

Using the Matlab Programming Environment in the Course of Student Training in the Electrical Machines Discipline

V. S. Ruseva *, A. Hr. Krasteva **

* Angel Kanchev University of Ruse, Ruse, Bulgaria

** Angel Kanchev University of Ruse, Ruse, Bulgaria

e-mail address: vruseva@uni-ruse.bg; akrasteva@uni-ruse.bg

Abstract – This article presents the results of the use of simulation models in the MATLAB software environment in the course of student training in the Electrical Machines module, which is included in the curriculum for acquiring the Bachelor's educational – qualification degree in Electrical Power Engineering and Electrical Equipment. The processes for implementing innovative educational technologies gained momentum during the Covid-19 pandemic and are currently increasingly being adopted. The students, pursuing this course, use various computer-based tools such as MS Excel and MATLAB in their training to plot the performance and mechanical characteristics of a DC motor with parallel excitation. The article presents an approach for plotting these characteristics using a virtual laboratory bench and analyses the students' opinions on its use in the Electrical Machines module.

Keywords – DC motor; Matlab; simulation.

I. INTRODUCTION

The COVID - 19 pandemic presented us with new challenges along with a purpose to search for solutions regarding the performance of virtual laboratory exercises in the Electrical Machines module as part of the training of students enrolled in the degree programme of Electrical Power Engineering and Electrical Equipment. In the course of teaching the curriculum material, two methods of learning - synchronous and asynchronous - were employed [1]. Asynchronous communication is appropriate in cases where students prepare individually on a given topic, with the e-Learning Shell system (<https://e-learning.uni-ruse.bg>) being used for this purpose at Ruse University. The materials published in the system help students enhance their knowledge of the topics of the lectures, to practice and solve tests. Synchronous online communication at our university is conducted mainly through the use of the BigBlueButton system. Synchronous learning in the Electrical Machines module allows students to use the MATLAB programming environment to develop virtual models that simulate the operation of real laboratory benches with sufficient accuracy. The virtual laboratory benches provide a solution to the distance learning problem when students do not have the opportunity to work in a real laboratory setting. The virtual laboratory exercises are carried out using the same methodology as the actual experiments, in order to compare the results obtained.

There are numerous projects in which the processes in real machines are compared with the results obtained with the Matlab-synthesized model. By linking well-selected blocks and finished DC motor models in **MATLAB**, virtual test benches can be obtained for studying and analysing the performance of DC machines [2, 3, 4]. It is possible to create such benches for a specific motor whose parameters must be calculated in advance according to the methodology described in [4]. In [5, 6], the operating modes of a DC motor with independent excitation using a starting rheostat are modelled, while in [7], other methods for modelling such systems are analysed. In [8], a new topology of a power electronic circuit providing the operation of a series excitation DC motor in a regenerative braking mode is proposed. A refined SimPowerSystem model of a real motor operating in a Matlab/Simulink environment has been created.

Through virtual laboratory studies, data can be obtained to plot various characteristics when students do not have the opportunity to take the readings in a real laboratory setting, which is the case in online learning.

In this paper, the structure of the Electrical Machines module, included as a compulsory module on the curriculum of the students from the Electrical Power Engineering and Electrical Equipment programme leading towards a Bachelor of Science degree, is presented. The aim of the paper is, first, to present methodological guidelines for creating a virtual bench in the MATLAB programming environment that can simulate with sufficient accuracy the operation of a real DC motor with parallel excitation used in conducting face-to-face laboratory exercises of the module; and second, to identify an approach for plotting the operating characteristics through a virtual laboratory bench and to analyse the students' opinions on its use for online learning in the Electrical Machines module.

II. EXPLANATION

A. Aim of the Electrical Machines module, structure and expected learning outcomes

The aim of the training in the module is to provide students with theoretical knowledge of DC machines and transformers, and practical skills for testing them. The

module content covers the structure, operating principles, characteristics and applications of DC machines and transformers, as well as their test methods.

