

A Virtual-Lab Tool for Teaching the Fundamentals of a DC Motor-Generator Operation using Excel-VBA

Cleber Gustavo Dias

Informatics and Knowledge Management Graduate Program
Nove de Julho University - UNINOVE
São Paulo - Brazil

Luiz Carlos da Silva

Informatics and Knowledge Management Graduate Program
Nove de Julho University - UNINOVE
São Paulo - Brazil

ABSTRACT

This paper presents an Excel-VBA implementation tool for teaching some fundamentals of rotating electrical machines in undergraduate and graduate level, particularly for electrical engineering curriculum. The basic concepts of a Direct Current (DC) motor operation and a DC generator have been simulated for several operational scenarios. The simulation results have been compared to mathematical models implemented in the Matlab/Simulink© environment using the 4th Runge-Kutta method for numerical solution of the differential equations that correspond to the dynamic behavior of the electrical machine. In addition, some experimental results have shown a good approximation between the simulation results obtained from the proposed virtual tool and the experimental data. Therefore, the present development is capable of serving as a potential virtual lab for a better understanding of rotating electrical machines concepts, particularly for undergraduate courses.

Keywords

Engineering Education, Virtual Lab, Rotating Machines, STEM Learning, Visual Basic for Applications

1. INTRODUCTION

The study of rotating electrical machines is a huge challenge for many students, since it requires a good background on advanced calculus and electromagnetics [1]. In many cases, engineering and engineering technology students lack the required background, and they have difficulties to learn these subjects. Even for graduate level, the mathematical concepts belong to Direct Current (DC) and Alternating Current (AC) rotating machines are quite complex to understand. In this sense, the dynamic behavior of the electrical motors is governed by different type of equations, such as mechanical, electrical and thermal conditions. Other works have addressed this kind of problem, particularly in the field of electrical machines [2]. In this work, the authors have mentioned the fact that it is not possible to understand the depth of some concepts without exploring the practical aspects of electrical machines.

As cited by a recent work [3], the economic limitations for the acquisition of material and the limitations of laboratory availability makes some experimental practices be carried out in a limited duration and controlled extension within excessive rigid sessions, which

means that the students have a restricted contact with the practical issues related to the learning of electrical machines concepts.

As cited by [4], usually the engineering experiments are carried out in small groups of students and often at specified times, in fixed laboratories and with custom lab benches, thus, the use of computer tools are emerging in the field of education, such as the virtual laboratories.

For over a decade, other researchers have demonstrated the relevant use of such tools in the education environment. In [5], for example, the authors have described the importance of the development and use of the simulation and remote labs for improving the students learning experiences. They have also mentioned that the simulations play a vital role in engineering education, especially considering laboratory exercises.

In the work published by [6], the authors have presented a critical overview of existing concepts and technologies in the field of virtual laboratories, being possible to identify some trends, advantages and drawbacks. The researchers have shown that virtual systems provide a cost-efficient way for schools and universities and several students can use the same virtual equipment at the same time. On the other hand, this work cited a drawback related to this kind of solution, being often time-consuming to configure. However, a simple software tool, such as the solution proposed in this paper could be very useful and user-friendly, since MS-Excel is well known by the general public, including engineering students, for example.

In [7], the authors have proposed a virtual laboratory for supporting high school learning activities and a survey applied to 40 students have shown that 90% of them said that virtual laboratory is ease to use.

In [8], for example, the authors have presented a virtual learning laboratory environment for undergraduate mathematics education in some real-world applications spanning signal processing, data science and analytics with good results that can enhance students' learning.

In the engineering field, virtual and remote laboratories are becoming powerful tools that let the students better understand concepts and simulate several operational conditions similar to those found in a real equipment. More particularly, the virtual laboratories allow the students to learning not only regular, but also fault scenarios [9], [10] and [11]. For electrical engineering simulations, there are some works ([2],[3],[12],[13],[14],[15]) that have addressed electrical machines and/or the behavior of the rotating magnetic fields

in virtual environments.

In addition, the use of Microsoft Excel Solver and Excel Visual Basic for Applications (VBA) have been demonstrated an efficient and interesting tool for simulation in distinct knowledge fields. In [16], for instance, the authors have used an Excel VBA-based education module for simulation and energy optimization of spray drying process, widely used in chemical, ceramic, food and pharmaceutical industries for manufacturing of high-volume, as well as high-value particulate products.

In [17], the researchers have addressed the application of the Microsoft Excel Solver tool in the optimization of distillation sequence problems. In [18], Excel-VBA has been used for teaching hydraulics of pipe flow in engineering curricula and in [19], Excel-VBA has been applied for 2-dimensional finite-element (FE) stress analysis.

