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Experimental investigation of a series wound dc motor for modeling purpose in electric vehicles and mechatronics systems

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# EXPERIMENTAL INVESTIGATION OF A SERIES WOUND DC MOTOR FOR MODELING PURPOSE IN ELECTRIC VEHICLES AND MECHATRONICS SYSTEMS

## EXPERIMENTAL INVESTIGATION OF A SERIES WOUND DC MOTOR FOR MODELING PURPOSE IN ELECTRIC VEHICLES AND MECHATRONICS SYSTEMS

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### Abstract

*In our previous publication a model for serial wound DC motors was presented and a simulation program was described that is based on this model and had been developed in MATLAB environment. The recent publication presents the latest, extended version of the program and deals with the measurement of the electromagnetic and dynamic characteristics (electric resistances, dynamic inductances, bearing resistance and brush friction torque) of the above motor. From the measured characteristics, the program simulates the operation of the motor, calculating its torque, rpm and current intensity, as a function of time. To check the accuracy of the measured characteristics, and also the proper operation of our program, locked rotor response test measurements were carried out on the motor and their results were compared with the simulated ones. Finally, a recently developed heat energy recovery system is presented, which can be used on electrical drives.*

### Highlights

- A simulation model is presented for series DC motors in MATLAB environment.
- The model applies characteristics depend on current intensity and rpm as input.
- The set-up and procedure for measuring the above characteristics is described.
- The reliability of the characteristics and model were proved by test measurements.
- A heat energy recovery system applying TEG modules was developed and tested.

**Keywords:** *series DC motor, electromagnetic characteristics, dynamic simulation, MATLAB, heat energy recovery, thermoelectric generator*

### Introduction

# EXPERIMENTAL INVESTIGATION OF A SERIES WOUND DC MOTOR FOR MODELING PURPOSE IN ELECTRIC VEHICLES AND MECHATRONICS SYSTEMS

Student teams of the Faculty of Engineering of the University of Debrecen are regular participants of competitions for vehicles with alternative drive (Shell Eco-marathon, Széchenyi Race, MVM Energy Race (It is a race for vehicles with electric drive organized and sponsored by the Hungarian Electrical Works Ltd. -Magyar Villamos Művek)). The permanently efficient racing requires continuous development applying highly developed mathematics and computer science as in many other fields of science [1, 2, 3, 4]. As a part of this development a simulation program was created by the authors in MATLAB environment, which is capable of calculating the dynamic functions (e.g. the acceleration-, velocity- and covered distance-time functions) of an electric vehicle, driven by series wound DC motor, from its technical data [5,6,7]. The above simulation program enables the calculation of optimal technical parameters at which the best dynamic characteristics (performance) can be achieved. Constructing a vehicle applying the above optimal parameters efficient racing is more possible.

A particularly important part of vehicle dynamic simulation is the modeling of the electric motor [8, 9, 10] and the development of a simulation program, on the basis of the model, which is capable of calculating the angular speed and torque of the motor, and also the intensity of current flowing through it, from its basic electromagnetic and dynamics characteristics as a function of time. In the recent publication the above model and simulation program for series wound DC motors is presented, and then the experimental set-up and procedure for the determination of its electromagnetic and dynamics characteristics. The accuracy of the measured characteristics and also the proper operation of the program were checked by test measurements. These measurements and their results are also presented here.

Finally, a heat energy recovery system is presented, which converts the waste heat of the motor to electric energy. The above energy can be fed back to the accumulator of the car, making its operation more energy-saving and also extending its range per charge. In the case of competitions like Shell-Eco marathon, where energy-saving operation is vital, it increases the possibility of successful racing.

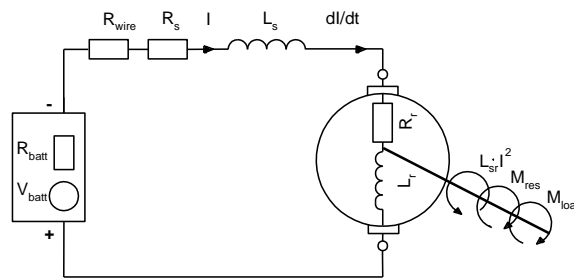
## 1. Motor model

The nominal values of the tested series wound DC motor (SWM) are shown in *Table 1*.

Type	Voltage (V)	Power (kW)	Current (A)	RPM (1/min)	Torque (Nm)
DC/T4-48	48	4	104	2800	14.7

*Table 1* The nominal values of the tested series wound DC motor

In *Figure 1* the latest version of our applied model for SWMs is presented.



