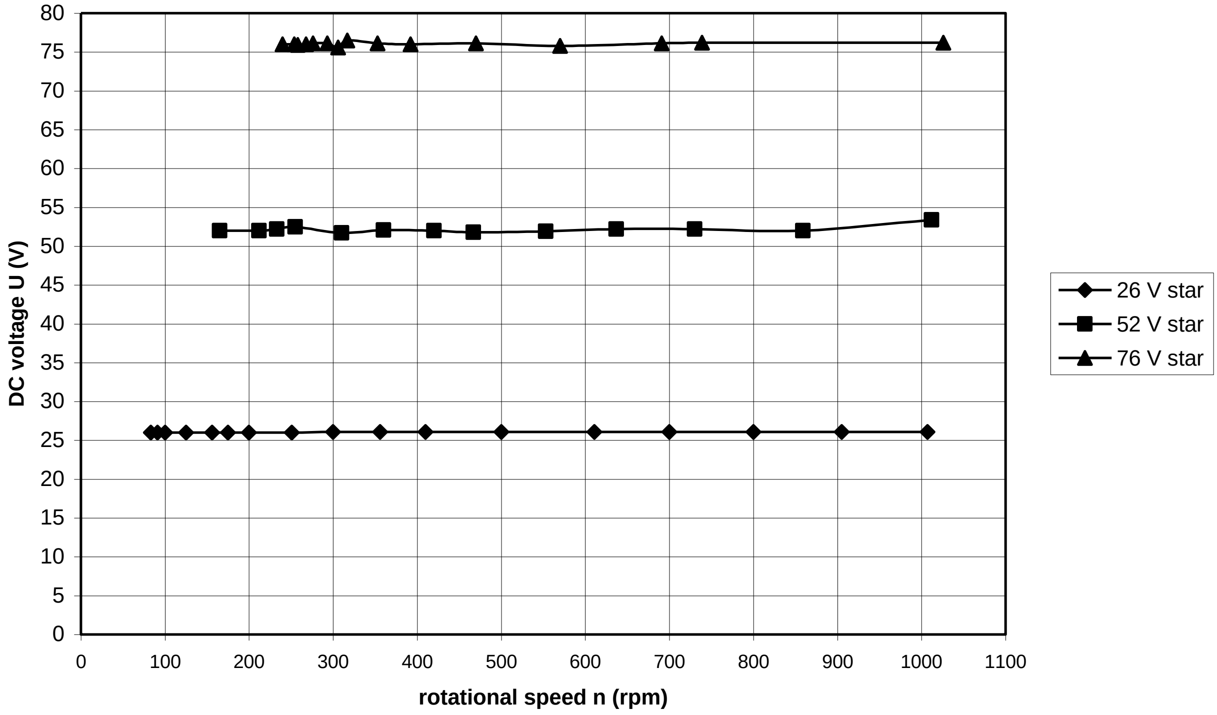

fig. 6 DC voltage U as a function of n for U = 26 V, U = 52 V and U = 76 V in star

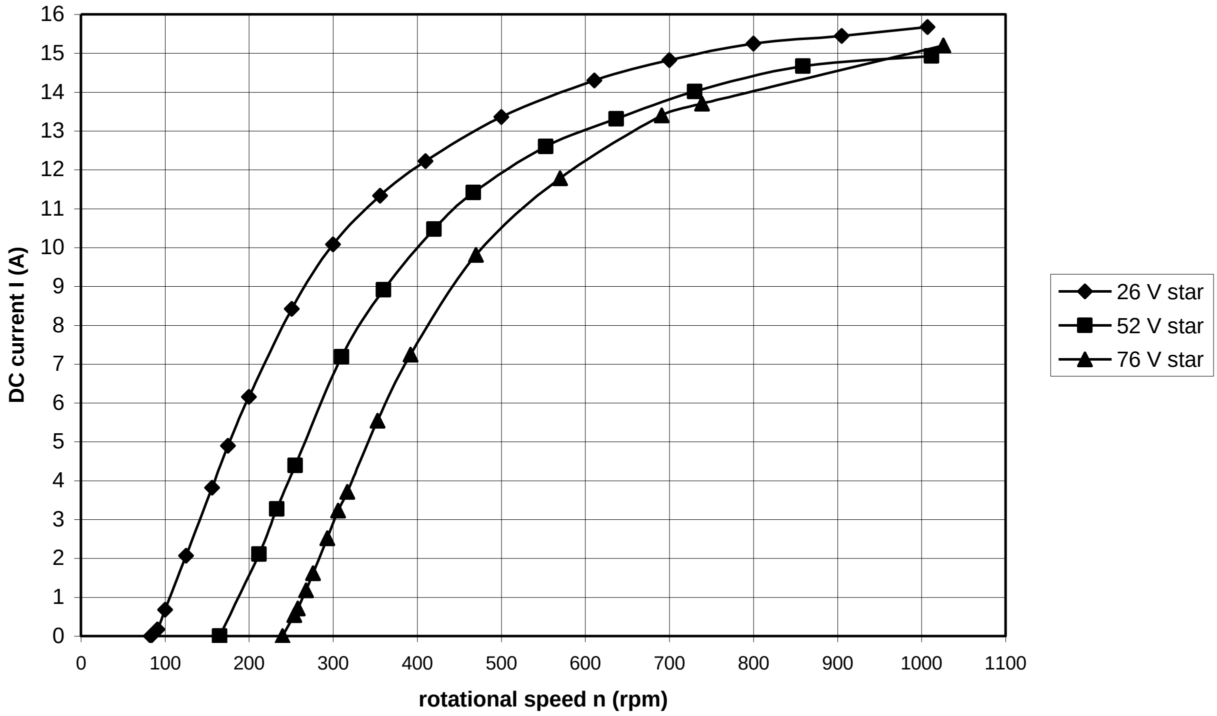

fig. 7 DC current I as a function of n for U = 26 V, U = 52 V and U = 76 V in star

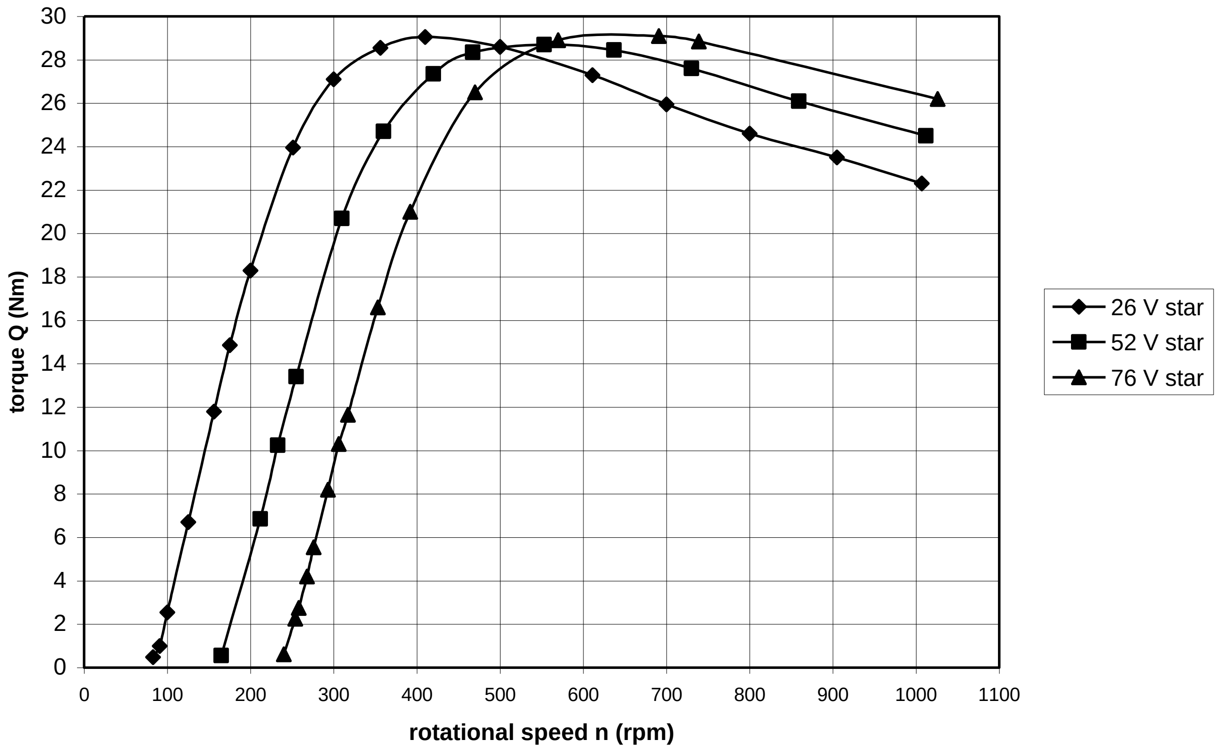

fig. 8 Torque Q as a function of n for U = 26 V, U = 52 V and U = 76 V in star

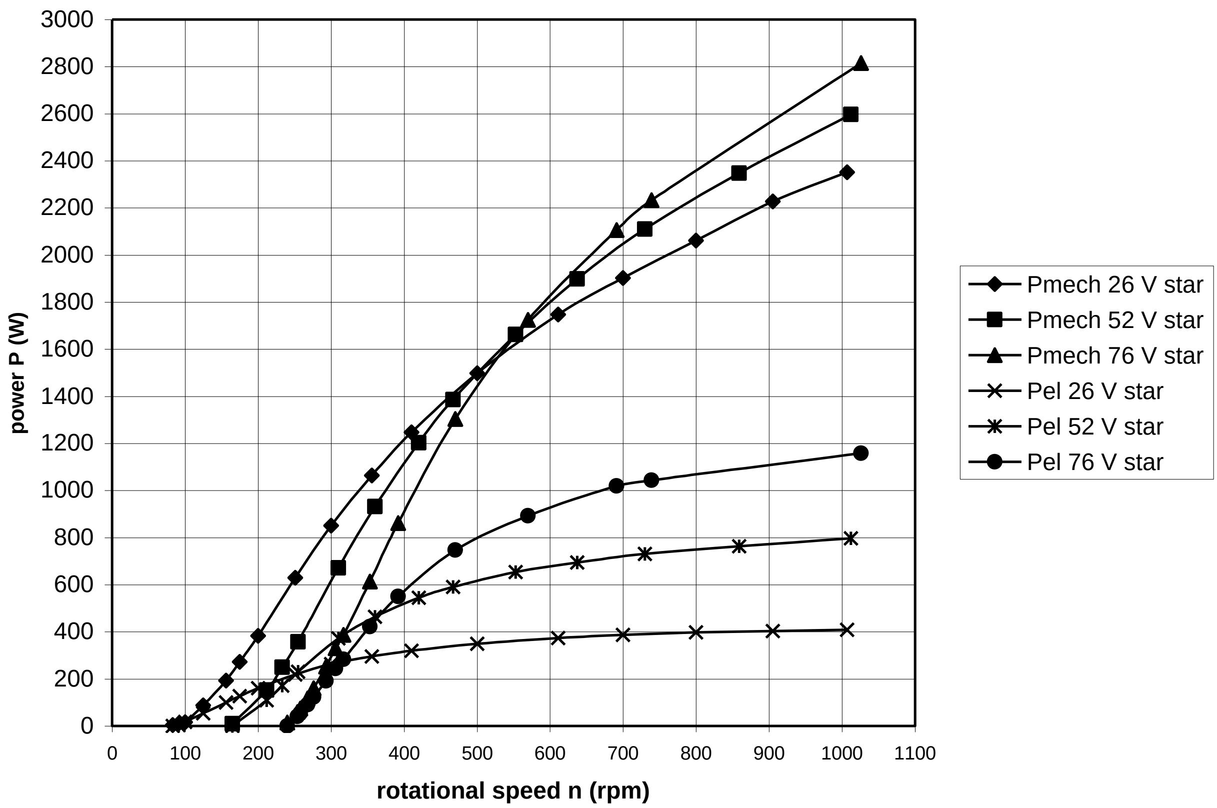

fig. 9 Mechanical power P_{mech} and electrical power P_{el} as a function of n for U = 26 V, U = 52 V and U = 76 V in star

