Measurements performed on a generator with housing 5RN132M04V with a standard 400/690 V winding provided with a 4-pole armature with neodymium magnets

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Contains page

1 Introduction

The measured generator was originally developed for the former VIRYA-5A windmill. The windmill rotor is mounted directly to the generator shaft. The generator is made from the housing of a standard 4-pole, 3-phase asynchronous motor which is provided with a stainless steel shaft and an armature with neodymium magnets. The following motor was chosen:
Manufacture: Rotor B.V. Eibergen, The Netherlands, type 5RN132M04V (with lengthened stator iron), provided with a standard 400/690 V winding, nominal mechanical motor power 10 kW, mass 78 kg.

The generator of the VIRYA-4.6B2 windmill is derived from the generator of the VIRYA-5A windmill. Only the shaft is shortened. The standard 400/690 V winding can be used for 96 V battery charging if the winding is rectified in star. Rectification of the winding is explained in the free public report KD 340 (ref. 1). The drawing number of the VIRYA-4.6B2 generator is 0501-02/A.

For 48 V battery charging of the VIRYA-4.6B2, the standard 400/690 V winding has to be modified into a 200/345 V winding by connecting the first and second layer in parallel in stead of in series. Modification of the winding is explained in the free public report KD 341 (ref. 2). The generator has not been measured with a modified winding.

The generator was measured in June 2001 and the measuring report was in Dutch and contained hand written graphs. The report was reviewed in February 2005 by adding an English translation but it still contained hand written graphs. Therefore not the whole report was digital and it could not be sent to someone by e-mail. For this new review of May 2015, all graphs are made digital and the Dutch version is removed. A new chapter 7 with estimated characteristics for a voltage of 104 V star is added.

The generator is developed by engineering office Kragten Design.

2 Description of the measurements

The generator has been measured at two different locations. This has the following reason:
In the past KD has used a test rig with air film bearings of the Faculty of Electro Mechanics of the University of Technology Eindhoven for measuring of generators. This test rig has a maximum torque level of 30 Nm. For the VIRYA-5A generator it was expected that the maximum torque level would be about 135 Nm and therefore the test rig with air film bearings would be too small. The UT-Eindhoven has also a test rig with a maximum torque level of 200 Nm but this test rig was occupied till the end of the year. The UT-Eindhoven has also a test rig of which it was said that the maximum torque level would be 70 Nm. The company ROTOR, which supplies the generator housing, has a test rig with a torque level of 240 Nm but this test rig was defect. As we could find no other test rig, it was decided to use the 70 Nm test rig of the UT-Eindhoven because it was expected that a fairly good impression of the generator characteristics could be gained.

The measurement at the UT-Eindhoven were performed at 31-5-2001. However, during the measurements it appeared that the practical maximum torque level was only 35 Nm because the driving motor was switched off by a relay at this torque. This maximum torque is too low to draw conclusions about the behaviour of the generator. Fortunately, the test rig of ROTOR was repaired the day before, so on 1-6-2001 measurements for higher torques were performed at ROTOR in Eibergen. The measurements at the UT-Eindhoven and at ROTOR were both performed by A. Kragten of Kragten Design and by H. Weekhout of ROTOR.

At the UT-Eindhoven it was possible to use heavy adjustable resistors and an accurate DC current meter. The voltage was measured by a digital volt meter of Kragten Design. ROTOR is using their test rig normally only for measuring of motors and therefore they don’t have adjustable resistors and a DC current meter.

For the load resistance, we therefore used the stator winding of different motors with size 132 and 160. As these windings are made of normal copper and not of resistance wire, the resistance increases during a measurement because of warming up.

For measuring if the DC current, a digital DC ammeter was used with a range of 12 A. For higher currents an eddy current meter of Kragten Design with a range of 40 A was used. The eddy current meter is inaccurate at low currents but it was calibrated at 10 A using the digital ammeter. The eddy current ammeter was only used for currents larger that 12 A. The generator was measured for the following configurations:

1. Unloaded, rectified in star and in delta for $0 < n < 519$ rpm. These measurements were performed at the UT-Eindhoven (see chapter 3).
2. Short-circuited before the rectifier in star and in delta for $0 < n < 366$ rpm. These measurements were performed at ROTOR (see chapter 3).
3. Rectified in star for a constant voltage of 52 V. This is the average charging voltage of a 48 V battery. For several values of the resistance, the rpm was adjusted such that the voltage was 52 V. The measurements for high values of the resistance were performed at the UT-Eindhoven. The measurement for low values of the resistance were performed at ROTOR (see chapter 4).
4. Rectified in star for six different constant values of the resistance. The measurements for high values of the resistance were performed at the UT-Eindhoven. The measurements for low values of the resistance were performed at ROTOR (see chapter 5). The unloaded measurements can be seen as measurements for an infinitive high resistance and these measurements are therefore also given in chapter 5.

The following units were measured: The rotational speed n (rpm), the torque Q (Nm), the rectified voltage U (V) and the current I (A). Calculated were: The resistance R (Ω), the mechanical power P_{mech} (W), the electrical power after rectification P_{el} (W) and the efficiency η (%). The measurements were performed for rotational speeds in between 0 and about 360 rpm. The generator was not cooled but after every set of measurements it was waited for about 10 minutes up to the resistance of the generator winding was about identical to the starting value. An exception was made for the measurement for short-circuit. At the beginning of the measuring day at ROTOR some measurements were performed for delta rectification up to n = 179 rpm for a cold generator. The other measurements for short-circuit in delta and for short-circuit in star were performed at the end of the measuring day. After the measurements for short circuit in delta, the generator became so warm that it would take too long to let it cool dawn. The measurements for short circuit in star are therefore performed for a warm generator and the maximum torque level is therefore lower than for a cold generator.