*Figure 1* The applied model for the simulation of series wound DC motors

The model [5] is based on the following differential equations [11, 12]:

$$V_{batt} - (R_s + R_r + R_{batt} + R_{wire}) \cdot I - (L_s(I) + L_r(I)) \cdot \frac{dI}{dt} - L_{sr}(I) \cdot \omega \cdot I = 0 \quad (1)$$

$$L_{sr}(I) \cdot I^2 - M_{res}(\omega) - M_{load}(\omega) = J_r \cdot \frac{d\omega}{dt} \quad (2)$$

In the equations  $V_{batt}$  is the electromotive force of the battery,  $R_s$ ,  $R_r$  are the electric resistances of the stator and the rotor windings of the motor, while  $R_{batt}$  and  $R_{wire}$  are the internal resistance of the accumulator and the resultant resistance of the wires connecting the motor to the accumulator. Characteristics  $L_r(I)$ ,  $L_s(I)$  and  $L_{sr}(I)$  are the self

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dynamic inductances of the rotor and stator windings, and the mutual dynamic inductance respectively [11]. The above characteristics depend on the intensity of the current flowing through the motor. Characteristics  $M_{res}(\omega)$  and  $M_{load}(\omega)$  are the bearing resistance, brush friction and loading torques on the rotor of the motor and  $J_r$  is its moment of inertia. Characteristics  $L_r(I)$ ,  $L_s(I)$ ,  $L_{sr}(I)$  and  $M_{res}(\omega)$  have to be measured, while the value of  $J_r$  sometimes can be found in the catalogue of the motor. In *Figure 2* the block diagram of our simulation program is shown created on the basis of differential equations (1) and (2).

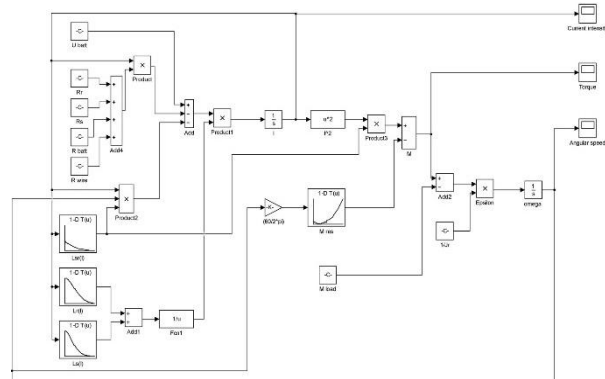


Figure 2 The block diagram of our simulation program created in MATLAB [13] environment.

Voltage  $V_{batt}$  and electric resistances  $R_r$ ,  $R_s$ ,  $R_{batt}$ ,  $R_{wire}$  are represented in the above block diagram as constants, while dynamic inductances  $L_r(I)$ ,  $L_s(I)$ ,  $L_{sr}(I)$  and torques  $M_{res}(\omega)$  and  $M_{load}(\omega)$  are presented in the form of „Lookup Tables“. In the following, the measurement process of the above described electromagnetic and dynamic characteristics is presented.

## 2. Measurements

For the measurements the experimental set-up in *Figure 3* was used.

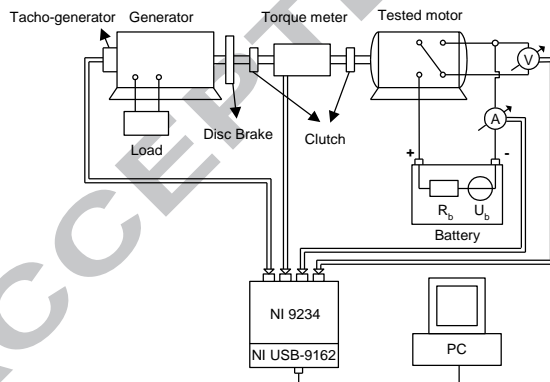


Figure 3 Experimental set-up applied for the measurements

In the following the method and set-up that was applied for the measurements is described.

### 2.1 Measurement of electric resistances

*Figure 4* shows the experimental set-up that was applied for the measurement of electric resistances.