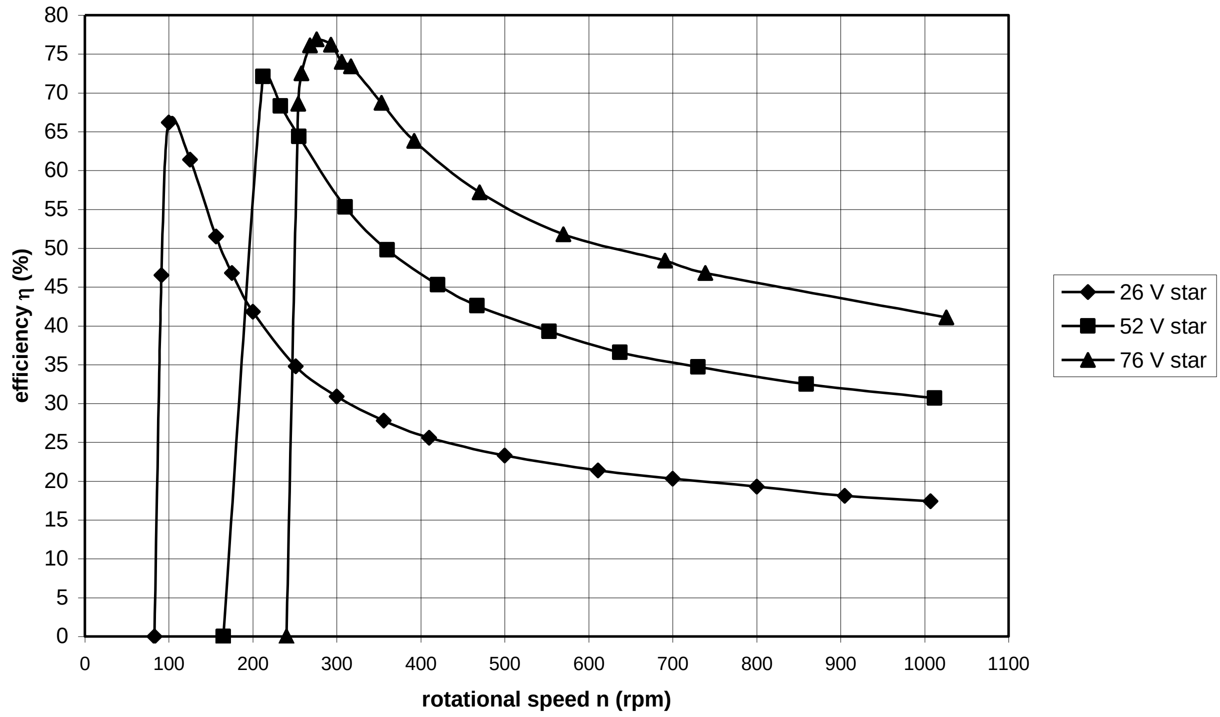

fig. 10 Efficiency η as a function of n for U = 26 V, U = 52 V and U = 76 V in star

5 Measurements for different constant voltages in delta

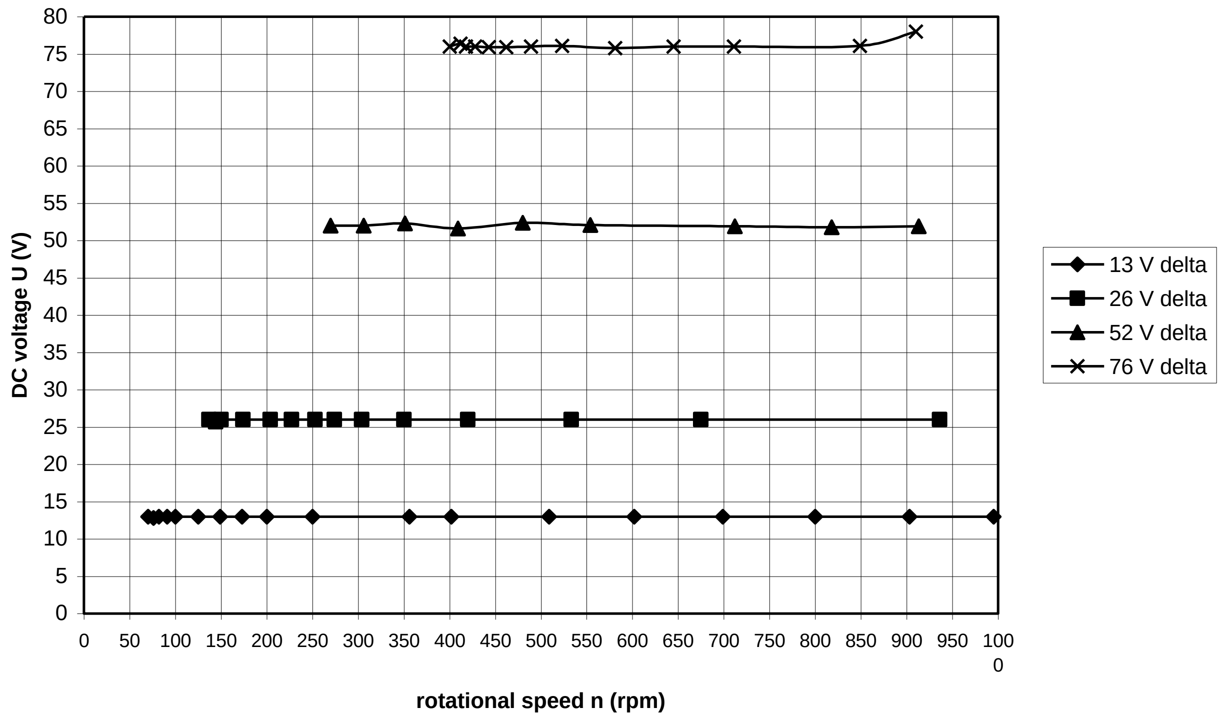

fig. 11 DC voltage U as a function of n for U = 13 V, U = 26 V, U = 52 V and U = 76 V in delta

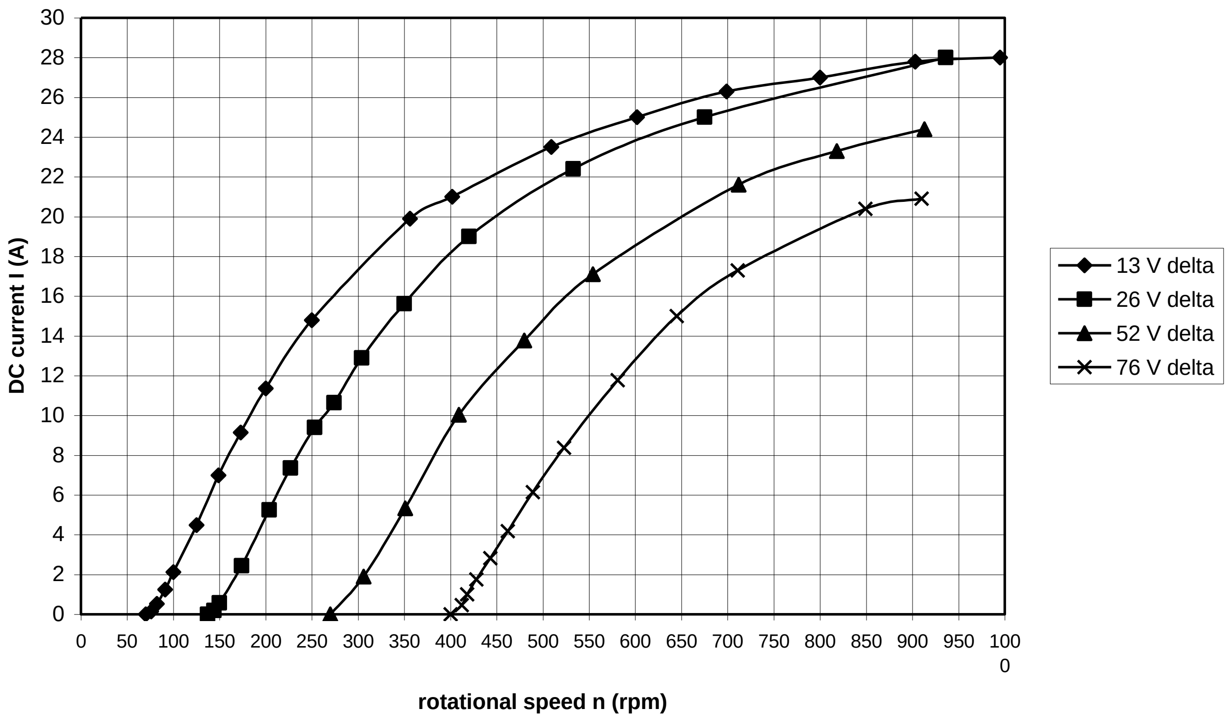

fig. 12 DC current I as a function of n for U = 13 V, U = 26 V, U = 52 V and U = 76 V in delta

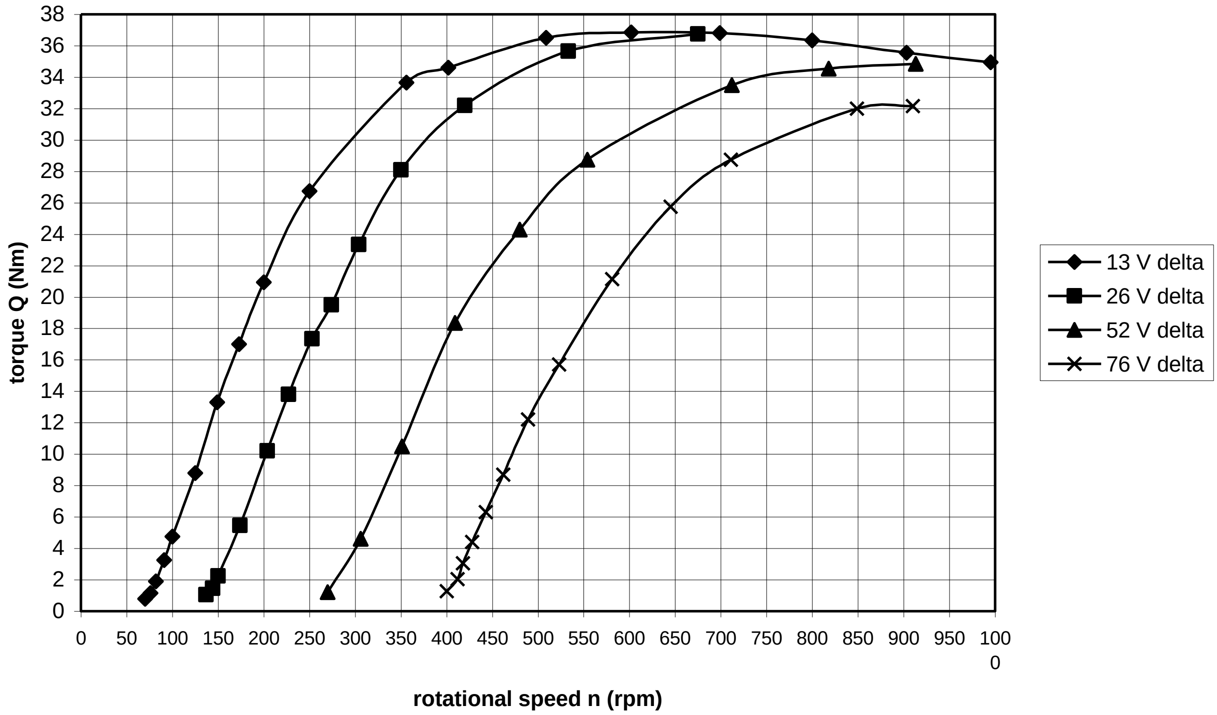

fig. 13 Torque Q as a function of n for U = 13 V, U = 26 V, U = 52 V and U = 76 V in delta