3 Unloaded and short-circuited measurements for star and delta

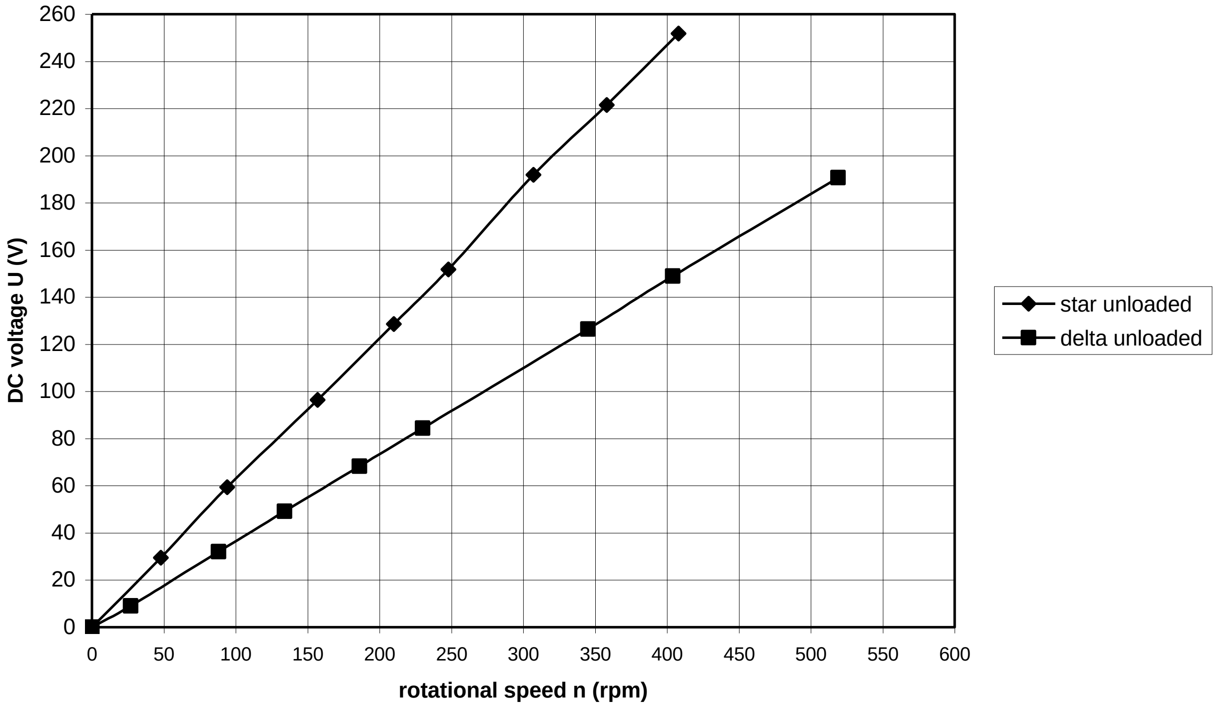

fig. 1 Unloaded DC voltage U as a function of n for star and delta

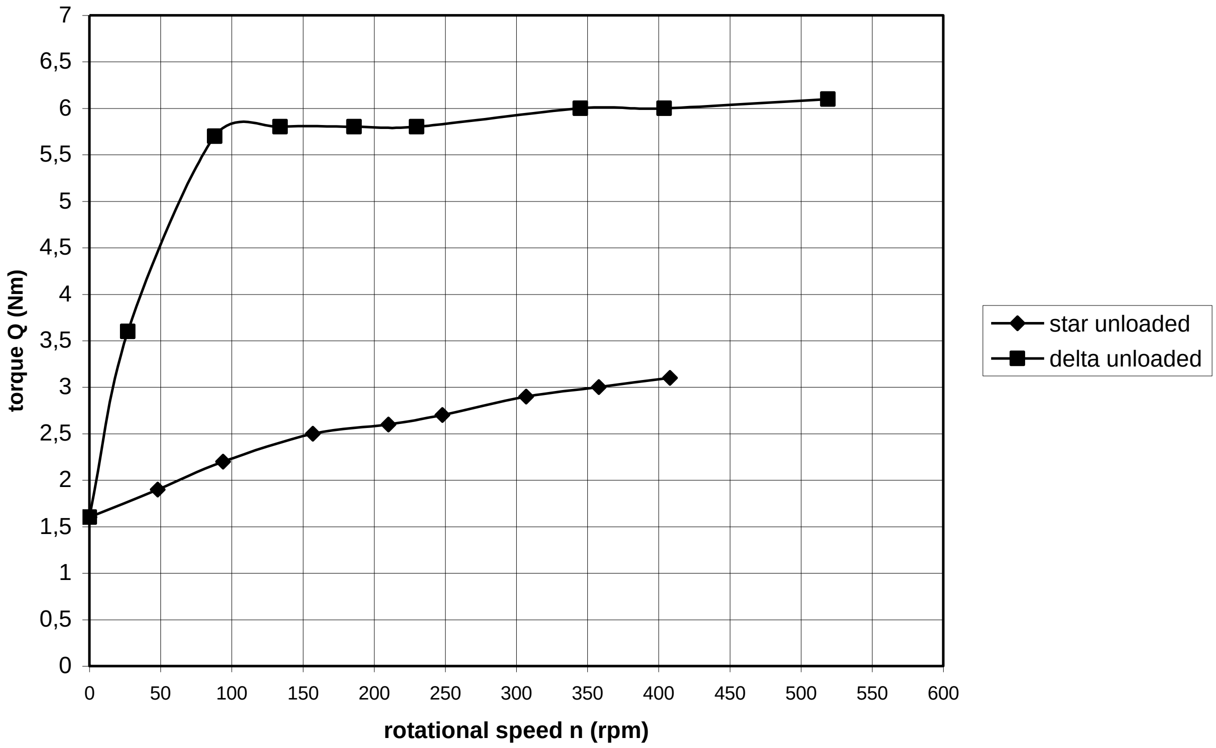

fig. 2 Unloaded torque Q as a function of n for star and delta

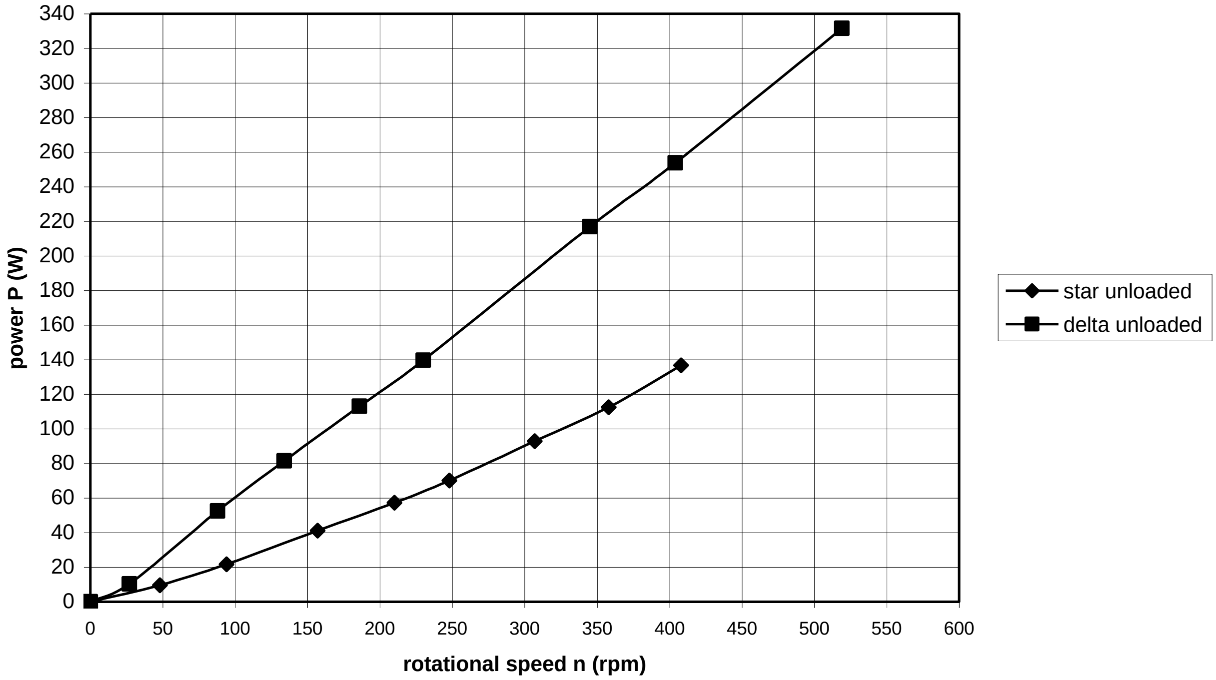

fig. 3 Unloaded power P as a function of n for star and delta