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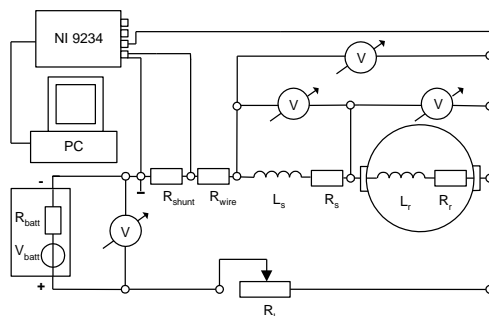


Figure 4 Experimental set-up for the measurement of electric resistances

During the measurements the rotor of the motor was fixed with a disc brake (Figure 3). As a DC supply, a battery with a nominal voltage of 12 [V] was used. The intensity of current was varied in the 0-190 [A] range adjusting the resistance of the load resistor ( $R_l$ ). The measurement of current intensity was realised as the measurement of voltage on a shunt resistor (0.6 m $\Omega$ ) with a NI 9234 dynamic signal acquisition module, which was connected to the PC through an NI USB-9162 Hi-Speed USB carrier. The voltage was measured on the stator and rotor winding separately and also on the windings in series with digital multimeters. In the later case the voltage was also measured with the NI 9234 device independently. The relative difference between the voltages measured with the two different devices was always less than 1%. Figure 5 shows voltages measured on the two windings separately and also in series.

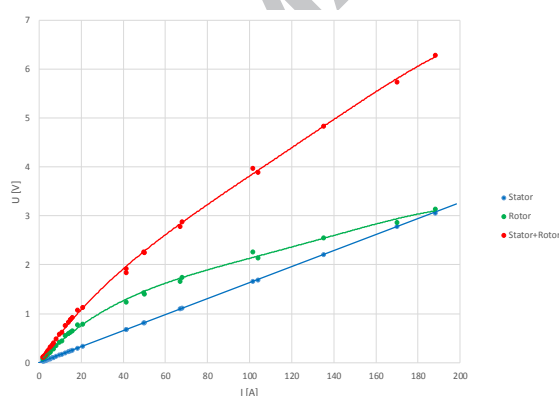


Figure 5 Voltages measured on the stator and rotor windings of the motor separately and in series

The figure clearly shows that in the case of the stator winding the connection between the current intensity and the voltage is linear, in accordance with Ohm's law, while in the case of the armature winding it is nonlinear. It is important to emphasise here that the multimeter was connected to the rotor winding through the carbon brushes of the motor. Our hypothesis was that the contact voltage between the copper segments of the motor and the carbon brushes causes the above nonlinear behaviour. To prove our hypothesis we replaced the carbon brushes of the motor with copper blocks ("brushes") of the same size and repeated the measurement on the rotor winding. The results are shown in Figure 6.

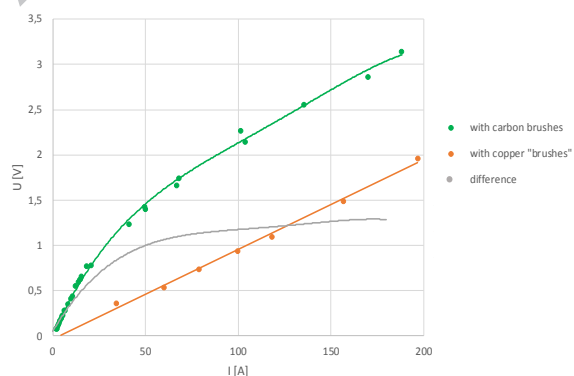


Figure 6 Voltages measured on the rotor winding of the motor through carbon and copper "brushes".

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Figure 6 clearly shows that measuring the voltage through copper “brushes” the connection between current intensity and voltage is linear. Consequently carbon brushes are responsible for the nonlinear behaviour. In Figure 6 the difference between voltages – measured through carbon and copper “brushes” – is also presented as a function of current intensity. The above voltage difference is the voltage drop on the carbon brushes. It must be emphasis here that the voltage drop was measured on the locked rotor motor. If the rotor is moving then the value of voltage drop also depends on the angular speed of the rotor [14]. The authors intend to study the above phenomenon in the near future in detail and try to find a way of taking the above voltage drop into account in the simulation program.

## 2.2 Measurement of self dynamic inductances

Before the measurement of self dynamic inductances the main field and armature windings were electrically disconnected. After that both windings were supplied separately with sinusoidal AC voltage of 5, 10, 15, 20, 25 and 50 [Hz] frequencies. The experimental arrangement is shown in Figure 7.