In this sense, the present research proposes the use of Excel-VBA for teaching the fundamentals of a DC motor running at several operational conditions. As cited by [18], for example, a virtual tool implemented in Excel-VBA is very similar to MS Excel's built-in worksheet functions, being possible to obtain real-time solutions and the user is able to view the results immediately after changing any parameter of the system. As cited by [16], the familiarity with Excel interface and the rich graphical user interface of developed Excel VBA enable students to accomplish the requested tasks independently in a short time.

Therefore, the proposed Excel environment allows the student to obtain an user-friendly operational interface and the results quickly. The operational scenarios simulated with a DC machine, running as a motor and as a DC generator, have been compared to a mathematical model implemented in the Matlab/Simulink software. The developed tool has been demonstrated good results and can be used as a potential virtual lab for a better understanding of rotating electrical machines concepts.

2. THEORETICAL BACKGROUND

2.1 DC Motor Mathematical Model (Separately Excited DC motor)

Over the last century, many articles and textbooks have addressed the design, theory and the operation of DC machines ([20],[21],[22] and [13]). The dynamic characteristics of this electrical machine are usually solved by using Laplace transformation techniques [20]. Essentially, this type of motor has two windings, the field winding (LFF) and the armature (LAA) coil, as shown in Fig. 1.

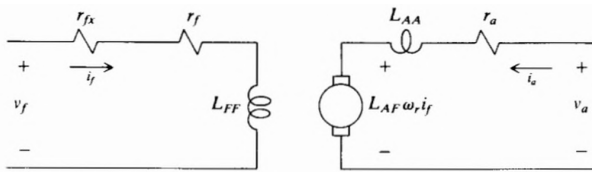


Fig. 1: Equivalent circuit for separate field and armature excitation [20]

Both windings are feed with a DC supply, or the field may be created by permanent magnets. The called main flux is those produced by the field winding i_f . In this machine, the current flowing through the armature coil i_a interacts with the main flux to produce the rotational force (torque). A simulation model of a separately excited DC motor was built using Excel-VBA. In matrix form, the field and armature voltage equations of this machine can be written as [20]:

$$\begin{bmatrix} v_f \\ v_a \end{bmatrix} = \begin{bmatrix} r_f + r_{fx} + \rho L_{FF} & 0 \\ \omega_r L_{AF} & r_a + \rho L_{AA} \end{bmatrix} \cdot \begin{bmatrix} i_f \\ i_a \end{bmatrix} \quad (1)$$

Where L_{FF} and L_{AA} are the self-inductances of the field and armature windings, respectively, and ρ is the short-hand notation for the operator d/dt .

The voltage equations of a DC motor are also given by:

$$V_f = R_f \cdot I_f \quad (2)$$

$$v_a(t) = r_a \cdot i_a(t) + L_{AA} \left(\frac{di_a(t)}{dt} \right) + \omega_r L_{AF} I_f \quad (3)$$

Where $R_f = r_{fx} + r_f$ and capital letters are used to denote steady-state voltage and currents. In this work, the resistance value of r_{fx} is set to zero, since this parameter is related to the use of an external field rheostat and this research employed a DC supply for this case. The torque and rotor speed of the DC motor are related by (4):

$$T_e = J \left(\frac{d\omega_r(t)}{dt} \right) + B_m \omega_r + T_L \quad (4)$$

Where J is the inertia of the rotor and, in some cases, the connected mechanical load. As described by [20], the load torque T_L is positive for a torque, on the shaft of the rotor, which opposes a positive electromagnetic torque T_e .

The constant B_m is a damping coefficient associated with the mechanical rotational system of the machine and ω_r is the rotor speed of the rotor. In this paper, equations 2, 3 and 4 are used to simulate a separately DC motor and/or generator as shown in section 4. In the next section, the development of the virtual lab environment is presented.

3. THE IMPLEMENTATION OF THE VIRTUAL LAB ENVIRONMENT

3.1 The Graphical Interface Development

In the present work the DC electrical machine mathematical model has been implemented using Excel Visual Basic for Application (VBA) environment. In addition, the graphical interface has been built using the activeX controls on a worksheet, such as text box, command button, option button, scroll bars, among others. In Fig.2 it is possible to observe the main interface used to set up the DC motor simulation parameters.

In this interface, the student can easily set up the electrical parameters of the motor, such as the r_f , r_a , armature and field voltage levels and other machine parameters like armature inductance, inertia of the rotor, damping coefficient, initial load torque and mutual inductance. By using the red command button, labeled "Simulation Parameters and Results", it is possible to navigate to the simulation results interface, as shown in Fig.3.

