Measurements performed on a generator with housing 5RN112M04V and a 4-pole armature equipped with neodymium magnets

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Contents page

1 Introduction

The generator was originally developed for the VIRYA-4.2 windmill but it may also be used in other VIRYA-windmills. 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 35 mm stainless steel shaft and an armature with neodymium magnets. The following motor was chosen:
Manufacture: Rotor B.V. Eibergen, type: 5RN112M04V (with over-sized stator), provided with a 230/400V 3-phase winding, nominal mechanical power 5.5 kW, mass 49 kg. The drawing number of the generator is 0401-02.
The generator was developed by ing. A. Kragten of engineering office Kragten Design.

2 Measurements general

The generator was measured on two different torque measuring devices of the Laboratory of Electro-mechanics of the University of Technology Eindhoven. For torques up to about 30 Nm, a measuring device was used of which 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. For measuring higher torques than about 30 Nm a second test rig was used with a maximum torque level of 250 Nm. For this test rig the rotational speed was measured with an accurate counter which works on reflection of a beam on a white dot on the clutch. The counter is hold in the hand. The torque measuring devices were hired at a tariff of 15,- euro / hour.

The unloaded open characteristics were measured in star and in delta for rotational speeds up to 1500 rpm.

The generator was measured for short circuit in delta (before the rectifier) because this gives the highest torque level. The windmill rotor is stopped by making short circuit in the generator.

The three phase alternating current of the generator is rectified using a heavy three phase rectifier. The DC current was first measured using an accurate analogue soft iron meter and for high currents using a very modern digital current tong. The DC voltage was measured with a digital volt meter.

For the application of the windmill as battery charger, the generator was measured rectified in star and in delta for several constant voltages. For star it was measured for 30 V, 52 V and 104 V. For delta it was measured for 15 V, 26 V and 52 V. The real voltage may differ a little from the nominal value. 26 V is the average charge voltage for a 24 V battery, 52 V is the average charge voltage for a 48 V battery and 104 V is the average charge voltage for a 96 V battery. 15 V is a factor √3 lower than 26 V which means that the measured characteristics are identical for 26 V, if one uses a 400/690 V winding in stead of a 230/400 V winding. 30 V is a factor √3 lower than 52 V which means that the measured characteristics are identical for 52 V, if one uses a 400/690 V winding in stead of a 230/400 V winding.

To get more inside in the generator characteristics at higher rpm, the generator was also measured for several loads with a constant resistance, for rectification in star and for rotational speeds of 100, 200, 300, 400, 500, 750, 1000, 1250 and 1500 rpm. In practice it appeared to be impossible to adjust the driving motor such that the exact rpm values were gained, so the real rpm may differ a little from the nominal value. Although the adjustment of the variable resistance has not been changed during a series of measurements, it appears that the resistance at low rpm is somewhat higher than at high rpm. The average resistance is mentioned in the graphs. All measurements with constant resistance have been executed on the large 250 Nm test rig.

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:

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

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

$$U_{DC} = 0,955 * \sqrt{2} * \sqrt{3} * U_{AC\ eff} = 2,3393 * U_{AC\ eff} \quad (V) \qquad (2)$$

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

$$U_{DC} = 0,955 * \sqrt{2} * U_{AC\ eff} = 1,3506 * U_{AC\ eff} \quad (V) \qquad (3)$$

The measured magnitudes are: torque Q (Nm), rotational speed n (rpm), rectified voltage U (V) and 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.

3 Measurements detail

The generator was measured for the following configurations:

1 Unloaded (open), rectified in star (λ) for 0 < n < 1500 rpm (see figure 1 + 2 + 3)
2 Unloaded (open), rectified in delta (Δ) for 0 < n < 1500 rpm (see figure 1 + 2 + 3)
3 Short-circuit before the rectifier in delta (see figure 4 + 5)
4 Rectified in star for 30V, 52V and 104V (see figure 6 + 7 + 8 + 9 + 10)
5 Rectified in delta for 15V, 26V and 52V (see figure 11 + 12 + 13 + 14 + 15)
6 Rectified in star for several values of a resistance as load for n = 100, 200, 300, 400, 500, 750, 1000, 1250 and 1500 rpm (see figure 16 + 17 + 18 + 19 + 20 + 21)

All figures are given after chapter 4.

4 Description of the results

The line $Q_{open\ \Delta}$ is laying a lot higher than the line for $Q_{open\ star}$ and (see figure 1). This is caused by higher harmonic currents circulating in the delta. Therefore delta rectification may cause starting problems if the windmill rotor has a low starting torque at low rotational speeds. For the VIRYA-4.2 windmill the generator is rectified in star and used for 48 V battery charging.

The ratios between the measured open voltages correspond about to formulas 2 and 3 (see figure 3). The effective alternating voltage of 1-phase was not measured so this voltage could not be checked but earlier measurements have shown that this ratio is also correct.

The maximum torque level for short circuit in delta is 77.8 Nm (see figure 1) which is very high for this size of generator. Short circuit in delta is the same as short circuit in star if the star point is short circuited too.

The maximum torque level for the constant voltages in delta is about 75 Nm (see figure 11). The maximum torque level for the constant voltages in star is about 59 Nm (see figure 6) which is a lot lower.

As the voltage is taken higher, the efficiency η increases because the I^2R losses are relatively smaller. The rpm range with good efficiency is also larger (see figures 8 and 13).

For measurements with a resistance as load, efficiencies of more than 80 % are measured if the resistance is not too low (see figure 19). This is very good for a generator of this size especially because the rectifier losses are included in the generator efficiency. At high values of the resistance R, the efficiency is maximal for 1250 or 1500 rpm. At the lowest resistance the efficiency is maximal for about 750 rpm. However the difference is not large and efficiencies of more than 75 % are obtained for an rpm range in between 200 and 1500 rpm. The highest efficiency has been measured for 1000 rpm. It was found that η_{max} = 84,7 % for R = 22,3 Ω.

The maximum electrical power of about 6.7 kW has been measured for R = 11,05 Ω at n = 1500 rpm (see figure 16). This is very high for a 5.5 kW motor. This power is a factor 1,22 higher than the nominal motor power of 5.5 kW. The efficiency at this power is 75,4 % which is still rather good.

In figure 3 it can be seen that the unloaded DC voltage in star at n = 1500 rpm is 505 V. A rotational speed of 1500 rpm corresponds with a frequency of 50 Hz for a 4-pole generator. Using formula 2 it can be calculated that $U_{AC\ eff}$ = 505 / 2.3393 = 215.9 V.

In figure 20 it can be seen that the DC voltage in star at 1500 rpm for R = 53,5 Ω is 457 V. Using formula 2 it can be calculated that $U_{AC\ eff}$ = 457 / 2.3393 = 195.4 V. This means that the AC phase voltage is in between 215.9 V and 195.4 V if the resistance of the load is more than 53.5 Ω.

In figure 18 it can be seen that the electrical power at 1500 rpm and for R = 53.5 Ω is 3885 W. This means that the electrical power is in between 0 and 3885 W, if the resistance of the load is more than 53.5 Ω. If one accepts a somewhat lower voltage than 230 V AC, the generator can be used for generation of a small 50 Hz mini 3-phase grid if the required power is less than about 4 kW. It might als be possible to use the generator to drive the 3-phase motor of a large centrifugal pump.

