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Dynamic electronic model for a DC motor - simulation and experimental validation

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***Abstract* – Modelling of a real system using different approaches is wide spread in the research and academic communities. There are many studies in literature that treats different ways of simulating systems more or less complex. In this paper, we developed a different approach for modelling a separate excitation DC motor. The proposed article is focused on finding a suitable model that represents the dynamic regime of such motors. Our approach uses an electronic implementation of the mathematical model of the DC motor. A special attention was given to the experimental determination of the mechanical parameters. By this approach the beneficiaries of this system, which will be engineering students, can have a better understanding on how the electronic circuits could be used to simulate a real system. Also our approach could serve for implementing remote laboratories for systems modelling-simulation for electrical engineering studies.**

Keywords- DC motor; transfer function; operational amplifier; RC network;remote laboratory

I. INTRODUCTION

The DC machine is widely studied in the educational programs. This is part because its wide spread use in practice and its mathematical model is easier to be implemented comparing with other types of electric machines. For this reason, the DC motor model is encountered in almost every book and manual regardless of the level of its target audience in the field of Control Systems [1].

Modelling of a real system using different approaches is wide spread in the research and academic communities[2][3][4]. There are many studies in literature that approaches different ways of simulating different systems more or less complex. Most of these studies use mathematical description of such systems[5][6][7].

A.M. Kassem [8] and O. Atlam [9] have studied the various aspects of applications of the DC motor in renewable energy systems, mostly in systems containing solar panel on different configurations of movements: one two axis orientation.

The application of DC motors in electrical vehicle dates since some time ago. A. Derdiyok, s.a. [10] indicates in 2004 a vehicle system driven by two DC motor, each one for one wheel. L. Kumar, s.a. states that traditionally for electric propulsion systems were used DC motors due to mechanical characteristics that are appropriate for vehicles [11]. F.K.Wu et all states that one of the advantages of using DC motors in electrical vehicles is that there is no slip between the tires and the road [12]. Besides traction applications in electrical or hybrid electrical vehicles, the DC motor finds its application integrated in different types of actuators. F. S. Ahmed et all have studied the application of the DC motor in automobile engine air path actuators [13]. The model they discuss is suitable for control purposes and incorporates friction and nonlinearities and temperature effects on the actuator. G. Zhang et all design a controller for a DC motor based suspension able to provide comfort by active control and harvest energy from irregularities of the roads [14]. The DC motor suspension system proved to be high efficient, have fast response and good controllability. It came to the attention of researchers that the DC motor could find its use also in two wheels vehicles, like motorbikes. F. Todeschini and his team studied the application of such motors in the braking systems of a motorbike [15].

The aeronautical industry also uses DC motors for different types of actuators. M. Ristanovic and his team studied the application of DC motor in an actuation system of an aerodynamic surface [16].

DC motors finds its application in medical actuators. B. Gonenc and H. Gurocak have studied the application of a DC motor in development of hybrid actuator combining a DC servomotor and magneto-rheological brake in order to study needle insertion with haptic feedback [17].

Because of use of the DC motors in a large variety of actuators, many researchers approach modern control techniques for it. In the scientific interests of researchers lies the application of modern control technique for the DC motors. R. Mondal, et all., implements an embedded closed loop speed control system for a DC motor based on 8051 microcontroller [18]. A. T. Alexandridis and G. C. Konstantopoulos present a nonlinear PI controller for a series-excited DC motor [19]. F. Beltran-Carbajal, et all, proposed a generalized proportional-integral output feedback dynamic control scheme with additional integral compensation of the output tracking error for DC motors [20]. R. Morales, et all, introduces the algebraic derivative estimation control for a DC motor [21].

A. B. Yildiz introduces a model for DC motors based on passive elements and controlled voltage and current sources in which all variables are electrical implemented [22].

In order to use the DC motors in present day applications, in many situations it is needed to determine its parameters as indicated by M. Knudsen and J. G. Jensen [23], A. A. Al-Qassar and M. Z. Othman [24], A. A. Bature, M. Muhammad, and A. M. Abdullahi [25], I. Völlmecke [26], M. S. Salah, P. Gaza, and M. Abdelati [27]. In these works the authors propose different methods to estimate and determine the DC motors' parameters. A special interest and research effort is used to determine parameters that intervene in dynamic model of the motor.