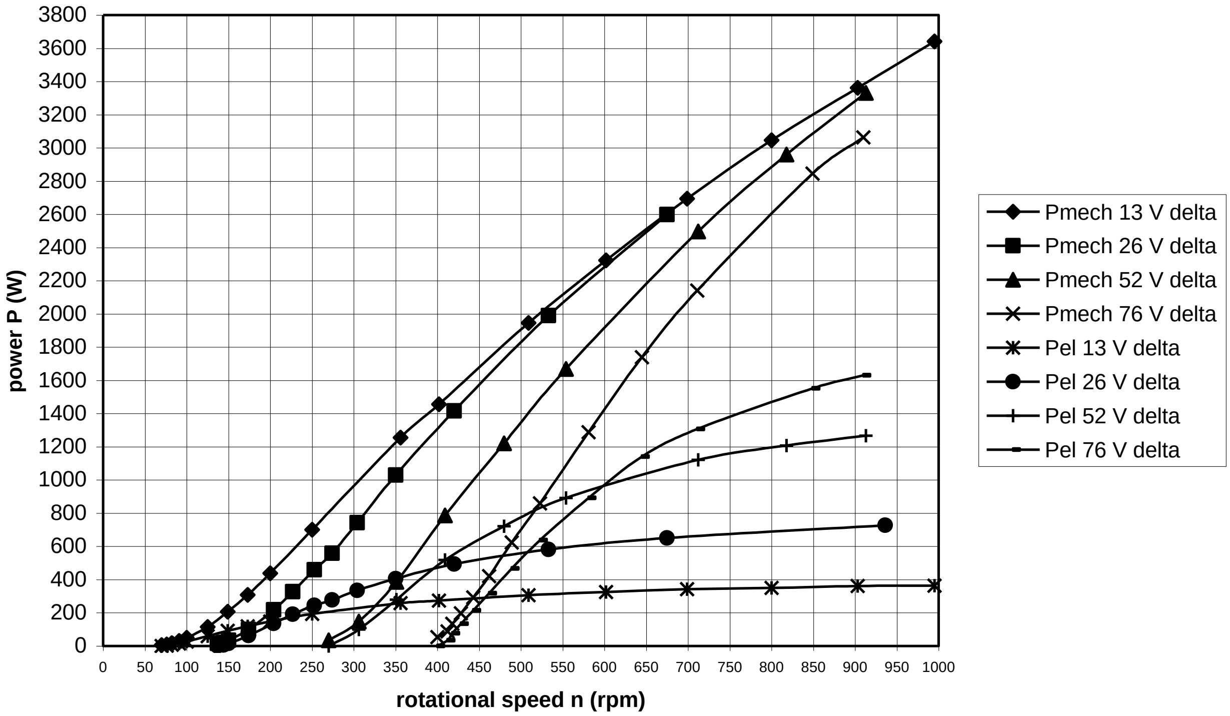

fig. 14 Mechanical power P_{mech} and electrical power P_{el} as a function of n for U = 13 V, U = 26 V, U = 52 V and U = 76 V in delta

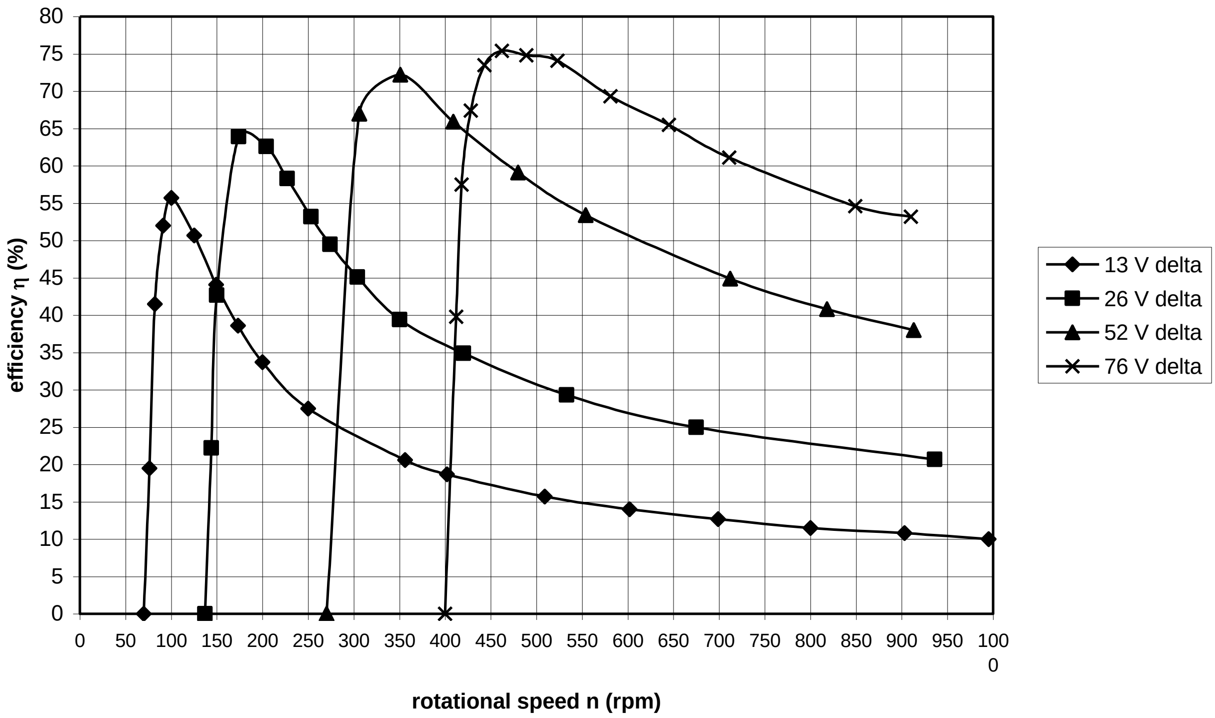

fig. 15 Efficiency η as a function of n for U = 13 V, U = 26 V, U = 52 V and U = 76 V in delta

6 Measurements for different constant currents in star

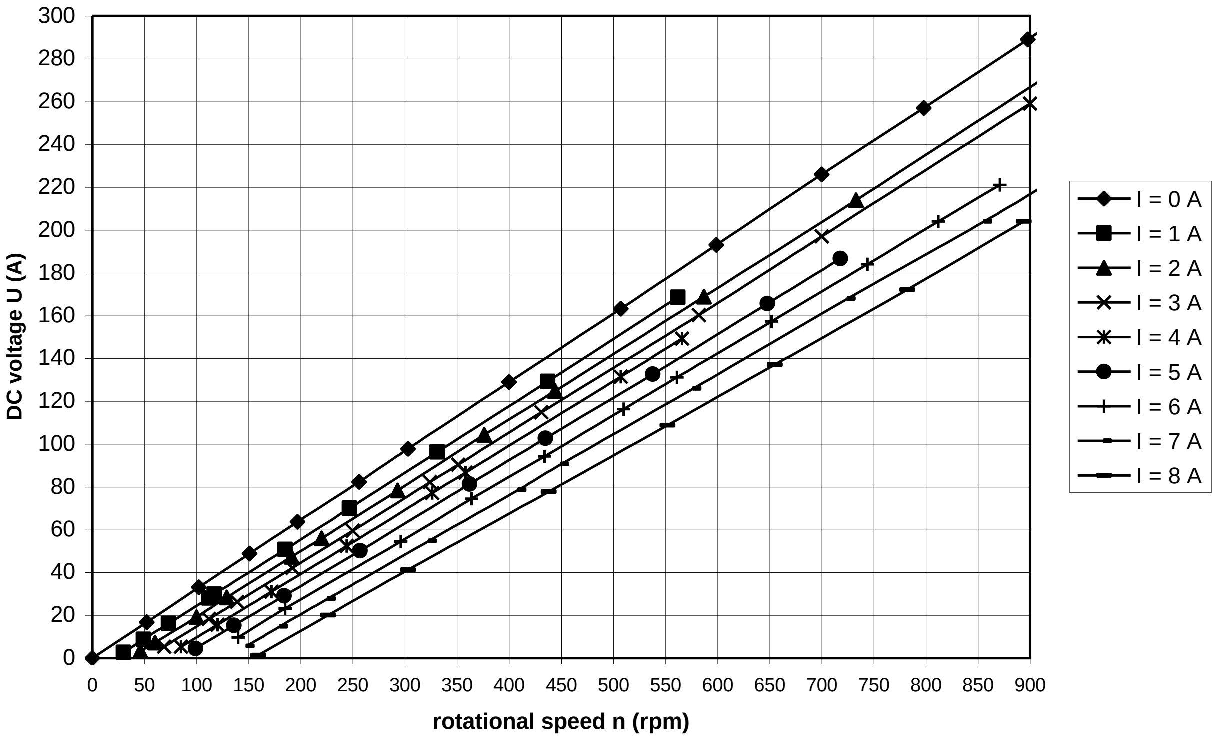

fig. 16 DC voltage U as a function of n for D C currents I = 0 A, I = 1 A, I = 2 A, I = 3 A, I = 4 A, I = 5 A, I = 6 A, I = 7 A and I = 8 A

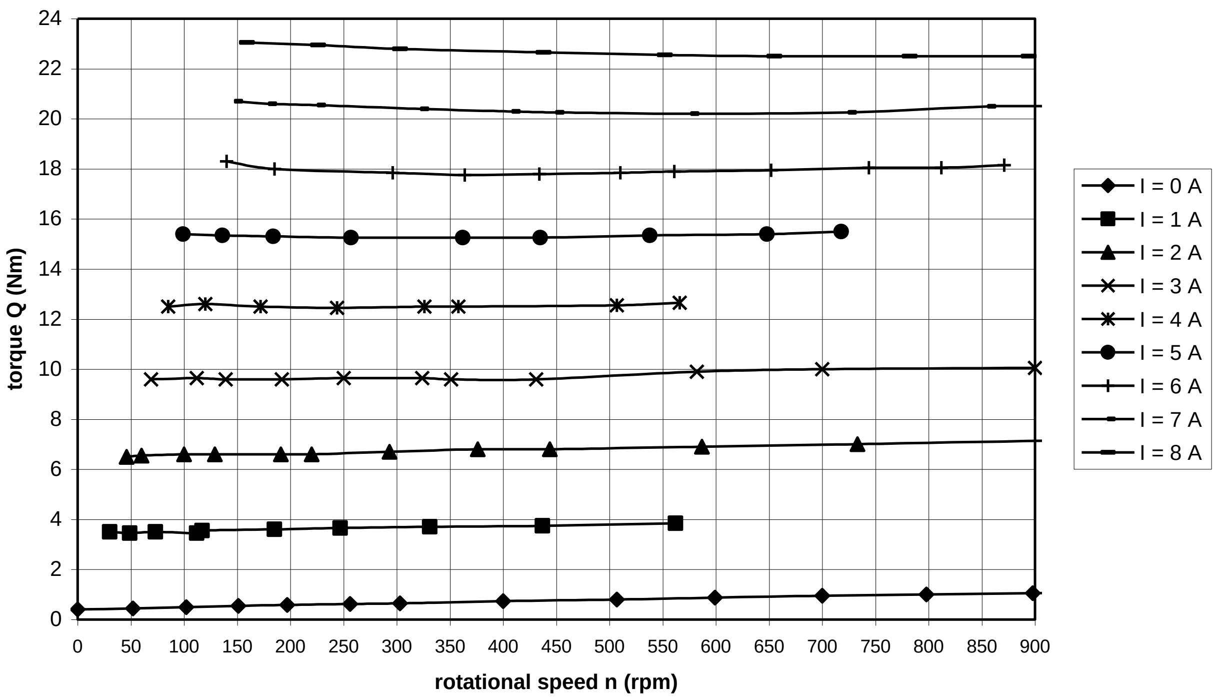

fig. 17 Torque Q as a function of n for D C currents I = 0 A, I = 1 A, I = 2 A, I = 3 A, I = 4 A, I = 5 A, I = 6 A, I = 7 A and I = 8 A