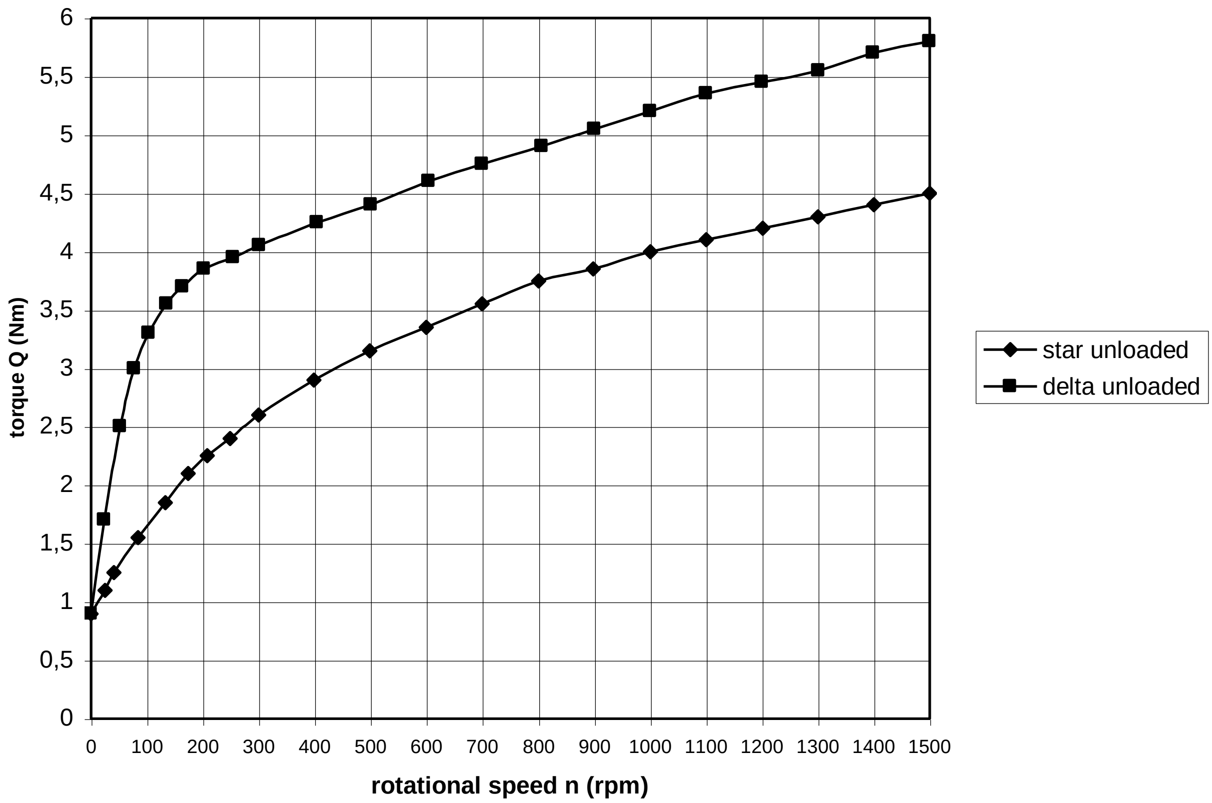

fig. 1 Unloaded torque as a function of n for star and delta

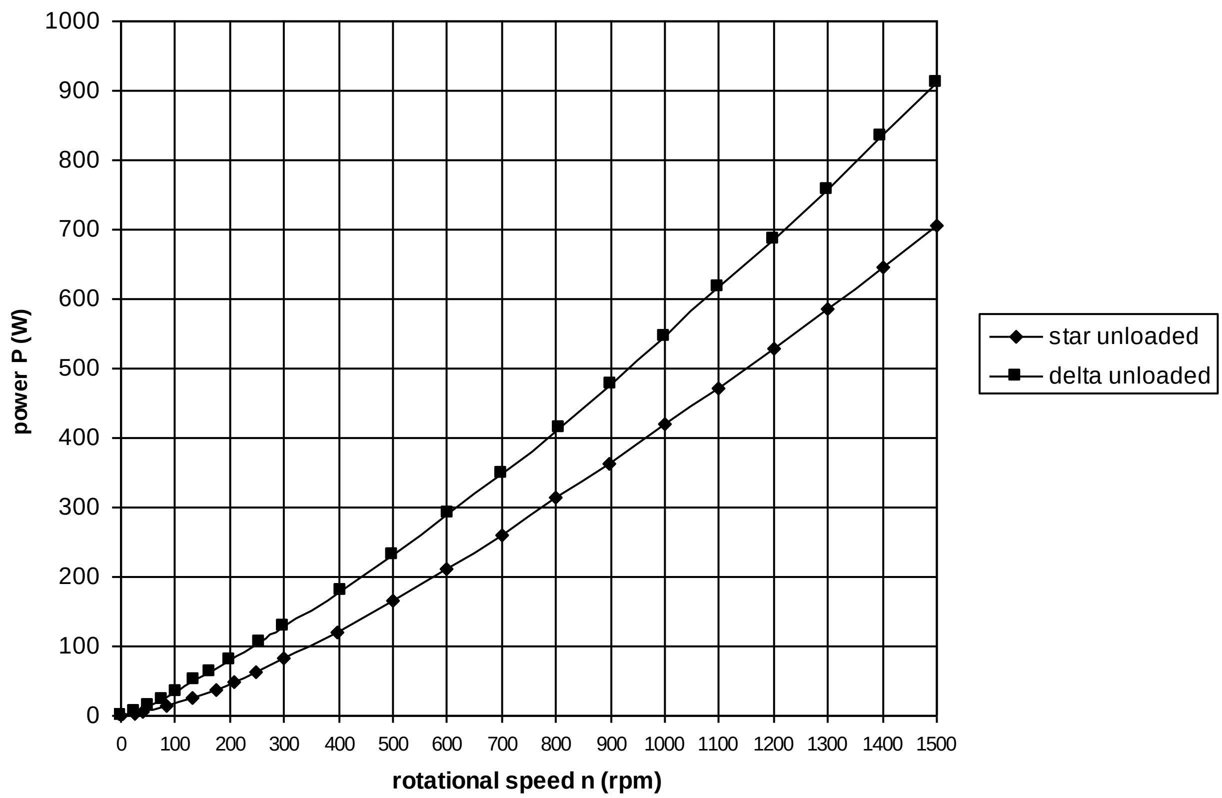

fig. 2 Unloaded power as a function of n for star and delta

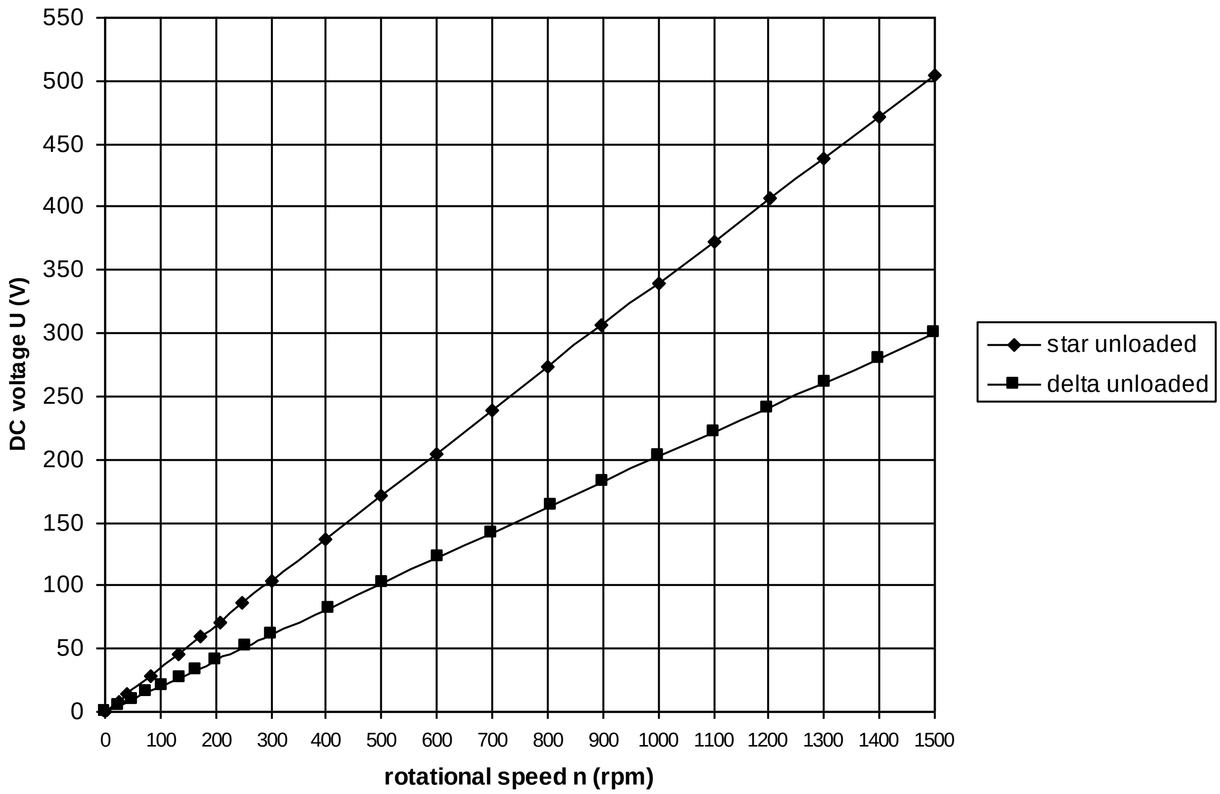

fig. 3 Unloaded DC voltage as a function of n for star and delta

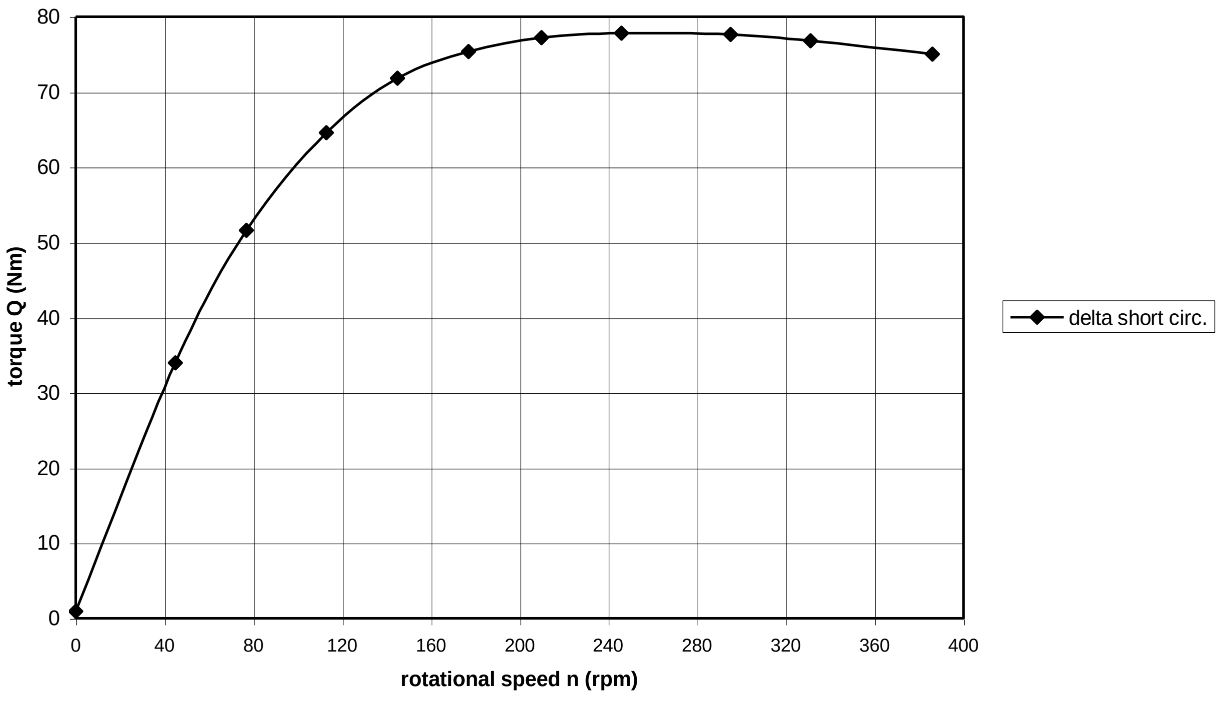

fig. 4 Torque for short circuit in delta as a function of n

