

Performance of two permanent magnet generators  
For use with small windchargers

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## Summary

- ™ The non-governmental organisation CESADE (Centro de Estudios y Acción para el Desarrollo) in Nicaragua is determined to provide affordable electricity for the low income group. With AMEC (Aerobombas de Mecate) it has developed a small windcharger for charging 12 V batteries. One of the bottlenecks is the lack of a small (approximately 100W) generator that is affordable (approximately US\$ 50) and reliable.
- ™ Results of the tests on two small DC permanent magnet generators that may be suitable are described: a Bosch generator and an Omni Instruments generator.
- ™ The rotational speed of the Omni Instruments generator has to be over 5500 RPM to reach an output voltage of 12V. Therefore the generator is not suitable to charge a 12 V battery with the AMEC windrotor, in an unmodified state.
- ™ Without modifications, the Bosch generator is capable of charging a 12 V battery, starting at rotational speeds of approximately 900 RPM. At approximate 2200 RPM the generator can deliver 50 W which is more or less the maximum power that can be generated without overheating when charging a battery, because of the small diameter of the wires. The maximum efficiency that can be reached with this generator is approximately 65% at rotational speeds of over 3500 RPM.
- ™ A generator model has been developed which may be used with permanent magnet DC generators in general. Using the model, generator performance can be determined with a minimum of measurements. The model is also useful for matching the generator with the windrotor.

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## 1. Introduction

The non-governmental organisation CESADE (Centro de Estudios y Acción para el Desarrollo) from Nicaragua is determined to provide affordable electricity for the low income group. Existing 50 Wp solar home systems (SHS) cost about US\$ 600 in Nicaragua. It is felt that there is a market for small windchargers when they are cost effective, compared to SHS's. The cheapest commercial small windcharger that is available costs US\$ 700. Therefore two prototype windchargers have been developed locally by AMEC (Aerobombas de Mecate) with assistance from Mr. Henk Holtslag of CESADE. Tests indicate that design and performance are promising [1]. However, a bottleneck is the availability of a small generator and therefore CESADE, through Mr. Henk Holtslag, has asked *Renewable Energy Development vof* (RED) to test two small DC permanent magnet generators that may be used with the AMEC windcharger. The results of the tests are described in this report. Only a technical analysis is given here. A financial comparison between a small wind charging system and a SHS is given in [1].

The figure below shows a picture of the type of the AMEC windcharger that is meant to be used with the generator. The generator is mounted at the bottom of the round rim. The rotor diameter is approximately 2 m. A detailed technical description of the system is given in [1].



(Photo: Remi Rijs)

## 2. Description of the generators

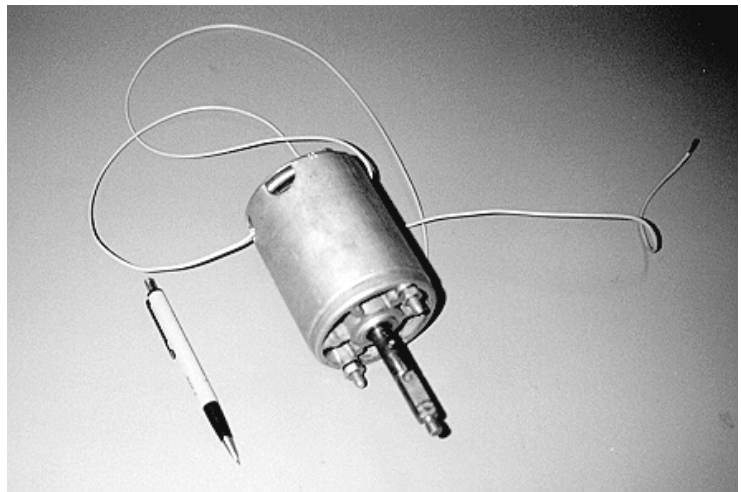
The design philosophy of AMEC is not to develop a windcharger that has a maximum energy efficiency but a machine which is cheap (competitive to SHS's) and suitable for local production. For the generator this leads to the following criteria:

- ™ maximum power output of approximately 100 W,
- ™ capable of charging a 12 V battery at a maximum rotational speed of 1500-2000 RPM (depending on the type of transmission that is used),
- ™ sealed construction,
- ™ low maintenance and a long life,
- ™ cost of approximately \$US 50.-.

It is difficult –if not impossible- to buy a generator off the shelf that has the above characteristics. Two generators were identified by CESADE that might be suitable: a Bosch and an Omni Instrument generator.

### 2.1 Bosch generator

The generator is manufactured by American Bosch and has the specification: 8(?)078524M030MM. 41080 110V CCW. The nominal voltage is 110 V DC at 10.000 RPM. It has two permanent magnets in the stator and 16 poles in the rotor. The diameter of the coil wires is 0.3 mm. The diameter of the shaft is 12 mm with on one side a ball bearing and on the other side a brass bush. It has a commutator with brushes.



### 2.2 Omni Instruments generator

The figure shows the dismantled Omni Instruments generator with the rotor on the right and the stator housing with the magnets at the back. Originally the generator has been designed for driving an electric bicycle but no further information is available from the manufacturer (Omni Instruments USA, 133 Novak Drive Petaluma, California). It is a 12 VDC permanent magnet type with 16 poles in the rotor and 4 permanent magnets in the stator.

(Photo: Remi Rijs)



The generator has a commutator with brushes. The shaft diameter of the generator is 8.0 mm and the copper wire in the coil has a diameter of 0.7 mm. There is a combination numbers and letters is printed on the casing: SHI(?)I(?)T2B, 30/97DE, 6002626, 12V.

### 3. Generator performance

#### 3.1 Optimisation of the generator

In its simplest form, a generator is a coil of wire, passing through a magnetic field. By the process an alternating voltage is induced, of which its magnitude depends on the length of the coil, the number of turns in the coil, the flux density of the magnetic field and how rapidly the coil passes through the magnetic field (the effective rate of change of the magnetic field flux through the coil). Two different methods are used to change alternating current (AC) into direct current (DC): by using a commutator and brushes (in a DC generator), and using diodes (in an alternator).