It should be noted that, the electrical parameters and some mechanical values, such as the speed (rpm) and the load torque (N.m) are arranged in such a way that allow the student to better understand their connection to the equivalent electrical circuit (Fig. 1).

In Fig.2, the student can set up the simulation parameters such as the start time, stop time and the simulation step. Moreover, it is possible to modify the load torque during simulation, the armature voltage level and the field voltage level. These values can be easily adjusted by entering new values in the text box components. In Fig. 2, the students can monitor and observe the simulation results using graphic components of the Excel software, thus, in a very intuitive visualization.

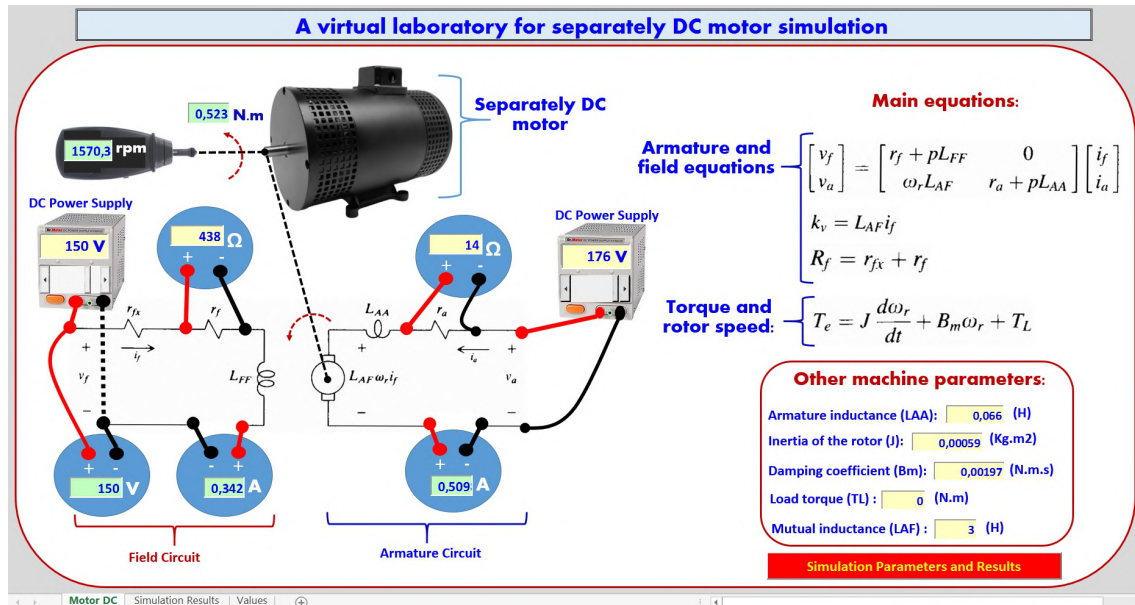


Fig. 2: Main user interface used for a separately DC motor parameter configuration