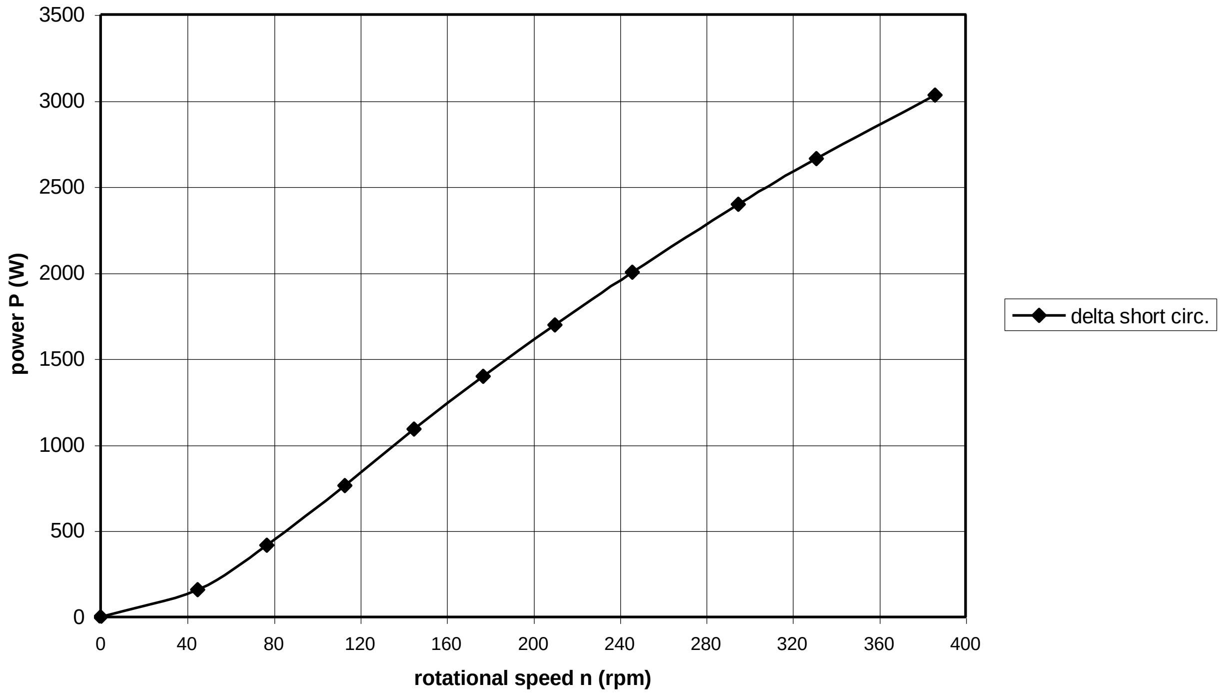

fig. 5 Power for short circuit in delta as a function of n

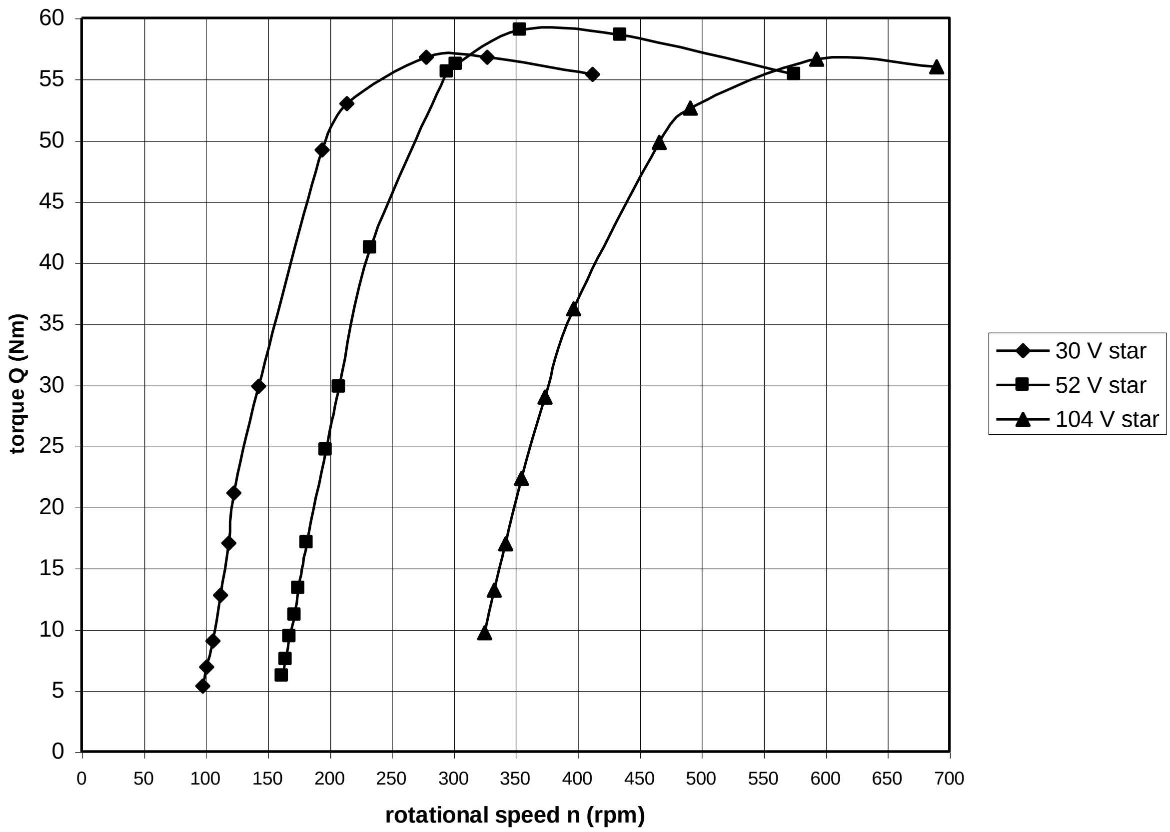

fig. 6 Torque as a function of n for U = 30 V, U = 52 V and U = 104 V in star

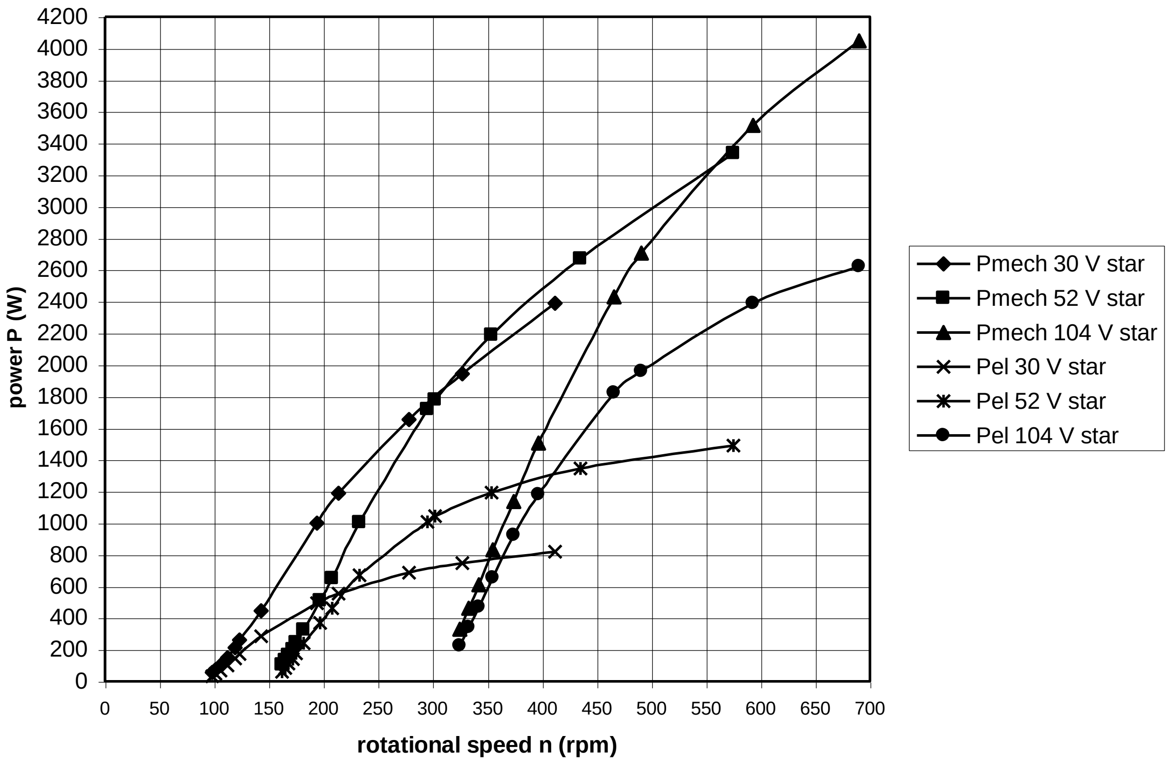

fig. 7 Mechanical and electrical power as a function of n for U = 30 V, U = 52 V and U = 104 V in star