In this paper, we developed a different approach for modelling a separate excitation DC motor. The proposed article is focused on finding a suitable model that represents the dynamic regime of such motors. Our approach uses an electronic implementation of the mathematical model of the DC motor. A special attention was given to the experimental determination of the mechanical parameters. By this approach the beneficiaries of this system, which will be engineering students, can have a better understanding on how the electronic circuits could be used to simulate a real system.

This work is structured in five parts. In the introduction it is presented some updated applications of the DC machines and the necessity of studying it, its control and representations. The second part of the work presents the classical mathematical model of this machine. The third part of the paper studies the block schematic resulted from the application of Laplace transform to dynamic regime system equations. In this part of the work it is analysed a new representation of the DC machine using Operational Amplifiers (OA) structure in order to implement the mathematical equations that describe the transient functional regime of the DC motor. In the fourth part are presented experimental results in order to confirm the reliability of this implementation. There were done experimental tests under different function conditions and were compared the experimental with the simulation behaviour. The mechanical parameters of the dynamic regime are experimentally determined from direct acquisition data and numeric processing. The fifth part of the paper presents the conclusions.

II. MATHEMATICAL MODEL OF THE DC MOTOR

The schematic of a DC motor is indicated in Figure 1.

With the notations from Figure 1, in transitory regime, it could be written the system equations that describe the function of the motor:

$$\begin{cases} u_A(t) = R_A i_A(t) + L_A \dfrac{di_A(t)}{dt} + K\Phi\Omega(t) \\ J\dfrac{d\Omega(t)}{dt} = m - m_f - m_s \end{cases} \tag{1}$$

Where:

$m_f = f\cdot\Omega$ - is the viscous friction torque

f - is the viscous friction coefficient

m_s - is the kinetic friction torque

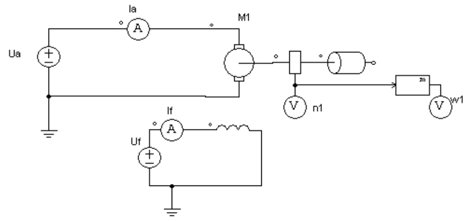

Figure 1. Schematic of a DC motor

In the system equation (1), by applying the Laplace transform it could be obtained system equations 2:

$$\begin{cases} U_A = R_A \cdot I_A(s) + L_A \cdot s \cdot I_A(s) + K \cdot \Phi \cdot \Omega(s) \\ J \cdot s \cdot \Omega(s) = K \cdot \Phi \cdot I_A(s) - f \cdot \Omega(s) - m_s \end{cases} \tag{2}$$

The system equation (2) can be rearranged in such a way that the expressions of the internal variables of the machine $I_A(s)$ and $\Omega(s)$ can be expressed as dependant of electrical parameters R_A, L_A and mechanical parameters J, f of the DC machine, as in system equations 3:

$$\begin{cases} I_A(s) = \left[U_A - K \cdot \Phi \cdot \Omega(s)\right] \cdot \dfrac{1}{R_A + s \cdot L_A} \\ \Omega(s) = \left[K \cdot \Phi \cdot I_A(s) - m_s\right] \cdot \dfrac{1}{s \cdot J + f} \end{cases} \tag{3}$$

III. THE EQUIVALENT CIRCUIT IMPLEMENTATION OF THE DC MOTOR

Translating system equations 3 in block diagram, results the block diagram for the DC motor, indicated in Figure 2. This is a classic representation of the block diagram of the DC motor, especially used in studying the transient functional regime. The block schematic in Figure 2 represents both the electrical as the mechanical parameters of the DC machine. This block schematic is used to model a DC machine with an independent excitation flux *Φ* with permanent magnets. Thus the excitation flux is independent of any other external circuit, and the *KΦ* constant can be determined from the nominal parameters of the machine. If it would have been the case of a shunt or a series DC machine, the *KΦ* constant would be generated by the field windings and constructive characteristics of it.