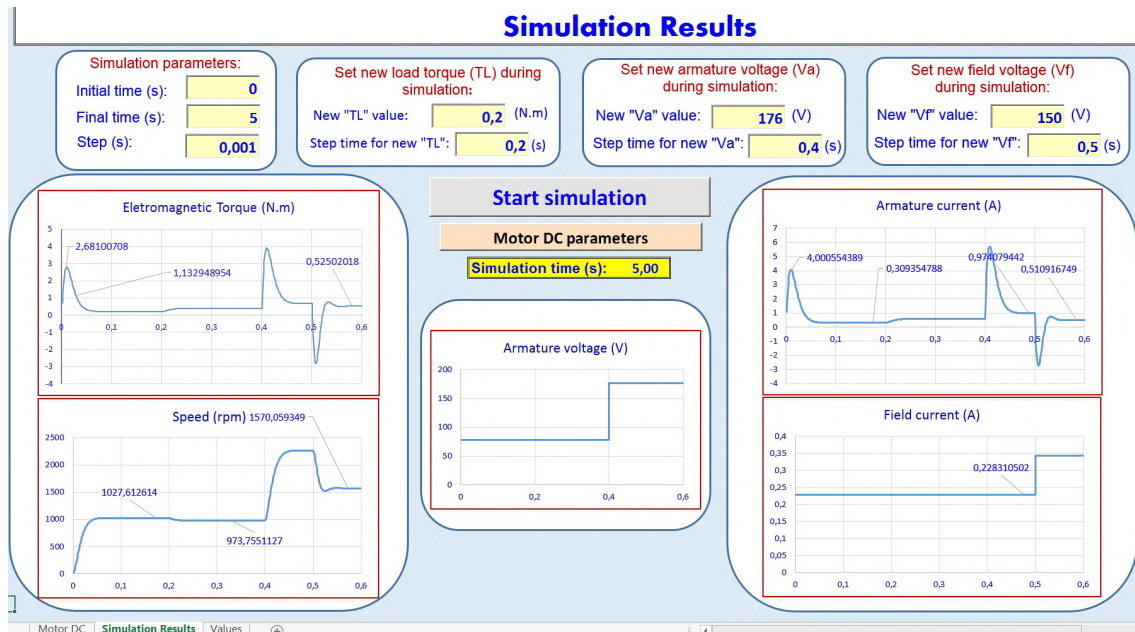


Fig. 3: Interface used for monitoring the simulation results

Finally, by clicking on the orange command button, labeled "Motor DC parameters", the user will return to the previous screen (Main interface). In Fig.4, the student has the possibility to debug the simulation results for each step simulation.

3.2 The DC motor mathematical model implementation

The mathematical model of the DC machine has been built using the 4th order Runge-Kutta (RK4) numerical integration routine, since this kind of solution provides an acceptable tradeoff between accuracy and computational cost ([23]-[24]). For simulation purposes, equation (3) and (4) have been rewritten respectively as fol-

Simulation Values							
Time (s)	Torque (N.m)	Previous speed	Next speed	Previous armature current (A)	Next armature current (A)	Field current (A)	Armature voltage (V)
0.001	0	2,64409221	0	0,419639712	0,777307592	0,130151844	30
0.002	0,163850647	2,64409221	7,533904821	0,419639712	0,777307592	0,130151844	30
0.003	0,303504049	7,533904821	14,31867029	0,777307592	1,080648895	0,130151844	30
0.004	0,421945338	14,31867029	22,69254962	1,080648895	1,336407347	0,130151844	30
0.005	0,521807641	22,69254962	32,38788222	1,336407347	1,550530084	0,130151844	30
0.006	0,605413048	32,38788222	43,17093947	1,550530084	1,728260407	0,130151844	30
0.007	0,674808836	43,17093947	54,83789337	1,728260407	1,874219795	0,130151844	30
0.008	0,731799486	54,83789337	67,21125535	1,874219795	1,992480403	0,130151844	30
0.009	0,777974994	67,21125535	80,13673087	1,992480403	2,086629144	0,130151844	30
0.01	0,814752891	80,13673087	93,48044142	2,086629144	2,159824348	0,130151844	30
0.011	0,843315363	93,48044142	107,1264714	2,159824348	2,214845836	0,130151844	30
0.012	0,864798808	107,1264714	120,974702	2,214845836	2,254139187	0,130151844	30
0.013	0,880141114	120,974702	134,9388991	2,254139187	2,279854864	0,130151844	30
0.014	0,890181942	134,9388991	148,945025	2,279854864	2,293882794	0,130151844	30
0.015	0,89569225	148,945025	162,929749	2,293882794	2,297882936	0,130151844	30
0.016	0,897221103	162,929749	176,8391323	2,297882936	2,29312252	0,130151844	30
0.017	0,89543647	176,8391323	190,6274688	2,29312252	2,281448776	0,130151844	30
0.018	0,890804294	190,6274688	204,2562619	2,281448776	2,263412317	0,130151844	30
0.019	0,883761859	204,2562619	217,6933221	2,263412317	2,240183494	0,130151844	30
0.02	0,874692037	217,6933221	230,9119722	2,240183494	2,212620008	0,130151844	30

Fig. 4: Simulation results interface (each integration step)

lows, in order to solving the initial value problem for each ordinary differential equation (ODE):

$$\frac{di_a(t)}{dt} = \frac{v_a(t) - r_a \cdot i_a(t) - \omega_r L_{AF} I_f}{L_{AA}} \quad (5)$$

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L - B_m \omega_r}{J} \quad (6)$$

As cited by [25], the RK4 is an interesting numerical solution for differential equations, thus, in the present research RK4 has been applied to solve equations (5) and (6). The RK4 method is given by the following equations:

$$y_{k+1} = y_k + \frac{h(k_1 + 2k_2 + 2k_3 + k_4)}{6} \quad (7)$$

Where the slope approximations are given by:

$$\begin{cases} k_1 = f(x_k, y_k), \\ k_2 = f(x_k + \frac{h}{2}, y_k + k_1 \frac{h}{2}), \\ k_3 = f(x_k + \frac{h}{2}, y_k + k_2 \frac{h}{2}), \\ k_4 = f(x_k + h, y_k + hk_3). \end{cases} \quad (8)$$