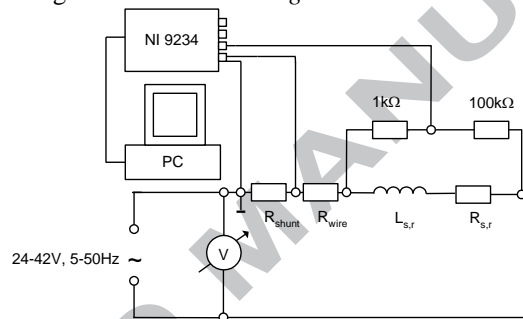


Figure 7 Experimental set-up for the measurement of self dynamic inductances

The AC voltage was generated applying the experimental arrangement in Figure 8.

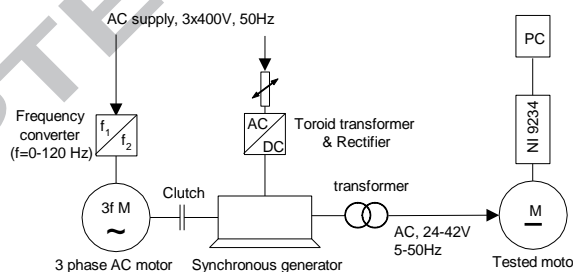


Figure 8 Experimental arrangement for generating AC voltage of 5-50 Hz frequencies

The intensity of the current flowing through the winding was measured applying a shunt resistor (see in section 2.1). While measuring the voltage on the windings, a voltage divider of 1:100 voltage ratio was applied, so that the voltage could not exceed the maximum value of 5 [V] permitted for the NI 9234 device. The voltage on the winding ( $U(t)$ ) and the current intensity flowing through it ( $I(t)$ ) were measured simultaneously as a function of time using the NI 9234 device. The magnetic flux ( $\psi(t)$ ) can be calculated from the two functions above using the following procedure [11]:

$$\psi(t) = \int_0^t (U(\tau) - I(\tau) \cdot R) d\tau + \psi(0) \quad (3)$$

The procedure was carried out with the Simulink module of the MATLAB program. From the  $\psi(t)$  and  $I(t)$  functions the magnetic flux can be given as a function of current intensity. Figure 9 and 10 show the magnetic flux as a function of current intensity in the case of the stator and rotor windings respectively.

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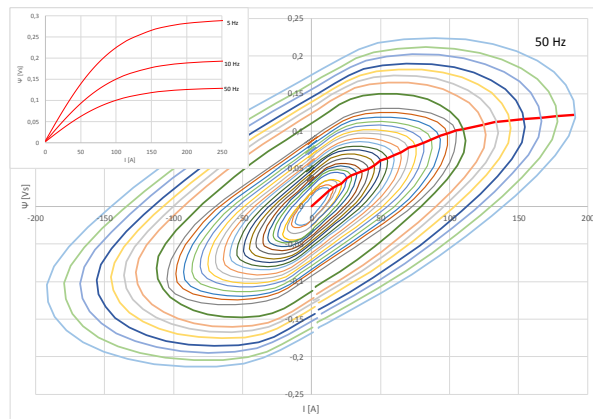


Figure 9 The magnetic flux of the stator winding as a function of current intensity

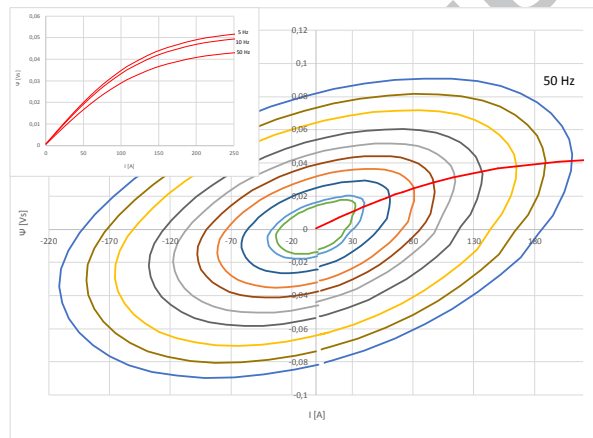


Figure 10 The magnetic flux of the rotor winding as a function of current intensity

As it can be seen in *Figure 9* and *10* – for an alternating current with a given peak value the magnetic flux versus current intensity graph is a closed curve. An AC current with a higher peak value will result in a curve with a bigger perimeter. Connecting the points belonging to the peak values of current (red line), the result is characteristic  $\psi(I)$ . The derivative of  $\psi_s(I)$  and  $\psi_r(I)$  with respect to variant  $I$  will give the self dynamic inductances  $L_s(I)$  and  $L_r(I)$ . *Figure 11* and *12* show functions  $L_s(I)$  and  $L_r(I)$  respectively at 5, 10 and 50 [Hz] frequencies.