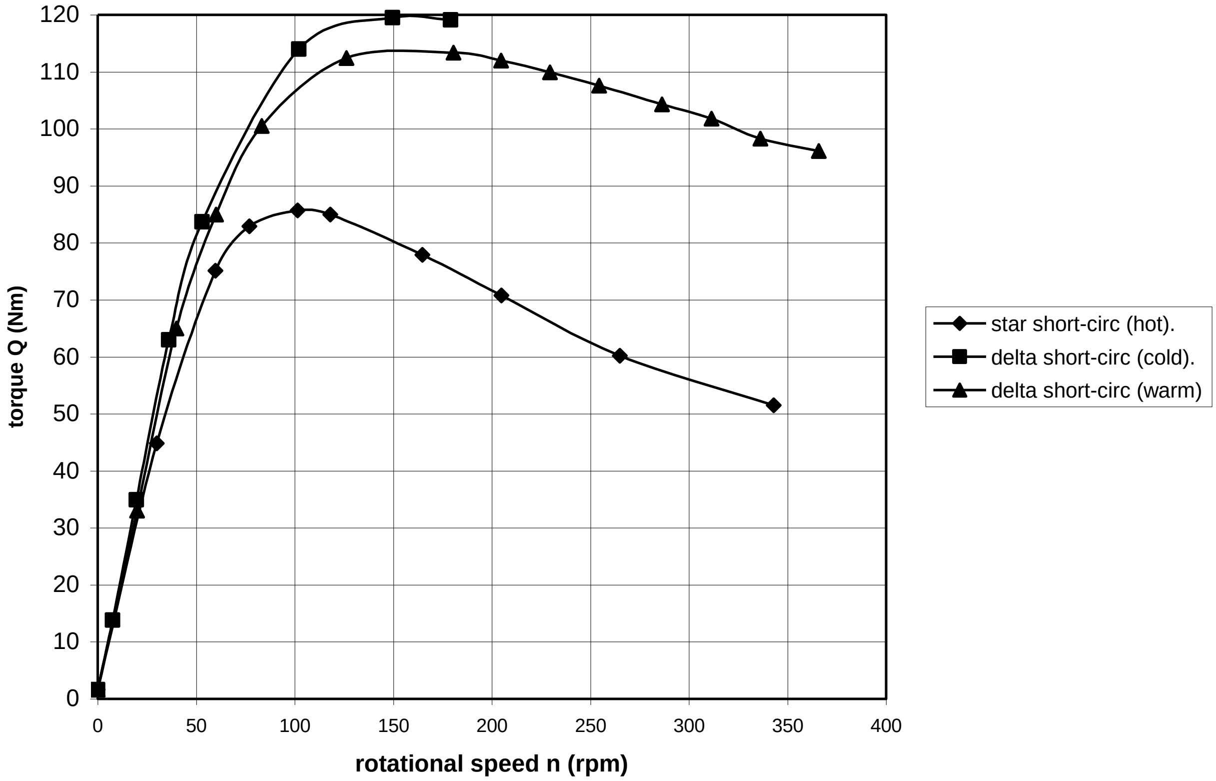

fig. 4 Torque Q for short circuit in star and delta as a function of n

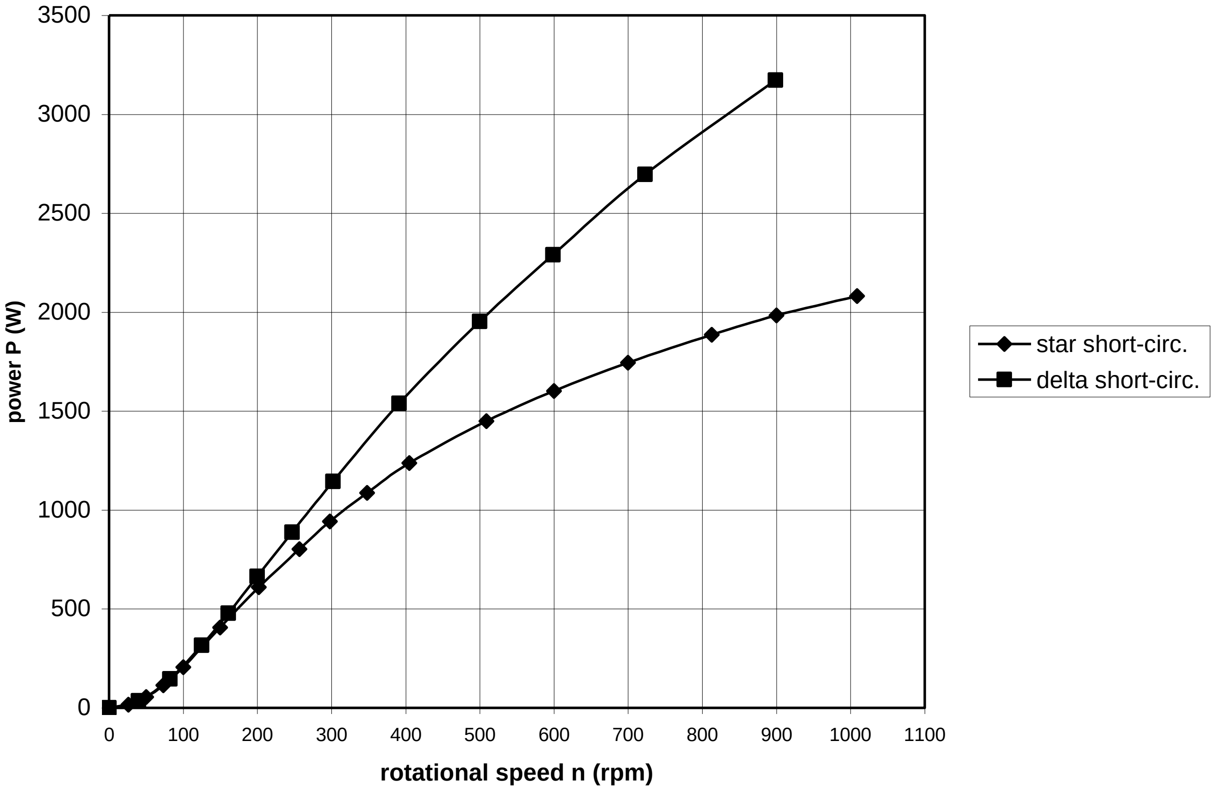

fig. 5 Power P for short circuit in star and delta as a function of n

4 Measurements for 52 V star

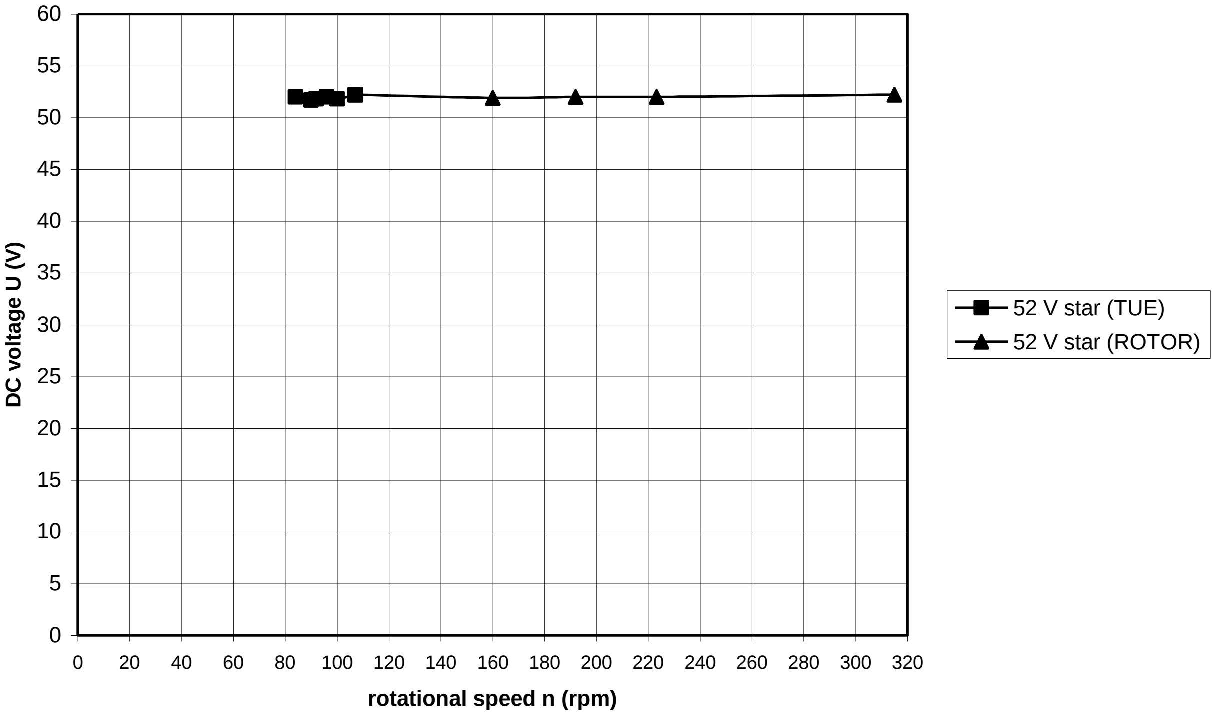

fig. 6 DC voltage U as a function of n for U = 52 V star