Figures 5 and 6 shows a piece of code in VBA for calculating i_a and ω_r using RK4 method. In the present study, the step h has been set up to 0.001s.

```
K1ia = (V1 - Ra * Iaanterior - kv * Omegaanterior) / La
K2ia = (V1 - Ra * (Iaanterior + K1ia * passo / 2) - kv * (Omegaanterior + K1ia * passo / 2)) / La
K3ia = (V1 - Ra * (Iaanterior + K2ia * passo / 2) - kv * (Omegaanterior + K2ia * passo / 2)) / La
K4ia = (V1 - Ra * (Iaanterior + K3ia * passo) - kv * (Omegaanterior + K3ia * passo)) / La
DERIVADAia = 1 / 6 * (K1ia + 2 * K2ia + 2 * K3ia + K4ia)
```

Fig. 5: Piece of VBA code for calculating i_a using RK4 method

```
K1Omega = (Torqueposterior - B * Omegaanterior - Torquecarga) / J
K2Omega = (Torqueposterior - B * (Omegaanterior + K1Omega * passo / 2) - Torquecarga) / J
K3Omega = (Torqueposterior - B * (Omegaanterior + K2Omega * passo / 2) - Torquecarga) / J
K4Omega = (Torqueposterior - B * (Omegaanterior + K3Omega * passo) - Torquecarga) / J
DERIVADAOmega = 1 / 6 * (K1Omega + 2 * K2Omega + 2 * K3Omega + K4Omega)
```

Fig. 6: Piece of VBA code for calculating ω_r using RK4 method

4. SIMULATION RESULTS AND DISCUSSION

In this section the simulations results are presented and discussed for a separately excited DC machine running as a motor and generator. For all simulation scenarios, the DC machine has the parameters shown in Table 1. For each case, the simulation results have been compared to the DC machine mathematical model (equations 5 and 6) simulation implemented in the Matlab/Simulink®. For this purposes, the differential equations have been modeled using Laplace Transform functions, as shown in Fig. 7.

Table 1. : Separately Excited DC Machine Parameters

Parameter	Value
Rated Power (P)	0.5 CV
Rated Armature Voltage (V_a)	160 V
Rated Field Voltage (V_f)	190 V
Armature Resistance (R_a)	10.3 Ω
Field Resistance (R_f)	461 Ω
Armature Inductance (L_{AA})	0.066 H
Mutual Inductance (L_{AF})	3 H
Inertia of the Rotor (J)	0.000591 $Kg.m^2$
Damping Coefficient (Bm)	0.00197 $N.m.s$

In this work, the following operational scenarios have been carried out and simulated:

- DC machine running as a motor and subjected to constant torque from start-up;
- DC machine running as a motor with load torque variations; and
- DC machine running as a generator with a constant resistive load.

4.1 Simulation Results for a DC machine running as a motor

The first two simulations have been carried out for a DC machine configured as a motor. For the first scenario, the DC machine has been configured as a motor which has been started without load torque.

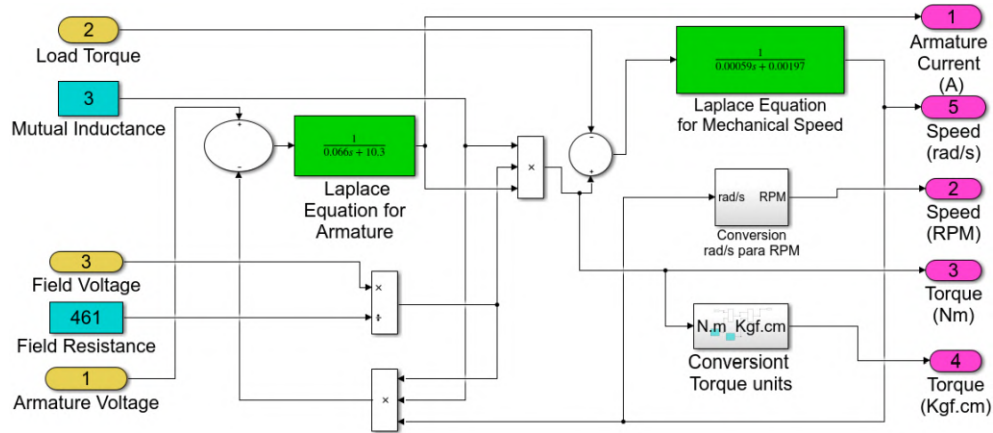


Fig. 7: DC machine mathematical model implemented in the Simulink environment

4.1.1 DC motor starting without load ($T_L = 0 \text{ N.m}$): In this scenario, the following values has set up: $V_a = 30\text{V}$, $V_f = 100 \text{ V}$, start time = 0, stop time = 1s, fixed-step size = 0.001s. As shown in Fig.8, it is possible to observe a good approximation between the present virtual lab results and those obtained from the mathematical model implemented in the Matlab/simulink©. In Fig. 9, the armature current simulated with both models shows a good approximation. It is also possible to note in Fig. 9 some numerical results obtained with the same Runge-Kutta (RK4) numerical integration routine.