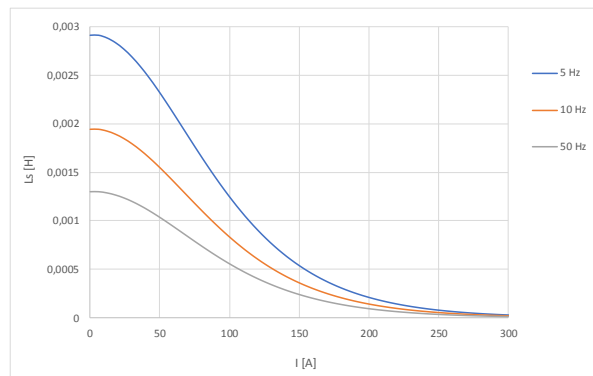


Figure 11 The self dynamic inductance of the stator winding as a function of current intensity

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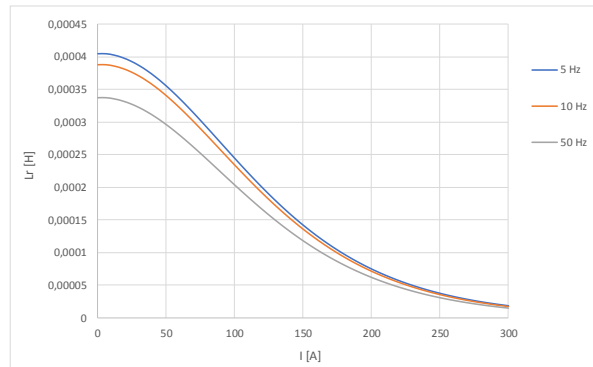


Figure 12 The self dynamic inductance of the rotor winding as a function of current intensity

It must be mentioned here that – in lack of measured data – at higher current intensities functions  $L_s(I)$  and  $L_r(I)$  were extrapolated, in the case of measurements at 50[Hz] and 5[Hz] frequencies above 190[A] and 70[A] respectively, at other frequencies above a value between them.

### 2.3 Measurement of mutual dynamic inductance

The following experimental set-up was applied to measure the mutual dynamic inductance between the stator and rotor windings:

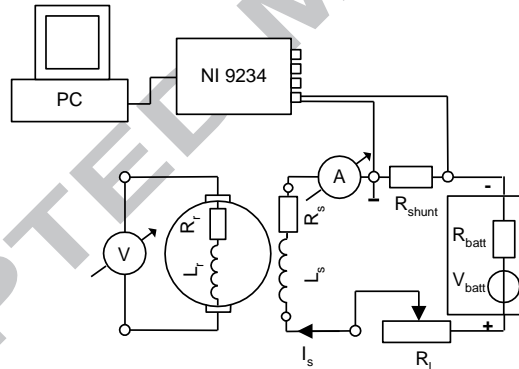


Figure 13 Experimental set-up for the measurement of mutual dynamic inductance

Before the measurements, the stator and rotor windings had been electrically disconnected. After that the stator winding was supplied with direct current. Following this, the armature winding was rotated at a constant angular velocity  $\omega$  in the magnetic field of the stator winding, and the voltage ( $U_r$ ) induced in it was measured with a multimeter. For rotating the armature winding our generator (Figure 3) was applied, operating it in motor mode. The intensity of current  $I_s$  flowing through the main field winding was varied within the 0-380 [A] range adjusting the resistance of the load resistor ( $R_l$ ). The mutual dynamic inductance can be calculated from the values of  $U_r$ ,  $I_s$  and  $\omega$  according to the following formula [11]:

$$L_{sr} = \frac{U_r}{\omega \cdot I_s} \quad (4)$$

Figure 14 shows the mutual dynamic inductance as a function of current intensity.



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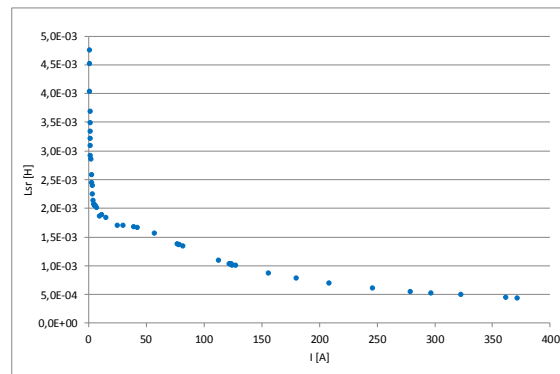


Figure 14 Mutual dynamic inductance as a function of current intensity

## 2.4 Measurement of bearing resistance and brush friction torque

During the measurements, the stator and rotor windings were electrically disconnected, and the rotor of the motor was turned by the generator with a constant angular speed. In the meantime, the bearing resistance and brush friction torque was measured belonging to the constant angular speed rotation with a torque meter (Figure 3). Varying the rpm within the range of 0-1000 [1/min], the characteristic shown in Figure 15 was determined.