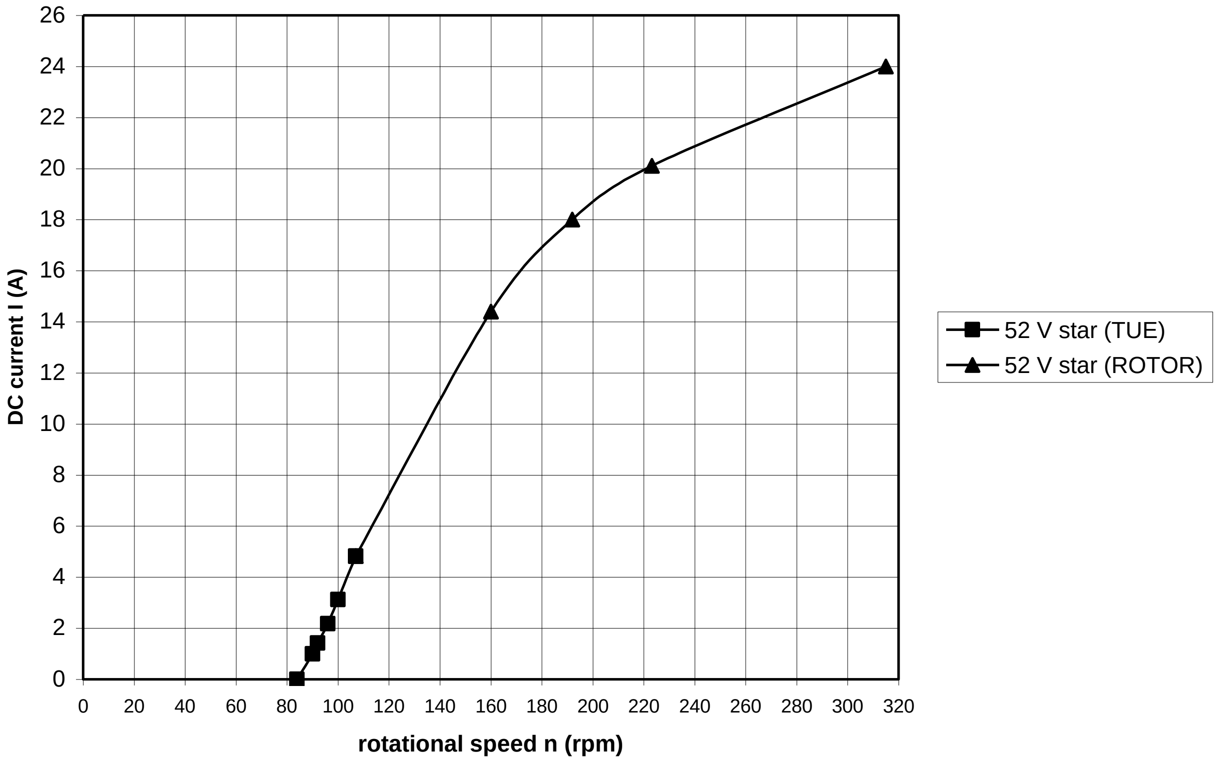

fig. 7 DC current I as a function of n for U = 52 V star

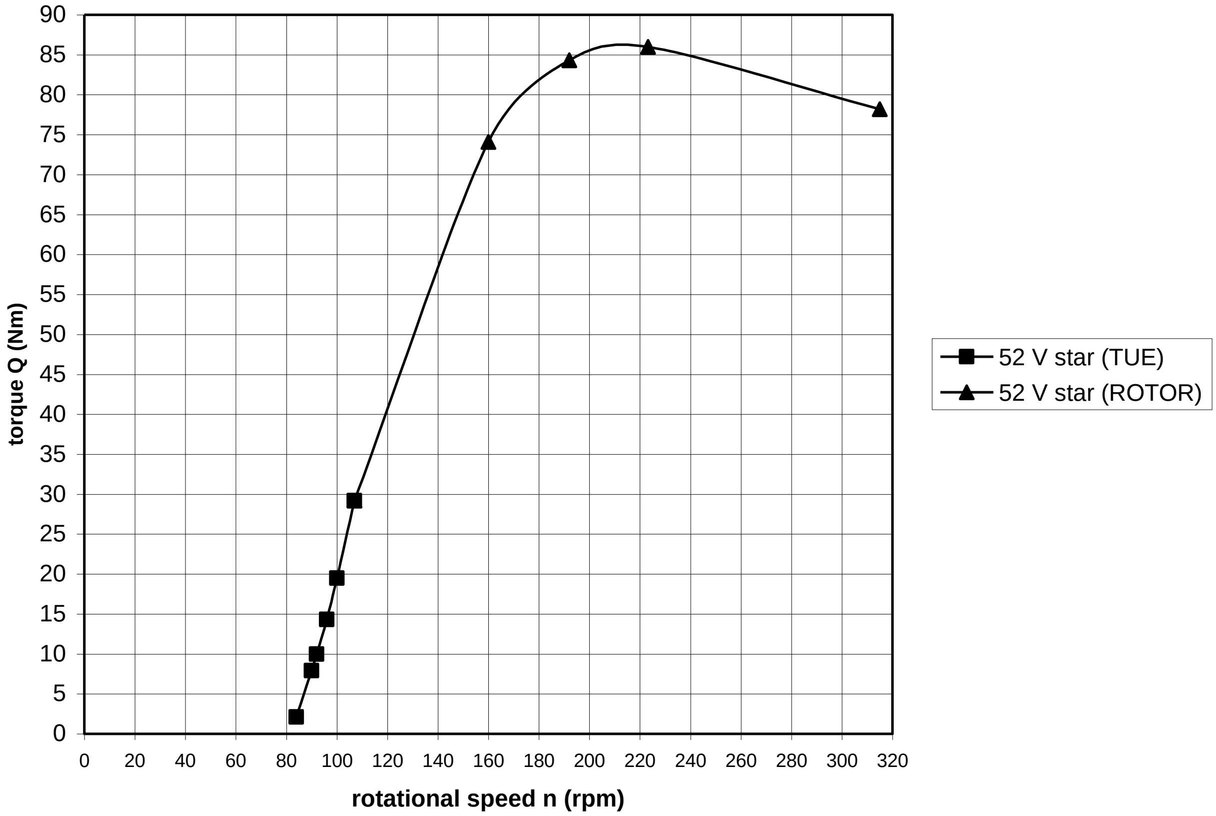

fig. 8 Torque Q as a function of n for U = 52 V star

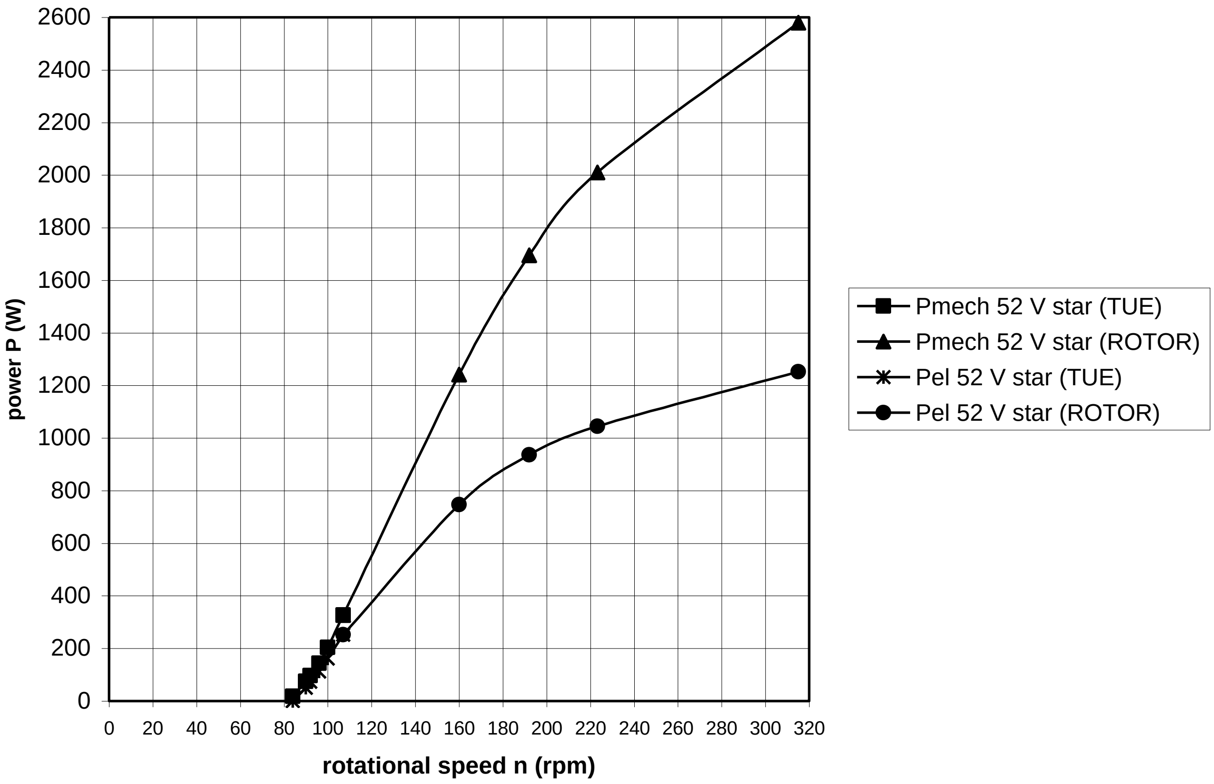

fig. 9 Mechanical power P_{mech} and electrical power P_{el} as a function of n for U = 52 V star