The learning outcomes achieved by the students in the Electrical Machines module include:

Knowledge: of the structure and principle of operation of electrical machines and transformers, the characteristics of generators, the operating and mechanical characteristics of DC motors, the parallel operation of single-phase and three-phase transformers, their modes of operation, and the methods of voltage regulation of transformers. Students must independently interpret the acquired knowledge, using it in the implementation of electrical circuits and the analysis of the results obtained.

Skills: proficiency in methods and tools available for solving complex problems; demonstrating innovative thinking and creativity in solving non-standard problems; ability to think logically in analysing the processes occurring in DC machines and transformers.

Competences: a personal approach in analysing the processes taking place in DC machines and transformers, ability to apply the acquired knowledge and skills in laboratory or production settings, constant improvement and learning, communication in performing creative work. In this way, students acquire professional and specific competences.

Training in the Electrical Machines module is conducted via lectures and laboratory exercises. Most of the laboratory exercises are organised in a cycle on the topics shown in Tab. I. The exercises are concluded with the preparation of an individual paper.

TABLE I. Topics of the laboratory exercises in the Electrical Machines module

N ^o	LABORATORY EXERCISES	Credit hours
1.	Familiarisation with the rules of work in the Electrical Machines laboratory. Instruction in occupational safety. Familiarisation with the main parts of DC machines and transformers and the methods of testing electrical machines.	3
2.	Changing the excitation type of a DC machine, the direction of rotation of a DC motor and the polarity of a DC generator.	3
3.	Detecting faults in the armature winding of a DC machine.	3
4.	Plotting the magnetic field curve in the air gap of a DC machine.	3
5.	Drawing up the armature winding diagram of a DC machine.	3
6.	Studying the characteristics of a DC generator with separate excitation.	3
7.	Studying the characteristics of a DC generator with mixed excitation.	3
8.	Studying the characteristics of a DC motor with parallel excitation.	3
9.	Studying the characteristics of a DC motor with series excitation.	3
10.	Studying the characteristics of a DC tachogenerator.	3
11.	Studying the characteristics of a single-phase transformer.	3
12.	Studying the characteristics of a three-phase transformer.	3
13.	Determining the winding terminals and connection group of a three-phase transformer.	3

N ^o	LABORATORY EXERCISES	Credit hours
14.	Studying the characteristics of an autotransformer.	3
15.	Familiarisation with manufacturers' catalogues of DC machines and transformers.	3
	Total	45

B. Work procedure of studying a particular DC motor using a virtual bench in the MATLAB programming environment

Creating a virtual bench in the Matlab programming environment to study the operating characteristics of a particular DC motor with parallel excitation.

The operating characteristics of DC motors with parallel excitation are the functional dependencies of the rotational frequency n , the effective torque M_2 , the current I consumption from the supply network, the power P_1 consumption and the efficiency η on the effective power P_2 delivered by the motor shaft, with constant values of the supply voltage and the excitation current, i.e. n , M_2 , I , P_1 , $\eta = f(P_2)$, $U = \text{const.}$ and $I_f = \text{const.}$ For the students to set up a virtual bench to study a DC motor with parallel excitation within a synchronous training session, it is necessary for them to:

- become familiar with the blocks and the parameters thereof, needed to build the virtual bench, from the **Simulink Library Browser/SimPowerSystems** library;
- create a virtual stand to simulate the operation of a DC motor with parallel excitation in the **Matlab/Simulink** programming environment under the guidance of the lecturer;
- set up the model blocks;
- simulate the operation of the motor and plot the curves defined as the objective of the specific exercise they are performing.

The virtual bench is created using the Simulink library, which contains a large number of functional blocks. The required ones are selected and moved into the window of a newly created file. The necessary links are placed. By modifying the parameters of these blocks during the process of modelling, the behaviour of the system being tested can be observed.

From the laboratory exercise topics shown in Tab. 1, the students work on the topic: Studying the characteristics of a DC motor with parallel excitation.