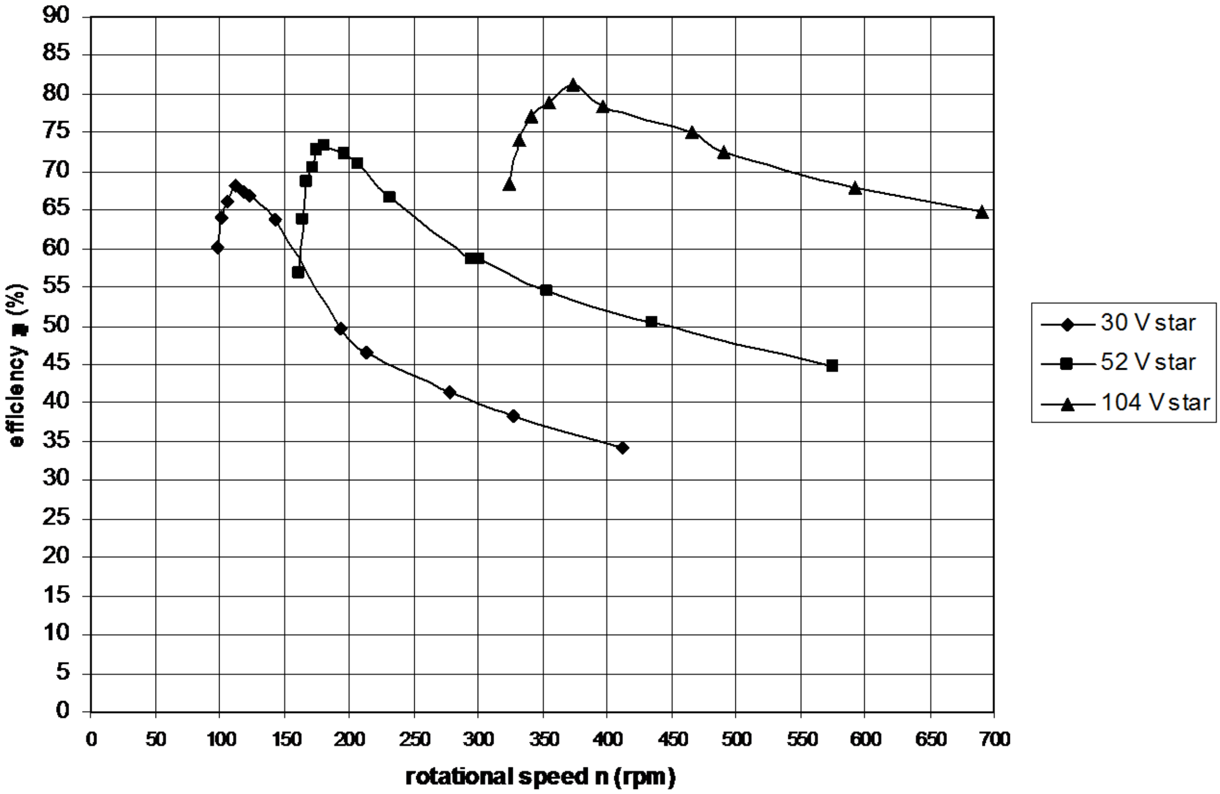

fig. 8 Efficiency as a function of n for U = 30 V, U = 52 V and U = 104 V in star

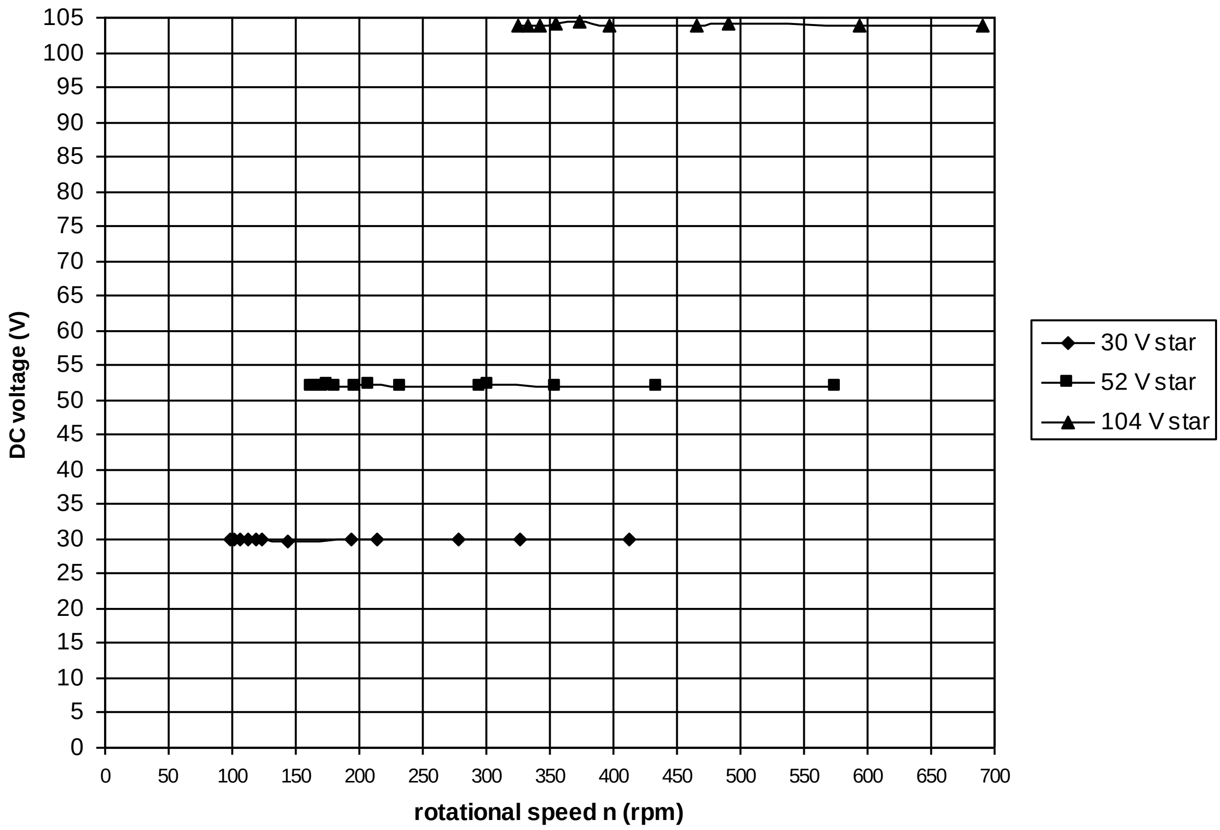

fig. 9 DC voltage as a function of n for U = 30 V, U = 52 V and U = 104 V in star