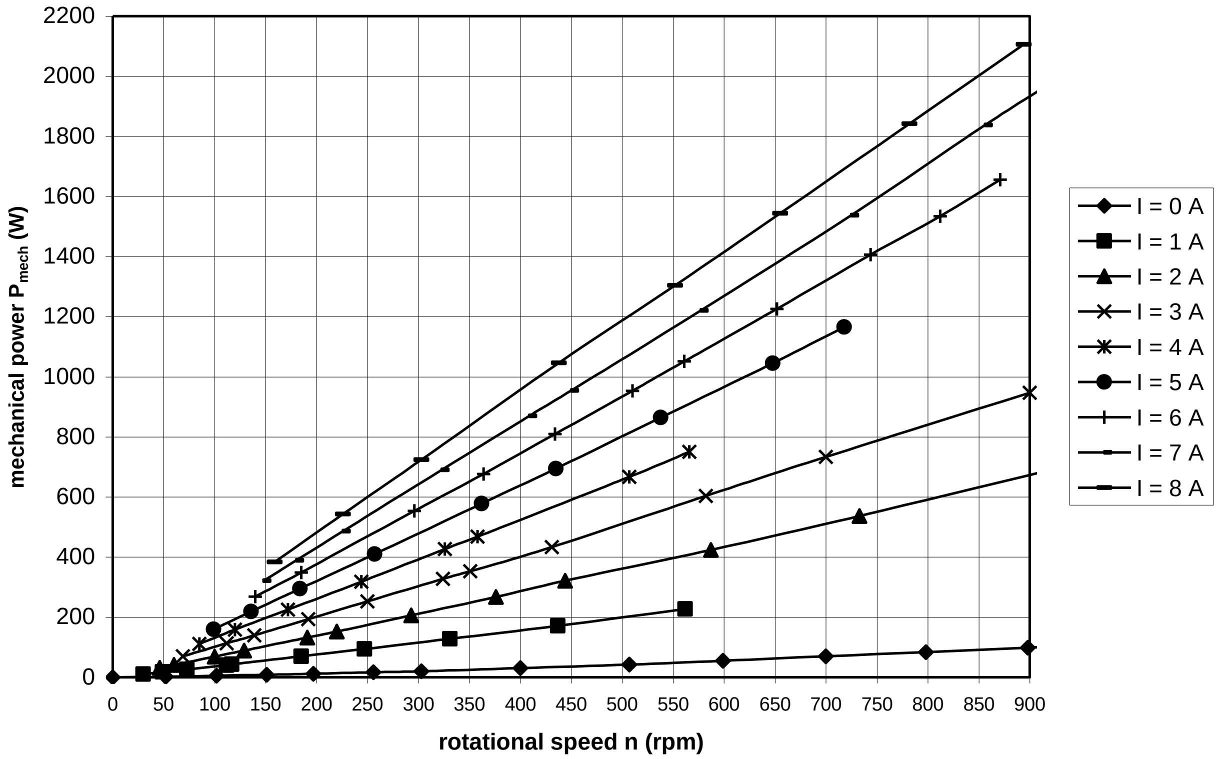

fig. 18 Mechanical power P_{mech} as a function of n for D C currents I = 0 A, I = 1 A, I = 2 A, I = 3 A, I = 4 A, I = 5 A, I = 6 A, I = 7 A and I = 8 A

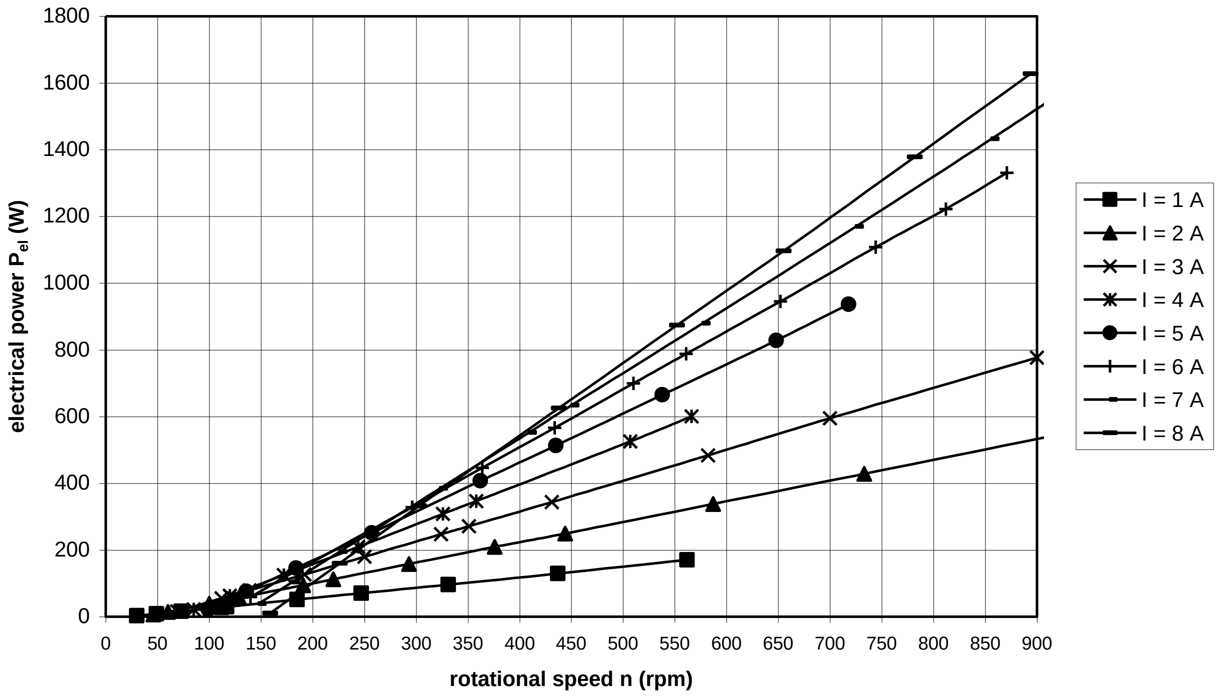

fig. 19 Electrical power P_{el} as a function of n for D C currents I = 0 A, I = 1 A, I = 2 A, I = 3 A, I = 4 A, I = 5 A, I = 6 A, I = 7 A and I = 8 A

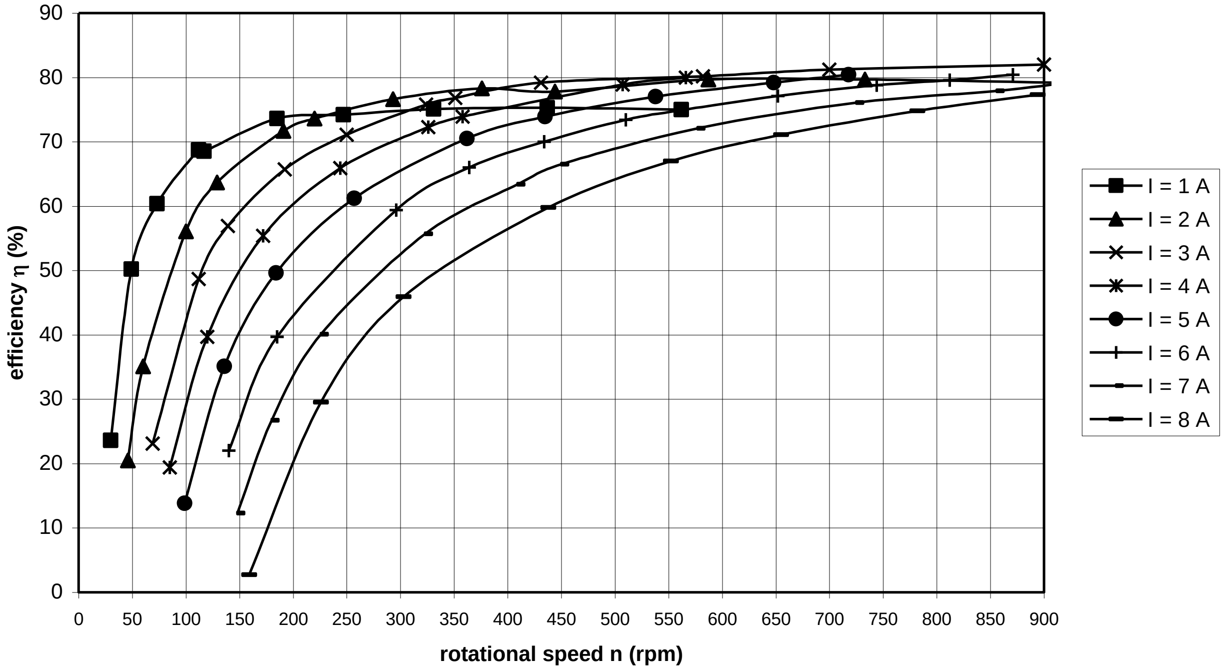

fig. 20 Efficiency η as a function of n for D C currents I = 0 A, I = 1 A, I = 2 A, I = 3 A, I = 4 A, I = 5 A, I = 6 A, I = 7 A and I = 8 A

7 Measurements for different constant rotational speeds in star

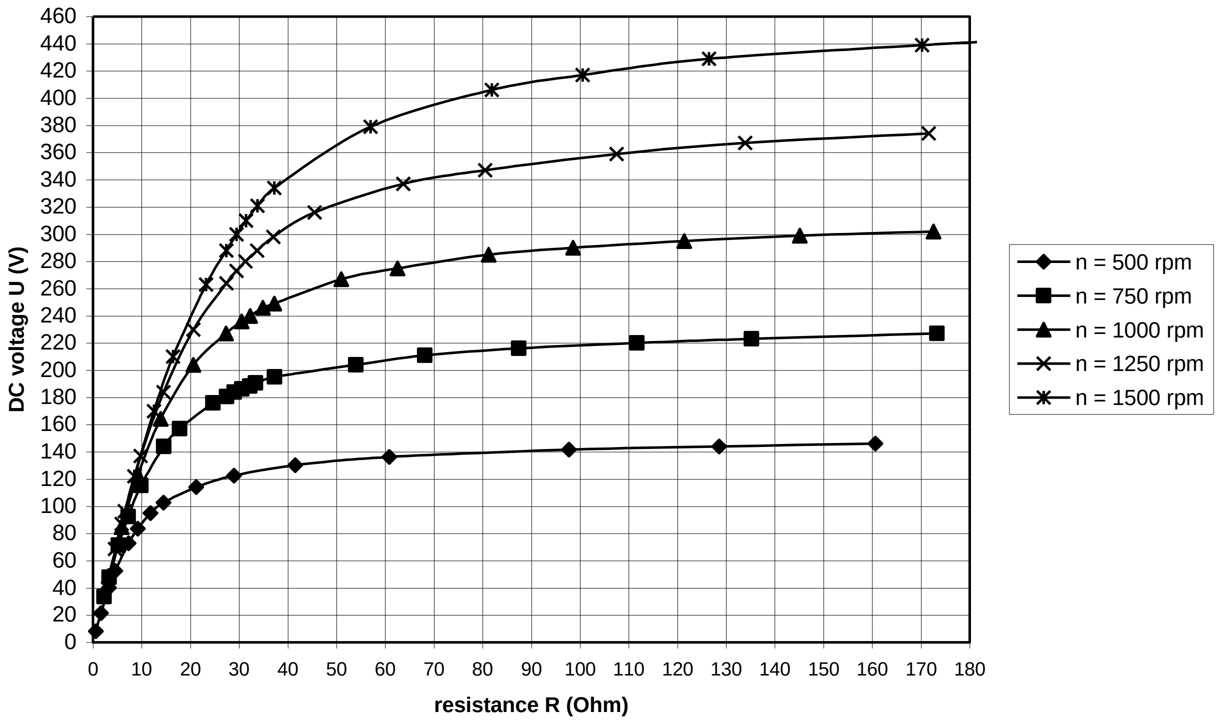

fig. 21 DC voltage U as a function of R for n = 500 rpm, n = 750 rpm, n = 1000 rpm, n = 1250 rpm and n = 1500 rpm in star