Fig. 1 shows the schematic of a virtual bench created in the Matlab programming environment to study the operating characteristics of a particular DC motor with parallel excitation. The following appropriate basic blocks of the Matlab/Simulink programming environment which were selected, are presented in Tab.II.

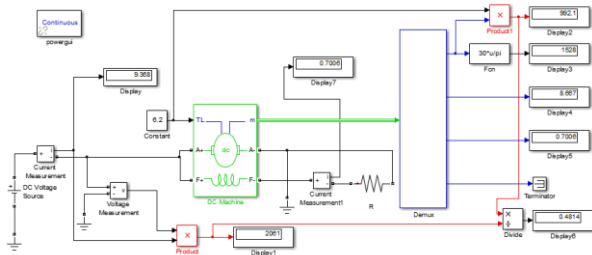


Figure 1. A schematic of a virtual bench to study the operation of a DC motor with parallel excitation

TABLE II. Blocks used in Figure 1

№	Names of the blocks	Purpose
1.	DC Machine	A model of a DC machine
2.	Constant	For setting the shaft load (the moment of resistance)
3.	DC Voltage Source	A source of constant voltage
4.	Voltage Measurement	To measure the supply voltage value
5.	Current Measurement	To measure the value of the current I, consumed by the motor
6.	Current Measurement 1	To measure the value of the current through the field winding
7.	Product	A block for calculation of the power P ₁ consumption
8.	Product 1	A block for calculation of the effective power P ₂ delivered by the motor shaft
9.	Divide	A block for calculation of the efficiency η
10.	Fcn	A block for calculation of the rotational frequency n
11.	Display	A block for taking the readings of current I consumption from the supply network
12.	Display 1	A block for taking the readings of consumption effective power
13.	Display 2	A block for taking the readings of the effective power of the machine
14.	Display 3	A block for taking the readings of the rotational frequency
15.	Display 4	A block for taking the readings of the current I _a through the armature circuit
16.	Display 5	A block for taking the readings of the current through the excitation circuit
17.	Display 6	A block for taking the readings of the efficiency factor η
18.	Display 7	A block for taking the readings of the value of the current through the field winding

The block Product performs a calculation procedure according to the formula:

$$P_1 = U \cdot I \quad (1)$$

where U is the supply voltage of the armature and field windings, and I is the motor current consumption.

The block Product 1 performs a calculation procedure according to the formula:

$$P_2 = M \cdot \omega \quad (2)$$

where M is the moment of resistance applied to the motor, and ω is the motor angular velocity.

The block Divide performs a calculation procedure according to the formula:

$$\eta = \frac{P_2}{P_1} \quad (3)$$

where P₂ is the effective power of the machine;

P₁ – consumption effective power.

In the F_{cn} – block, a calculation procedure was performed using the following formula, which was entered in the Expression field:

$$n = \frac{30 \cdot \omega}{\pi} \quad (4)$$

The input value in the F_{cn} block was the angular velocity ω of the motor shaft, and the output value was the rotational frequency n.

All Display blocks are connected to block Demux. The resistance R (fig. 1) introduced in the excitation coil serves to regulate the excitation current.

Adjustment of the basic blocks of the model in Fig. 1.

The object of study was a DC motor with the following technical parameters: rated power P_n = 3 kW, rated voltage U_n = 220 V and rotational frequency n = 1500 min⁻¹. In the dialogue box shown in Fig. 2, in the fields for setting the motor parameters, the following values had to be pre-entered: R_a - resistance of the armature winding; L_a - inductance of the armature winding; R_f and L_f - resistance and inductance of the field winding; L_{af} - mutual inductance factor; J - moment of inertia applied to the armature; B_m - friction coefficient; T_f - friction torque and initial rotational speed of the shaft [4].

DC machine (mask) (link)

Implements a (wound-field or permanent magnet) DC machine. For the wound-field DC machine, access is provided to the field connections so that the machine can be used as a separately excited, shunt-connected or a series-connected DC machine.