To be able to charge a car battery, the DC voltage generated should be higher than the sum of the battery voltage and the voltage drop over the blocking diode, in case of a generator. If a generator does not satisfy this condition at rotational speeds that can be provided by a windmill, it can be modified. In redesigning the generator for higher voltage output, there are a number of parameters that should be taken into consideration [8]. These include:

- ™ the number of poles,
- ™ the magnetic flux density of the field,
- ™ the number of turns in the coils,
- ™ the maximum current through the commutator and the resistance of the wire,
- ™ the space available in the armature for the coils.

Since it is not easy to change either the number of poles or the magnetic flux density of the field of an existing generator, attention is given to the remaining points.

#### 3.2 Losses

There are several reasons why the efficiency of a generator is lower than 100%. These include: electrical losses:

- ™ heat generated in the coils ( $I^2R$  losses),
- ™ hysteresis losses in the iron of the armature,
- ™ eddy current losses,
- ™ voltage drop over the commutator (brushes and the commutator segments),

and mechanical losses:

- ™ pressure of the brushes on the commutator causes friction,
- ™ friction in the bearings.

The voltage induced in a coil of wire passing through a magnetic field is proportional to the number of turns in the coil. However, increasing the number of turns is limited by the available space. With a given space, decreasing the diameter of the wire can increase the number of turns. This will also increase the resistance of the wire. Apart from the  $I^2R$  losses in the coil, not much can be done about the mentioned losses in an existing generator. The generator voltage is proportional to the number of turns of the coil, whereas the maximum generator current is inversely proportional to the number of turns, given a fixed space available. Therefore the generator resistance is proportional to the number of turns squared and as a result the  $I^2R$  losses in the coil will not change at a given power. However,  $I^2R$  losses in the wires between the generator and the battery will increase with increasing current.

There is a trade-off between the rotational speed, voltage, current and efficiency of the generator. The characteristics of the generator (and also of the windmill and battery) and the relationship between the parameters have to be known to be able to optimise a generator for use in a windcharger. In the following paragraph some theory is given, followed by a discussion on how the generator characteristics have been obtained and what the results of the measurements are.

## 4. Theory

### 4.1 Permanent magnet DC generator model

The generator can be considered as an ideal generator with an internal resistance in series as illustrated in the figure. The torque  $T$  and rotational speed  $\omega$  are input parameters. The current  $I$  and the voltage  $U$  are output parameters. The external resistance is noted as  $R_u$

According to Faraday, the generated voltage is a linear function of the rotational speed (1) and according to Lorentz, the generated torque is proportional to the current (2):

$$U_g := \phi_m \cdot \omega \quad (1)$$

$$T_g := \phi_m \cdot I \quad (2)$$

In which  $\phi_m$  is a constant which is proportional to the magnetic flux ( $\phi_m$  in Vs or Wb).

The voltage  $U$  that is supplied at the generator clamps is equal to the voltage generated minus the voltage drop over the internal resistance, which is also equal to the generated current times external resistance:

$$U := \phi_m \cdot \omega - I \cdot R_i \quad \text{and also:} \quad U := I \cdot R_u \quad (3)$$

The torque required to drive the generator is equal to  $T_g$  plus the torque required to overcome losses ( $T_0$ ).

$$T := T_g + T_0 \quad \text{substituting } T_g: \quad T := \phi_m \cdot I + T_0 \quad (4)$$

The efficiency is defined as the ratio of electric power generated and mechanical power required:

$$\eta := \frac{P_{el}}{P_{mec}} \quad \eta := \frac{U \cdot I}{(T_g + T_0) \cdot \omega} \quad (5)$$

The losses  $L$  can be calculated as the sum of the power due to the lost torque and heat generated due to the internal resistance of the generator:

$$L := T_0 \cdot \omega + I^2 \cdot R_i \quad (6)$$

### 4.2 Refinement of the model

The model previously described has been verified with the measurements of the Bosch generator. It was found necessary to refine the model when describing the Omni Instruments generator because this generator operates at a much lower voltage. Brush voltage and torque losses are introduced in the revised model.

#### Brush voltage

A brush voltage  $U_b$  is introduced which has the opposite sign as  $U_g$ . Formula 1 changes into:

$$U_g := \phi_m \cdot \omega - U_b \quad (7)$$

The value that has been used for  $U_b$  is 0.1 V.

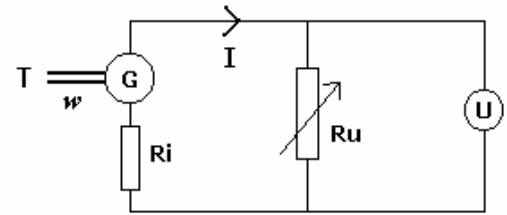


Figure 1

**Torque losses**

From the graph: torque versus rotational speed at zero load (chapters 6.7 and 7.7), it can be observed that the torque depends on the rotational speed.

This dependency was introduced in the model for the Omni Instruments generator as:

$$T_0 := C_1 + C_2 \cdot \omega$$

The torque  $T_0$  can be determined by measuring the torque as a function of the rotational speed at open circuit ( $I = 0$  A).

In appendix 1 it is shown how the efficiency can be written as a function of the rotational speed and voltage respectively, using the above equations.

Using the model, the characteristics of a DC permanent magnet generator can be determined accurately with a minimum of measurements. For instance, using a spring balance, a multimeter and RPM counter, the efficiency of a generator can be determined.