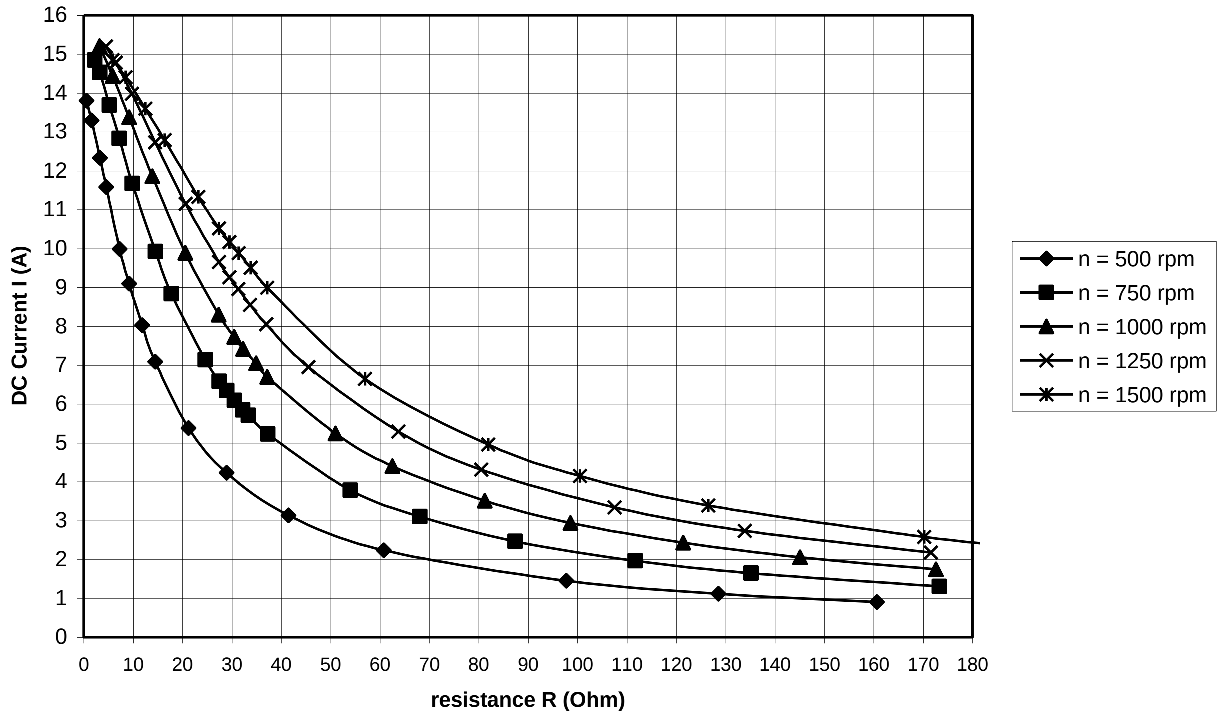

fig. 22 DC current I as a function of R for n = 500 rpm, n = 750 rpm, n = 1000 rpm, n = 1250 rpm and n = 1500 rpm in star

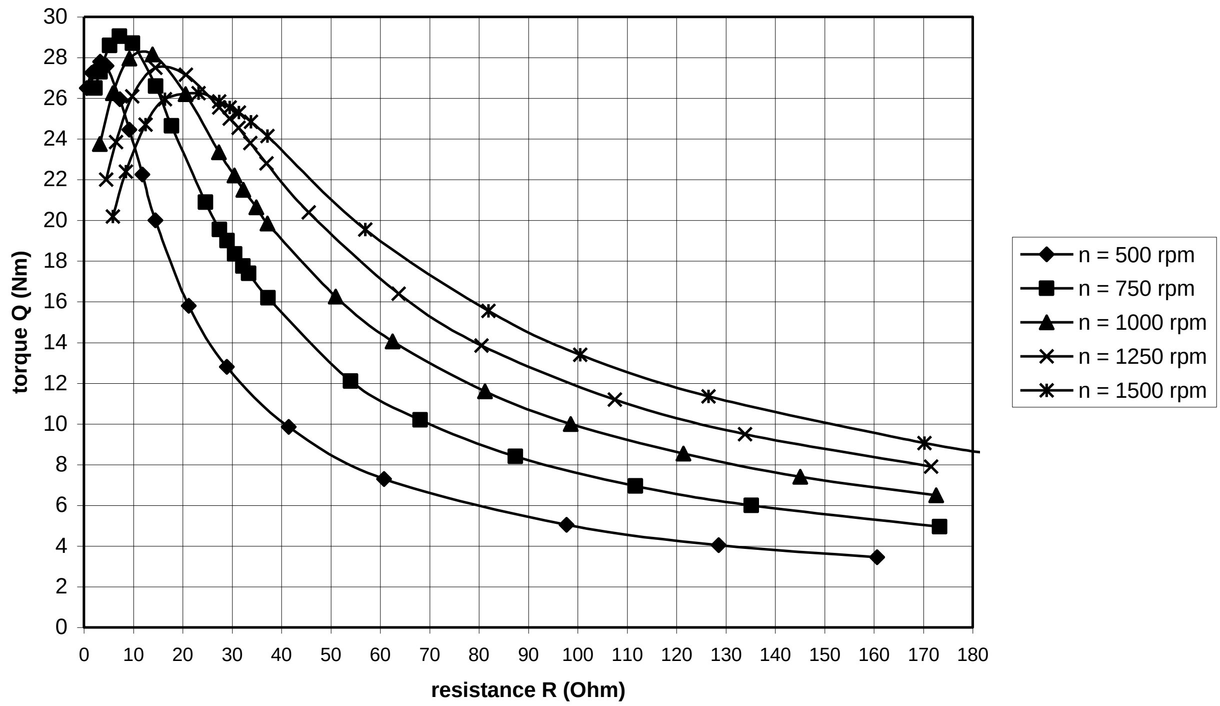

fig. 23 Torque Q as a function of R for n = 500 rpm, n = 750 rpm, n = 1000 rpm, n = 1250 rpm and n = 1500 rpm in star

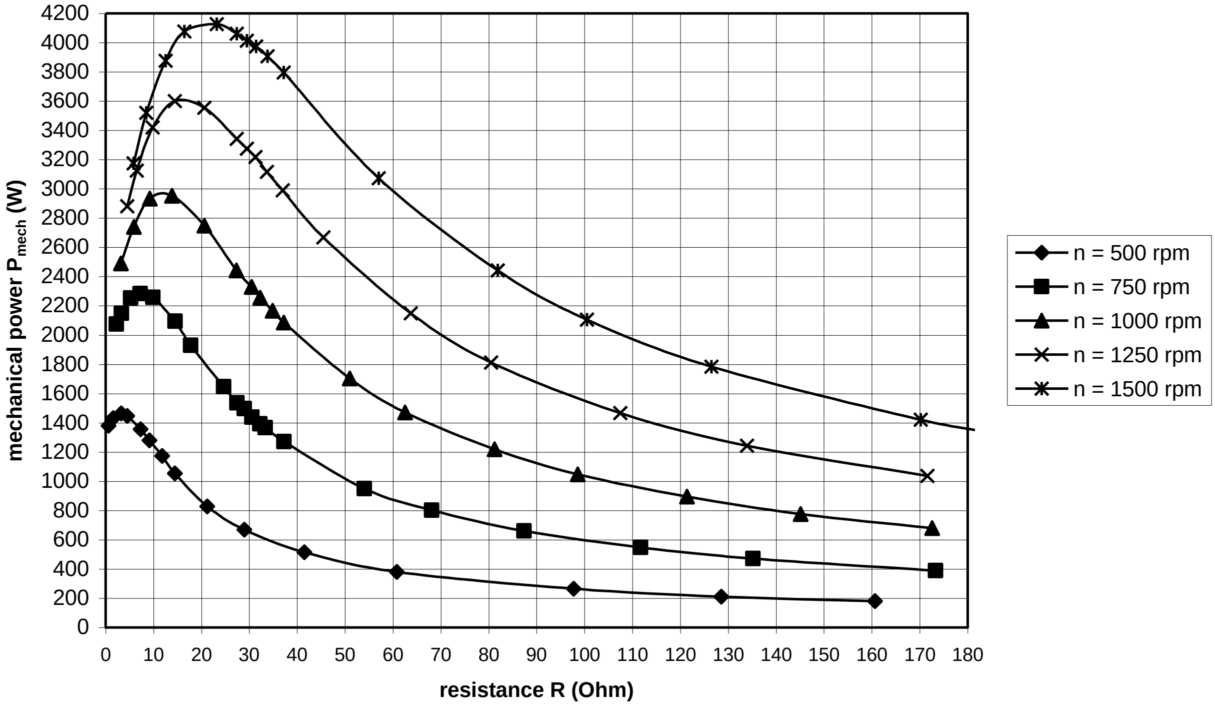

fig. 24 Mechanical power P_{mech} as a function of R for n = 500 rpm, n = 750 rpm, n = 1000 rpm, n = 1250 rpm and n = 1500 rpm in star

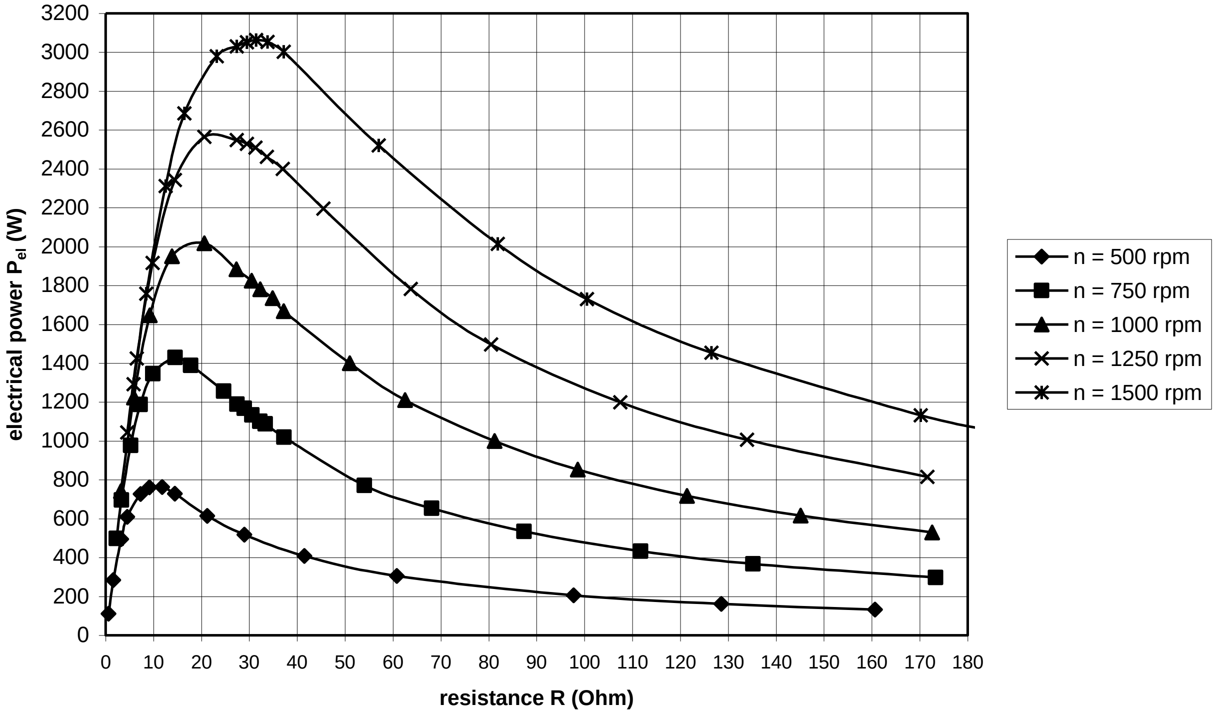

fig. 25 Electrical power P_{el} as a function of R for n = 500, n = 750, n = 1000, n = 1250 and n = 1500 rpm in star