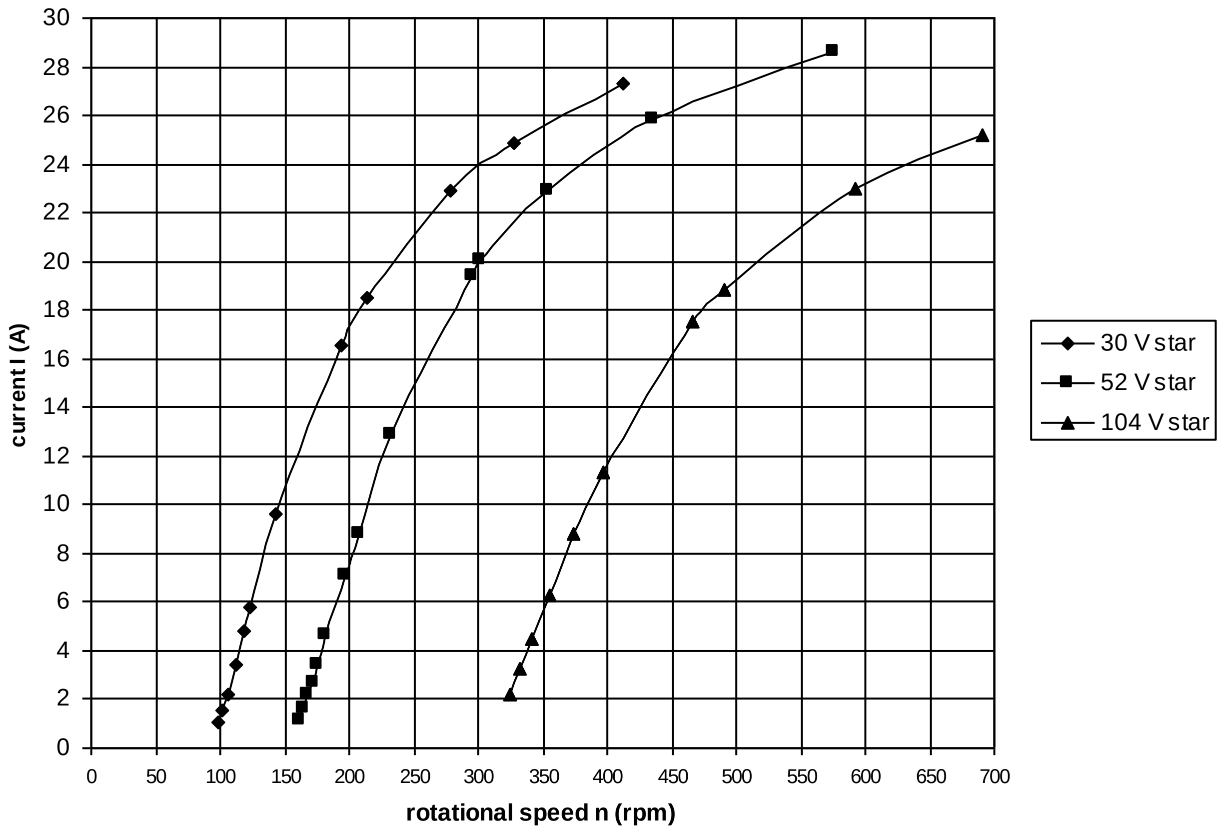

fig. 10 Current as a function of n for U = 30 V, U = 52 V and U = 104 V in star

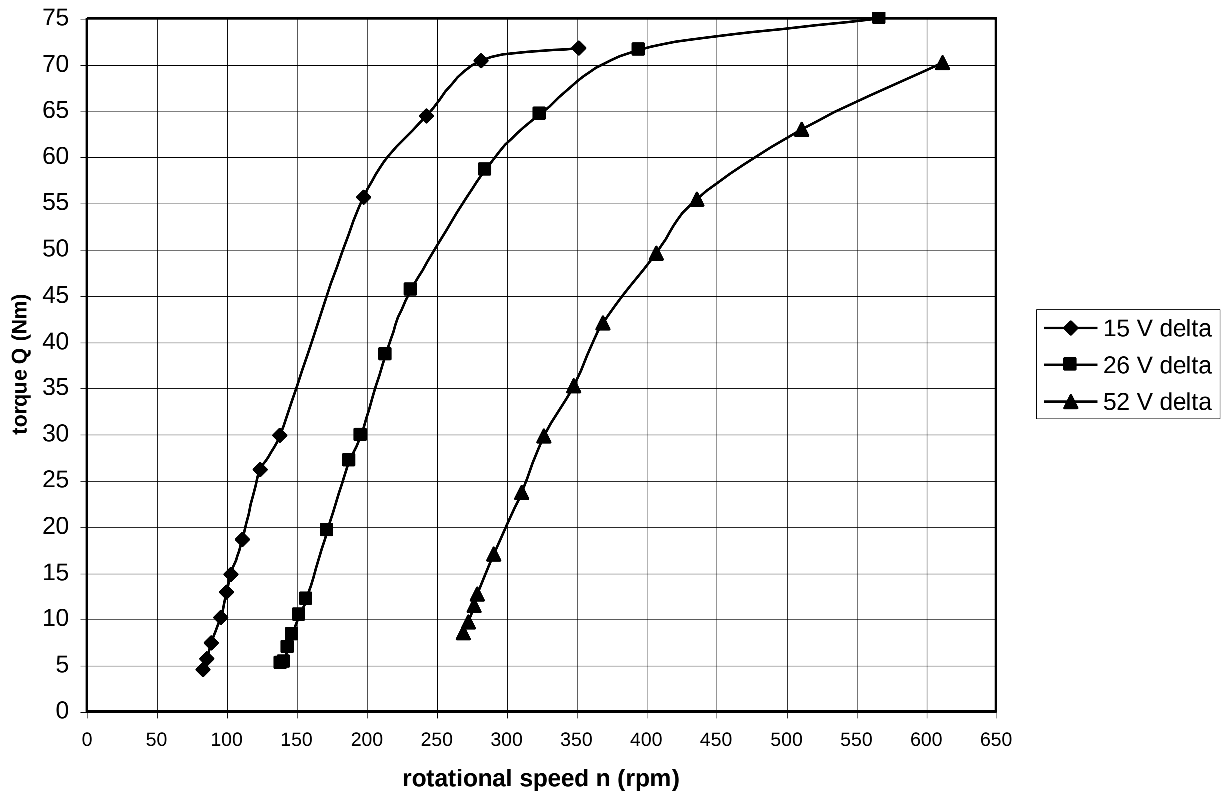

fig. 11 Torque as a function of n for U = 15 V, U = 26 V and U = 52 V in delta

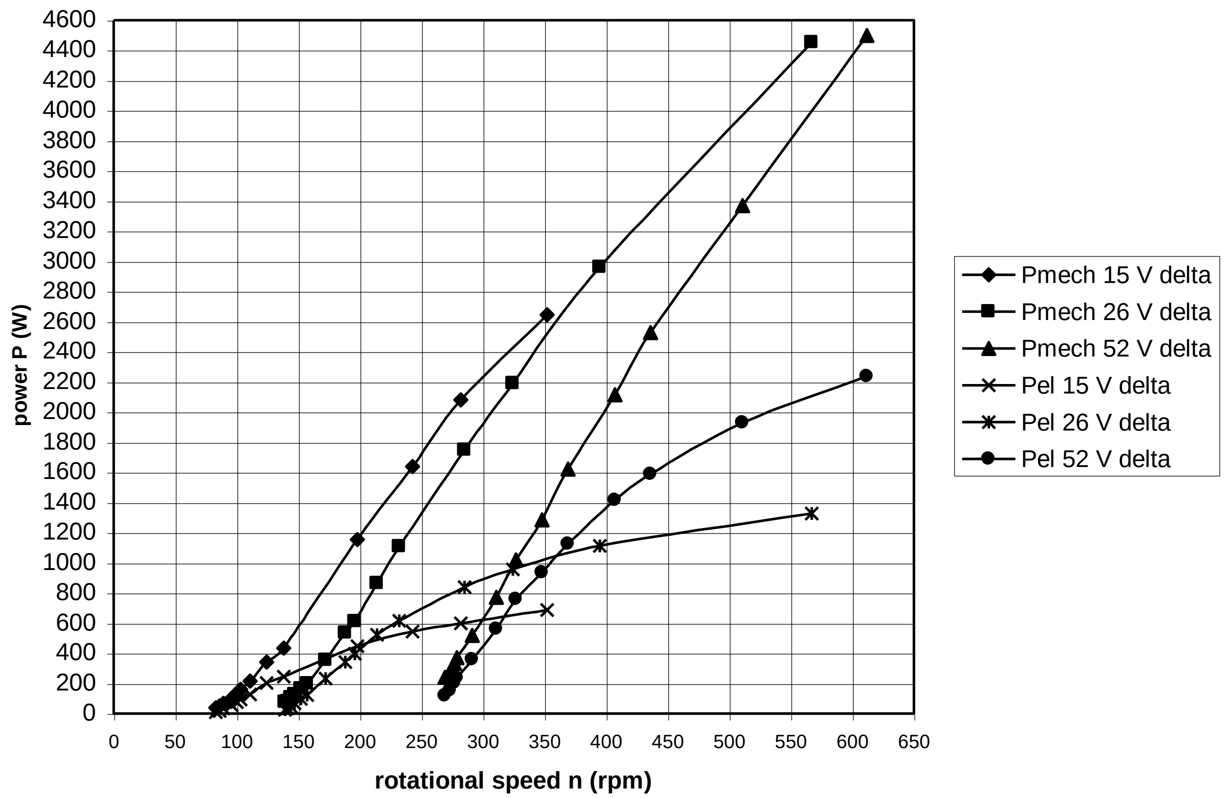

fig. 12 Mechanical and electrical power as a function of n for U = 15 V, U = 26 V and U = 52 V in delta

