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APPROACHES TO THE REALIZATION OF A VIRTUAL ELECTRIC MACHINE LABORATORY IN MATLAB&SIMULINK

BY

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Abstract. This virtual lab integrates the Matlab&Simulink experimental model, which gives students the opportunity to verify their theoretical knowledge. The paper proposes the development of the Simulink model of the DC motor, aiming to achieve a more effective speed control. We describe the implementation of a virtual lab based on mathematical models. Our virtual lab in Matlab&Simulink in correspondence with the traditional one implies particular advantages: the time allocated to the development of a virtual laboratory is shorter than that required for a classic one, the scalability is wider and the cost is lower. The paper presents with the three main blocks: the excitation, the inductor and the mechanical block. The parameters defining both the transient regime of the excitation circuit (application duration and excitation voltage) and the stabilized operating regime at idle are established. The new transient regime of operation under load is studied, followed by the stabilized regime of operation under load.

Keywords: Matlab&Simulink, digital technologies, machine learning, optimization, speed.

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1. Introduction

Nowadays Romanian education system is facing a problem with the learning resources, especially in the pre-university environment, where we are dealing with technological high schools with specific areas of electrical engineering that do not have the necessary materials to conduct classes with this specific; and to the same extent, another major issue is the problem of teaching management (OECD, 2019). Teaching management and learning resources are two basic building blocks for effective online teaching and learning. The complexity of the virtual lab system can be highly effective with good management of learning resources and teaching management. Also, good management of learning resources, can be titled independently, leading to excellent learning resources. In perspective, addition to good resource management freedom, the organization of the teaching process can be controlled according to specific learning needs and each subject will have the possibility to customize their learning environment (Vincent-Lancrin *et al*., 2019). Currently, the concept of building a virtual laboratory, especially after Coronavirus, based on digital learning resources and new teaching opportunities is highly and beneficial leading to a healthy and harmonious development of the Romanian education system. However, let us not miss a very important point, namely, to keep in mind that new modern digital technologies for teaching and learning must simultaneously comply with the curriculum standards of the current year. As we know very well that electrical engineering subjects are more practical based subjects, we will highlight the simulation of the DC motor in Matlab&Simulink, more precisely we will deal with aspects of DC motor speed control in a virtual environment, of course based on well developed theoretical aspects.

Therefore, we believe that such virtual lab have an extremely important role and can be a consistent field of information sources among pupils/students, digital learning, providing high quality services among learners, and at the same time, we can control the correctness of the simulation of an electrical machine (Teodoru *et al*., 2000).

2. Methodology

MATLAB is a programming language oriented towards performing numerical and symbolic calculations specific to various fields of engineering sciences, as well as modelling and simulating general dynamic systems (implementation of block diagrams developed with the Simulink programming language, since 1990) and particular physical systems (implementation of functional diagrams developed with the Simscape programming language, since 2008) (Preitl *et al*., 2001).

The main computational features of the MATLAB programming language are:

- Fundamentals of programming, common mathematical functions, 2D and 3D graphing, generating user-defined functions, defining and manipulating polynomials, functions for data and file control, for numerical integration and derivation, numerical solution of algebraic and transcendental equations and systems of equations, numerical solution of linear and non-linear equations and systems of equations;

- Statistical (Statistics Toolbox) and numerical (Curve Fitting Toolbox) analysis of experimental data. Methods of approximation of functions by interpolation and regression using polynomials, power functions, exponential, trigonometric, Gauss, Weibull, Fourier). Specific functions for analysing quality parameters of approximations: confidence level, error intervals, numerical quality parameters, plotting of residuals;

- Analysis, design and regulation of dynamic systems using the method of specialised numerical procedures (Control Systems Toolbox). Definition of dynamic systems using the transfer function method, input-state-output method, poly-zeros method. Analysis of dynamic and stability performance of dynamic systems in the time domain (step signal response) and in the frequency domain (Bode diagram);