Configuration
Parameters
Advanced

Armature resistance and inductance [Ra (ohms) La (H)]
[2.1 0.0199]

Field resistance and inductance [Rf (ohms) Lf (H)]
[271 11.1]

Field-armature mutual inductance Laf (H) :
1.8

Total inertia J (kg.m^2)
0.0002

Viscous friction coefficient Bm (N.m.s)
0.02953

Coulomb friction torque Tf (N.m)
0.005161

Initial speed (rad/s) :
1

OK Cancel Help Apply

Figure 2. Dialogue box for setting the parameters of a DC motor

The resistance and inductance of the armature and field windings of the motor were pre-measured using a *Sverker 760* - Fig. 3. This is an instrument designed to measure voltage, current, time, impedance, resistance, reactance, apparent power, active power, reactive power, phase angle and power factor. Its appearance can be seen in Figure 3.

The values of the resistance, the reactance and the other parameters were calculated according to the methodology given in [4].

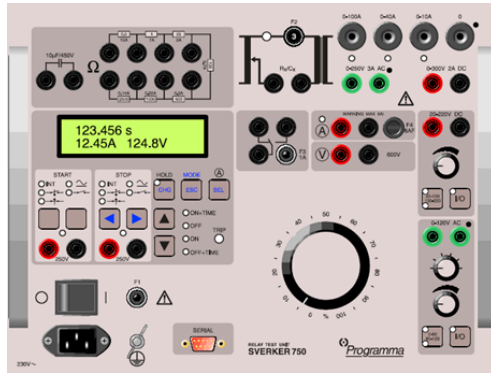


Figure 4. Front panel of *Sverker 760*

In addition to the DC Motor block, the DC Voltage Source, Demux, and Fsn blocks needed to be adjusted before simulating the operation in order to obtain data to plot the operating characteristics of the DC motor with parallel excitation.

In the Amplitude field of the DC Voltage Source block, the value of the rated supply voltage was set for the armature and field windings, respectively, which for the studied motor was $U_n = 220$ V. In the dialogue box of the Demux block, the number of observed values was specified.

Simulating the operation of the DC motor with parallel excitation under study and collecting data to plot its operating characteristics.

Before the simulation, the process simulation time must be preset in the Simulation/ Parameters control panel in the Matlab/Simulink programming environment [2]. The simulations for the motor studied were conducted at a rated supply voltage of $U = 220$ V and rated excitation current value $I_f = 0,7$ A. The shaft load (moment of resistance) of the motor studied was entered in the **Constant value** field of the **Constant** block. Data for plotting various characteristics using the virtual bench in Fig. 1 could be obtained by setting values of the moment of resistance M in the range $(0 \dots 1,1) M_n$. For each value of the moment of resistance, a new simulation was run, and the data read from the **Constant** (for the moment of resistance) and Display3, Display, Display1, Display6, Display2, blocks (for the rotational frequency n , the current consumption I from the supply network, the power consumption P_1 and the efficiency η on the effective power P_2 delivered by the motor shaft, respectively) were used to plot the operating characteristics.

The simulations were performed in such a way that the study corresponded to real experiments. Thus, it was

possible to compare the results obtained from the simulation with those obtained in a laboratory setting. The obtained operating characteristics are presented in Fig.5.

As with real experiments, it is recommendable to monitor the anchor current in simulations in virtual experiments as well.

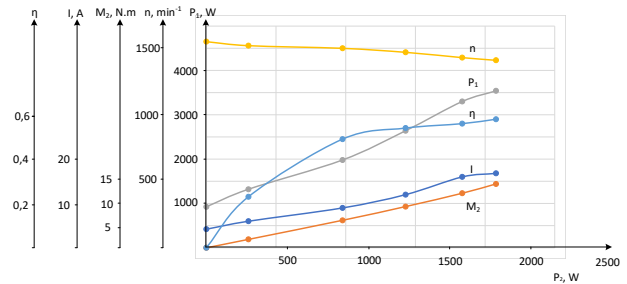


Figure 5. Operating characteristics of DC motor with parallel excitation, obtained via the virtual bench

C. Calculating the errors of the studied parameters obtained by the virtual bench presented in this paper and those obtained in real laboratory settings.