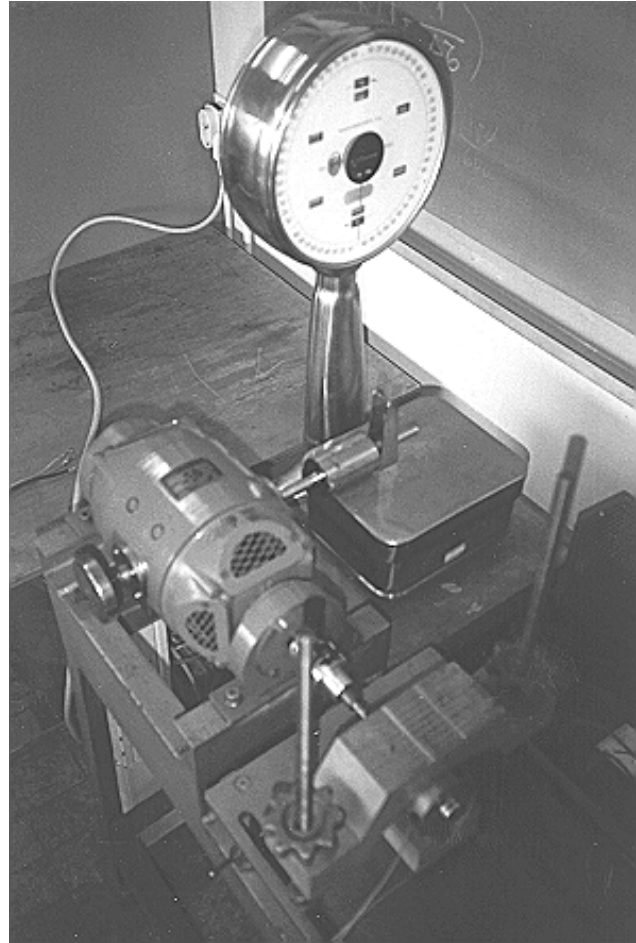


## 5. Measurements

### 5.1 Methodology

Tests of the generator have been carried out in the laboratory of the Department of Electrical Engineering, Group Electromechanics and Power Electronics of the Eindhoven University of Technology. The generator (at the bottom of the picture) is clamped-in between wooden blocks and is connected to a brakedynamo (shown on the left). The brakedynamo is mounted freely, so that the generated torque can be measured. The maximum rotational speed of the brakedynamo is 4000 RPM. Torque is calculated using the product of distance and force. Force is calculated from weight, which is measured with a scale with a resolution of 1 g. This results in a torque resolution of 0.003 Nm.

For determining the characteristics of the generator, torque, voltage, current and rotational speeds have been measured, using a rheostat as a load.



### 5.2 Calibration of RPM measurement

First the tachometer of the dynamo was calibrated with a handheld tachometer (Shimpo DT205). The calibration graph is given in Appendix 2. The RPM of the brakedynamo can be calculated using:  $RPM = 33.8 + 19.35 * V_{dyn}$ . The calibration was made without any load connected to the brakedynamo. It was found that when a load is connected to the brakedynamo there is an over-estimation of the rotational speed of not more than 2%.

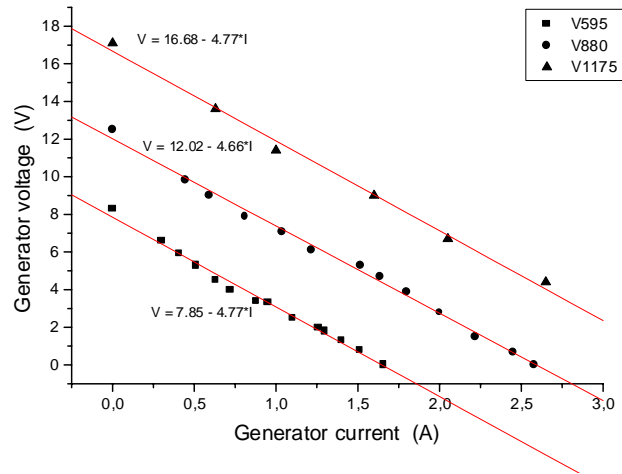
In the following chapter, first the results of the measurements on Bosch generator are discussed, followed by a discussion of the measurements on the Omni Instruments generator.

## 6. Bosch generator test results

First the values of the internal resistance (paragraph 6.1), load resistance (paragraph 6.2) and the magnetic flux constant (paragraph 6.3) are determined.

### 6.1 Internal resistance

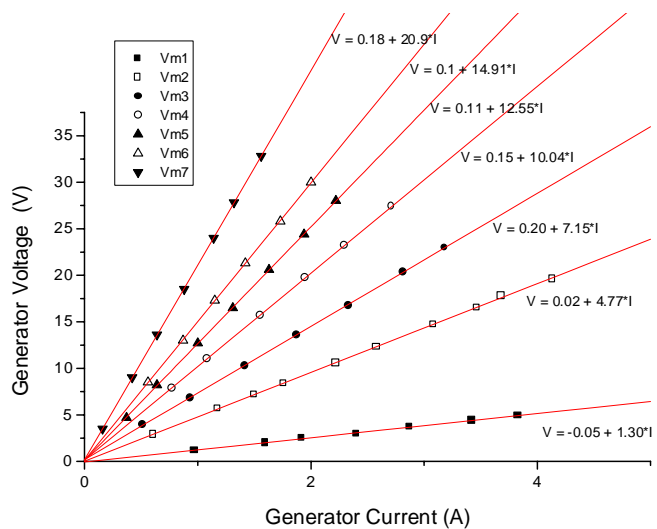
The internal resistance of the generator was measured by varying the resistance of the rheostat and maintaining the rotational speed constant, using the circuit of figure 1, (p7) with an ammeter connected in the circuit. This was done for rotational speeds of 595, 880 and 1175 RPM. From the slopes of the graphs it can be determined that the internal resistance of the generator is approximately 4.7 Ω. The straight lines have been determined by linear regression. It should be noted that this 'dynamic' internal resistance (impedance) is different from the 'static' internal resistance that is measured with an Ohm-meter.