For the purposes needed in this paper, the equations (3) are expressed as indicated in equations (4):

$$\begin{cases} I_A(s) = [U_A - K\cdot\Phi\cdot\Omega(s) - R_A\cdot I_A(s)]\cdot\dfrac{1}{s\cdot L_A} \\ \Omega(s) = [K\cdot\Phi\cdot I_A(s) - m_s - f\cdot\Omega(s)]\cdot\dfrac{1}{s\cdot J} \end{cases} \quad (4)$$

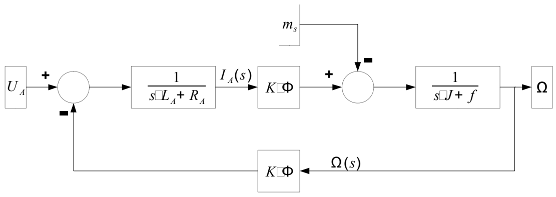

Figure 2. Block diagram of the DC motor

Consequently the block diagram of the machine is modified so that the integration operation in the block schematic to be independent of other mathematical operation and thus to obtain the expanded block diagram of the machine (Figure 3). The representations from Figure 2 and Figure 3 are equivalent.

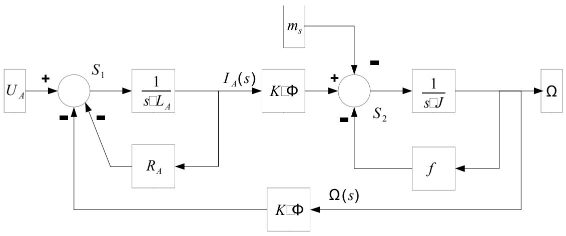

Figure 3. Expanded block diagram of the DC motor

The electrical and the mechanical representations of the block diagram can be divided into two block representations (Figure 4 and Figure 6).

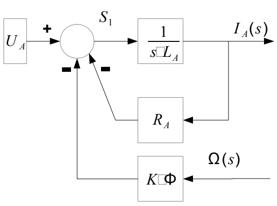

Figure 4. Block schematic of the implementation for the electrical functional equation

The representation of Figure 4 can be implemented with electronic schematics using Operational Amplifiers that combined with an *RC* network implement the same mathematical model of the machine.

In the schematic from Figure 5 both IOP3 as IOP8 are connected in the non-inverting configuration. The output signals of these structures are given by the equations 5 and 6.

$$\begin{cases} V_{outIOP3} = \left(1+\dfrac{R_3}{R_4}\right)\cdot V_{inIOP3} \\ V_{inIOP3} = -I_A \\ V_{outIOP3} = -R_A \end{cases} \Rightarrow [R_A] = 1+\frac{R_3}{R_4} \quad (5)$$

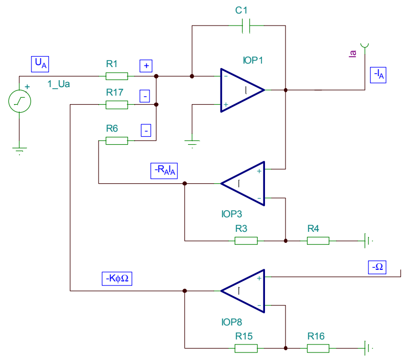

Figure 5. Electronic implementation of the electrical functional equation for the DC permanent magnet machine

$$\begin{cases} V_{outIOP8} = \left(1+\dfrac{R_{15}}{R_{16}}\right)\cdot V_{inIOP8} \\ V_{inIOP8} = -V_\Omega \\ V_{outIOP8} = -[K\Phi]V_\Omega \end{cases} \Rightarrow [K\Phi] = 1+\frac{R_{15}}{R_{16}} \quad (6)$$

$$\begin{cases} V_{outIO1} = -\dfrac{1}{s\cdot C_1}\cdot\left(\dfrac{U_A}{R_1} - \dfrac{[K\Phi]V_\Omega}{R_{17}} - \dfrac{R_A V_{I_A}}{R_6}\right) \\ R_1 = R_{17} = R_6 = R_{el\_circuit} \end{cases} \quad (7)$$

$$V_{outIO1} = -\frac{1}{s\cdot C_1 R_{el\_circuit}}\cdot\left(U_A - [K\Phi]V_\Omega - R_A V_{I_A}\right)$$