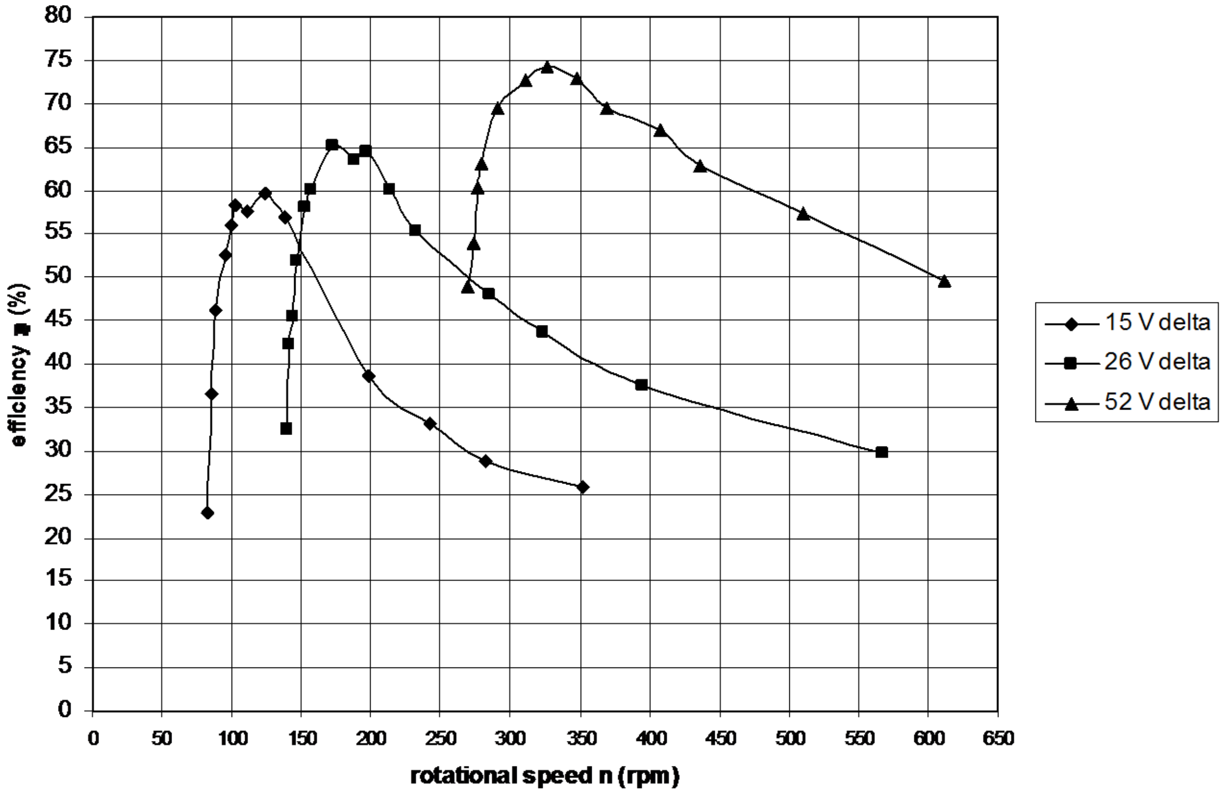

fig. 13 Efficiency as a function of n for U = 15 V, U = 26 V and U = 52 V in delta

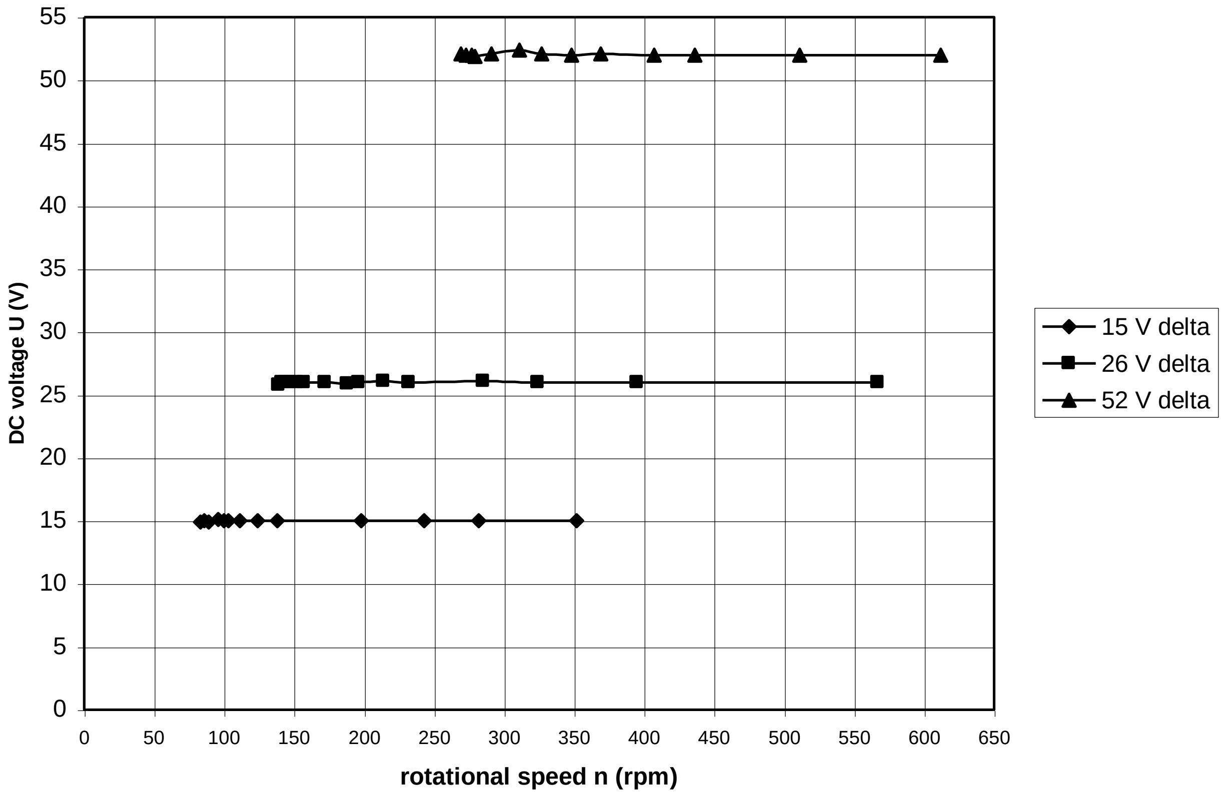

fig. 14 DC voltage as a function of n for U = 15 V, U = 26 V and U = 52 V in delta