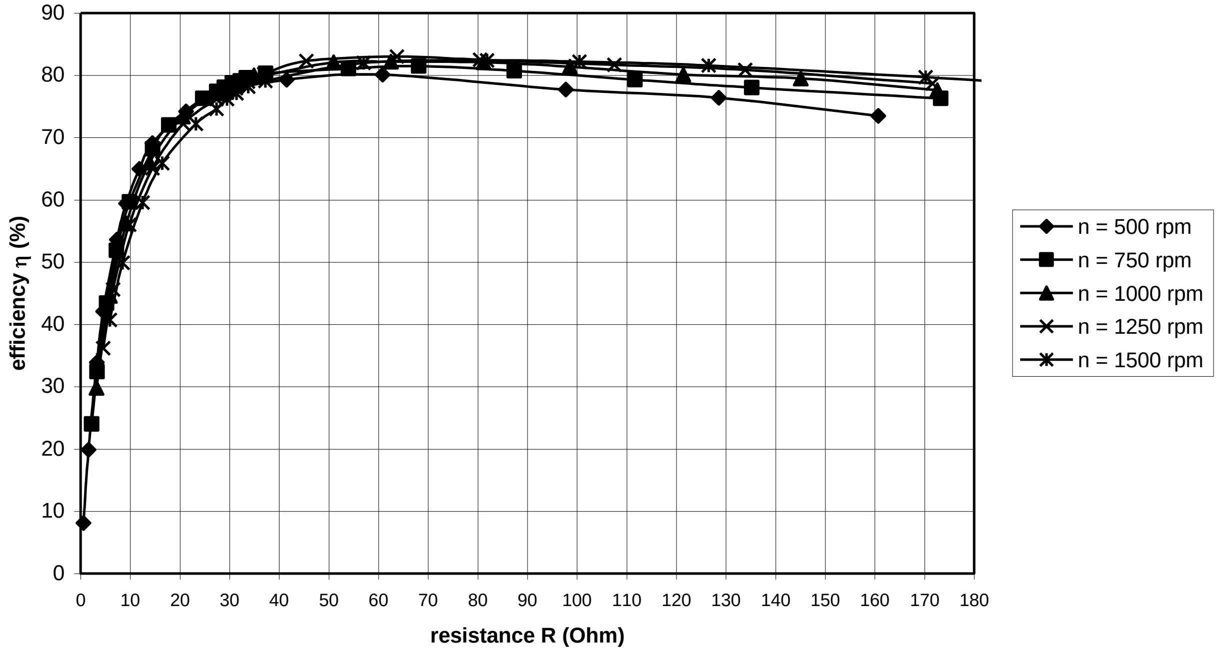

fig. 26 Efficiency η as a function of R for n = 500, n = 750, n = 1000, n = 1250 and n = 1500 rpm in star

8 Discussion about the results

The unloaded U-n curves are straight lines through the origin (see figure 1). The ratios between the measured open voltages correspond about to formulas 2 and 3 (see figure 1). The effective alternating voltage of 1-phase was not measured so this voltage could not be checked but earlier measurement has shown that this ratio is also correct. The unloaded Q-n line for delta is lying a lot higher than the unloaded Q-n line for star (see figure 2). This is caused by higher harmonic currents circulating in the triangle for delta rectification. Therefore delta rectification may cause starting problems if the windmill rotor has a low starting torque coefficient.

The maximum short-circuit torque level for delta rectification is a lot higher than for star rectification (see figure 4). The maximum torque for short-circuit in delta is 37.7 Nm and short-circuit in star is 30.2 Nm. Short-circuit in delta gives a maximum torque which is about a factor 1.25 higher. So stopping the windmill rotor by making short-circuit of the generator winding is most effective if short-circuit is made in delta. However, the braking effect for short-circuit in star will be the same as for short-circuit in delta if the star point is short-circuited too.

The Q-n curves for constant voltages all have about the same shape and the same maximum value. The curve for a higher voltage can be found by shifting the curve of a low voltage to the right over a certain distance (see figures 8 and 13). The P_{mech}-n curves and the P_{el}-n curves can be drawn in one graph (see figure 9 and 14). In these figures it can be seen that the maximum electrical power at high rpm is highest for the highest voltage. As the voltage is taken higher, the efficiency η increases because the I^2 R losses are relatively smaller. The rpm range with good efficiency is also larger for higher voltages (see figures 10 and 15).

The U-n curves for measurements with constant currents are all straight lines (see figure 16). For some currents (I = 1 A, I = 4 A and I = 5 A) the measurements have not been performed for high rotational speeds but the values for high rotational speeds can easily be found by interpolation. The Q-n lines for constant currents are almost straight horizontal lines (see figure 17). The P_{mech}-n and the P_{el}-n curves are also almost straight lines (see figure 18 and 19). The efficiencies increase very fast at increasing rotational speed (see figure 20).

The Q-R lines for a resistance as load and for the five constant rotational speeds have a maximum at very low values of the resistance R (see figure 23). For these measurements, efficiencies of more than 80 % are measured if the resistance is not too low (see figure 26). This is very good for a generator of this size especially because the rectifier losses are included in the generator efficiency. Efficiencies of more than 75 % are obtained for all rpm if the resistance is larger than about 25 Ω. The highest efficiency has been measured for 1250 rpm. It was found that η_{max} = 83 % for R = 63.7 Ω. The electrical power at this load, P_{el} = 1783 W (see figure 25). At n = 1500 rpm, a maximum electrical power, P_{el} = 3063 W is generated for a resistance R = 31.4 Ω (see figure 25). This power is a factor 1.225 higher than the nominal motor power of 2500 W. The efficiency at this power is 77.1 % which is still rather good.

9 Measurements for different constant resistances in star

In chapter 7 measurements are given for a variable resistor as load. For all these measurements, the resistance R is given on the x-axis. The reason has to do with the way the measurements are performed. During the measurements, the resistance is lowered in random steps and this results in a increase of torque and therefore also in decrease of rotational speed. The rotational speed of the driving motor is then increased until the wanted rotational speed is reached again. But in this case the graphs can easiest be made if the calculated resistance R is placed on the x-axis.

For some use of the generator it is nice to have the graphs with the rotational speed n on the x-axis and the resistance R as parameter. It is possible to transform the original P_{mech}-R graph given in figure 24 and the P_{el}-R graph given in figure 25 into P_{mech}-n and P_{el}-n graphs in the following way. The value of P_{mech} and P_{el} is read from the graphs for a certain range of R values and for the five rotational speeds for which the measurement have been performed. For every point the efficiency η can also be calculated. The result of this procedure is given in table 1.

	n = 500 rpm			n = 750 rpm			n = 1000 rpm			n = 1250 rpm			n = 1500 rpm		
R (Ω)	P_{mech} (W)	P_{el} (W)	η (%)	P_{mech} (W)	P_{el} (W)	η (%)	P_{mech} (W)	P_{el} (W)	η (%)	P_{mech} (W)	P_{el} (W)	η (%)	P_{mech} (W)	P_{el} (W)	η (%)
10	1260	770	61.1	2260	1370	60.6	2940	1690	57.5	3420	1910	55.8	3670	2020	55.0
20	870	640	73.6	1830	1350	73.8	2760	2030	73.6	3580	2550	71.2	4130	2880	69.7
30	660	510	77.3	1450	1140	78.6	2350	1850	78.7	3260	2530	77.6	4000	3060	76.5
40	540	430	79.6	1190	960	80.7	2000	1610	80.5	2830	2310	81.6	3700	2950	79.7
60	395	310	78.5	890	720	80.9	1520	1250	82.2	2240	1860	83.0	2980	2450	82.2
80	310	250	80.6	700	570	81.4	1240	1020	82.3	1830	1500	82.0	2480	2050	82.7
100	260	210	80.8	590	480	81.4	1050	850	81.0	1570	1270	80.9	2110	1740	82.5
120	230	180	78.3	550	420	76.4	900	720	80.0	1350	1100	81.5	1850	1490	80.5
140	210	160	76.2	460	360	78.3	800	640	80.0	1200	970	80.8	1650	1320	80.0
160	195	140	71.8	420	320	76.2	720	570	79.2	1090	870	79.8	1500	1180	78.7

table 1 Read values of P_{mech} and P_{el} and calculated value of η as a function of R

The P_{mech}-n curve is given in figure 27. The P_{el}-n curve is given in figure 28. The η-n curve is given in figure 29. The P_{mech}-n curve and the P_{el}-n curve start at the origin (n = 0, P = 0) but, as no measurements were performed for n = 250 rpm, curves can’t be drawn accurately for the region 0 < n < 500 rpm and these parts of the curves are therefore left out of the graphs.

The generator has been measured unloaded which means that the resistance is infinite. The measured P_{mech}-n curve in star for R = infinite is also given in figure 27. The electrical power and the efficiency are both zero, so no curve for R = infinite is given in figure 28 and figure 29.