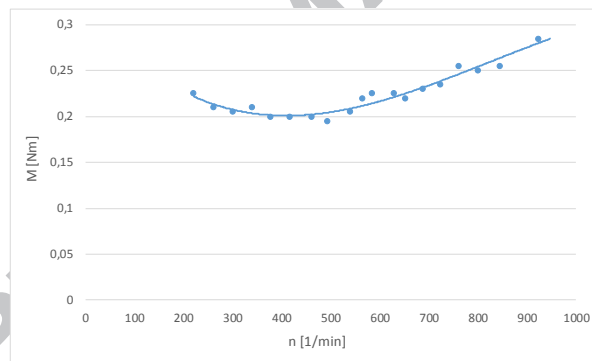


Figure 15 Bearing resistance and brush friction torque as a function of the rpm of the motor

As the axial symmetry of the machine parts – connecting the generator and the motor – was not perfect, the measurement system was heavily shaking above rpm 1000 [1/min]. Thus the measurements could not be carried out at higher rpm-s.

## 2.5 Test measurements. Comparison of measured and simulated results

The accuracy of the measured electric resistances and dynamic inductances, as well as the appropriate operation of our simulation program was checked, via test measurements. During the test measurements, the rotor of the motor was locked applying a disc brake, so that it could not rotate. After that, the voltage of the battery was switched on the motor, without using any additional load resistors in the circuit, and the time dependence of current intensity, torque and voltage on the windings and also between the electrodes of the accumulator was measured with a device NI 9234. It must be pointed out here that the measurements of the respective quantities could not be carried out simultaneously, only subsequently, with short breaks between them. Figure 16 shows the measuring set-up that was applied for the locked-rotor response tests in the case of current intensity measurements.

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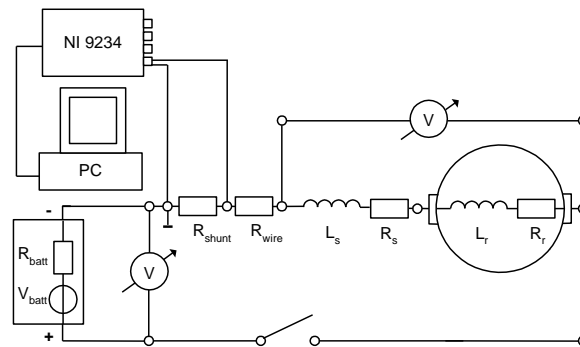


Figure 16 Experimental set-up for locked-rotor response test.

During the simulation of the locked-rotor response tests the angular speed was adjusted to be zero in our simulation program, modelling the locked-rotor this way. It must be mentioned here that the locked rotor can be also simulated by adjusting the moment of inertia of the rotor ( $J_r$ ) to be “infinite”. In the case of self dynamic inductances the program performed the calculation with data that were measured at 5 [Hz] frequency. The voltage drop on the carbon brushes was also taken into consideration as a Lookup Table in the program. Figure 17 and 18 show the results of the test measurements and also the simulation in the case of current intensity and torque respectively.

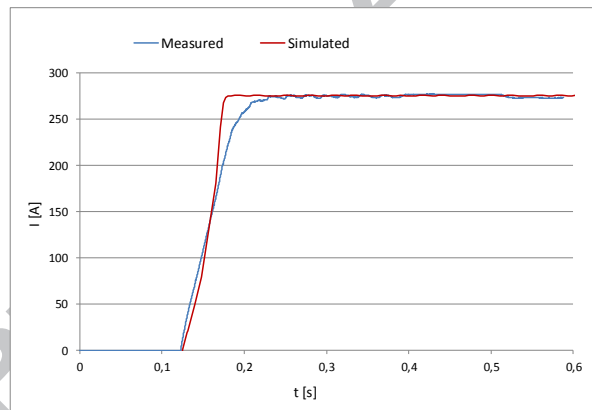


Figure 17 Locked-rotor response test. Comparison of the measured and the simulated current intensity-time functions