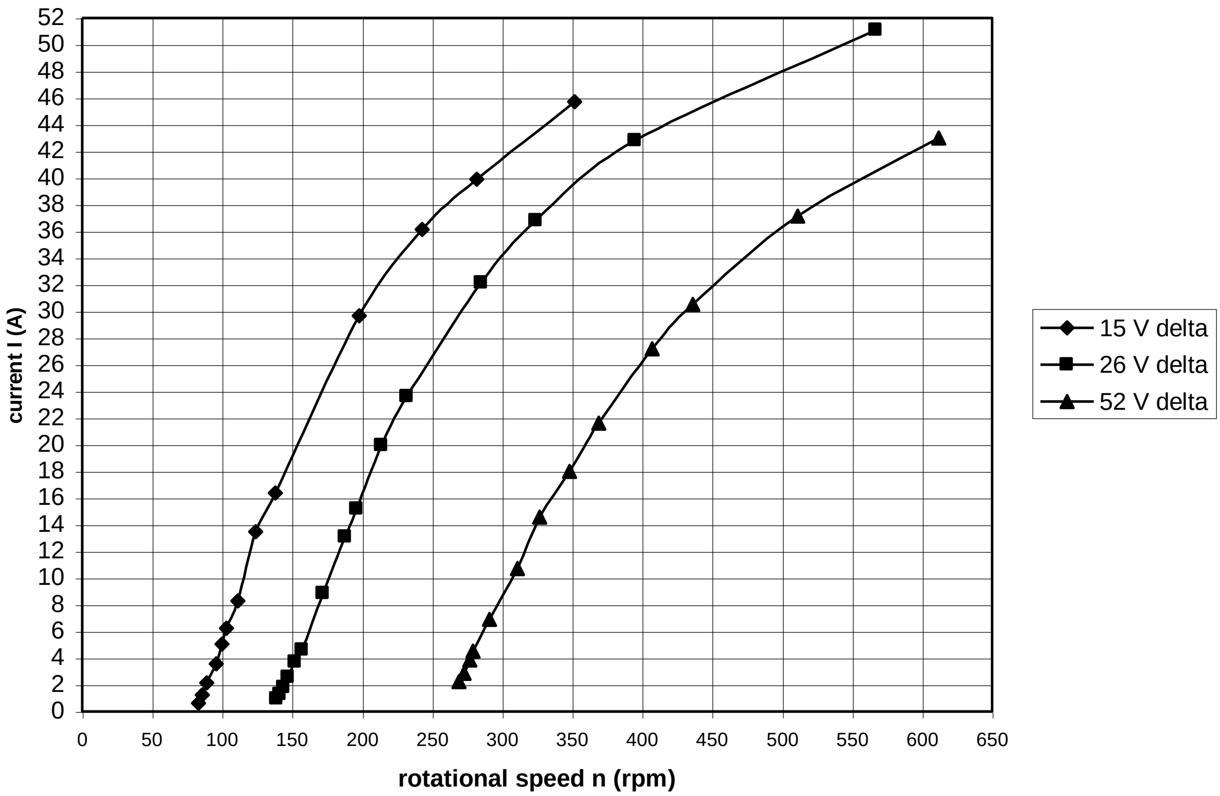

fig. 15 Current as a function of n for U = 15 V, U = 26 V and U = 52 V in delta

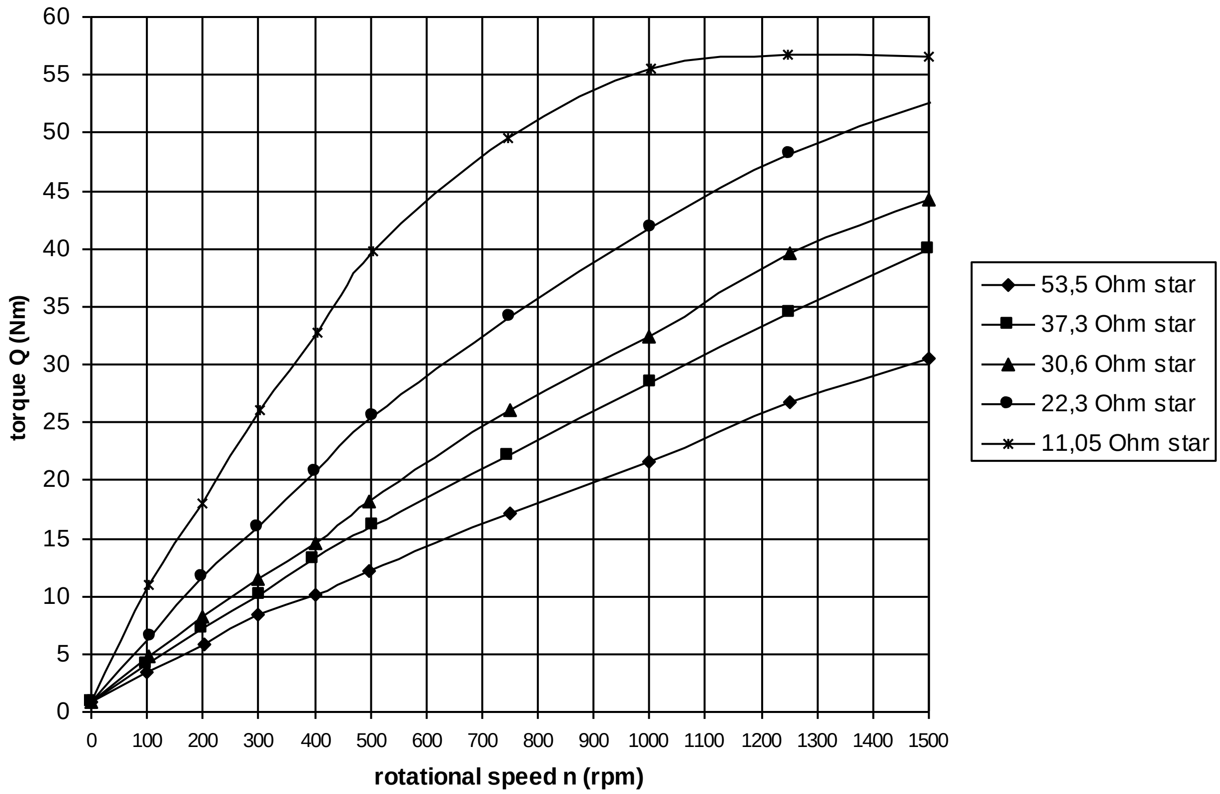

fig. 16 Torque torque as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star

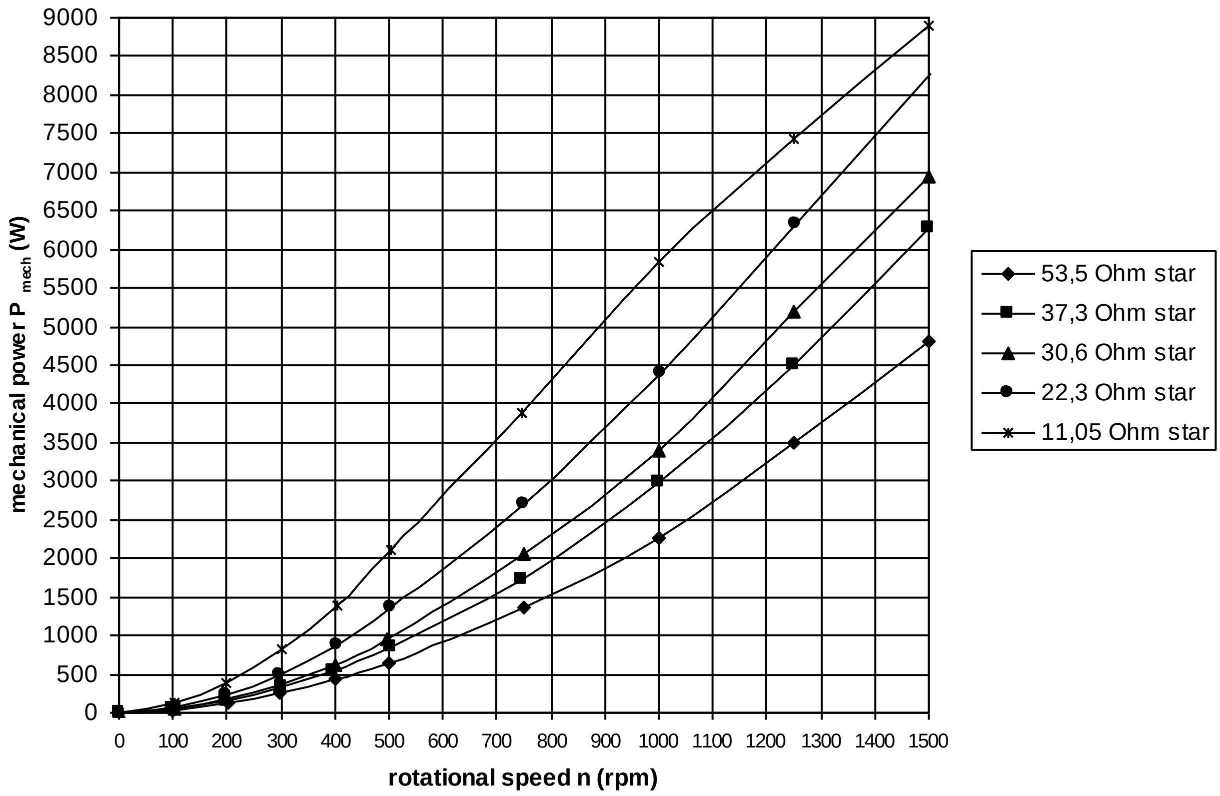

fig. 17 Mechanical power as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star

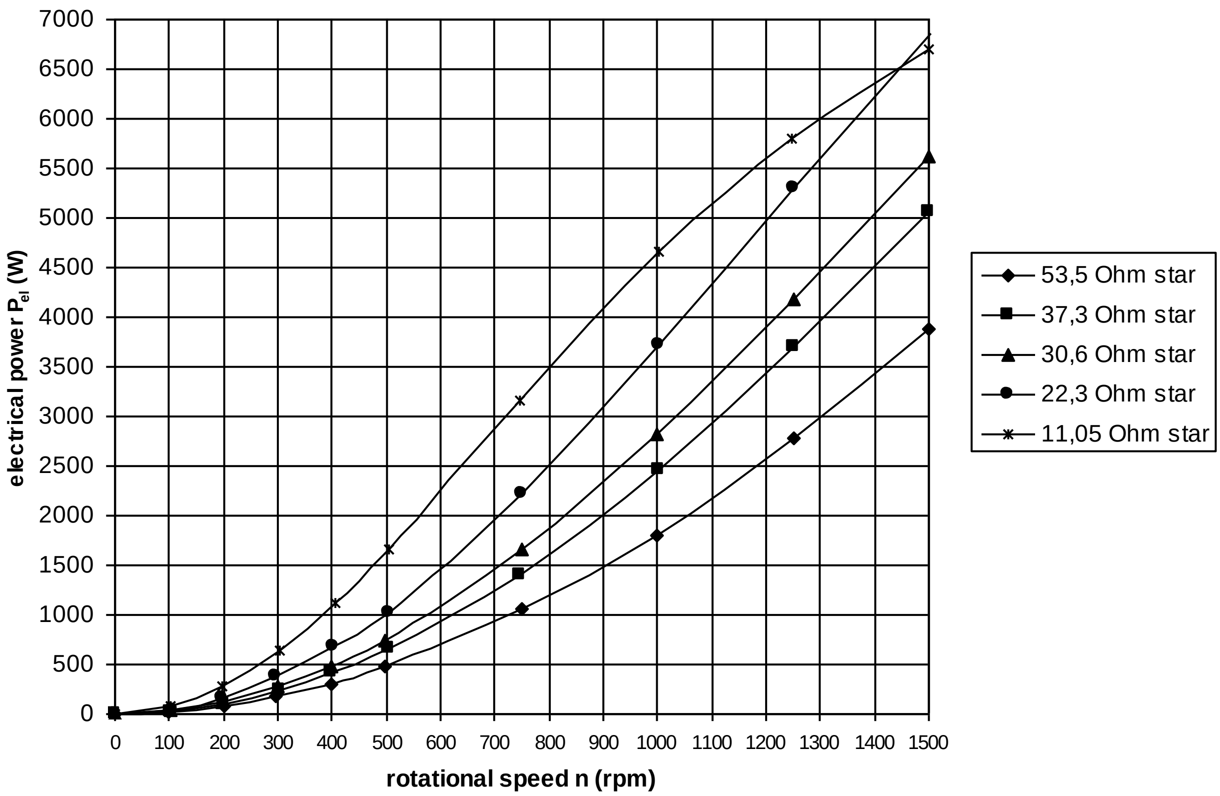

fig. 18 Electrical power as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star