The errors were calculated at different unit load values (UL), shown in Tab. III. The unit load was calculated using the expression:

$$UL = \frac{P_2}{P_{2n}} \cdot 100, \% \quad (5)$$

where the rated effective power of the machine is $P_{2n} = 3$ kW.

The relative error of the studied parameters was calculated by the formula:

$$\delta = \left| \frac{(X_2 - X_1)}{X_1} \right| \cdot 100, \% \quad (6)$$

where X_1 is the magnitude obtained by analytical calculations and X_2 is the one obtained by simulating the operation of a DC motor with parallel excitation using the virtual bench.

TABLE III. Data about the relative errors obtained for the studied parameters at different values of the unit load

UL	δ_I	δ_n	δ_{P1}	δ_η	δ_{P2}
%	%	%	%	%	%
10	1,5	3,8	1,4	0,0	0,0
33	4,4	1,8	3,9	2,0	2,1
48	2,3	1,3	2,3	3,7	3,6
62	6,7	1,7	7,1	7,0	6,7
70	4,5	1,5	4,7	5,8	5,4

The greatest relative error in the conducted study – 7,1%, was obtained for the power consumption P_1 at a unit load of 62 %.

D. Students' opinion

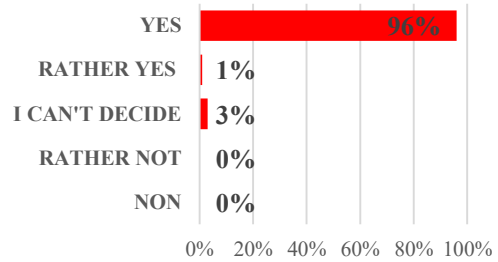
At the end of the semester in which the Electrical Machines module was taught, a survey was conducted among the students regarding synchronous learning and the use of the Matlab/Simulink programming environment in carrying out the laboratory exercises. The questions are presented in Table IV, and the answers to them are displayed in the same table. All of the students who were questioned were 100 in count.

Table IV. Questions and answers for the survey conducted during the 2022 academic year

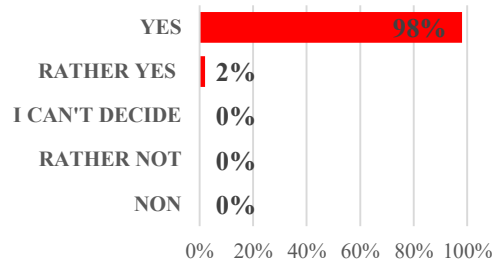
№	QUESTION	ANSWERS				
		NON	RATHER NOT	I CAN'T DECIDE	RATHER YES	YES
1	Is the content of the module up to date?	0	0	3	1	96
2	Has your interest in the subject of this module increased while you studied it?	0	0	0	2	98
3	Did you manage to create a virtual bench in the Matlab programming environment in the synchronous class?	0	0	0	6	94
4	Were you able to set up, under the guidance of the lecturer, the basic blocks of the virtual bench in an online learning format of the Electrical Machines module?	0	0	2	3	95
5	Did you master the method of calculating the resulting errors between the values of the studied parameters from the virtual bench and those obtained in real laboratory settings?	0	0	5	4	91
6	Do you evaluate in a positive way the use of the Matlab/Simulink programming environment in online learning for creating virtual benches, on which to simulate the operation of electrical machines, in cases where real laboratory settings cannot be used?	0	0	0	0	100

The analysis of the results obtained shows that more than 96% of the students identified the content of the module as relevant. Electrical machines are among the most ubiquitous in industry and the knowledge obtained about their structure, principle of operation and application is very important for future electrical engineers, such as our students.