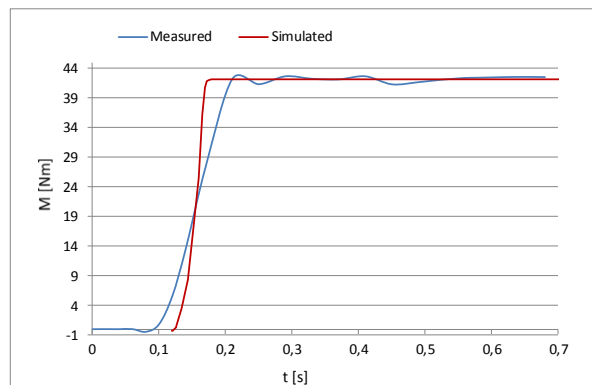


Figure 18 Locked-rotor response test. Comparison of the measured and the simulated torque-time functions

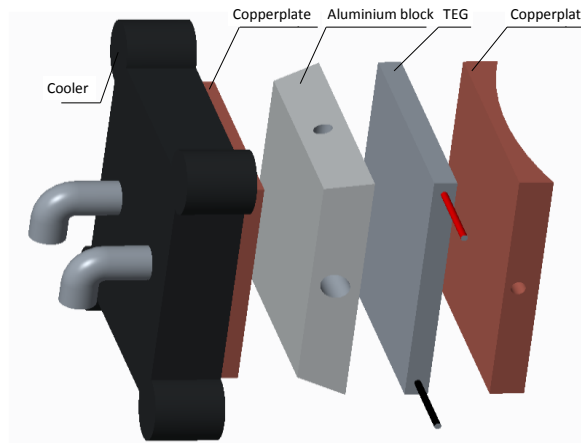
On the basis of our results it can be concluded that the relative difference between the simulated and measured data – in the case of saturation values – is less than 1% in both cases, while the slopes of the simulated torque-time function is slightly greater than the slope of the measured one. The possible causes of this can be the non-ideally rigid connection between the generator and the motor, as well as the inner elasticity of the torque meter.

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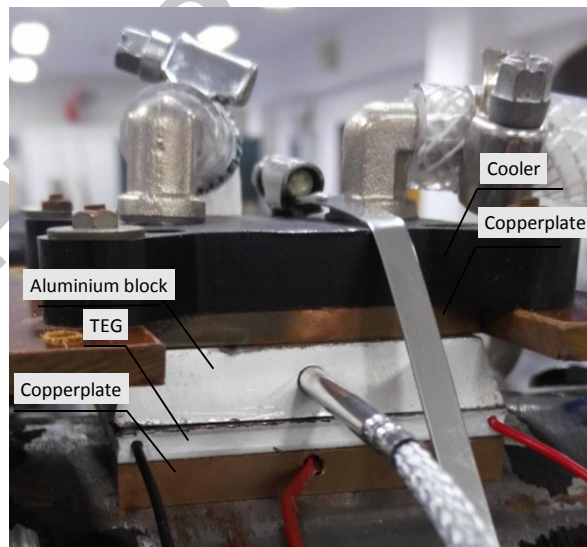
### 2.6 Measurements on the heat energy recovery system

The largest part of electrical losses is dissipated in the form of heat. Electrical and electronic producers allocate considerable financial resources to develop ideal cooling systems for electrical equipment. The great advantage of thermoelectric generators – apart from energy harvesting – is that they also function as a cooler [15, 16].

A heat energy recovery system was designed to investigate the heat energy losses of the tested DC motor. First a fixing system was designed so that the TEG could be fixed on the surface of the motor during the measurements. *Figure 19* and *20* show the 3D model and the realised version of the heat recovery system respectively.



*Figure 19* 3D model of the heat energy recovery system



*Figure 20* The realised heat energy recovery system

During the examinations, the cold- and hot-side temperatures of the TEG were measured with K type thermocouples, and also its output voltage and current. For cooling the cold point a flow water cooler was used, which was connected to a household water tube. The motor was connected to the hot side through a copperplate (*Figure 20*). The DC motor was loaded through a generator (*Figure 3*) and the load was increased continuously. The results are shown in *Figure 21*.

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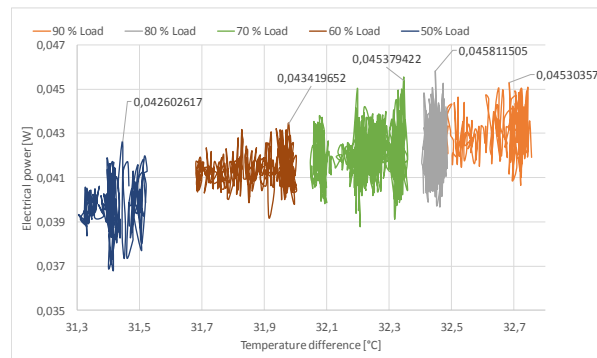


Figure 21 Test results

Figure 21 shows the power produced by TEG as a function of temperature difference. It is clearly shown by the figure that with an increasing load on the motor – therefore with its increasing surface temperature – the power produced by TEG is also increasing. The maximum power produced was 45.8 [mW] during the measurements.