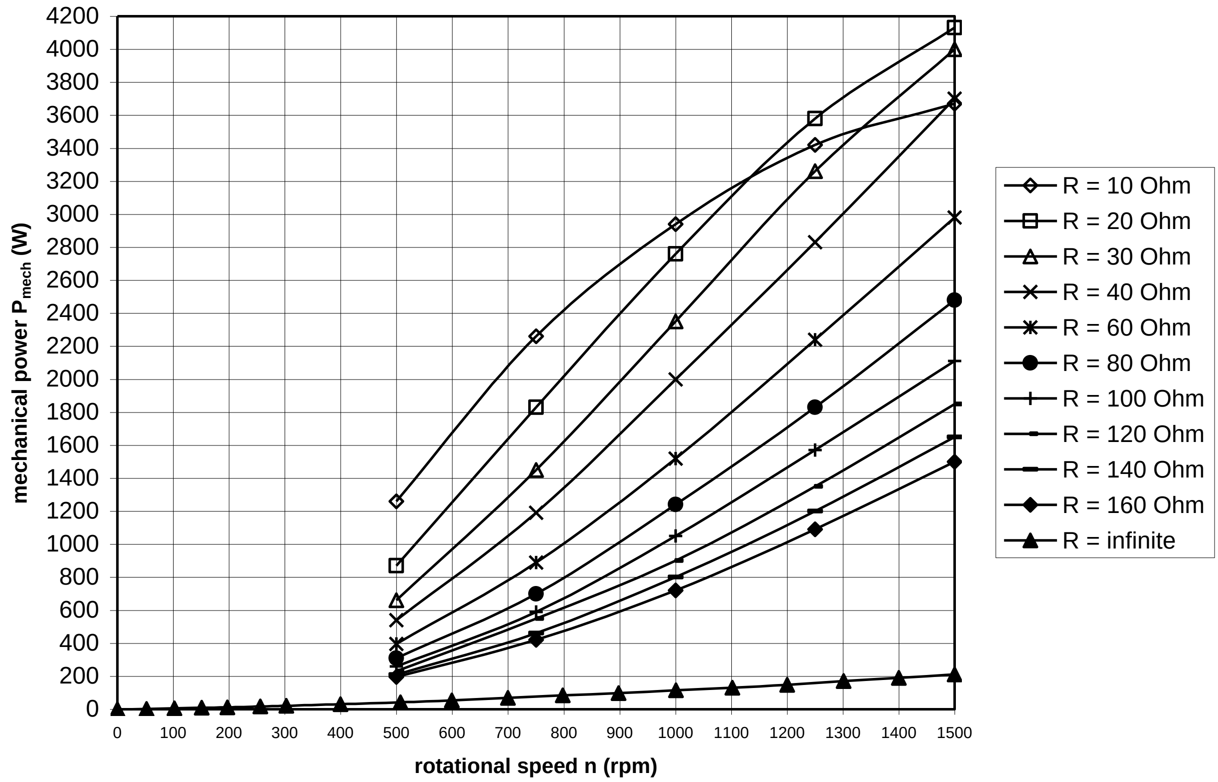

fig. 27 Mechanical power P_{mech} as a function of n for different values of R

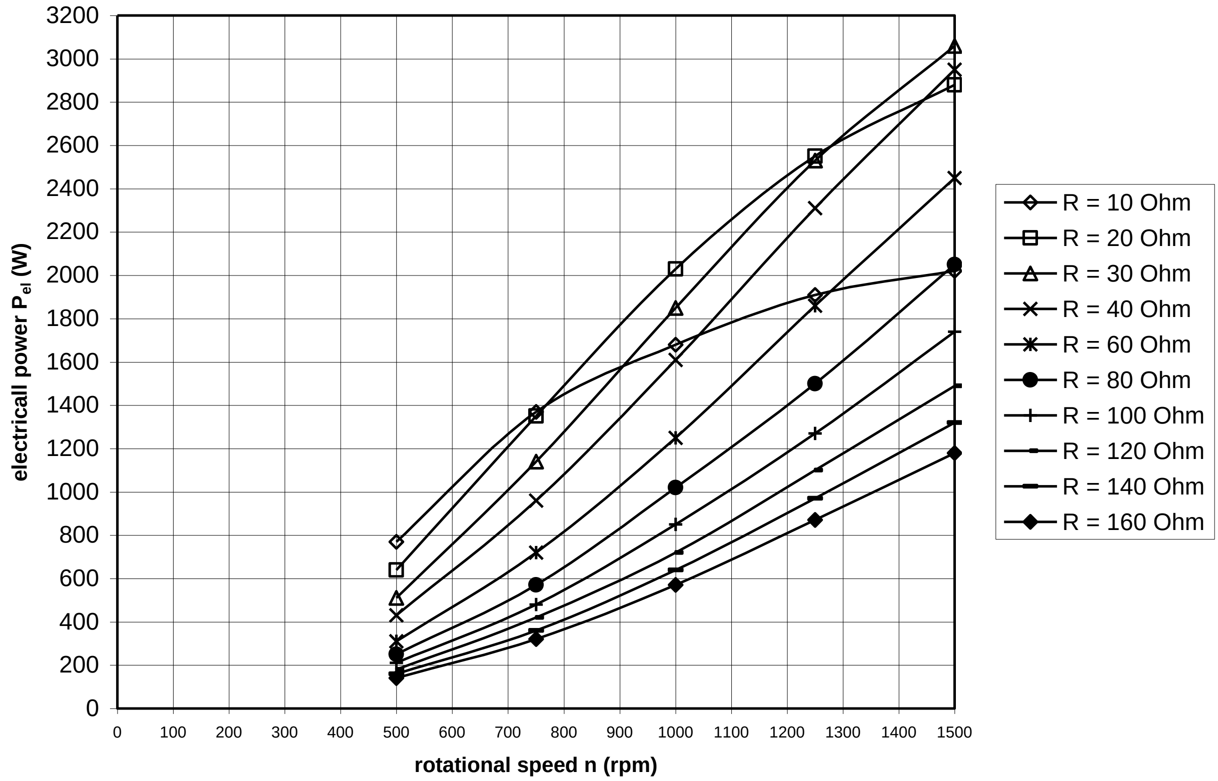

fig. 28 Electrical power P_{el} as a function of n for different values of R

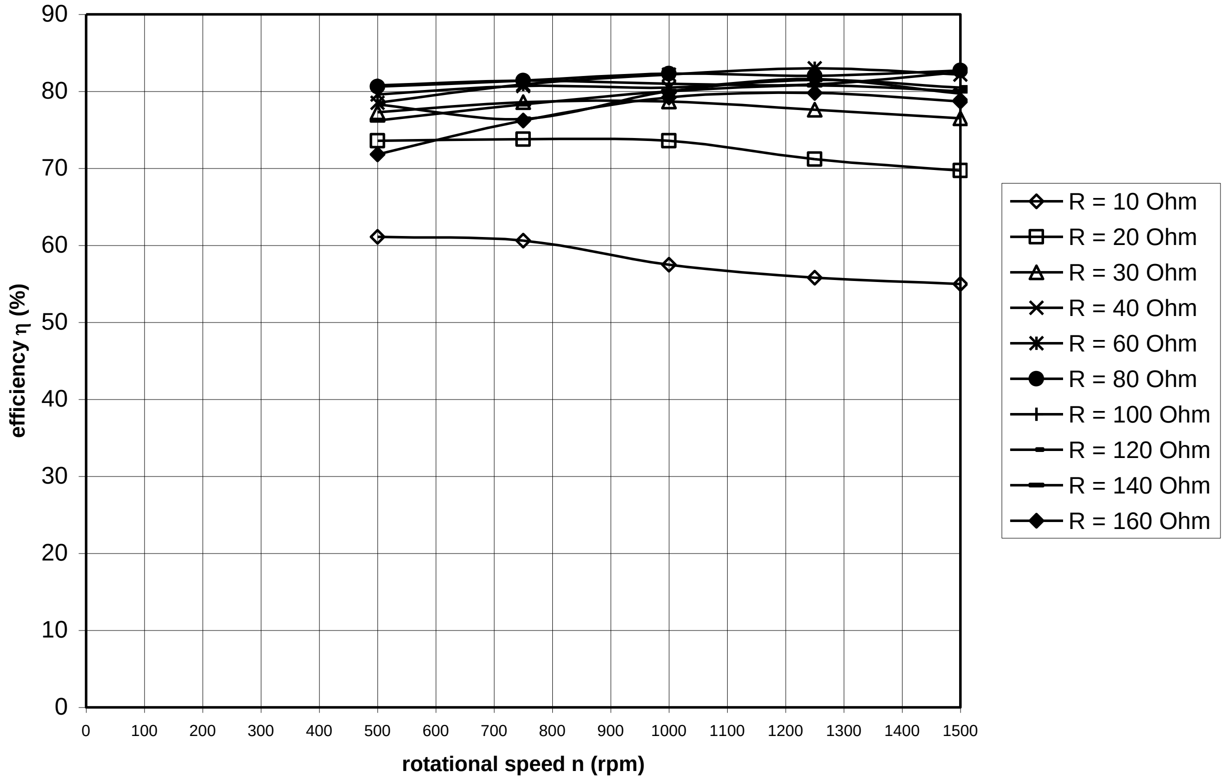

fig. 29 Efficiency η as a function of n for different values of R

In figure 29 it can be seen that the η-n curves are about horizontal lines if the load is a resistor. The efficiency can be more than 80 %, even for the lowest rotational speed n = 500 rpm, if the value of the resistance is taken not very low or not very high. This efficiency is rather high for the given generator size, also because the efficiency of the rectifier is included in the generator efficiency.

It has to be kept in mind that the given curves of figure 27, 28 and 29 are not as accurate as the original curves given in chapter 7 because a small error is made when the values of P_{mech} and P_{el} are read from the P_{mech}-R and P_{el}-R curves. Very accurate curves can only be obtained if the generator is measured for different rotational speeds for a fixed value of the resistance R.

It is a pity that the curves can't be drawn in the region for $0 < n < 500$ rpm because no measurements for constant resistance's have been performed for n = 250 rpm. However, measurements have been performed for constant currents I = 1 A, 2 A, 3 A, 4 A, 5 A, 6 A, 7 A and 8 A for the rpm range in between 0 and 900 rpm. These measurement are given in chapter 6. The P_{mech}-n curves, the P_{el}-n curves and the η-n curves are given in respectively figure 18, 19 and 20. The values for P_{mech}, P_{el} en η can be read in these figures for the eight currents and for n = 250 rpm. The resistance R (Ω) can be calculated with $R = P_{el} / I^2$. The read and calculated values are given in table 2.

I (A)	P_{mech} (W)	P_{el} (W)	η (%)	R (Ω)
1	94.0	70	74.5	70.00
2	170.4	128	75.1	32.00
3	250.0	178	71.2	19.78
4	321.8	214	66.5	13.38
5	397.4	240	60.4	9.60
6	457.9	245	53.5	6.81
7	534.5	240	44.9	4.9
8	572.6	205	35.8	3.2

table 2 Read values from figures 18, 19 and 20 for P_{mech}, P_{el} and η as a function of I for n = 250 rpm. Calculated values of R

The values for P_{mech} and P_{el} are given as a function of R in figure 30 for n = 250 rpm.

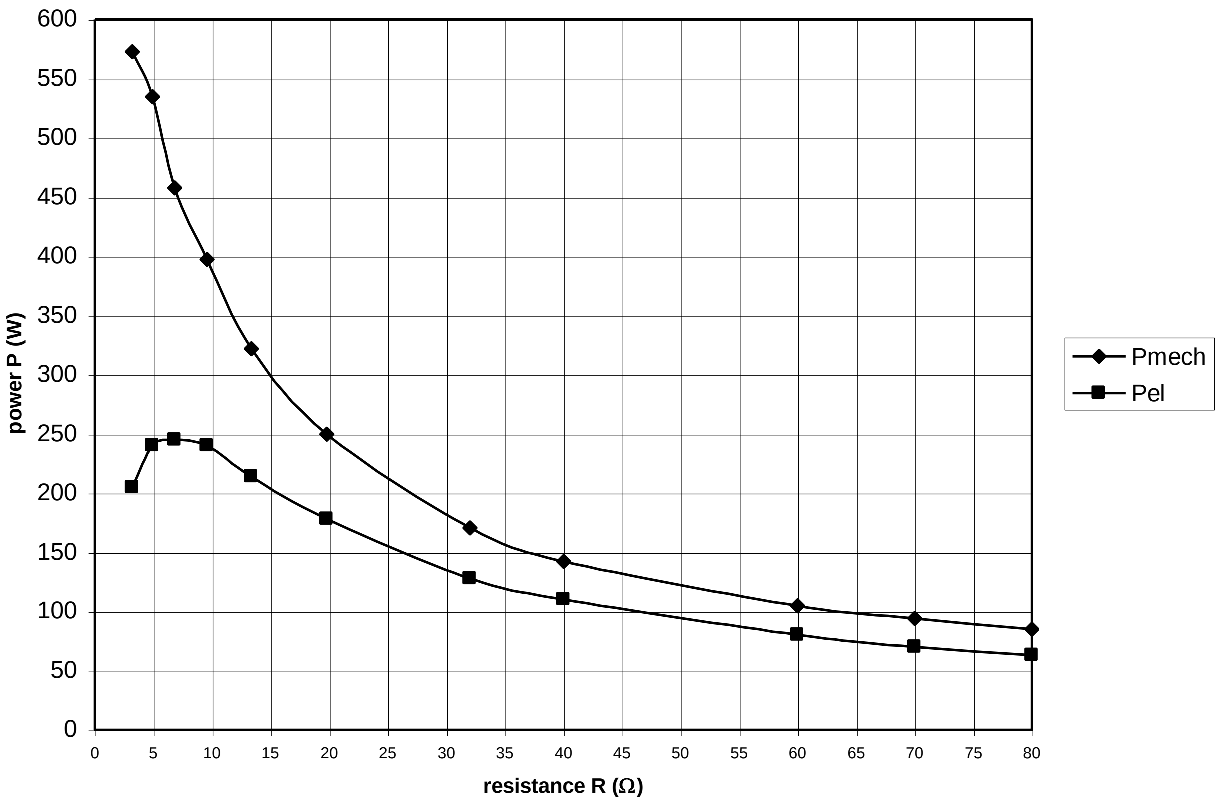

fig. 30 P_{mech} and P_{el} as a function of R for n = 250 rpm

From figure 30 it is possible to read the values of P_{mech} and P_{el} for a certain value of R. This is done for R = 10 Ω, R = 20 Ω, R = 30 Ω, R = 40 Ω, R = 60 Ω and R = 80 Ω. The corresponding efficiency can be calculated. The result is given in table 3.