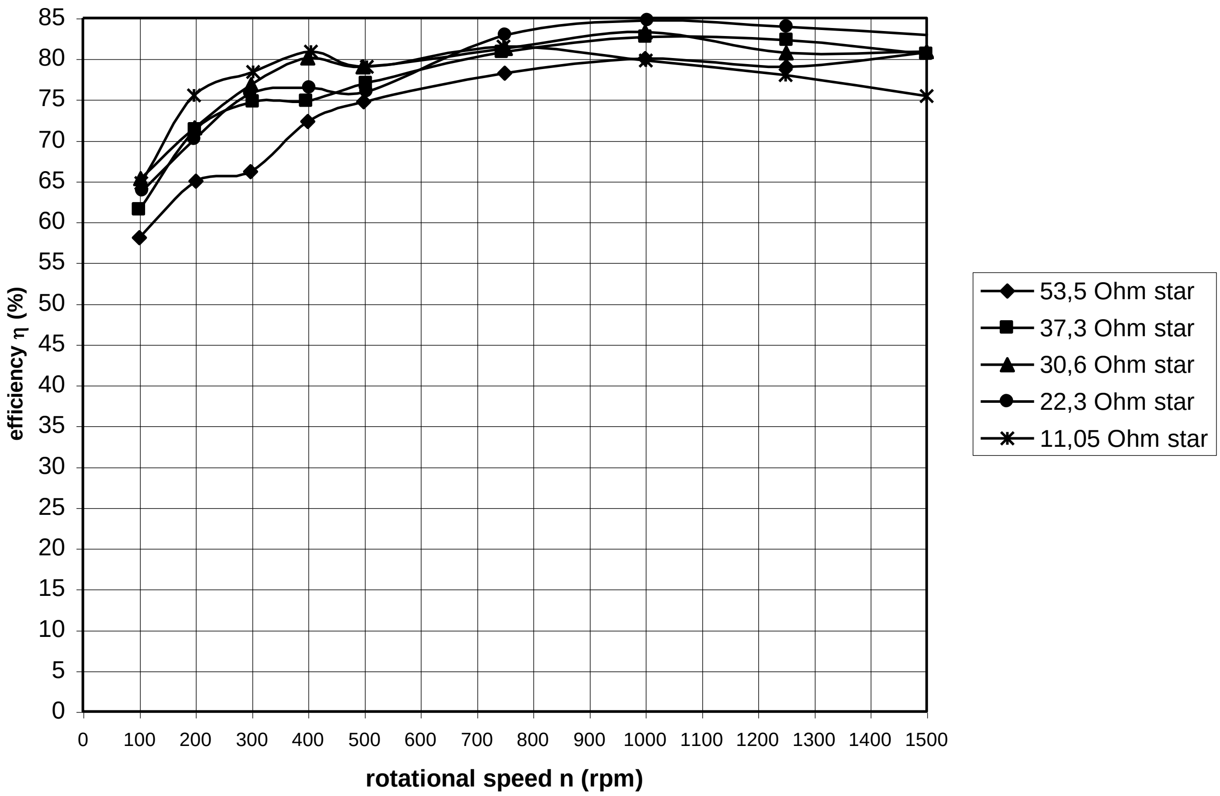

fig. 19 Efficiency as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star

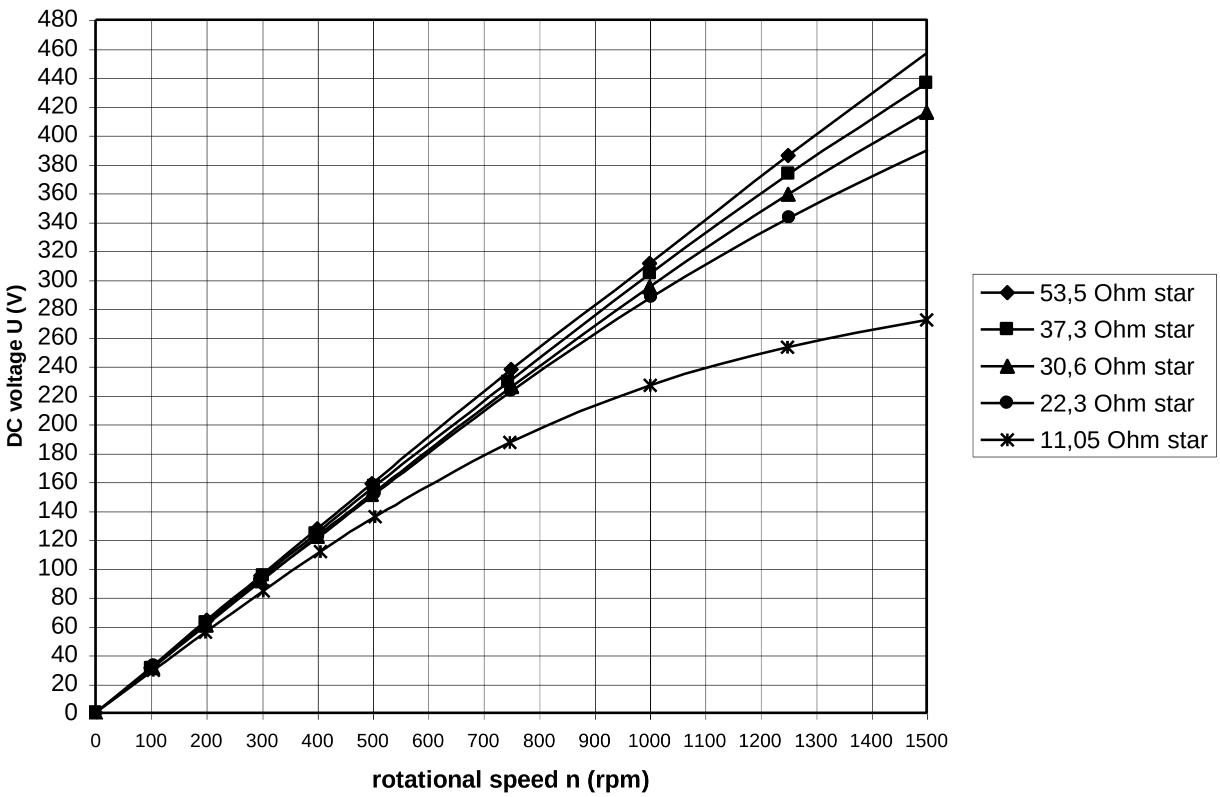

fig. 20 DC voltage as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star

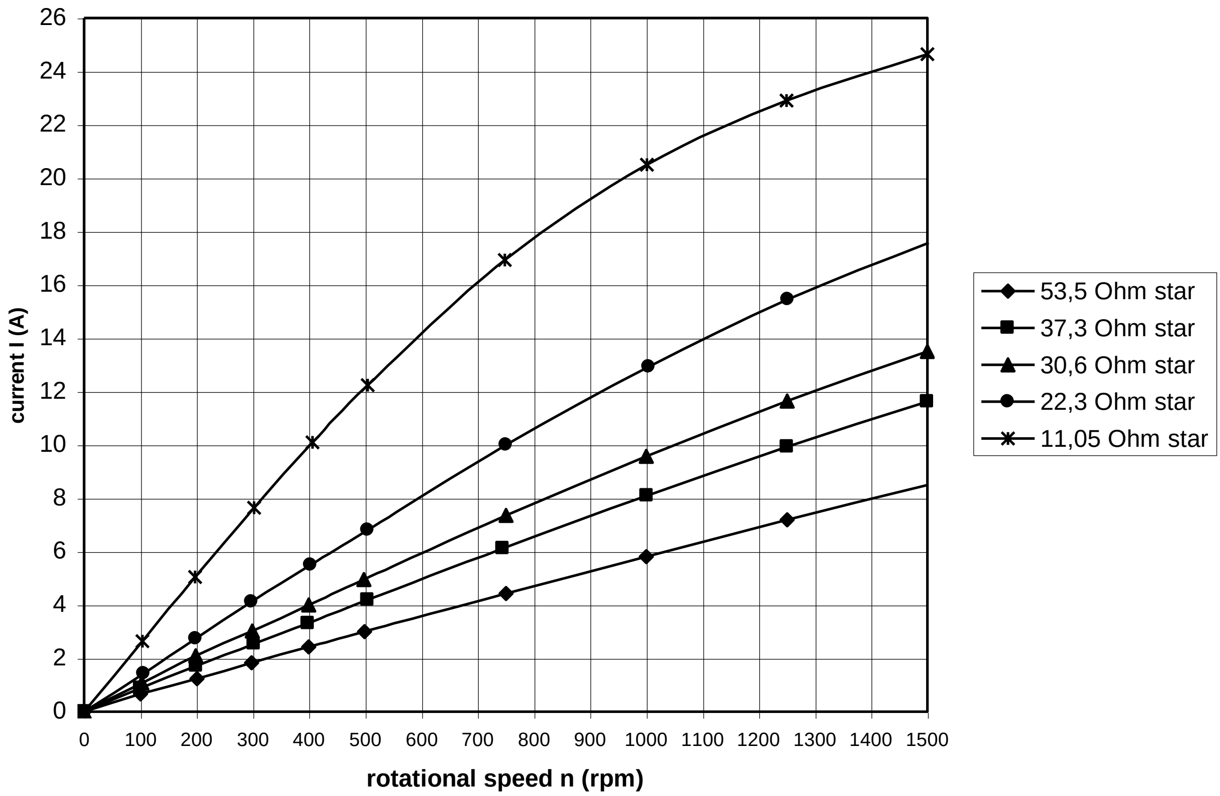

fig. 21 Current as a function of n for R = 53,5 Ω, R = 37,3 Ω, R = 30,6 Ω, R = 22,3 Ω and R = 11,05 Ω in star