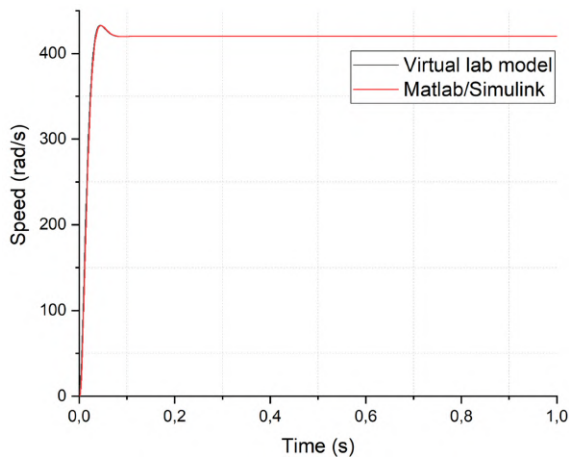


Fig. 8: Comparison between the rotor speed simulated with the present model and the model implemented in the Simulink

4.1.2 DC motor running with constant load ($T_L = 1.2 \text{ N.m}$): In this scenario, the following values has set up: $V_a = 30\text{V}$, $V_f = 100 \text{ V}$, start time = 0, stop time = 1s, fixed-step size = 0.001s. It should be mentioned that the motor rated load is around 1.65 N.m. As can be seen in figures 10 and 11 there is a good approximation between the results obtained with the present virtual lab tool and the model implemented in the Matlab.

In Fig.11 it is possible to observe, during the start of the DC motor, the integration values on each step using the RK4 routine and the approximation between the values obtained during simulation.

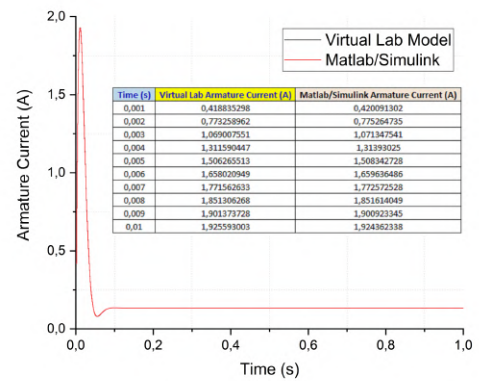


Fig. 9: Comparison between the armature current simulated with the present model and the model implemented in the Simulink

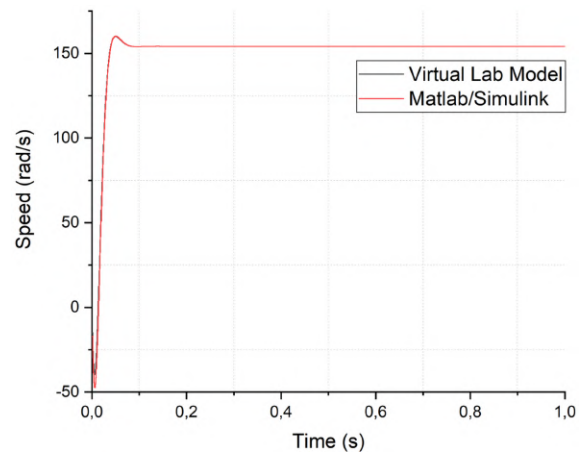


Fig. 10: Comparison between the rotor speed simulated with the present model and the model implemented in the Simulink ($T_L = 1.2 \text{ N.m}$)

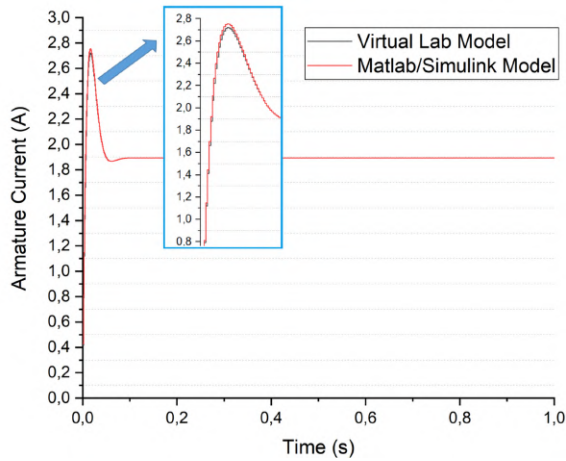


Fig. 11: Comparison between the armature current simulated with the present model and the model implemented in the Simulink ($T_L = 1.2$ N.m)