### 6.2 Load resistance

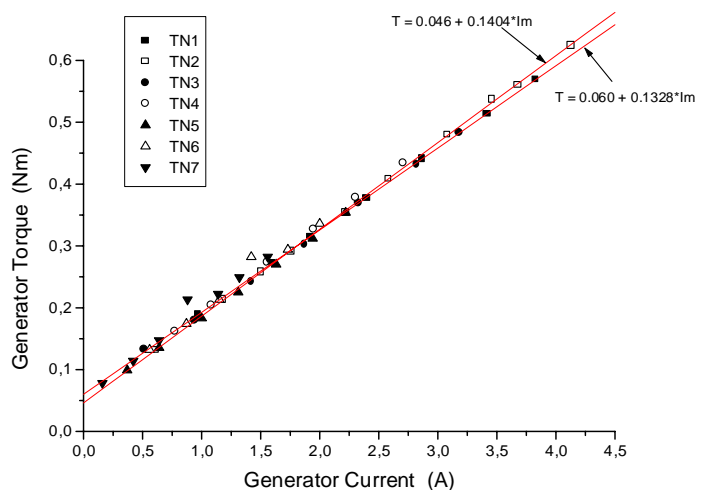
The load resistance is the sum of the resistance of the rheostat and the internal resistance of the ammeter. It has been determined by plotting generator voltage versus generator current at different rotational speeds with the load resistance as parameter and calculating the slope of the graph using linear regression. The values of the load resistances are:

Resistance (Ω)	Label in all graphs
1.30	....1
4.77	....2
7.15	....3
10.04	....4
12.55	....5
14.91	....6
20.90	....7



### 6.3 Magnetic flux constant

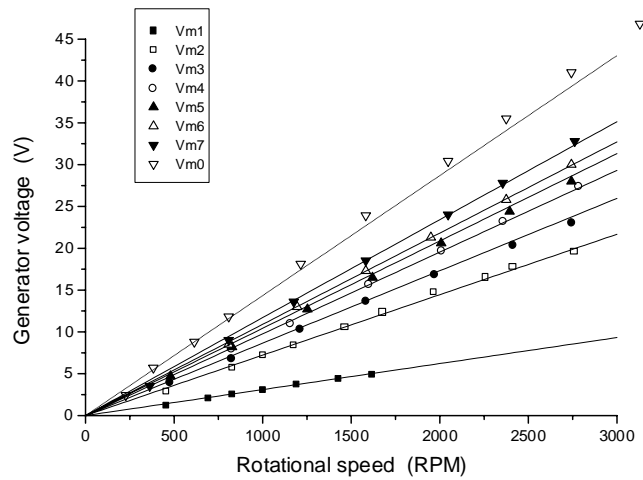
According to formula (4), the magnetic flux constant can be determined from the slope of the torque versus current graph. The values of  $\phi_m$  and  $T_o$  that have been used in the model are 0.137 Vs and 0.053 Nm respectively.



In the paragraphs 6.4 up to 6.8 the squares, circles and triangles represent measured data; the straight lines and curves have been determined using the generator model which is discussed in chapter 4.

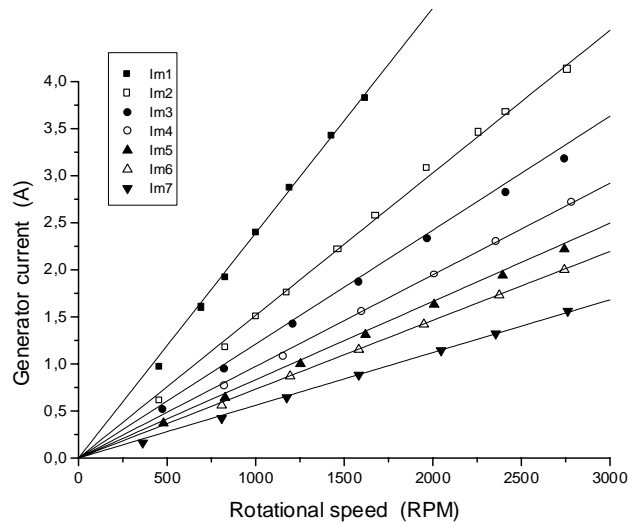
### 6.4 Generator voltage

The figure shows the generator voltage as a function of rotational speed with different loads. The straight lines have been obtained by using formula (3), without correction for the brush voltage, and writing the current  $I$  as a function of the rotational speed (see appendix 1).



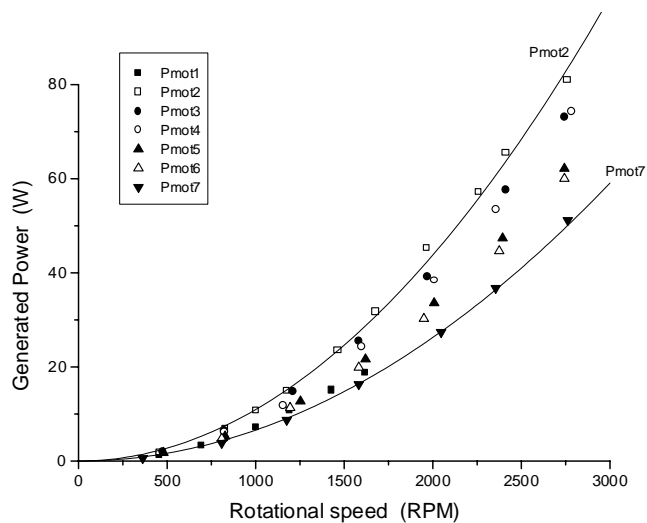
### 6.5 Generator current

Indicated is the generator current versus rotational speed at different loads. The generator model has been used to obtain the straight lines.



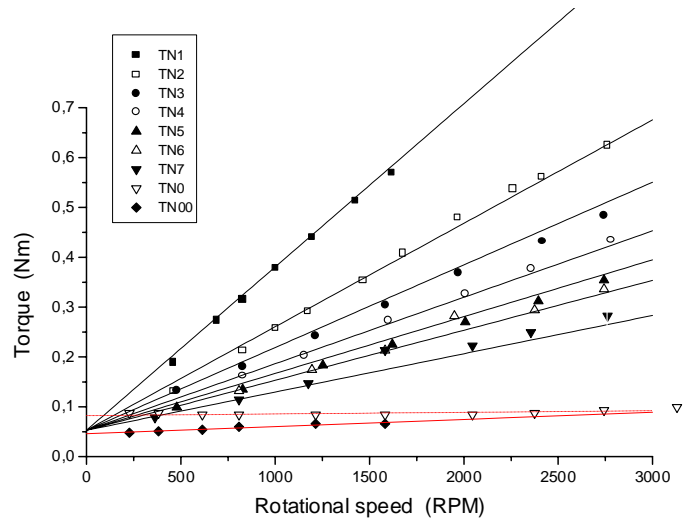
### 6.6 Generator electrical power

Since the electrical power is the product of voltage and current, the power increments exponential with the rotational speed. The generated power depends on the load: with  $R$  infinite, no current is flowing and with  $R = 0 \Omega$ , no voltage is created, so that the generated power is equal to zero in both cases. The power reaches a maximum if the load resistance is equal to the internal resistance of the generator. For clarity only two curves are shown but all curves calculated with the model fit equally well with the measured data.