- Modeling and simulation of dynamic systems using the block diagram method (Simulink) with block libraries for: simulation of continuous dynamic systems; simulation of discrete dynamic systems; simulation of discontinuities; basic mathematical operations; logic operations; bit-level operations; approximation of 1D, 2D and nD functions; simulation of input signals; simulation of elements for graphical and numerical visualization of output signals; manipulation of signals; modification of signal parameters; checking the range of variation of numerical values of signals;

- Creating a Simulink model is done by selecting the File/New/Model command or by selecting the new model button from the program's button bar. The modification of the characteristic parameters of the blocks is done according to the numerical specifications of the equations characterising the behaviour of the system under analysis (George, 2004; Guo *et al*., 2019).

3. Modeling

The mathematical model of the DC motor is given by Eqs. (1), (2) and (3), being implemented in Simulink as in Fig. 1.

$$u_a = R_a i_a + \frac{d\Psi_a}{dt} + \omega_r \Psi_{rq} \tag{1}$$

where: u_a - supply voltage, R_a - resistance of the inductor, i_a - induced current, Ψ_a - the total magnetic flux created by the armature winding ($\Psi_a = L_A i_a$, L_A-

inductance of the inductor, i_a - induced current), Ψ_{rq} - the total magnetic flux useful rotor along the (q) axis, created by the excitation winding $\Psi_{rq} = L_{mq} i_e$ (L_{mq} - inductance magnetizing)

$$u_e = R_e i_e + \frac{d\Psi_e}{dt} \tag{2}$$

where: u_e - excitation circuit supply voltage, R_e - resistance of the excitation, i_e - excitation current, Ψ_e - the total magnetic flux created by the excitation winding $\Psi_e = L_E i_e$ (L_E - inductance excitation)

$$\frac{d\omega_r}{dt} = \frac{1}{J}(m_e - m_r - m_\alpha) \tag{3}$$

in which: ($m_\alpha = F_\alpha \omega_r$), where: ω_r - speed, m_e - electromagnetic torque it is describe $m_e = \Psi_{rq} i_a$, m_r - resistant torque, J - moment of inertia, $F_\propto$ - coefficient of viscous friction (in the Simulink scheme model is denoted *F_a* and *Psi_rq* is quadrature axis of the rotor oriented flux);

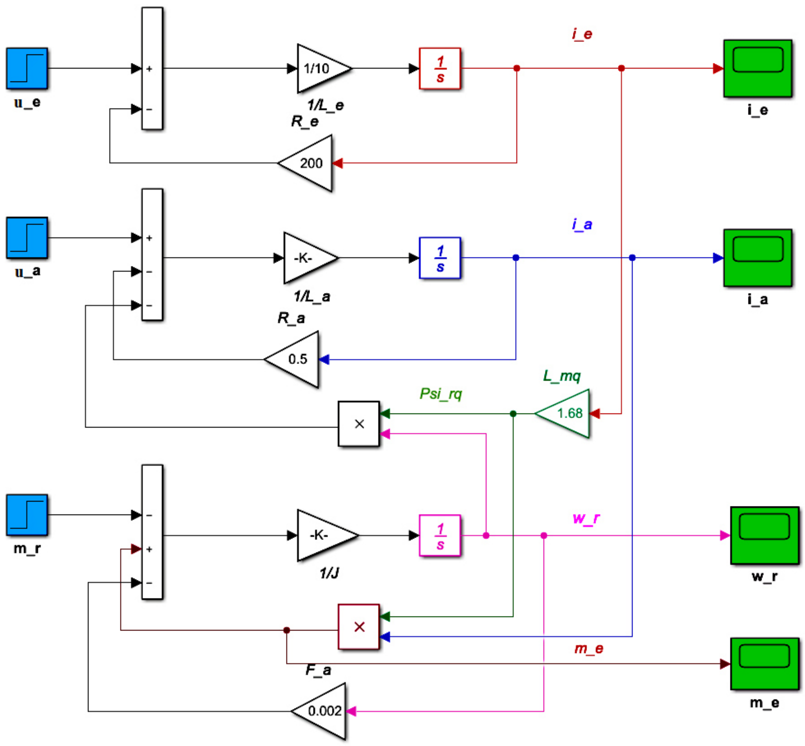

Fig. 1 – Simulink model of the DC motor.