IOP1 is implementing two functions: integration and summation. The C1 capacitor in the reaction of IOP1 ensures the integration operation. Applying several voltages (U_A-$R_A V_{IA}$-[*KΦ*]·*V*Ω) to the negative input of IOP1 it is obtained the summation function represented by S1 in the schematic block from Figures 3 and 4. The equation 6 describes the S1 function displayed in Figure 4.

$$\begin{cases} I_A(s) = [U_A - K\Phi V_\Omega(s) - R_A V_{I_A}(s)]\cdot\dfrac{1}{s\cdot L_A} \\ V_{outIO1} = -\dfrac{1}{s\cdot C_1 R_{el\_circuit}}\left(U_A - [K\Phi]V_\Omega - R_A V_{I_A}\right) \end{cases} \quad (7)$$

$$\Rightarrow [L_A] = C_1 R_{el\_circuit}$$

In the equations 5, 6 and 7 are indicated the relations for expressing the values of electric parameters of the dynamic representations of the machine: R_A, L_A and *KΦ*.

Figure 6 displays the second summation operation involving the mechanical parameters of the motor.

Figure 7 represents the electronic implementation of the block representation from Figure 6.

$$\begin{cases} V_{outIO4} = -\dfrac{1}{s\cdot C_2}\cdot\left(\dfrac{[K\Phi]V_{I_A}}{R_7} - \dfrac{[f]V_\Omega}{R_{10}}\right) \\ R_7 = R_{10} = R_{mec\_circuit} \end{cases} \quad (8)$$

$$\Rightarrow V_{outIO4} = -\frac{1}{s\cdot C_2 R_{mec\_circuit}}\left([K\Phi]V_{I_A} - [f]V_\Omega\right)$$

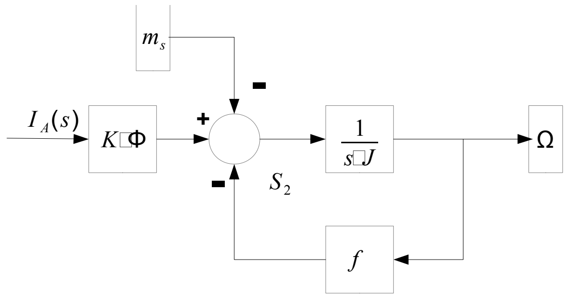

Figure 6. Block schematic of the implementation for the mechanical functional equation

$$\begin{cases} V_{outIO4} = -\dfrac{1}{s \cdot C_2 R_{mec\_circuit}}\left([K\Phi]V_{I_A} - V_{m_s}(s) - [f]V_{\Omega}\right) \\ \Omega(s) = \left[K\Phi V_{I_A}(s) - V_{m_s}(s) - [f]V_{\Omega}(s)\right] \cdot \dfrac{1}{s \cdot J} \end{cases} \quad (9)$$

$$\Rightarrow [J] = C_2 R_{mec\_circuit}$$

The IOP4 OA implements the integration and the summation functions for the mechanical dynamic representation of the machine. The implemented equations are 8 and 9.

The IOP14 and IOP9 are connected in the inverting configuration and they are the electronic implementation of the viscous friction coefficient expressed in the equations 10 and 11.

$$\begin{cases} V_{outIOP7} = -\dfrac{R_{14}}{R_{13}} \cdot V_{inIOP7} = -\dfrac{R_{14}}{R_{13}} \cdot V_{outIOP5} \\ V_{outIOP5} = -\dfrac{R_9}{R_8} \cdot V_{inIOP5} = -\dfrac{R_9}{R_8} \cdot V_{outIOP4} \end{cases} \quad (10)$$

$$\begin{cases} V_{outIOP7} = \dfrac{R_{14}}{R_{13}}\dfrac{R_9}{R_8} \cdot V_{outIOP4} \\ V_{outIOP7} = -[f]V_{\Omega} \\ V_{outIOP4} = -V_{\Omega} \end{cases} \qquad [f] = \frac{R_{14}}{R_{13}}\frac{R_9}{R_8} \quad (11)$$