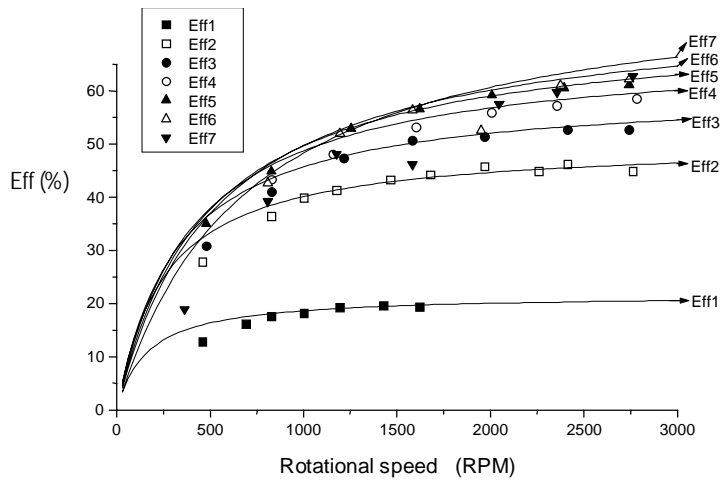
### 6.7 Generator torque

The torque is proportional to the rotational speed and increases with incrementing loads (smaller external resistance). The horizontal line (TN0) corresponds to the torque without load ( $I = 0$  A). First TN0 was determined and later the torque with different loads. After analysing the results it became clear that the torque without load had decreased probably due to the lubrication of the bearings and settling of the brushes. Therefore the torque without load was again measured (TN00, bottom line) with results that better fit the model.

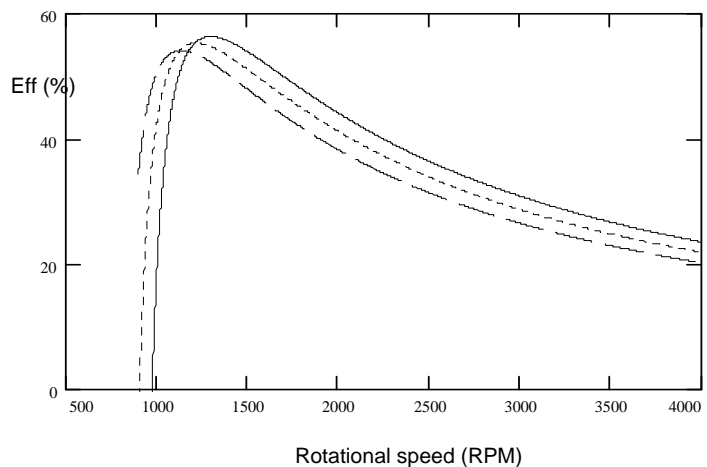


### 6.8 Generator efficiency

The generator efficiency is calculated using formula (5) with the load resistance as parameter. The generator reaches a maximum efficiency of just over 65% at rotational speeds up to 3000 RPM. The model gives an overestimation of the efficiency at low rotational speeds because the brush voltage has been ignored. Its presence becomes most obvious at low RPM. Due to the high torque at no load, the efficiency decreases rapidly at low rotational speeds of the generator.



Using the generator model, the efficiency can also be calculated with the battery voltage as parameter. The results are shown in the figure for battery voltages of 12V (dashed line), 13 V (dotted line) and 14V (solid line). After the battery voltage is reached, the efficiency increases rapidly and reaches a clear maximum.

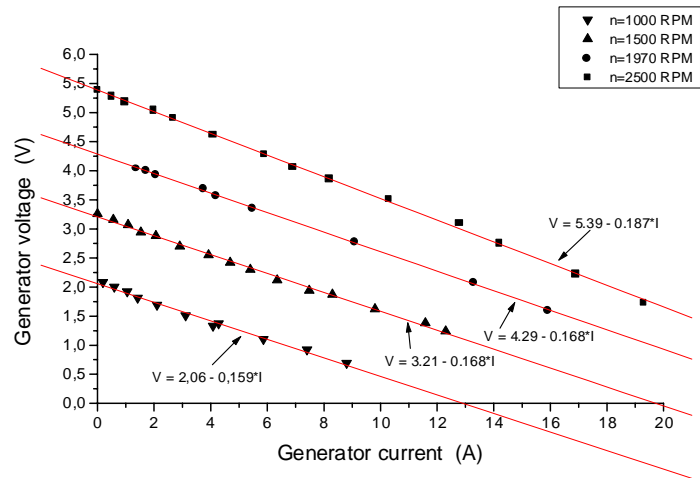


## 7. Omni Instruments generator test results

Like in chapter 6, first the values of the internal resistance (paragraph 7.1), load resistance (paragraph 7.2) and the magnetic flux constant (paragraph 7.3) are determined.

### 7.1 Internal resistance

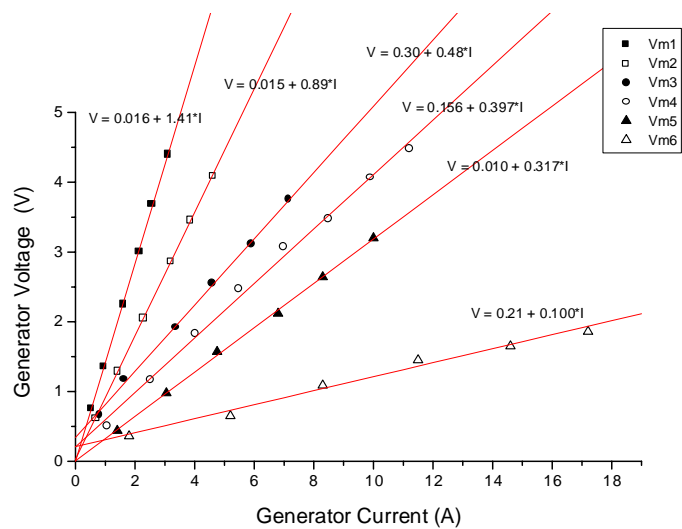
From the figure it can be determined (see paragraph 6.1) that the internal resistance of the generator is approximately 0.17 Ω. The straight lines have been determined by linear regression.