In the following we have developed a virtual laboratory for a DC motor model in Matlab&Simulink with the following nominal values:

- P_n = 3 [kW] - rated power;
- u_a = 115 [V] - supply voltage;
- u_e =115 [V] - excitation circuit supply voltage;
- R_a = 0.5 [Ω] - winding resistance of the inductor;
- L_a = 0.008 [H] - inductance of the inductor;
- R_e = 200 [Ω] - excitation circuit winding resistance;
- L_e = 10 [H] - excitation inductance;
- L_{mq} = 1.68 [H] - main magnetizing inductance reduced to inductance;
- J = 0.024 [Kgm^2] - moment of inertia;
- $F_\propto$ = 0.002 [Nms] - coefficient of viscous friction;
- m_r = 14 [Nm] - resistant torque.

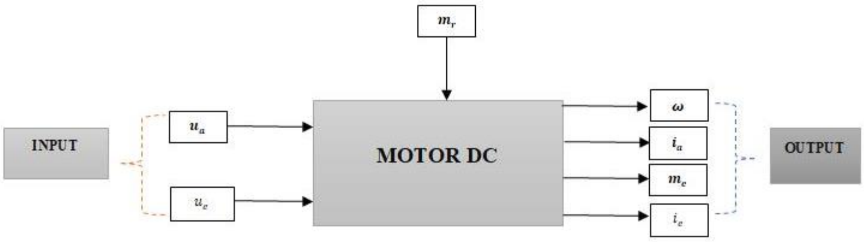

Fig. 2 – DC motor block diagram.

The output quantities of the DC motor are:

- ω [rad/s] - engine speed;
- i_a [A] - induced current;
- i_e [A] - excitation current.

4. Numerical Simulation

The most important purpose of implementing this Simulink model is to support the educational process. The model can be used for practical training purposes in the electrical engineering area. The present simulation will be intended to illustrate the wide range of possible topics in which the DC motor model can significantly enrich the teaching-learning lessons in the education system. We created the Simulink model of the DC motor and, by introducing different values of input quantities, we experimented the evolution of the parameters.

4.1. Block that Models the DC Motor Excitation Circuit

This block is described by the equation: $u_e = R_e i_e + \frac{d\Psi_e}{dt}$ and is implemented in the Simulink program as in Fig. 3.

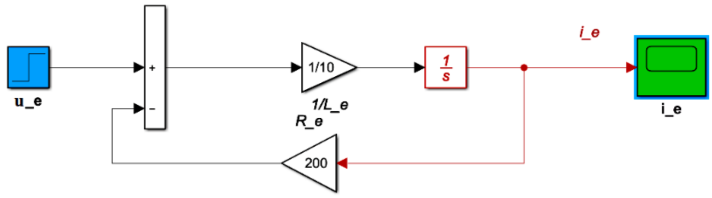

Fig. 3 – Simulink model representation for the block modeling the excitation circuit.

Thus, for the excitation block (input size u_e, output size i_e) the following were used:

- At time t = 0, supply the circuit from a Step Source with the excitation circuit supply voltage u_e = 115 V;
- Rectangular shaped summator with 2 inputs, the positive input of which is applied the supply voltage of the excitation circuit;
- Gain block, which is designed to remove the variable L_e variable in front of di_e/dt;
- Integrator, which has the function of integrating the di_e/dt, resulting in the current i_e;
- Scope, is used to show the time-varying form of the excitation current (i_e).

The simulation obtained the current variation curve in Fig. 4.