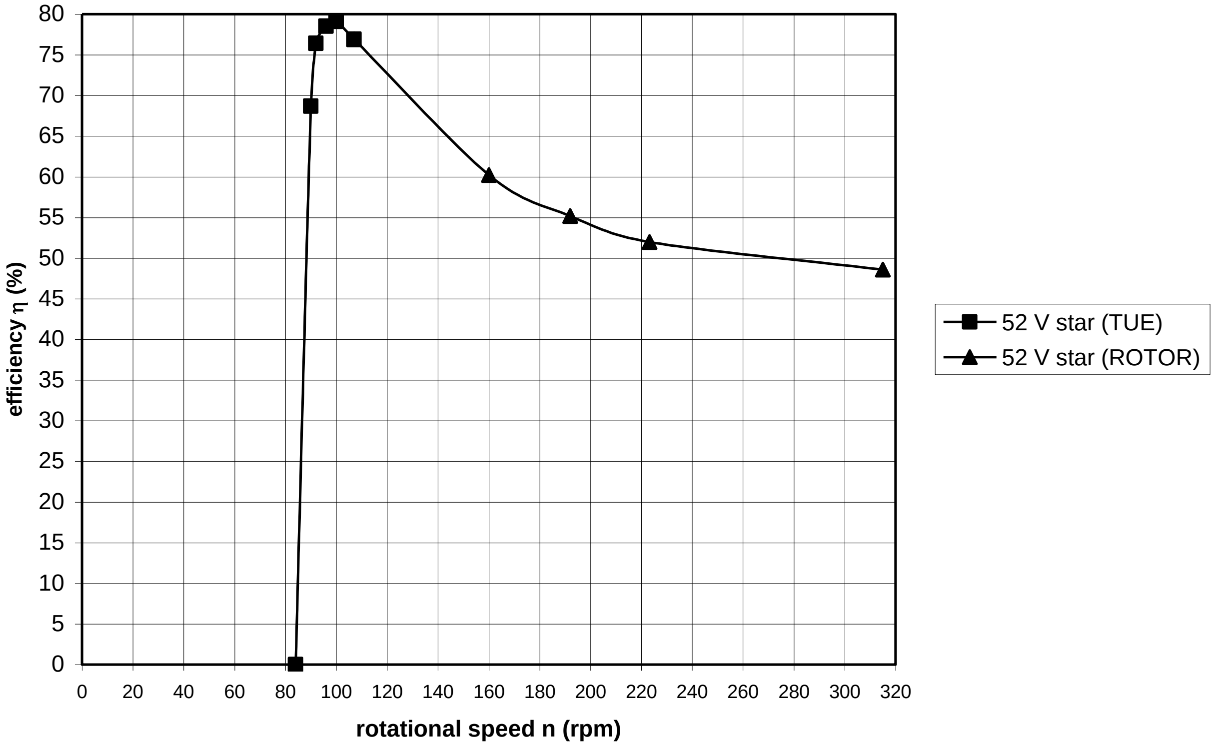

fig. 10 Efficiency η as a function of n for U = 52 V star

5 Measurements for different resistances in star

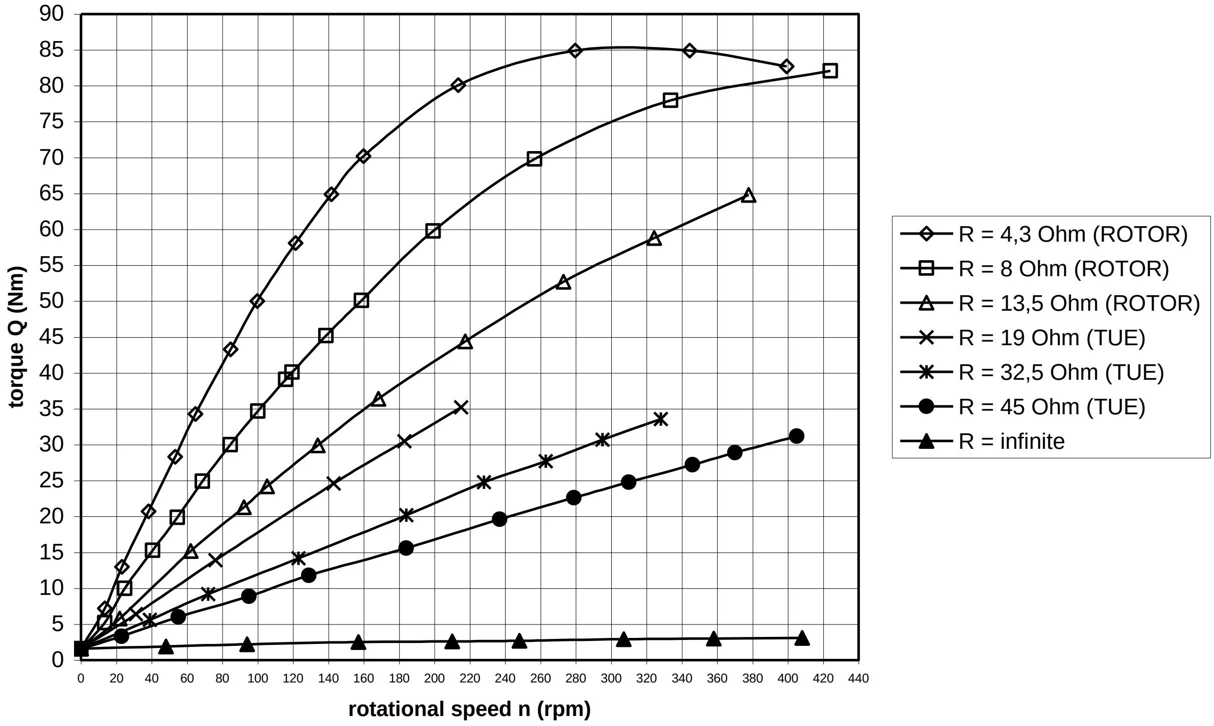

fig. 11 Torque Q as a function of n for different values of R

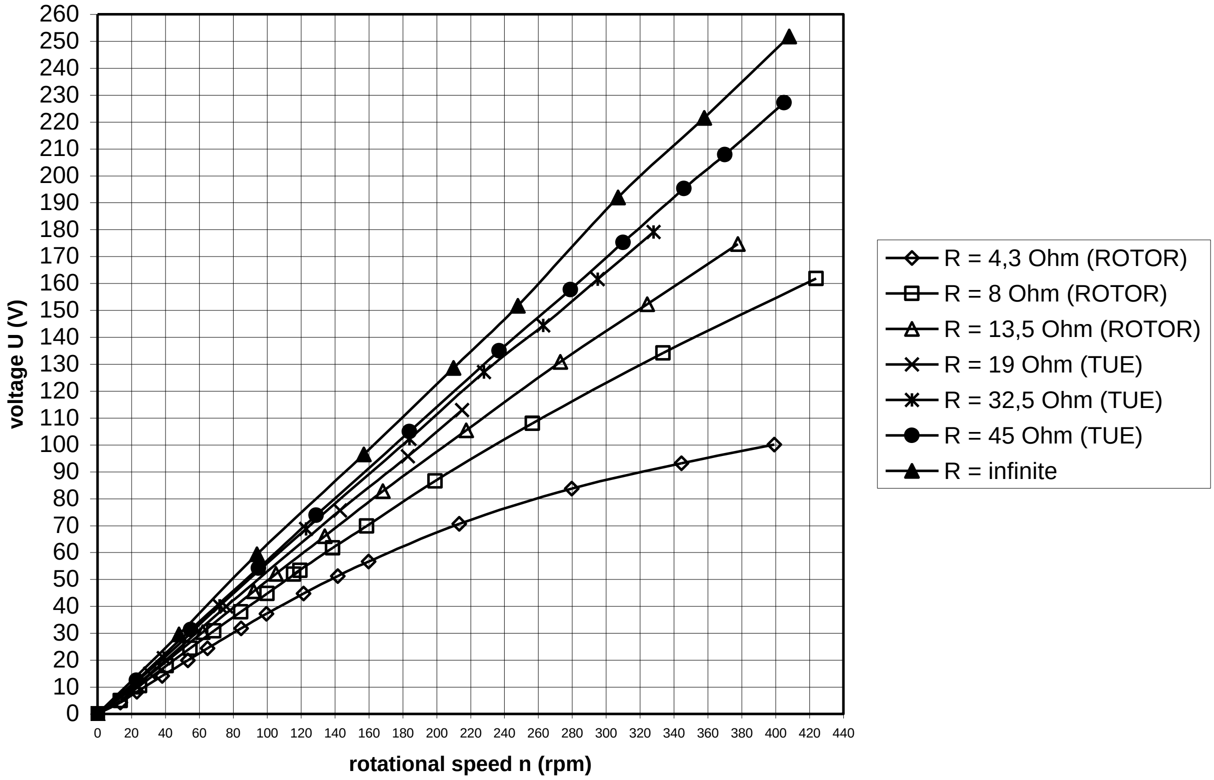

fig. 12 Voltage U as a function of n for different values of R

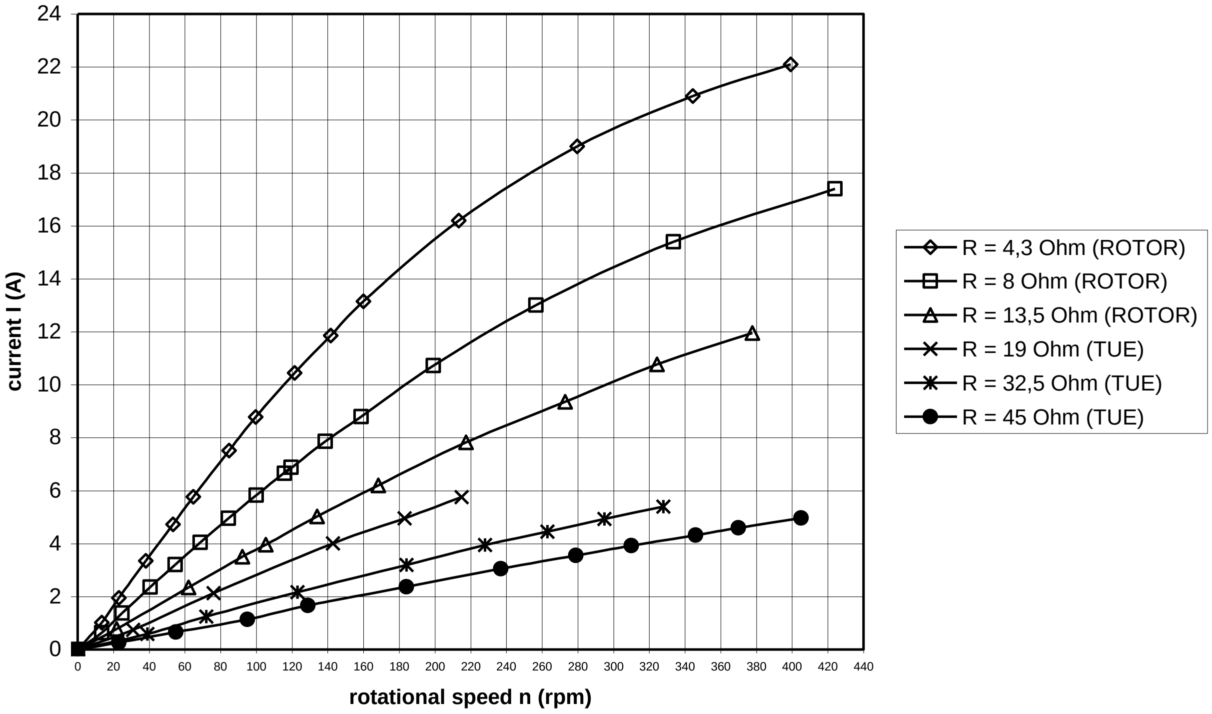

fig. 13 Current I as a function of n for different values of R

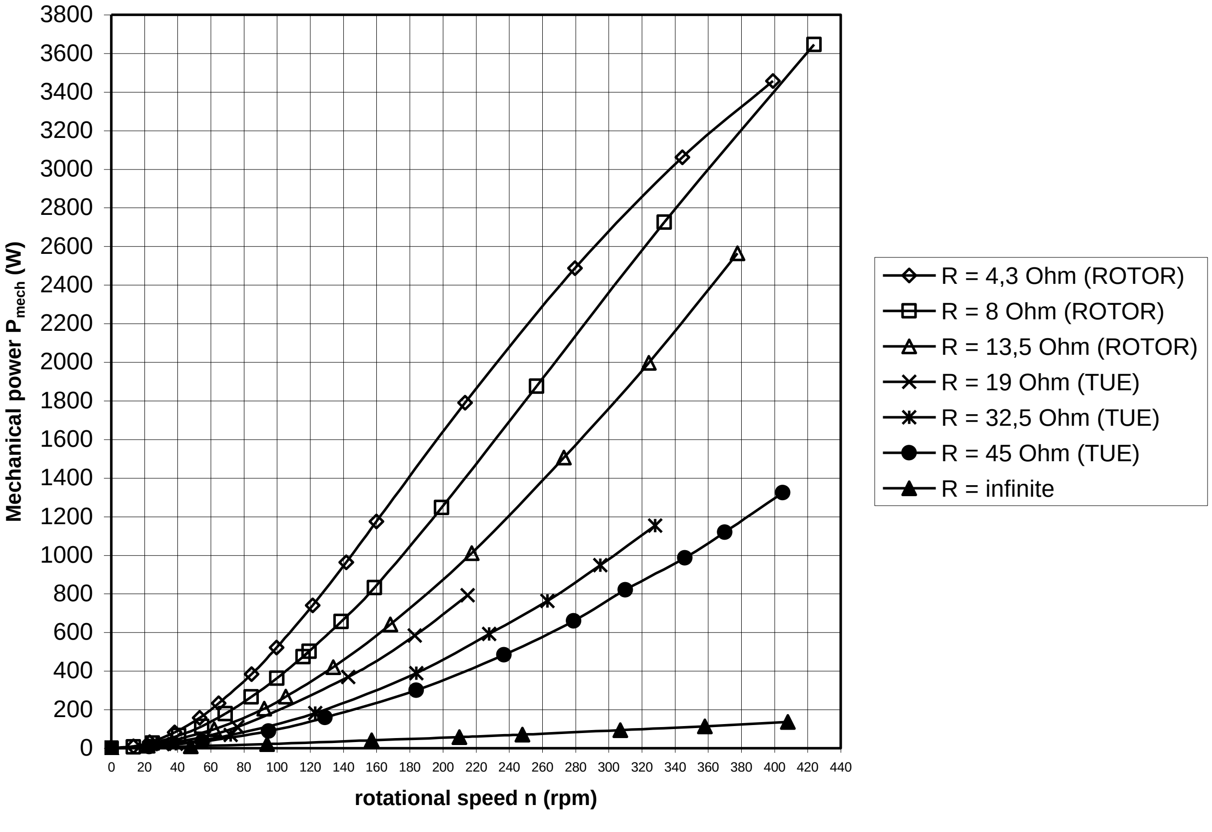

fig. 14 Mechanical power P_{mech} as a function of n for different values of R

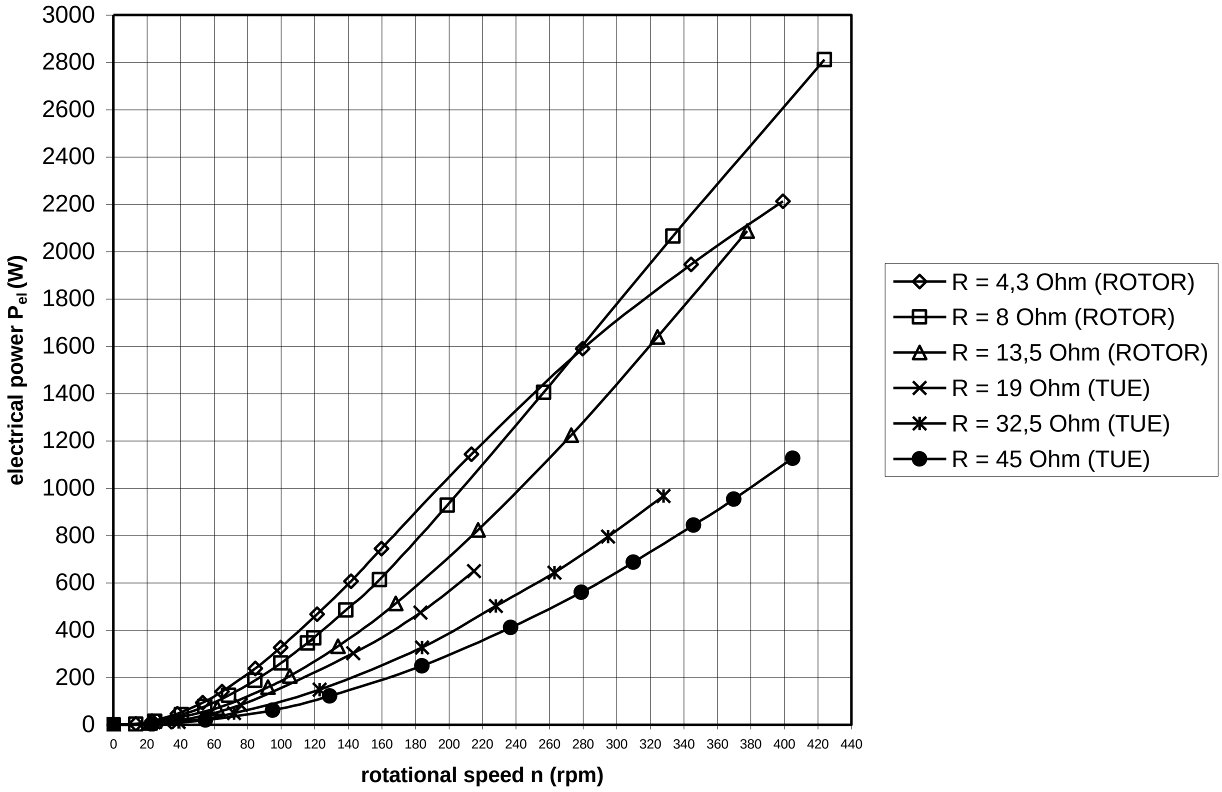

fig. 15 Electrical power P_{el} as a function of n for different values of R

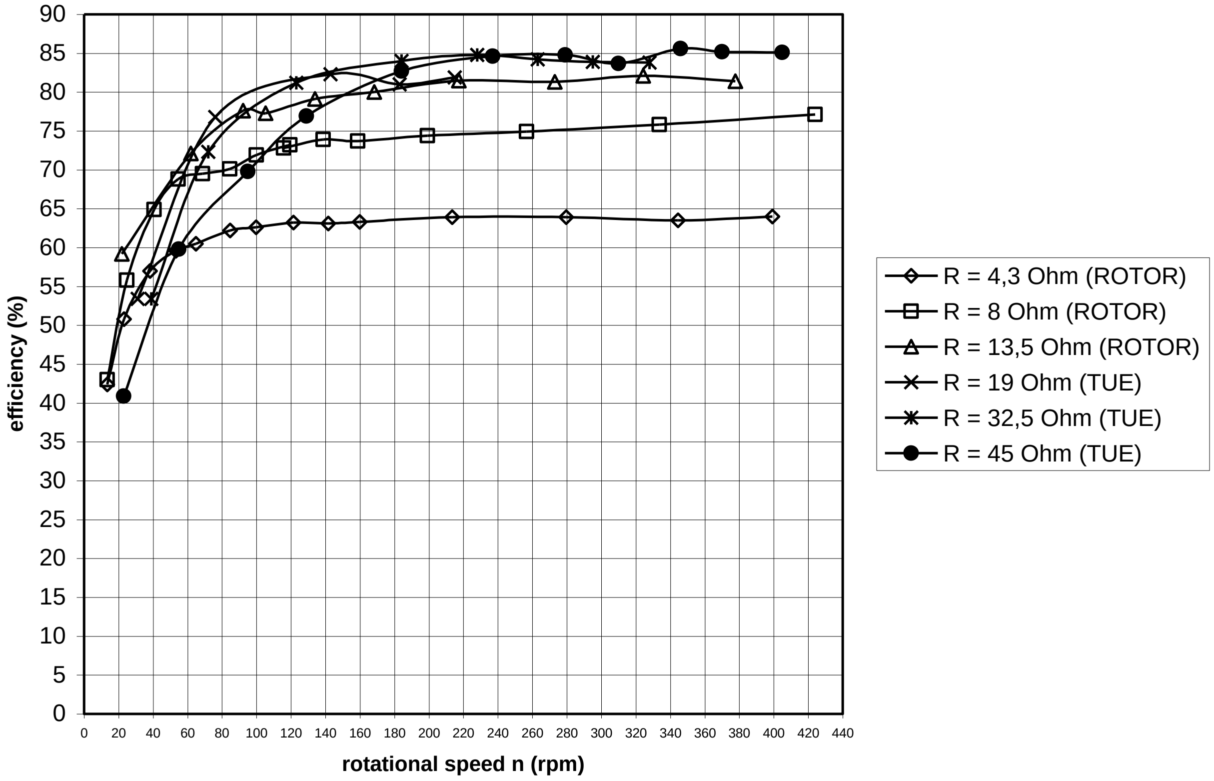

fig. 16 Efficiency η as a function of n for different values of R

6 Discussion about the results

The unloaded U-n curves are straight lines through the origin (see figure 1). The open voltage in star is about a factor √3 higher than the open voltage in star which matches with the theory given in report KD 340 (ref. 1). 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 torque level for short circuit in delta is lying a lot higher than for short-circuit in star and the torque is decreasing less for higher rotational speeds (see figure 4). Warming up of the generator winding results in decrease of the maximum torque level. This is caused by increase of the resistance of the stator winding but it might also be caused by a temporary decrease of flux density of the permanent magnets due to the warming up. There was not enough time available for cooling down of the generator in between the short circuit measurement for delta and star. The maximum torque level for short-circuit in star for a cold generator will be about 95 Nm.