## Summary

- 1) The electromagnetic and dynamic characteristics (electric resistances, dynamic inductances, bearing resistance and brush friction torque) of a series wound DC motor were measured, in the case of the electromagnetic ones on a sufficiently wide current intensity range for simulation purpose. In the case of bearing resistance and brush friction torque measurements above rpm 1000 [1/min] could not be performed due to technical reasons. The authors intend to perform further developments on the set-up to extend the range of measurements enabling dynamic tests above rpm 1000 [1/min] this way.
- 2) The accuracy of the measured electromagnetic characteristics and also the proper operation of our simulation program were checked by locked rotor response tests. During the tests DC power was switched on the locked rotor motor, and the rise of current intensity and torque were measured and simulated. The relative difference between the measured and simulated data – in the case of saturation values – is less than 1%, while the slope of the simulated torque-time functions is slightly greater than the one of the measured one. The possible causes of this will be studied in the near future.
- 3) The voltage drop on the carbon brushes of the motor was also studied. It can be concluded that for accurate simulation, it has to be taken into consideration during the simulation. The above phenomenon is planned to be studied in detail in the near future and the authors try to find a way of taking it into account in the simulation program.
- 4) Applying our heat energy recovery system the maximum produced power was 45.8 [mW], which is rather a small value, but only one TEG module was applied on a surface area of 56x56 [mm<sup>2</sup>]. In our further studies the authors intend to apply several TEG modules connected in series and parallel covering an increased surface area of the motor this way.
- 5) The way of controlling DC motors is also planned to be studied. In the literature several control methods are mentioned [17, 18, 19], like the Imperialist Competitive Algorithm and Firefly Algorithm. In the Shell Eco-marathon our team can be the most successful, if appropriate energy recovery systems (e.g.: heat energy recovery and regenerative braking recovery system) and efficient control method are applied on the electric vehicle.

## List of Abbreviations

Abbreviation	Meaning
DC	direct current
AC	alternating current
MVM	Hungarian Electrical Works Ltd.
e.g.	for example
SWM	series wound DC motor

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PC	personal computer
NI	National Instruments
rpm	Revolutions per minute
TEG	Thermoelectric generator
3D	three-dimensional

ACCEPTED MANUSCRIPT

# EXPERIMENTAL INVESTIGATION OF A SERIES WOUND DC MOTOR FOR MODELING PURPOSE IN ELECTRIC VEHICLES AND MECHATRONICS SYSTEMS

## Nomenclature

Symbol	Definition	SI unit
$R_{batt}$	internal resistance of the battery	ohm [ $\Omega$ ]
$V_{batt}$	electromotive force of the battery	volt [V]
$R_{wire}$	resultant resistance of the wires connecting the motor to the battery	ohm [ $\Omega$ ]
$R_s$	electric resistance of the stator winding	ohm [ $\Omega$ ]
$I$	current	ampere [A]
$L_s$	self dynamic inductance of the stator winding	henry [H]
$L_r$	self dynamic inductance of the rotor winding	henry [H]
$R_r$	electric resistance of the rotor winding	ohm [ $\Omega$ ]
$L_{sr}$	mutual dynamic inductance	henry [H]
$M_{res}$	bearing resistance and brush friction torque on the rotor of the motor	newton [N]
$M_{load}$	loading torque on the rotor of the motor	newton [N]
$J_r$	moment of inertia	newton meter [Nm]
$\omega$	angular velocity	radian per second [rad/s]
$R_{shunt}$	resistance of the shunt resistor	ohm [ $\Omega$ ]
$R_l$	resistance of the load resistor	ohm [ $\Omega$ ]
$\Psi$	magnetic flux	weber [Wb]

## References

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## Highlights

- A simulation model is presented for series DC motors in MATLAB environment.
- The model applies characteristics depend on current intensity and rpm as input.
- The set-up and procedure for measuring the above characteristics is described.
- The reliability of the characteristics and model were proved by test measurements.
- A heat energy recovery system applying TEG modules was developed and tested.

ACCEPTED MANUSCRIPT