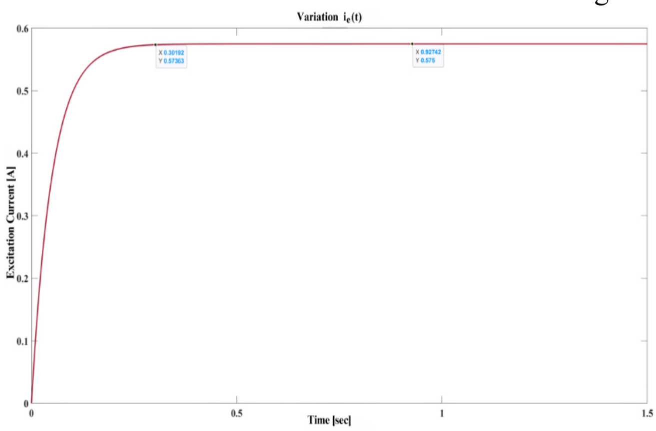

Fig. 4 – Excitation current variation.

To start the motor, first energize the excitation winding at t = 0 s with 115 V. Between t = 0 and t = 0.3 s, the aperiodic transient starting regime is observed. After t = 0.3 s, the circuit enters the steady state where i_e is set to 0.573 A.

4.2. Block that Models the DC Motor Inductance Circuit

This block is described by the equation: $u_a = R_a i_a + \frac{d\Psi_a}{dt} + \omega_r \Psi_{rq}$ and is implemented in the Simulink program as in Fig. 5.

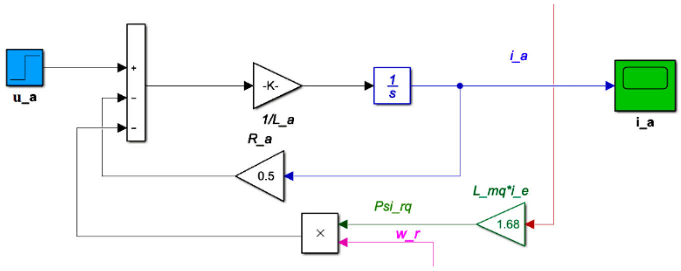

Fig. 5 – Simulink model representation for the block modeling the inductor circuit.

Thus, for the induced block (input quantity u_a, output quantity i_a) the following were used:

- At time t = 0.3 s, the circuit is supplied from a Step Source, with supply voltage u_a= 115 V;
- Rectangular shaped summator with 3 inputs, the positive input of which is applied to the supply voltage of the inductor;
- Gain block, which is designed to remove the variable L_a variable in front of di_a/dt;
- Integrator, which has the function of integrating the di_a/dt, resulting in the current i_a;
- In the 3rd input of the summing unit, the negative input is connected to the signal from the relationship $\Psi_{rq} = L_{mq} i_e$ via a gain block with the amplification factor L_{mq}= 1.68 H. Ψ_{rq} is multiplied by the Product block by the speed ω_r;
- Scope, is used to show the time-varying form of the induced current (i_a).

From simulation, the current variation curve in Fig. 6 is obtained.

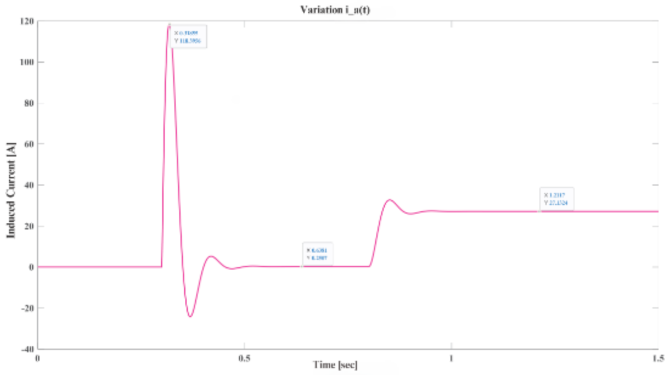

Fig. 6 – Variation of induced current.