Because the generator is used as a brake by making short-circuit of the winding, the torque level must be as high as possible because slowing down is then possible for a high wind speed. Therefore, the generator has to be short-circuited in delta before the rectifier. However, the generator is rectified in star and therefore it is necessary to short-circuit the star point too. This gives the same short-circuit curve as for short-circuit in delta.

In figures 6 - 10 it can be seen that the measurements which haven been performed on the UT-Eindhoven and at ROTOR match very well together. The maximum torque level for 52 V star is 86 Nm which is about the same as the maximum torque level for short-circuit in star (see figure 4 and 8). Although the torque decreases above n = 230 rpm, the current is still increasing rather strongly (see figure 7).

In figure 10 it can be seen that for 52 V, a maximum efficiency is realised of 79 % for a rotational speed of 100 rpm. This is very good. However, at higher rotational speeds, the efficiency is decreasing rather fast because of heat dissipation in the winding. The efficiency is larger than 70 % for 90 < n < 128 rpm. For rotational speeds lower than 86 rpm, the efficiency is zero because the open voltage of 52 V is not yet reached.

In figure 11 it can be seen that the torque Q increases for low rotational speeds, about linear with the rotational speed for all values of the resistance. For the higher values of the resistance this is also the case for higher rotational speeds. However, for low values of the resistance and specially for R = 4.3 Ω, the torque increases no longer linear and it has the same maximum value of about 86 Nm. In figure 12 it can be seen that the voltage U increases about linear with the rotational speed for high values of the resistance. For low values of the resistance and especially for R = 4.3 Ω, the voltage increases less than linear. In figure 13 it can be seen that the current I increases about linear with the rotational speed for high values of the resistance. For low values of the resistance and especially for R = 4.3 Ω, the current increases less than linear.

In figure 14 it can be seen that the mechanical power P_{mech} increases about quadratic with the rotational speed for high values of the resistance. For low values of the resistance and especially for R = 4.3 Ω, the mechanical power increases less than quadratic. In figure 15 it can be seen that the electrical power P_{el} increases about quadratic with the rotational speed for high values of the resistance. For a value of the resistance of R = 8 Ω, the increase is about linear for higher rotational speeds. For a value of the resistance of R = 4.3 Ω, the P_{el}-n curve bends downwards and for higher rotational speeds the current becomes even lower than for R = 8 Ω. In figure16 it can be seen that for the higher values of the resistance, maximum efficiencies of 85 % can be realised which is very good. Even for a rather low value of R = 8 Ω, the efficiency at higher rotational speeds is still about 75 %. A resistance of R = 4.3 Ω gives a maximum efficiency of about 64 %.

7 Deriving the characteristics for 104 V star

The generator has been measured in star for a constant voltage of 52 V which is the average charging voltage of a 48 V battery. The measured generator has a standard 400/690 V winding. However, the P_{mech}-n curve for 52 V star is lying too much to the left for good matching with the VIRYA-4.6B2 rotor. Thereby, the generator efficiency is rather low for 52 V and high powers (see figure 10). It is expected that the matching is better for a voltage which is a factor 2 higher, so for 104 V star. It can also be expected that the efficiency is higher and therefore the electrical power will be higher and the generator will become not too hot at high powers. Fortunately the generator has also been measured in star for different rotational speeds and for several values of a resistor as load. From these measurements, the P_{mech}-n and P_{el}-n curves for 104 V star can be derived.

A voltage of 104 V is the average charging voltage of a 96 V battery. If the windmill is used for 48 V battery charging, the winding has to be modified. This can be done by lying the first and second layer in parallel in stead of in series. The original 400/690 V winding now is transferred into a 200/345 V winding. The characteristics of a 200/345 V winding for 52 V star will be identical to those of a standard 400/690 V winding for 104 V star. The modification procedure is described in report KD 341 (ref. 2).

The derivation of the characteristics for 104 V star from the measurements for constant resistance’s goes as follows. The generator has been measured in star for six different values of the load resistance R being R = 45, 32.5, 19, 13.5, 8 and 4.3 Ω. The characteristics for these measurements are given in figures 11 up to till 16. The generator has also been measured unloaded which means that the resistance of the load is infinitive ($R = \infty$ Ω). These measurements are given in figures 1 up to 3.

In figure 1 it can be read that n = 168 rpm for U = 104 V star. In figure 2 it can be read for star that Q = 2.5 Nm for n = 168 rpm. In figure 4 it can be read for star that P_{mech} = 44 W for n = 168 rpm. P_{el} = 0 W and $\eta = 0$ because the generator was measured unloaded. These values are given in the first line of table 1.

Figure 12 gives the voltage U as a function of n for the six values of R. In this figure a horizontal line is drawn for U = 104 V. The points of intersection of this line with the line of a constant resistance gives the rpm for the resistance and 104 V. No point of intersection is found for R = 4.3 Ω. The rpm found this way is also given in table 1.

Next the corresponding values of Q, P_{mech}, P_{el} and η as a function of n and R are read from figures 11, 14, 15 and 16. These values are also given in table 1.
Using table 1, the Q-n curve is determined for U = 104 V. This curve is plotted as figure 17.
Using table 1, the η-n curve is determined for U = 104 V. This curve is plotted as figure 18.
Using table 1, the P_{mech}-n and the P_{el}-n curves are determined for U = 104 V. These curves are plotted as figure 19.

The highest value of P_{mech} which is found this way is P_{mech} = 1780 W for n = 247 rpm. Because the VIRYA-4.6B2 rotor is able to supply more power, it would be nice to have also values of P_{mech} and P_{el} for somewhat higher values of n like for instance n = 260 rpm, n = 280 rpm, n = 300 rpm and n = 320 rpm. It appears from other measurements that the Q-n curves for different voltages all have about the same shape but are shifted horizontally with respect to each other. The top of the Q-n curve for 52 V star is therefore shifted to the right so far till it coincides with the part of the Q-n curve which was already found for low rpm and for 104 V. The torque Q found this way for n = 260 rpm, n = 280 rpm, n = 300 rpm and n = 320 rpm is also given in figure 17. The efficiencies for higher rotational speeds are estimated and the η-n curve given in figure 18 is also lengthened up to 320 rpm. The values for η for higher rotational speeds are read from this figure and are given in table 1. Using this estimated value for η and P_{mech}, P_{el} can be determined. The P_{mech}-n and P_{el}-n curves found this way are plotted in figure 19.

R (Ω)	n (rpm)	Q (Nm)	P_{mech} (W)	P_{el} (W)	η (%)
∞	168	2.5	44	0	0
45	182	15.5	295	247	83.7
32.5	187	20.7	405	340	84.0
19	199	32.5	677	565	83.5
13.5	214	43.8	982	810	82.5
8	247	68	1759	1331	75.7
	260	75.5	2056	1501	73
	280	82.5	2419	1717	71
	300	85	2670	1848	69.2
	320	86	2882	1960	68