R (Ω)	P_{mech} (W)	P_{el} (W)	η (%)
10	390	240	61.5
20	245	175	71.4
30	175	130	74.3
40	142	110	77.5
60	105	80	76.2
80	85	63	74.1

table 3 Values of P_{mech} and P_{el} read from figure 30

The read values for R = 40 Ω, 60 Ω and 80 Ω are also given in figure 30 to check if the estimated values are correctly positioned on the P_{mech}-R and P_{el}-R curves.

Figure 27, 28 and 29 are now copied as figure 31, 32 and 33. Only the curves for R = 10 Ω, R = 20 Ω, R = 30 Ω, R = 40 Ω, R = 60 Ω, R = 80 Ω and R = infinite are given. However, the values of P_{mech}, P_{el} and η for n = 250 rpm as found in table 3 are now also included in the curves. The values for P_{mech} and P_{el} for n = 0 rpm are also included (all these values are zero). The efficiency is not given for n = 0 rpm because it is not allowed to divide by zero.

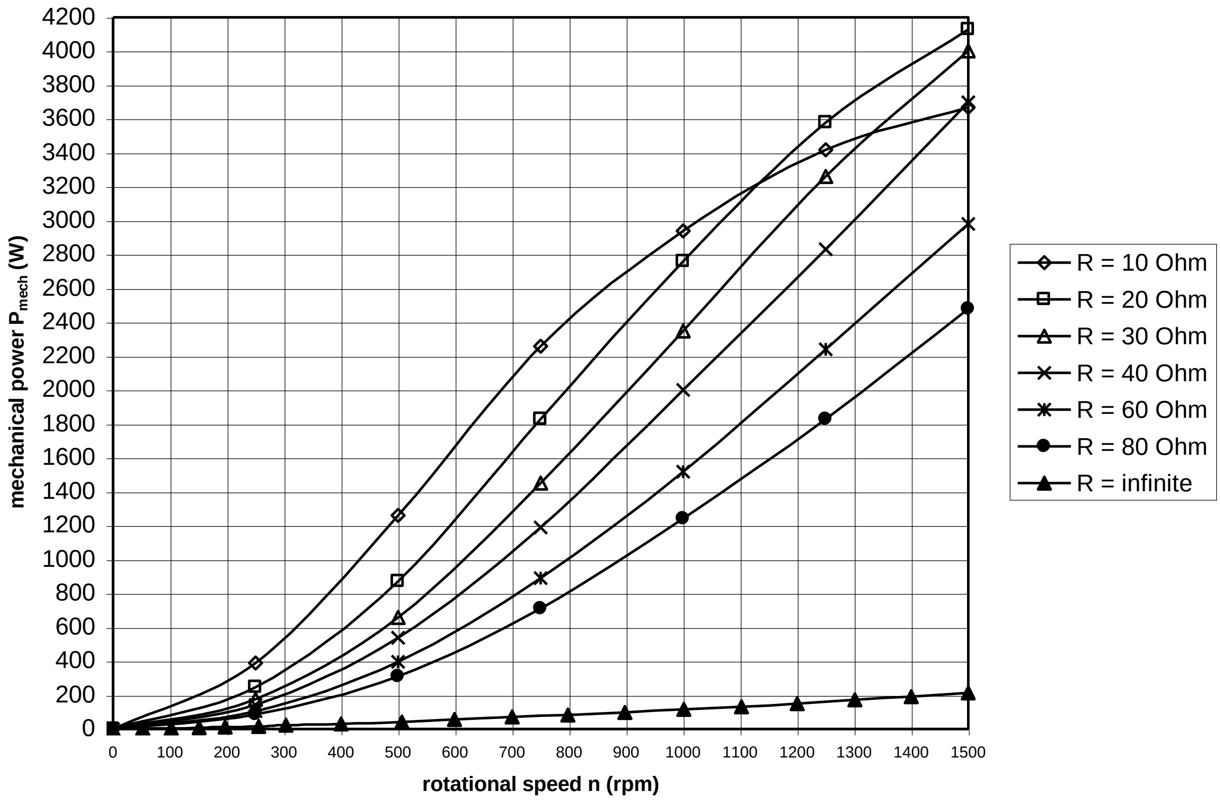

fig. 31 Mechanical power P_{mech} as a function of n for different values of R

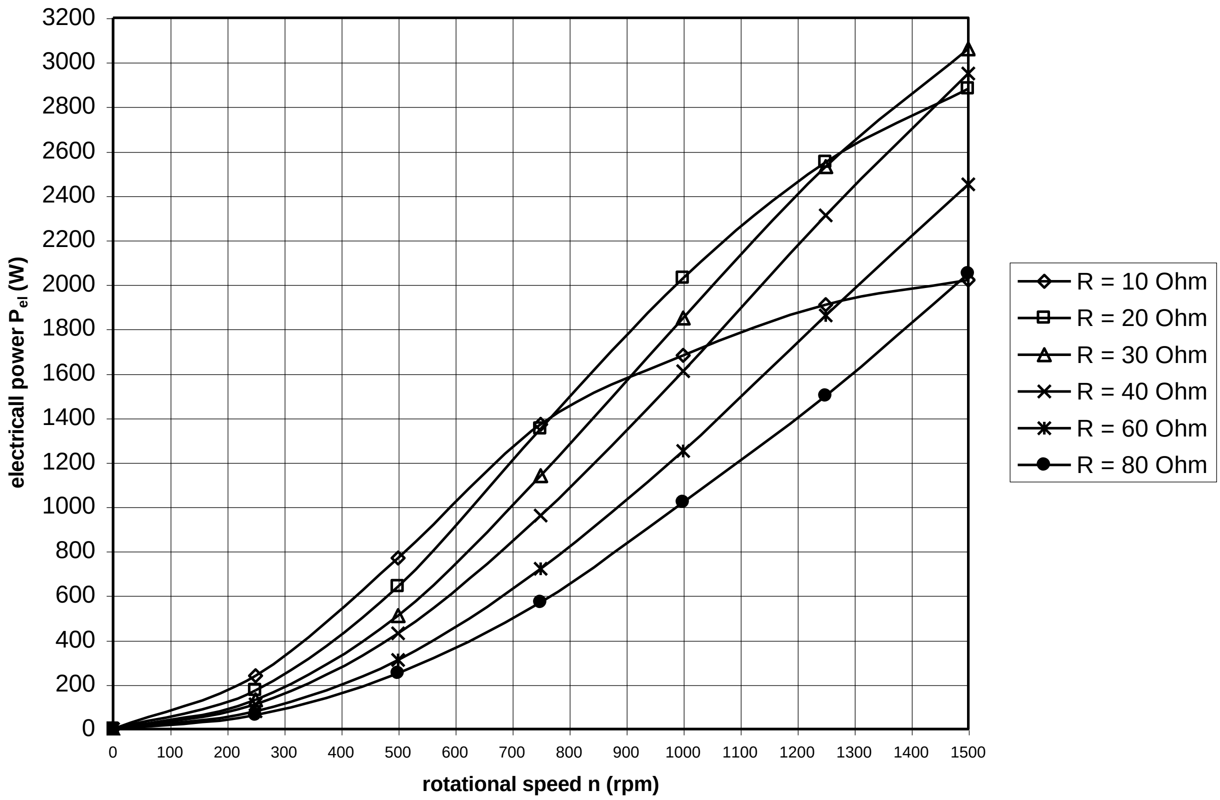

fig. 32 Electrical power P_{el} as a function of n for different values of R

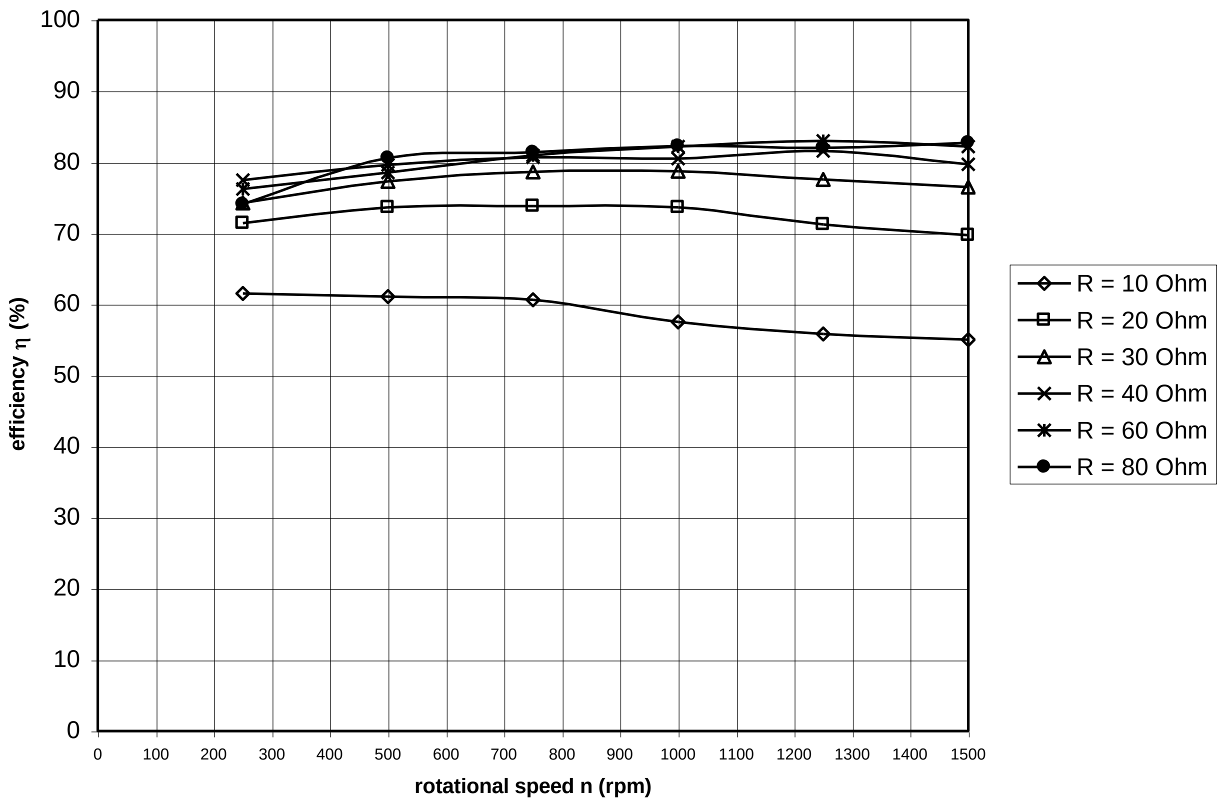

fig. 33 Efficiency η as a function of n for different values of R

10 References

1 Kragten A. Development of the permanent magnet (PM) generators of the VIRYA windmills, May 2007, reviewed March 2015, free public report KD 341, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Rectification of 3-phase VIRYA windmill generators, May 2007, reviewed October 2014, free public report KD 340, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.