After termination of the transient regime of the excitation circuit, t = 0.3 s, the inductor circuit is supplied with 115 V. The current has a sudden increase to 118.39 V, which is characteristic of a DC motor. After the end of the transient starting regime, the current is very low at 0.41 A due to friction force. The circuit enters a steady-state idling mode when the current is 0.25 A. At t = 0.8 s the motor is charged, at which point a new transient on-load mode begins and the current rises again to 32.68 A. After the transient is extinguished, the circuit enters steady-state on-load operation and the induced current settles at 27.13 A.

4.3. Block that Models the DC Motor Mechanical Circuit

This block is described by the motion equation:

$$\frac{d\omega_r}{dt} = \frac{1}{J}(m_e - m_r - m_{\propto}) \tag{4}$$

and by the electromagnetic torque expression:

$$m_e = \Psi_{rq} i_a \tag{5}$$

It is implemented in Simulink as in Fig. 7.

Thus, for the mechanical block (input quantity m_r, output quantity ω_r, m_e repectively) the following were used:

- The step source, which provides the resistive torque (m_r), which has Step time = 1, Initial Value = 0, Final value = 26 Nm;
- Rectangular shaped summator with 3 inputs; to its negative input, the resistant torque of the motor is added;

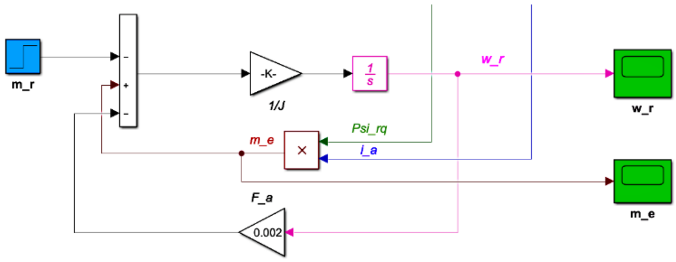

Fig. 7 – Simulink model representation for the block modeling the mechanical circuit.

- Gain block, which is designed to remove the variable J (moment of inertia) in front of $d\omega_r/dt$;
- Integrator, which has the function of integrating the $d\omega_r/dt$, resulting in the engine speed ω_r;
- Towards the end the value of the induced current (i_a) by the value of Ψ_{rq} for which a product block was also used, resulting in the value of the active torque (m_e), which was fed to the positive input of the summation unit;
- In the 3rd entry of the summing machine, the negative entry is brought F_a, this was determined by adding a Gain Block;
- Two scopes displaying the engine speed variation (ω_r) and the active torque variation (m_e), are finally mounted.

The simulation obtained for the engine speed is shown in Fig. 8.

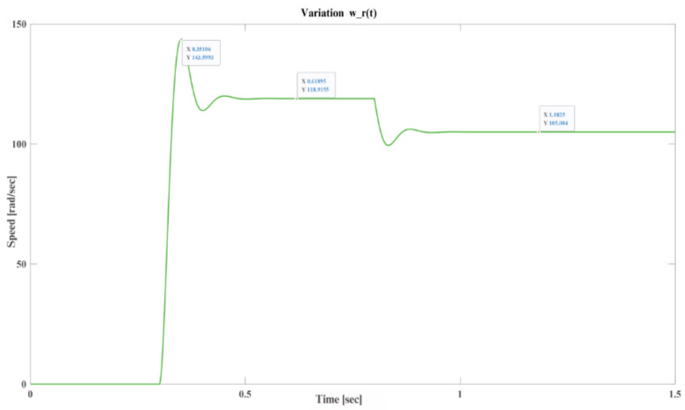

Fig. 8 – Speed variation simulation.

After completion of the transient regime of the excitation circuit t = 0.3 s, the mechanical circuit is supplied with a resistive torque of 26 Nm. The speed suddenly increases to 143.59 rad/s after which, at the end of the transient starting regime, the speed decreases to 113.91 rad/s. The circuit enters the steady-state operating mode when the speed is 118.91 rad/s. At t = 0.8 s, the engine is charged, at which point a new transient on-load mode begins and the speed increases again to 106 rad/s. After the transient is extinguished, the circuit goes into steady-state on-load operation and the engine speed settles at 105.004 rad/s.