table 1 Calculated values for U = 104 V and a generator with a 400/690 V winding

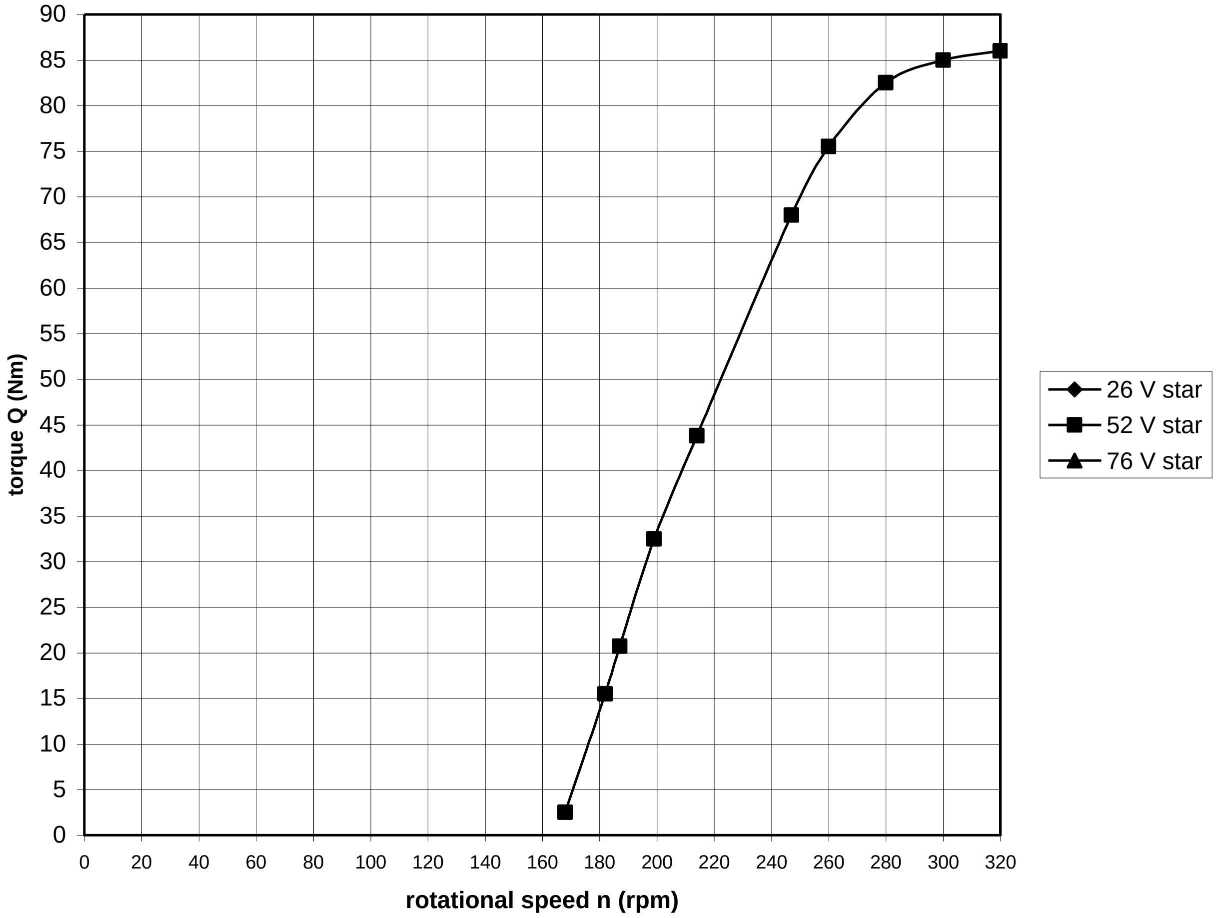

fig. 17 Torque Q as a function of n for U = 104 V star

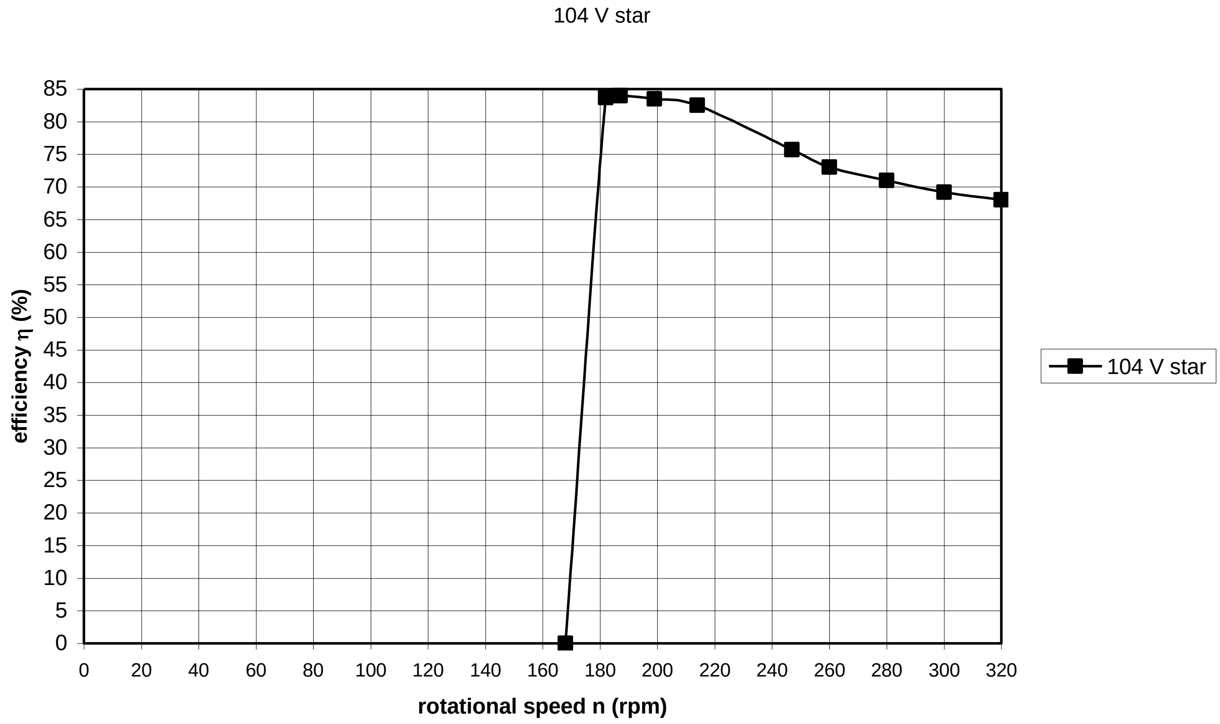

fig. 18 Efficiency η as a function of n for 104 V star

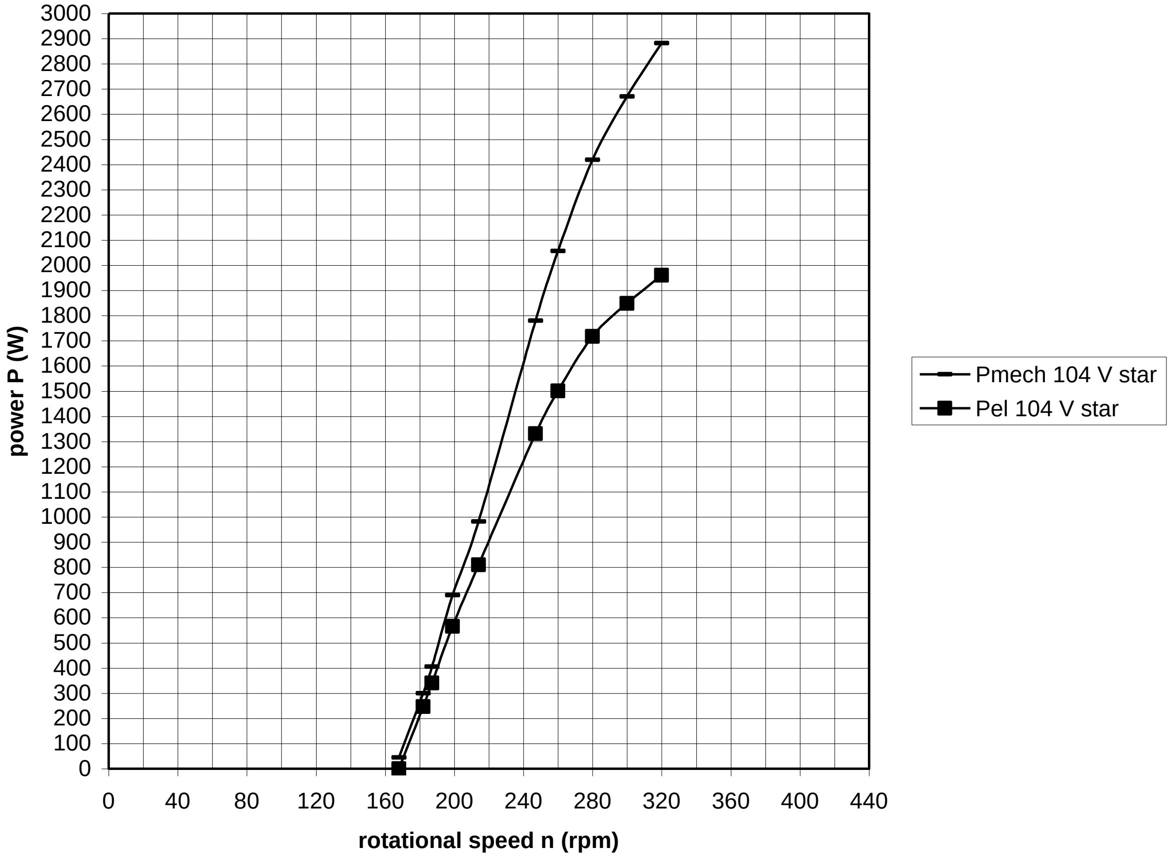

fig. 19 P_{mech}-n and P_{el}-n curves for 104 V star

8 References

1 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.

2 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.