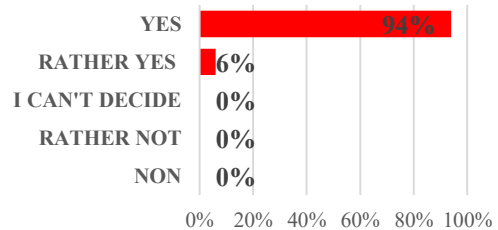
Answers to question 1 (tabl. III)



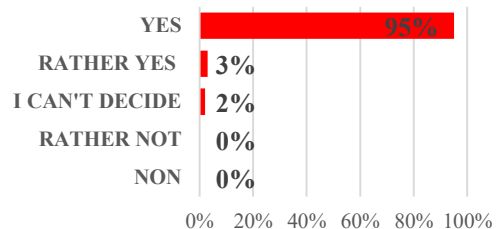
Answers to question 2 (tabl. III)



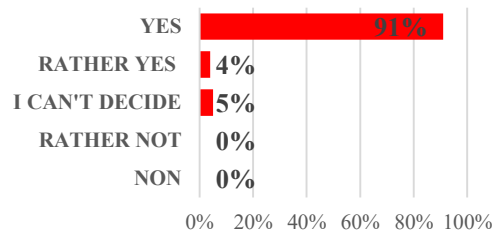
Answers to question 3 (tabl. III)

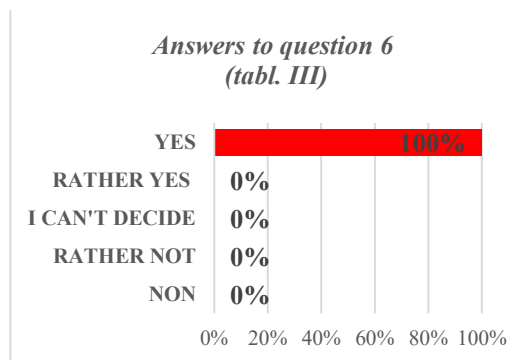


Answers to question 4 (tabl. III)



Answers to question 5 (tabl. III)





One hundred percent of the respondents answered that their interest in the subject had increased during their study, with 98% answering "yes" and 2% answering "rather yes". This, in our opinion, is associated with the way the curriculum material on Electrical Machines is taught using the Matlab/Simulink programming environment, a conclusion that is supported also by the answers to the sixth question in Table III, which is visualized above.

Again, 100% of the students approve of the use of Matlab/Simulink programming environment for online learning in cases where it is not possible to conduct face-to-face laboratory exercises.

The positive responses to question four: 95% "yes", 3% "rather yes", and 2% "do not know" indicate that the students received the necessary assistance from the lecturer during the online classes.

A survey was conducted amongst the teachers from Electrical Power Engineering and Electrical Equipment department, Angel Kanchev University of Ruse, regarding the value of the developed simulation models in the MATLAB software environment. All questioned teachers were unanimous in such models being useful for educational purposes, especially in times of global pandemic and distance learning.

III. CONCLUSION

This paper presents an approach used in synchronous training for conducting laboratory exercises in the Electrical Machines module for students from the Electrical Power Engineering and Electrical Equipment degree programme at the Angel Kanchev University of Ruse. The structure of the study module is analysed, as well as the

knowledge, skills and competences that the students acquire.

For the purpose of the study, a virtual bench was set up in the Matlab programming environment to explore the operating characteristics of a particular DC motor with parallel excitation, which simulated with the required accuracy the operation of a real DC motor with parallel excitation, used for conducting in-person laboratory exercises in the Electrical Machines module. Methodological guidelines for carrying out the virtual exercise were summarized. The operation of the studied DC motor with parallel excitation was simulated and data were collected for plotting its operating characteristics. The relative errors for the studied parameters obtained by the virtual bench presented in the paper and those obtained in real laboratory settings were calculated. The performance viability of the model was proven.

The results of the survey conducted among the students who studied synchronously the discipline of Electrical Machines are presented. These results confirm the appropriateness of the applied training approach using the Matlab programming environment.

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