4.1.3 DC motor running with load torque variations . In this case, the motor has started without load and in a step time equal to 0.5s a $T_L = 1.4$ N.m has been applied to the rotor shaft. The following values has set up: $V_a = 30$ V, $V_f = 100$ V, start time = 0, stop time = 1s, fixed-step size = 0.001s. The simulation results, showed in figures 12, 13 and 14, have demonstrated, once again, a good approximation between the present tool and the mathematical model implemented in the Matlab/Simulink®.

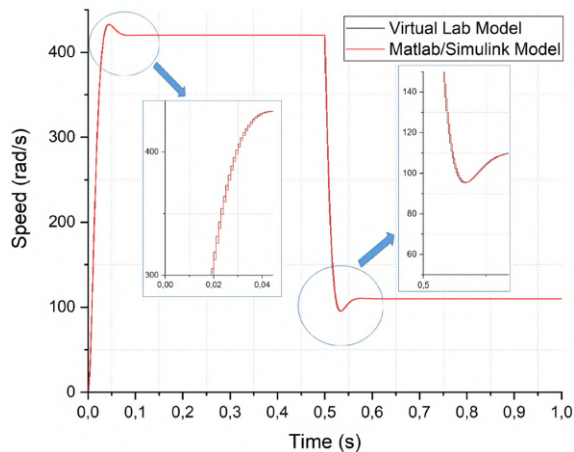


Fig. 12: Comparison between the rotor speed simulated with the present model and the model implemented in the Simulink (load torque variation)

4.2 Simulation Results for a DC machine running as a generator

The final simulation has been carried out for a DC machine set up as a DC generator. A load resistance $R_L = 50 \Omega$ has been connected to the armature terminals and several speed and field voltages have been tested. Table 2 shows the results obtained using the Excel-VBA model and the one implemented in the Matlab/Simulink®.

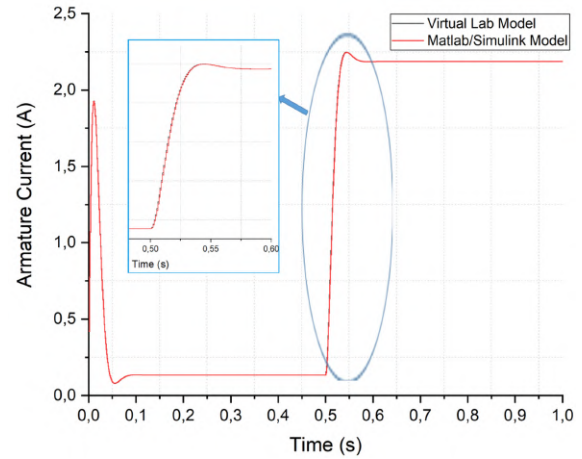


Fig. 13: Comparison between the armature current simulated with the present model and the model implemented in the Simulink (load torque variation)

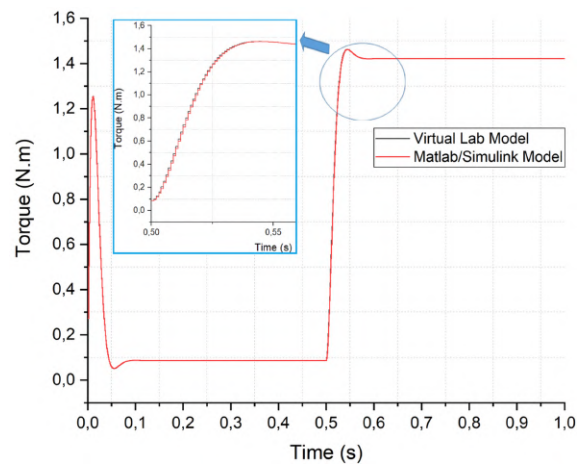


Fig. 14: Comparison between the torque simulated with the present model and the model implemented in the Simulink (load torque variation)

4.3 Experimental results for a DC machine running as a generator

An additional investigation has been carried out using some experimental data. Fig. 15 shows the experimental setup used for performing tests with DC machine running as a generator. In this case, DC machine has been driven by an induction motor (AC motor) and a load resistance has been connected to the armature terminals. The armature voltage has been evaluated for different field voltage levels and speed. In Table 3, for example, it is possible to observe a good approximation between voltage levels obtained for the present virtual lab tool and those results obtained from the experimental setup.