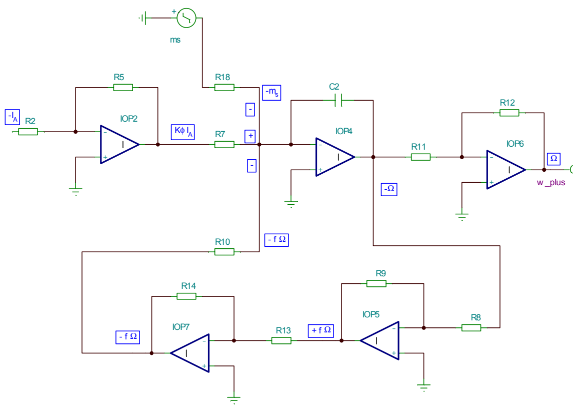

Figure 7. Electronic implementation of the mechanical functional equation for the DC permanent magnet machine

The equations (9) and (11) indicate the relations for expressing the values of the mechanical parameters of the dynamic representations of the machine: [*J*] and [*f*].

The IOP2 OA is connected in inverting configuration and its function is to express the value of [*KΦ*], as in equation(12). The [*KΦ*] parameter is also implemented by the IOP8 OA. The reason of different implementation of the same parameter in the same schematic is due to its placement and the sign of output voltages in different points of the electronic implementation of the machine model.

$$\begin{cases} V_{outIOP2} = -\dfrac{R_5}{R_2} \cdot V_{inIOP2} \\ V_{inIOP2} = -V_{I_A} \\ V_{outIOP2} = [K\Phi]V_{I_A} \end{cases} \qquad \Rightarrow [K\Phi] = \frac{R_5}{R_2} \quad (12)$$

From equations (6) and (12) it is determined the value [*KΦ*].

Combining all the configurations indicated in Figures 5 and 7 it is obtained the equivalent electronic implementation for a DC permanent magnets machine. The machine's parameters are implemented using OA in combination with *RC* networks (Figure 8). These electronic circuits implement different mathematical relations between electrical and mechanical parameters of the dynamic equivalent schematic (Figures 2 and 3).

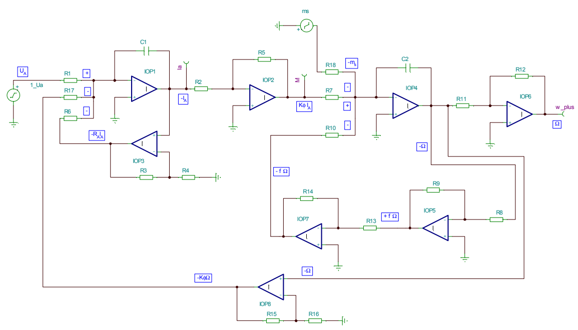

Figure 8. Electronic implementation of the DC permanent magnet machine

IV. Experimental Tests

To test the validity of the electronic equivalent schematic implementation of the DC machine (Figure 1) it was used a machine whose nominal parameters are indicated in table 1:

TABLE 1. Nominal Data for the DC Motor

	Nominal data		
	Data	***Value***	***Unit***
1	UA	200	V
2	IA	2,0	A
3	RA	15,8	Ω
4	LA	0,41	H
5	nn	1500	rot/min

Figure 10 indicates the behaviour of the motor when three levels of voltage are applied to its terminals. Using numerical and experimental methods as mentioned in [28][29][30] it was determined the mechanical dynamic parameters from the block schematic of the motor: *J* and *f*.

Table 2 indicates the parameters of the motor, determined during laboratory tests:

TABLE 2. DETERMINED DATA FOR THE DC MOTOR

	Measured data		
	Data	***Value***	***Unit***
1	J	0,29·10-3	kg·m2
2	f	1,48·10-3	Nm/rad/s

Figure 11 indicates that the dynamic comparison between the experimental acquisition data and simulation using the numerical values of the parameters *J* and *f*. The maximum error between the two curves is 0,92% for the stable function (2000 – 6000 ms) , and 4,48% for the speed decreasing domain (6000 – 7500 ms). These results conclude that parameters *J* and *f* are determined with enough precision.