### 7.2 Load resistance

The slopes of the graphs are a measure of the load resistance and are determined using linear regression. The values of the load resistances are:

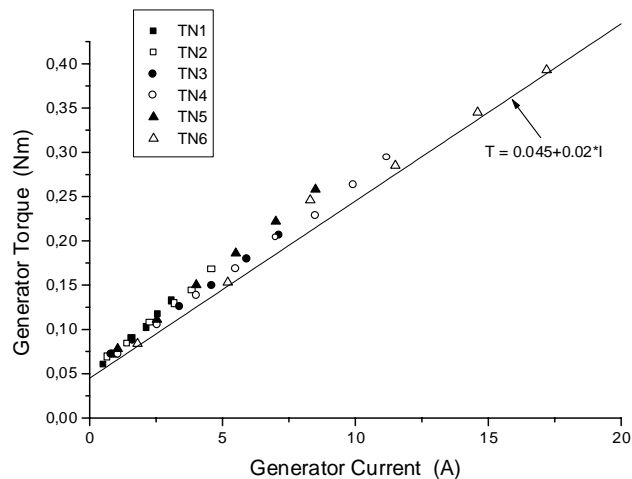
Resistance (Ω)	Label in all graphs
1.41	....1
0.89	....2
0.48	....3
0.397	....4
0.317	....5
0.100	....6



### 7.3 Magnetic flux constant

In theory the torque is independent from rotational speed. In practice, the value of  $\phi_m$  is best determined at high currents and low rotational speeds because  $T_o$  depends on the rotational speed.

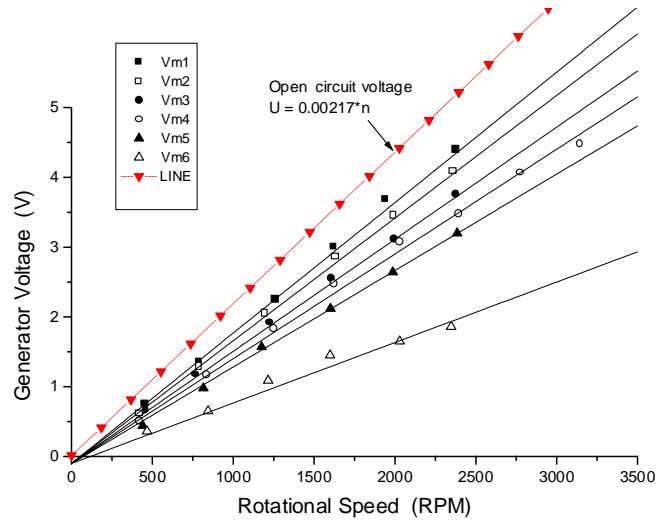
The values of  $\phi_m$  and  $T_o$  that have been used in the model are 0.02 Vs and 0.045 Nm respectively, which is indicated with the straight line in the graph.



In the paragraphs 7.4 up to 7.8 the squares, circles and triangles represent measured data; the straight lines and curves have been determined using the modified generator model which is discussed in chapter 4.

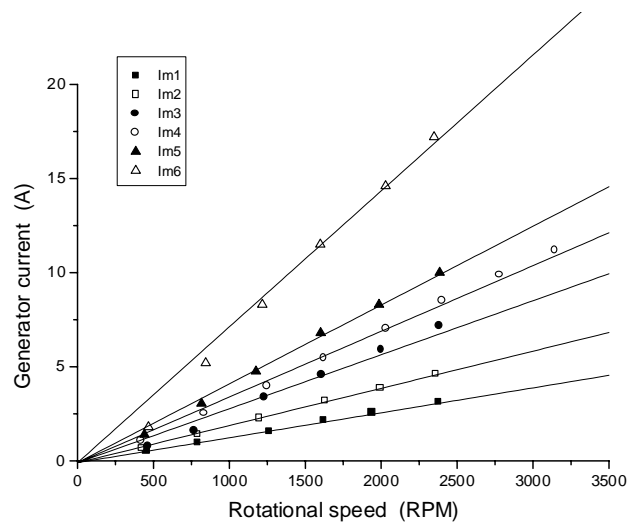
**7.4 Generator voltage**

The figure shows the generator voltage as a function of rotational speed with different loads. The straight lines have been obtained by using formula (3), modified with the brush voltage  $U_b = 0.1$  V, as described in the theory and writing the current  $I$  as a function of the rotational speed (see appendix 1). It can be observed that the graphs do not pass through the origin as a result of  $U_b$ .



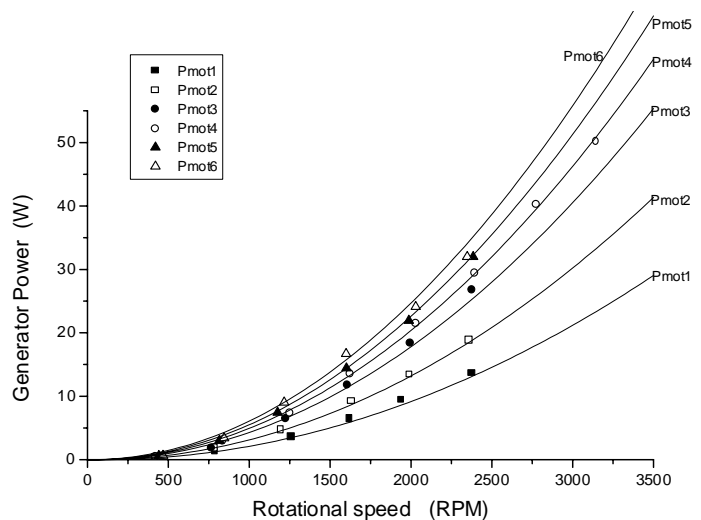
**7.5 Generator current**

Indicated is the generator current versus rotational speed at different loads. Again the generator model has been used to obtain the straight lines.