5. CONCLUSION

This paper presents the development of a virtual lab tool for teaching the fundamentals of a DC rotating machine. The lab tool has been implemented using Excel and Visual Basic for Applications

Table 2. : Comparison between the results using current model and the generator implemented in the Simulink

Operational Condition	Torque (N.m)	Torque (N.m)- Simulink	Armature Voltage (V)	Armature Voltage (V)- Simulink	Armature Current(A)	Armature Current(A)- Simulink
Speed = 180 rad/s and Field Voltage = 40 V	-0.2023	-0.2023	38.85	38.85	-0.777	-0.777
Speed = 180 rad/s and Field Voltage = 80 V	-0.8091	-0.8091	77.7	77.7	-1.5541	-1.554
Speed = 180 rad/s and Field Voltage = 120 V	-1.82	-1.82	116.55	116.6	-2.33	-2.331
Speed = 100 rad/s and Field Voltage = 140 V	-1376	-1.377	75.544	75.54	-1.51	-1.511
Speed = 150 rad/s and Field Voltage = 140 V	-2.064	-2.065	113.31	113.3	-2.266	-2.266
Speed = 250 rad/s and Field Voltage = 140 V	-3.441	-3.441	188.86	188.9	-3.777	-3.777

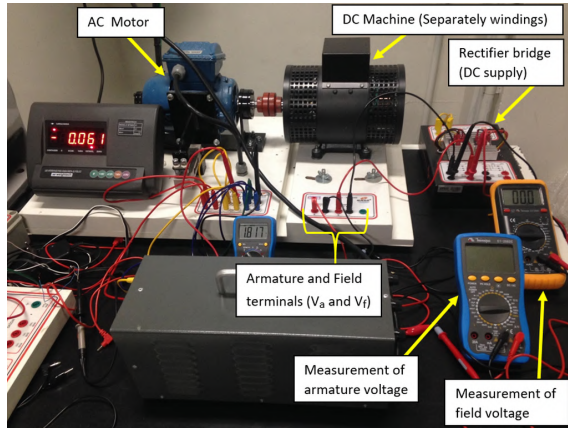


Fig. 15: Experimental setup used for DC generator tests

Table 3. : Comparison between some simulated and experimental results for armature voltage

Load (RL), V_f and speed (rpm)	V_a (Sim.)	V_a (Exp.)	Error
RL = 100Ω, V_f = 20V and ω_r = 1775 rpm	23.2 V	24.43 V	5.77 %
RL = 100Ω, V_f = 30V and ω_r = 1770 rpm	34.48 V	35.56 V	3.03 %
RL = 100Ω, V_f = 40V and ω_r = 1765 rpm	45.78 V	46.73 V	2.03 %
RL = 100Ω, V_f = 50V and ω_r = 1758 rpm	57.3 V	56.7 V	1.06 %
RL = 170Ω, V_f = 20V and ω_r = 1778 rpm	24.62 V	26.97 V	8.71 %
RL = 170Ω, V_f = 30V and ω_r = 1776 rpm	35.93 V	37.92 V	5.24 %
RL = 170Ω, V_f = 40V and ω_r = 1774 rpm	48.33 V	50.51 V	4.31 %
RL = 170Ω, V_f = 50V and ω_r = 1773 rpm	59.96 V	60.54 V	0.95 %

(VBA) environment. The graphical interface (screens) has been built using the active X controls on a worksheet and VBA has been applied to model the mathematical equations of a separately excited DC machine. The main equations have been implemented using the Runge Kutta numerical integration routine and several operational conditions have been carried out. The main interface allow students to set up the main parameters of the electrical machine and the simulation parameters are configured in other screen. It is possible to easily navigate between the screens. The machine has been set up as a motor and as a DC generator, being possible to achieve good simulation results using the present virtual tool and the same mathematical model implemented in the Matlab/Simulink software. Moreover, some experimental tests have shown a good approximation between the simulation results obtained from the present lab tool and those related to the experimental tests. Therefore, the authors understand that the present development is capable of serving as a potential virtual lab for a better understanding of rotating electrical machines concepts, particularly for undergraduate

courses.

Finally, the authors are conducting new studies, in order to develop new resources in the present VBA tool, like the scenarios for a speed or position control of the DC motor. Thus, it will be possible to add new features in the virtual lab and allow the students to better understanding concepts related to control engineering, for example, among others.

6. ACKNOWLEDGMENTS

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