Figure 9. Experimental stand for data measuring and acquisition

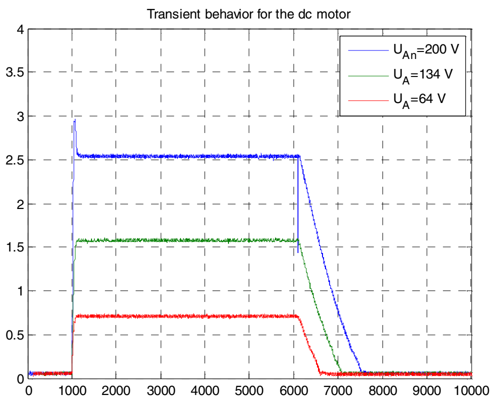

Figure 10. Dynamic behaviour of the DC motor with three level voltage supplies

Figure 12 presents the result simulation for the situations analysed in this present paper, data acquisition and simulations for the motor: model simulation program [32], transfer function and equivalent implementation using OA.

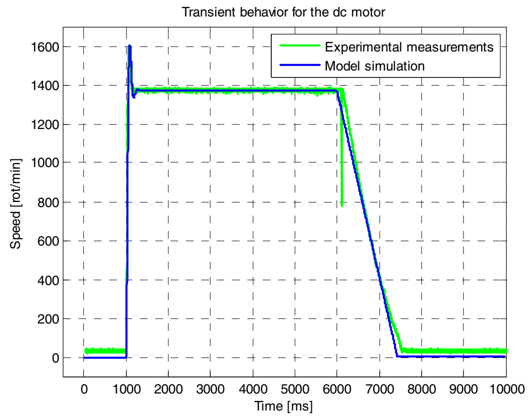

Figure 11. Transient representation of speed for confirmation of *J* and *f*

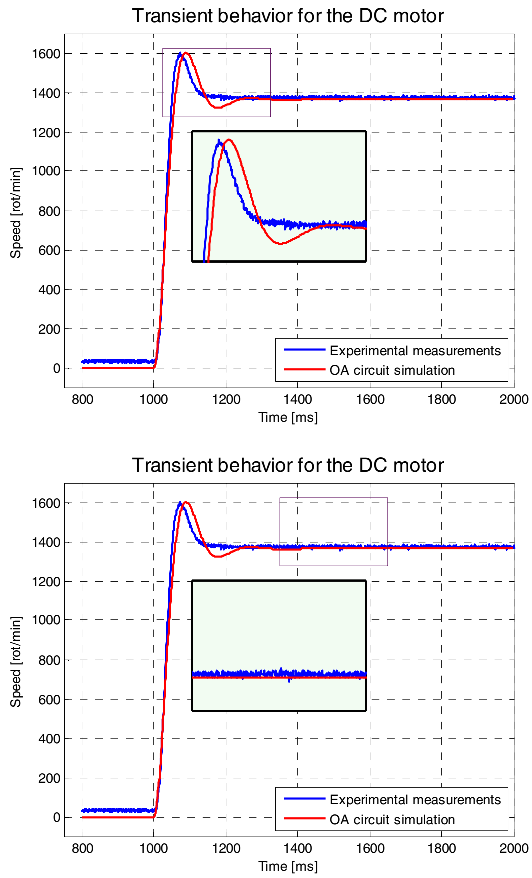

Figure 12. Experimental and simulation data

V. CONCLUSION

In this study was presented an equivalent circuit for permanent magnet DC motor implemented with OA.

The novelty of this approach lies in the implementation of the DC motor using electronic OA in combination with RC networks. By using the results of present work, it is easier to make connections between a real life system (DC motor), the mathematical representation as transfer functions and its electronic implementation with OA structures.

Another aspect of this approach is that it allows the manufacture several of platforms that could be offered to students to work at the same time. The stand displayed in Figure 9 is an expensive one and it is likely that universities and other educational institutions' laboratories don't have several of the same kind that could be used by different students at the same time. By using this approach, it is relatively easy to build and have available for laboratories different working platforms.

A different benefit is the possibility of creating remote laboratories for modelling and simulation of electric systems. By the fact that a physical system is converted and simulated by an electronic equivalent circuit, there is no preoccupation to have a teacher or technician to supervise the experiments. Other systems: mechanical, chemical, thermal, etc. could be also implemented in this way in order to give access to different people to study their behaviour.

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