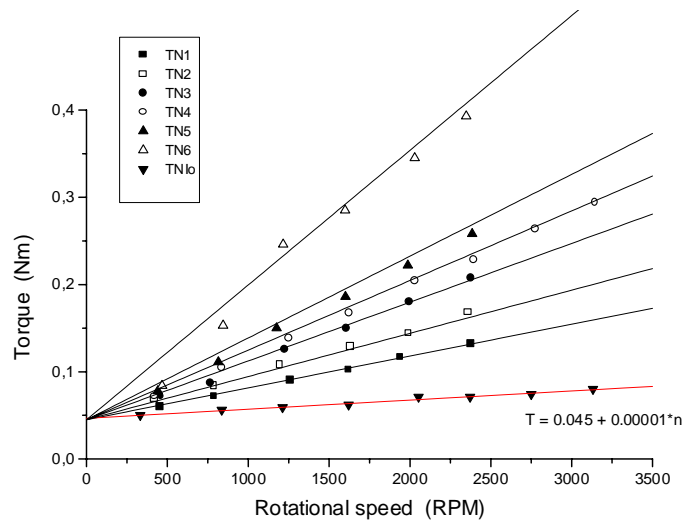
**7.6 Generator electrical power**

The graph shows a low power output at low rotational speeds and a good concordance of the model with the measurements.



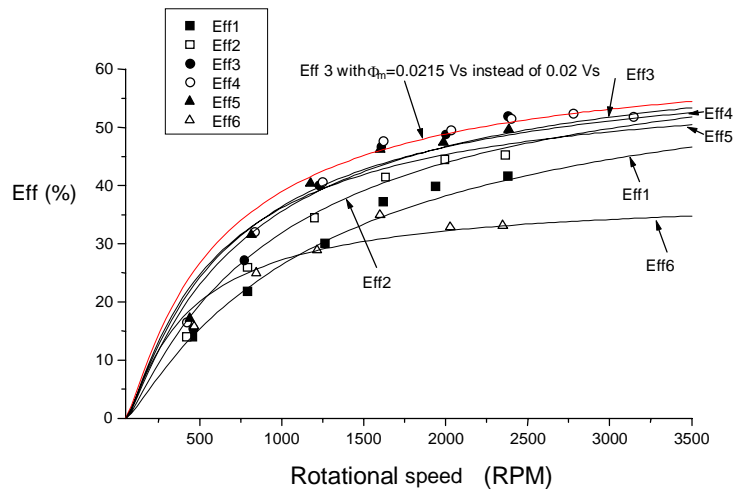
### 7.7 Generator torque

The line which is most horizontal (TN<sub>lo</sub>) gives the torque versus rotational speed at zero load (I = 0 A). It should be noted that there is a considerable torque required under zero load conditions, compared to the torque when the generator is turning. This gives an indication of high losses.



### 7.8 Generator efficiency

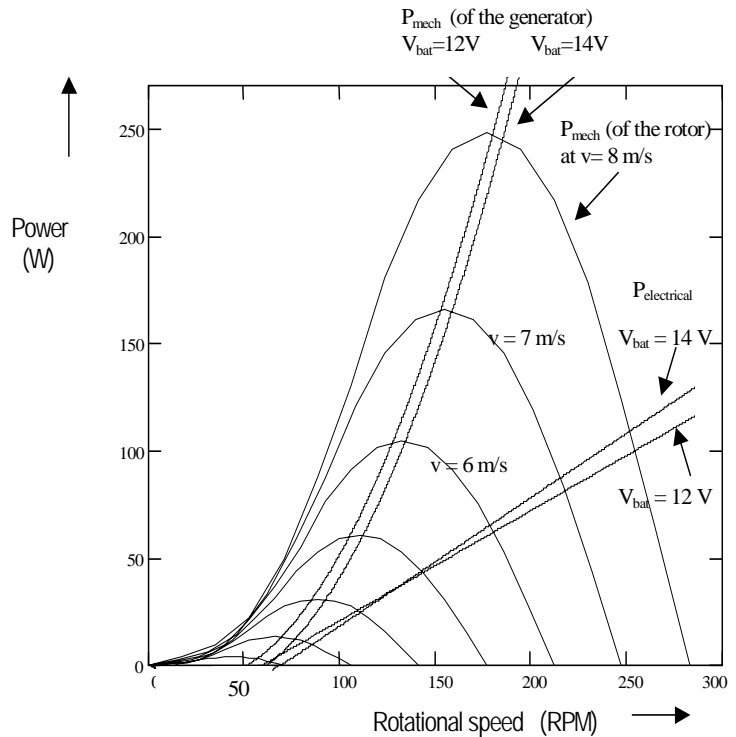
The generator efficiency is calculated using formula (5). The generator reaches a maximum efficiency of just over 50% at rotational speeds up to 3500 RPM. The model gives a slight underestimation of the efficiency, compared with the measured values, using  $\phi_m = 0.020$  Vs. The curve with the highest efficiency (circles) shows the results for Eff4 using  $\phi_m = 0.021$  Vs, which gives a good match. This shows the importance of determining the value of  $\phi_m$  accurately. Due to the high torque at low RPM the efficiency decreases rapidly at low rotational speeds of the generator. This is also observed with the Bosch generator.