The simulation of the active torque variation is presented curve in Fig. 9.

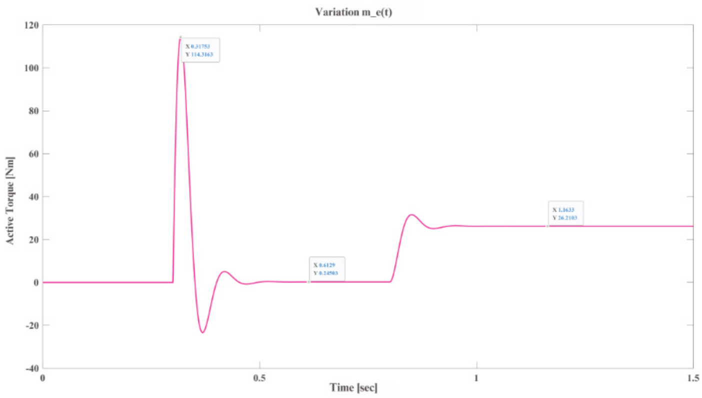

Fig. 9 – Variation of active torque.

Since, the active torque depends on the induced current (i_a), there is a sharp increase to 114.31 Nm. After the value of t = 0.41 s, a steady state idling condition is entered at a constant value of the active torque of 0.61 Nm, which is a very small value due to friction. When the engine is under load, the active torque increases to 31.53 Nm and then enters a steady state under load at 26.21 Nm.

5. Conclusions

We believe that the virtual lab is an experiment in teaching efficiency and has the ability to improve students' learning initiative. With this paper we want to describe in detail the implementation of a virtual lab to simulate an electric machine based on a mathematical model and input quantities, over time, observing the evolution of various parameters according to the input values that can be easily controlled.

This approach also describes that the development cycle of the Matlab&Simulink based virtual lab in correspondence with the traditional one implies particular advantages from our point of view, such as: the time allocated to the implementation of the virtual lab is less than in the traditional one, the efficiency of the virtual lab is higher and the scalability of the virtual lab is wider, and the cost of the virtual lab is much lower than in the traditional one.

That is why the virtual lab based on a Simulink model is more and more widely applied nowadays. However, the virtual lab is based on virtual technology, which is different from the actual laboratory in terms of the lack of physical system. Therefore, in practice, we aimed to make full use of the advantages of virtual labs, at the same time to manage the state of the virtual experiment correctly.

The DC motor is still widely used as a motor in electric drives with adjustable speed in wide limits, due to the high performance in terms of speed and accuracy of response to commands in speed, position or torque.

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ABORDĂRI PRIVIND REALIZAREA ÎN MATLAB&SIMULINK A UNUI LABORATOR VIRTUAL DE MAȘINI ELECTRICE

(Rezumat)

Acest laborator virtual integrează modelul experimental Matlab&Simulink, care oferă studenților posibilitatea de a-și verifica cunoștințele teoretice. Lucrarea propune dezvoltarea modelului Simulink al motorului de curent continuu, cu scopul de a realiza un control mai eficient al vitezei. Descriem implementarea unui laborator virtual bazat pe modele matematice. Laboratorul nostru virtual din Matlab&Simulink în

corespondență cu cel tradițional implică avantaje deosebite: timpul alocat dezvoltării unui laborator virtual este mai scurt decât cel necesar unuia clasic, scalabilitatea este mai largă și costul este mai mic. Lucrarea prezintă cele trei blocuri principale: excitația, inductorul și blocul mecanic. Se stabilesc parametrii care definesc atât regimul tranzitoriu al circuitului de excitație (durata de aplicare și tensiunea de excitație), cât și regimul de funcționare stabilizat la ralanti. Se studiază noul regim tranzitoriu de funcționare sub sarcină, urmat de regimul stabilizat de funcționare sub sarcină.