### 8. Matching of the windrotor and generator

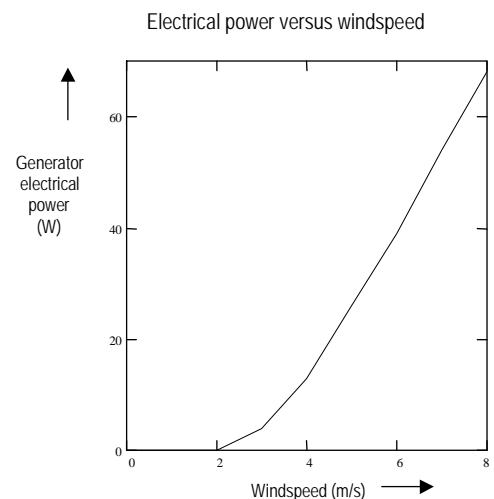
Using the proposed generator model, the mechanical power which is required to drive the generator at a constant voltage as a function of the rotational speed, can be calculated. With the procedure which is described in [4], the mechanical power of the rotor can be calculated. Combining the two procedures, the transmission ratio between rotor and generator can be optimised. The result of this procedure, using the characteristics of the AMEC rotor and Bosch generator, is shown in the figure on the right. Calculations of the mechanical power which is generated by the rotor at windspeeds of 2, 3, 4, 5, 6, 7 and 8 m/s are shown. Also the mechanical generator power and the electrical power of the generator for battery voltages of 12 V and 14 V is given. It can be observed that with a transmission ratio of 14, there is an almost perfect match between rotor and generator, considering the values of the parameters that are given at the top of the graph. It should be noted that the value of the transmission efficiency is estimated. The values of the maximum power coefficient ( $C_{pmax}$ ) and the design value for the tip-speed ratio ( $\lambda_o$ ) taken from [1].

Example of matching the AMEC windrotor with the Bosch generator  
 number of blades = 3    transmission ratio = 14  
 $\lambda_o = 2.5$     transmission efficiency = 0.85  
 $C_{pmax} = 0.22$



Using the graph above, the generator output as a function of the windspeed can be obtained. This is shown in the figure on the right.

It should be noted that this is only a rough estimation based on parameters which are not precisely known. For a better prediction of the electric output of the generator, also the starting and furling behaviour have to be taken into account.





## 9. Conclusions and recommendations

### 9.1 Conclusions

#### Model

The generator model shows a good correlation with the measured data. At low voltages the modified model has to be used, which takes the brush voltage and also the RPM dependency of the torque at zero load into consideration. The magnetic flux  $\phi_m$  should be determined carefully since it determines most characteristics of the generator and e.g. the relative error in the calculation of the efficiency is four times the relative error in  $\phi_m$ . The model may be used with permanent magnet DC generators in general. When the characteristics of the rotor are known, the model may be applied for determining the optimum match between rotor and generator.

#### Bosh generator

Without modifications the Bosch generator will be capable of charging a 12 V battery, starting at rotational speeds of approximately 900 RPM. At approximate 2200 RPM the generator can deliver 50 W. Due to the small diameter of the wires ( $D = 0.3$  mm) the generator gets hot when generating 50 W and for sure the generator is not capable of generating 100 W for prolonged periods of time.

The maximum efficiency that can be reached with this generator is approximately 65% at rotational speeds of over 3500 RPM.

#### Omni Instruments generator

The rotational speed has to be over 5500 RPM to reach an output voltage of 12V. Therefore the generator is not suitable to charge a battery using the AMEC windrotor and transmission, in an unmodified state. The maximum efficiency that can be obtained is 55%.

### 9.2 Recommendations

The Bosch generator might be used with the AMEC windrotor without modifications. However the transmission ratio has to be high (approximately 15) and the maximum power that can be generated is limited by the small diameter of the generator wire. It is estimated that the maximum power over prolonged periods of time is approximately 50 W (depending on ambient temperature, mounting of the generator, etc.).

For future development, instead of rewinding the generator, improving the rotor design can be considered. The power coefficient of the rotor is low ( $C_{pmax} = 0.22$ ) and a lot can be gained by improving the blade design because with a higher  $C_{pmax}$  the rotor may produce the same mechanical power with a smaller diameter. Keeping the design value of the tip-speed ratio constant, this results in higher RPM's so that a smaller transmission ratio is required, which improves the overall efficiency. An added advantage is that the cost of the rotor is reduced because less material is required.

#### Handling generators

<sup>TM</sup> Preferably a generator should not be opened. If a generator has to be opened, this should be done on a bench without any metal chippings because they are attracted to the permanent magnets and obstruct its normal operation. The generator should not be hammered to loosen the bolts because this might diminish the magnetic field or brake the magnets. Care should be taken that the magnets do not turn in respect to the commutator when assembling the generator. The tested Bosch and Omni Instruments generators are manufactured in the USA and require non-metric tools.

<sup>TM</sup> Care should be taken that the connecting wires do not brake.

<sup>TM</sup> The generator shaft should not be welded on. The heat might deform it. Welding will lessen the lubrication of the bearings and bushes and it might overheat the insulation of the coils.

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### Appendix 1 Calculation of the efficiency

$$U := \phi_m \cdot \omega - I \cdot R_i - U_b \quad \text{and} \quad U := I \cdot R_u \rightarrow$$

$$I \cdot R_u := \phi_m \cdot \omega - I \cdot R_i - U_b \rightarrow \phi_m \cdot \omega := I \cdot (R_u + R_i) + U_b \rightarrow I := \frac{\phi_m \cdot \omega - U_b}{R_u + R_i}$$

$$\text{and} \quad P_{el} := I^2 \cdot R_u \rightarrow P_{el} := \left( \frac{\phi_m \cdot \omega - U_b}{R_u + R_i} \right)^2 \cdot R_u$$

$$P_{mec} := T \cdot \omega \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} P_{mec} := (\phi_m \cdot I + T_0) \cdot \omega \quad P_{mec} := \left[ \phi_m \cdot \left( \frac{\phi_m \cdot \omega - U_b}{R_u + R_i} \right) + T_0 \right] \cdot \omega$$

Formula (4)

$$\eta := \frac{P_{el}}{P_{mec}} \quad \eta := \frac{\left( \frac{\phi_m \cdot \omega - U_b}{R_u + R_i} \right)^2 \cdot R_u}{\left[ \phi_m \cdot \left( \frac{\phi_m \cdot \omega - U_b}{R_u + R_i} \right) + T_0 \right] \cdot \omega}$$

It also can be shown that the efficiency can be written as a function of  $I$  and  $U$  :

$$\eta := \frac{U \cdot I}{(\phi_m \cdot I + T_0) \cdot \left( \frac{U + I \cdot R_i + U_b}{\phi_m} \right)}$$

### Appendix 2 Calibration of the RPM measurement

